Development towards low carbon and sustainable agriculture in Finland is possible with moderate changes in land use and diets

Heikki Lehtonen[1] · Janne Rämö[1]

Abstract

Food security under climate change, several sustainability problems, and ambitious climate targets are considered challenges for agriculture and food sectors in many countries. Since agricultural production and its land use produce appr. 20% of greenhouse gas (GHG) emissions of Finland, reducing agricultural GHG emissions is important for meeting national target of climate neutrality by 2035. Healthier food diets, maintenance of biodiversity, and reduced nutrient leaching from agriculture are also required for a more sustainable food economy. This paper aims to show how agriculture in Finland, traditionally dominated by livestock production, could decrease GHG emissions significantly and simultaneously respond to other sustainability concerns. Our results, based on economic modelling of the agricultural sector, suggest that moderate changes in food diets and land use can reduce GHG emissions of agriculture by more than 40% by 2050 if productivity growth and policy changes support the overall change in the agriculture and food sector. Adaptation to climate change, e.g. more higher crop yields efficient input use, is necessary for productivity growth. Decreased demand for meat and decreased cultivation of feed crops would decrease GHG emissions and free up land for carbon sequestration through afforestation. Whilst healthier food diets imply less livestock and increased imports of protein crops for food, a reasonable volume of livestock production is useful for maintaining food security, grasslands, crop rotations, soil carbon, and biodiversity. We conclude that transition to low carbon and more sustainable agriculture is possible without risking food security at northern latitudes.

Keywords Healthy diets · Agricultural production · Land use · Climate change mitigation · Adaptation to climate change · Economic modelling

Introduction

Agriculture and land use are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer opportunities for adaptation to climate change. Nature-based mitigation solutions, such as reforestation and carbon sequestration on agricultural land, can meet up to a third of the global emission reduction needs for the Paris Agreement aiming to limit global warming to 2 °C relative to the pre-industrial period (Roe et al. 2019). Biodiversity and climate strategies of different countries in Europe and globally should therefore develop integrated and coherent policies that cut across these domains. This, in turn, is much dependent on the developments in food consumption and production. In particular, reducing GHG emissions from agriculture has been widely considered necessary and potentially effective in climate change mitigation globally (Blandford and Hassapoyannes 2018).

The European Union (EU) aims to be carbon neutral by 2050, meanwhile, Finland has set itself the goal of becoming carbon neutral by 2035 (Government of Finland 2019). The goal won't be achieved unless new actions to cut GHG emissions are introduced in all sectors. GHG emissions from Finnish agriculture, currently at 16 million Mt CO_2eq., account for over 20% of the total GHG emissions in Finland (Statistics Finland 2021). Thus, reducing agricultural GHG emissions is important for meeting a national target

of climate neutrality by 2035. Recently, Government of Finland set a target of 29% reductions for agricultural GHG emissions 2020–2035 (Ministry of Agriculture and Forestry 2021).

Koljonen et al. (2020) concluded that pathways towards carbon neutrality in Finland have relatively small effects on the national economy in net terms. However, individual sectors of the economy may be significantly changed in terms of technology and volume of production.

Actions targeting agricultural peatlands would be efficient in reducing GHG emissions since peatlands produce more than 50% of total GHG emissions from agriculture whilst only comprising 11% of total cultivated land in Finland (Kekkonen et al. 2019). Peatlands are abundant in the northern and western regions, where the share of livestock production is high and of great socioeconomic importance. Maanavilja et al. (2021) constructed scenarios for effective GHG mitigation in agriculture. It was found that land use change-based measures, such as growing perennial crops instead of annual crops on peatlands, keeping water table high on peatlands, and diversifying crop rotations on mineral soils, are very potential ones in reducing agricultural GHG emissions. In addition, scenarios included measures for reducing GHGs from fertilisation (appr. 20% of GHG emissions) and GHG emissions from enteric fermentation of bovine animals (appr. 13%) and manure management (appr. 5% of GHG emissions). GHG emissions from energy use in agriculture account less than 10% of agricultural GHG emissions (Statistics Finland 2021).

Lehtonen et al. (2020) constructed a roadmap for reducing GHG emissions from agriculture whilst maintaining domestic agricultural production. It was found that 29% reductions in agricultural GHG emissions can be achieved by 2035 without any significant reductions of production if actions for land use-based emission reductions could be incentivised. GHG emissions from Finnish agriculture can be decreased especially from peatlands, improving nitrogen use efficiency in crop production (e.g. precision farming, new crop cultivars), increasing biogas or solar energy in agricultural energy use. Some recent studies show that some feed additives may reduce methane emissions from dairy cows more than 20% (van Gastelen et al. 2022). However, the cost of the feed additives and their availability is unknown and uncertain.

There are also other reasons for changes in agriculture, in addition to GHG emissions. Changed food diets could reduce cardiovascular diseases significantly, as well as obesity and diabetes which are all common in Finland (Valsta et al. 2018; Koponen et al. 2018). Food diets could also change agricultural production and land use significantly with possible positive consequences also for biodiversity and reduced nutrient leaching from agriculture. Climate change poses challenges for agriculture, and adaptation to climate change is one key factor influencing productivity, production and thus GHG emissions from agriculture. If any increase of crop yields due to successful adaptation to climate change, less land is needed for agricultural production and this increases land available for C sequestration and biodiversity, e.g. through afforestation. Hence, climate change adaptation is one key aspect to be considered in analysing future paths of agriculture.

There are gaps in previous research concerning more sustainable pathways of agri-food sector in Finland. Koljonen et al. (2020), Lehtonen et al. (2020) and Maanavilja et al. (2021), whilst providing pathways and scenarios for climate change mitigation, provide little climate change adaptation perspective. They also lack explicit trade effects to other countries which may also aim for food security and climate change mitigation. Both of these perspectives require more attention. This study contributes in filling these gaps when developing and analysing pathways to more sustainable agri-food system.

This paper aims to outline how responding to climate change adaptation and mitigation challenges whilst maintaining food security might change agriculture in Finland, compared to current trends of agriculture and food sector. In particular, we analyse joint effects of food diet change, productivity and changes in agricultural policy in the context of climate change adaptation. We evaluate how these changes could decrease GHG emissions and simultaneously respond to other sustainability concerns, and what are the likely impacts on agricultural production, land use, and farm income. Diet changes may also imply changes in trade of agricultural commodities. Hence, we follow the approach designed by FABLE Consortium (Mosnier et al. 2022, in this issue), capable of accounting for climate change adaptation effects on crop yields and changes in trade, in developing national level quantitative descriptions, of two different and somewhat contrasting scenarios. Current trends (CT) pathway corresponds to the lower boundary of feasible actions, following current diets and practices with minor adjustments for sustainability. CT is needed to show to what extent climate and sustainability targets could be met with current actions and policy incentives for agriculture and food sector, and as a reference and point of comparison for scenarios with more ambitious actions towards sustainability. Sustainability (SUST) pathway, well relevant and motivated because of ambitious national and international climate and sustainability targets, assumes diet change towards more plant-based direction and more effective adaptation to climate change implying higher crop yields than in the CT pathway. Food security, at least in terms of providing sufficient and nutritious food for population, is considered a necessary condition in both pathways, not to be compromised. Since different domestic demand and productivity imply different economic perspectives for farmers and food sector,

economic sector level modelling of agriculture, combined with the FABLE Calculator tool, is used to evaluate how agricultural production, land use, trade of agricultural commodities, GHG emissions, and farm incomes may develop in current trends and sustainability scenarios.

This paper proceeds as follows. The CT and SUST scenarios are specified with diet changes and land use policies, as well as climate change effects on crop yields. Next, the analysis framework is presented. It is made clear how the scenarios enter the national level sector model, capable of addressing the main drivers of change simultaneously and providing the changes in agricultural production and farm incomes, and how FABLE calculator is used in connecting the results to global trade balancing and in calculating the GHG emissions. Results at the whole country level and in four main regions are presented and discussed for plausibility and realism. The main findings and policy messages are considered in the conclusions.

Materials and methods

The main aim of this study is to analyse current trends (CT) and sustainability (SUST) scenarios with different diets, climate and policy, with implications on agricultural production, exports and imports, and GHG emissions from Finnish agriculture up to year 2050. To see how such drivers affect agricultural production and land use we use DREMFIA partial equilibrium (PE) economic sector model (Lehtonen 2001; Lehtonen and Niemi 2018) capable of addressing several changes in drivers simultaneously up to 2050. DREMFIA produces economically rational outcome of production and land use in Finland whilst considering changes in diets and productivity due to climate change adaptation. The common aim of the FABLE consortium was to link several national level CT and SUST scenarios to global markets through agricultural trade balancing (Fig. 1), and FABLE calculator (Mosnier et al. 2020, 2022) was used as a tool in this. Considering this study focussing on CT and SUST scenarios in Finland, DREMFIA model provides the main results, such as production volumes, land use and initial values of exports and imports of basic agricultural commodities. DREMFIA excludes production and consumption of fruits, vegetables and nuts, but these are considered in FABLE calculator, which includes a full diet description (Fig. 1). The FABLE Calculator connects the initial export and import results from DREMFIA to global markets to calculate revised exports and imports of agricultural commodities after trade balancing at the global level.

Aggregate exports and imports must be equal at the global scale. Trade is balanced using an approach with proportional increase or decrease of exports in individual countries, taking account for the feasible land areas for production of
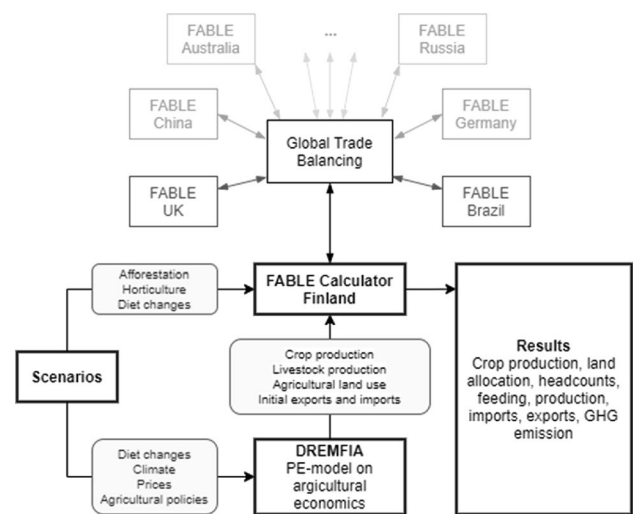

Fig. 1 Links between the scenario specifications, different models, and global trade balancing. Grey rounded boxes depict the data moving between models

certain products, to match global imports (Mosnier et al. 2020). If feasible land area does not exist or is very scarce in an individual country (with import demand) for production of a product which is scarce at the global market, then production must increase in other countries with feasible land area (Mosnier et al. 2020, 2022). After balancing, the trade assumptions become hard constraints for FABLE Calculator, and each country updates their pathways in FABLE calculator to balance national production with national demand and adjusted imports or exports. Countries may also make adjustments to fill in the remaining gaps both in national and global goals for e.g. climate change mitigation or land use (Mosnier et al. 2022). This process is repeated for multiple iterations to reach global goals. As a result, production possibilities and demands become balanced.

FABLE calculator is also used in calculating changes in GHG emissions of AFOLU (Agriculture, Forestry and Land Use) sector, consistent to the specifications of the FABLE consortium (Mosnier et al. 2022). Scenario specifications and main features of DREMFIA and FABLE models, are given below.

Scenarios

We present two alternative pathways for reaching sustainable objectives for food and land use systems in Finland. Both pathways share the same population and price projections to facilitate cross-scenario comparisons. The scenario assumptions are summarised in Table 1.

Current trends (CT) pathway is characterised by low population growth from 5.5 million inhabitants in 2020 to 5.9

Table 1 Summary of the scenario assumptions

Current trends (CT)	Sustainability (SUST)
Population 5.5→5.9 million	Population 5.5→5.9 million
Stable or slightly decreasing real prices of agricultural commodities (OECD-FAO 2020)	Stable or slightly decreasing real prices of agricultural commodities (OECD-FAO 2020)
Existing agricultural policy, low incentives for higher crop yields in northern conditions; low incentives for GHG reductions; some incentives for water protection and biodiversity, e.g. low intensity grasslands	Decreased farm support per ha, per animal; incentives for grain legumes, low intensity grasslands; incentivised SOC storage and GHG reduction, crop diversification
CAP pillar 1 payments and other subsidies unchanged, though their real value is reduced due to input price inflation	CAP pillar 1 payments decrease by 20%
	EU subsidies paid per dairy cow, and national subsidies paid per litre of milk, decrease by 10%
	EU and national subsidies per beef animal decrease by 50%
	Extra payments per ha of extensive grass, clover grass, grain legumes and oilseeds: €60/ha
Crop yields + 0–10% 2020–2045, under RCP 6.0	Crop yields + 0–20% 2020–2045, under RCP 2.6
Some adaptation to climate change	Planned adaptation, sustainable intensification: new cultivars, improved nitrogen use; rapid re-structuring of agriculture, less livestock production; more diverse crop rotations
Rapid farm size growth, high animal productivity, less attention to crop productivity, often monocultures	
Food diets unchanged 2015–2050:	Major change in food diets 2015–2050:
Medium meat consumption (<EU aver.); high consumption of dairy products; high protein and fat intake, medium fruit and vegetables; low consumption of peas, beans, nuts	Consumption of beef, pork − 50%; dairy products, poultry meat − 30%; fish + 50%, peas, beans, nuts + 500%; cereals, vegetables, fruits + 20%; 10–15% less protein, calorie and fat
No policy incentives for afforestation, small forest area loss continues	High policy incentives for afforestation, forest area loss avoided

It is assumed that the food diet and agricultural policy changes realise already by 2040, whilst crop yield change realises up to 2045

million in 2050, minimal agricultural expansion in line with historical trends, a low afforestation target, no change in the extent of protected areas, moderate productivity increases in the agricultural sector (low increase in crop yields, moderate increase in livestock productivity, and a significant increase in labour productivity on livestock farms), no change in diets, and no change in agricultural policy. This corresponds to a future based on current policy and historical trends that would also see considerable progress with regards to changes in farm structure, growth in farm size, and agricultural labour productivity (Lehtonen et al. 2017).

Under the current trends pathway, compared to the average Minimum Dietary Energy Requirement (MDER) (Wanner et al. 2014) at the national level, our computed average energy intake from diet (measured in calories) is 34% higher in both 2030 and 2050. The current average energy intake is mostly satisfied by cereals and animal products, especially dairy products and meat. We assume that the consumption of animal products, as well as other food categories, will stay the same between 2020 and 2050. Compared to the EAT-Lancet recommendations (Willett et al. 2019) animal products, especially red meat, white meat, and dairy products are over-consumed whilst fruits and vegetables, pulses and nuts are in the lower range of recommended intake. Moreover, whilst fat intake per capita exceeds the dietary reference intake (DRI) in 2030 and 2050, protein intake remains within the recommended range.

We embed this current trends pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 by 2100 (RCP 6), or a global mean warming increase likely between 2 and 3 °C above pre-industrial temperatures, by 2100. We assume that trends in technological change continue and that adaptation to climate change is moderate. Consequently, climate change challenges to crop production (Hakala et al. 2011) are sufficiently addressed to avoid crop yield losses and a small (0–10%) increase in crop yields is gradually attained by 2045 due to more adapted cultivars becoming available (Tao et al. 2015). This assumption is reasonable since the development and adoption of new cultivars takes time but is recognised as one of the key adaptations to climate change in northern latitudes (Palosuo et al. 2021; Tao et al. 2015), whilst improved drainage, appropriate use of inputs and crop rotations also provide means for more stable and higher crop yields (Lehtonen et al. 2018). The modelling approach of this study includes the corresponding climate change impacts on crop yields by 2045 for wheat, barley, oats, oilseeds, potatoes, peas, sugarbeet, and forage grass (Table 1).

Projected land use in the current trends pathway is based on several assumptions, including no changes in diets, a small increase in population, and no expansion of agricultural land beyond 2010 levels and no planned afforestation and reforestation of agricultural land. Protected areas remain unchanged at 5 Mha, representing 16% of total land cover.

Sustainable pathway (SUST) represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to an intermediate or upper boundary of feasible action.

Under the sustainable pathway, we assume that preferences of consumers change significantly over time and thus diets will transition towards fruits and vegetables and protein crops, and away from red meat and dairy products. It is not realistic to expect large changes in diets because of e.g. meat or milk taxes in a high-income country (such as Finland) where the share of food expenditures out of total income of consumers is relatively small, e.g. 10–12%, of the average (Allais et al. 2010; Tiffin and Arnoult 2011; Smed et al. 2016). Hence, we do not base future diet change on economic instruments targeted on certain food items but assume consumer preferences and thus food consumption to change gradually over time.

The ratio of the computed average energy intake from diet over the MDER decreases to 29% in 2030 and 25% in 2050 under the Sustainable pathway. Compared to the EAT-Lancet recommendations (Willett et al. 2019), the consumption of sugar, dairy products, and roots is high and still remains outside of the recommended range of consumption. However, fruit and vegetable consumption increases, and red meat consumption decreases by 50% and is then within the recommended range. The fat intake per capita still exceeds the dietary reference intake (DRI) in 2030 and also slightly in 2050, nevertheless showing significant improvement compared to the current trends pathway. Increased consumer guidance and information will be particularly important to promote this shift in diets.

Compared to the current trends pathway, we assume that this future would lead to slightly higher crop yields and significantly decreased consumption of livestock-based foods (Table 1). A significant decrease in the consumption of livestock-based foods, as well as higher crop yields, could lead to declining areas for grasslands and feed production. This may free up land for C sequestration by afforestation. Focussing these changes on peatlands could produce high reductions in GHG emissions (Koljonen et al. 2020; Maanavilja et al. 2021). Increasing production of plant-based food replacing livestock-based food, as well as land use measures for GHG emission reduction, require also changes in agricultural support payments (Table 1).

Protected areas and population growth would remain unchanged compared to the current trends pathway. This corresponds to a future based on responsible consumer behaviour, strategic and planned adaptation to climate change, and market changes at the farm and food-industry levels, also incentivized by effective climate policy.

We embed this pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2 °C. Higher crop yields aided by new crop cultivars adapted to longer and warmer growing seasons result in yield gains (+0–20%) between 2020 and 2045, which is consistent with Tao et al. (2015). Cereals yields increase only by 0–10% since overwintering conditions of winter cereals are estimated to become more difficult in the next decades, whilst the yields of spring cereals, peas, and oilseeds are estimated to increase. Yields of these crops are estimated to increase relatively more in northern and middle parts of the country where the low temperature sum of the growing season inhibits plant growth more than in southern Finland. However, grass growth is estimated to increase by 10–20% in all parts of the country during 2020–2045 (Höglind et al. 2013). This implies productivity gains and means of managing adverse weather events such as more frequent droughts, at dairy and beef farms which buffer against adverse weather by buffer storing roughage feed and keeping larger areas under grasslands than needed at average years (Kässi et al. 2015).

Structural change in agriculture in terms of farm size growth and increasing labour productivity develops in the same way as in the CT pathway. However, there is less livestock production, feed cereals and forage grass production, and more production of plant proteins for food in SUST pathway than in current trends pathway. In this sense there is more re-structuring of agriculture in SUST pathway.

Future prices of agricultural outputs and inputs are assumed to follow price development projected by OECD-FAO (2020). Global supply growth is expected to outpace demand growth over the next 10 years, causing real prices of most agricultural products to remain at or slightly below their current levels in the world markets.

Sector model and its regional disaggregation

Agricultural production, agricultural land use and farm income in different scenarios are simulated using the agricultural sector model DREMFIA (Lehtonen 2001). The model considers demand of agricultural products, EU level prices of agricultural inputs and outputs, and agricultural policy in relatively fine detail (Lehtonen and Niemi 2018). Four main areas are included in the model: Southern Finland, Middle Finland, Ostrobothnia (the western part of Finland), and Northern Finland. Production is further divided into sub-regions based on the support areas. In total, there are 17 different production regions (not all small regions are visible in Fig. 2). This allows a regionally disaggregated description of policy measures, crop yields, farm size structure of dairy farms, and related production technology. Almost all pork, poultry meat, and specialised crop production is concentrated in Southern
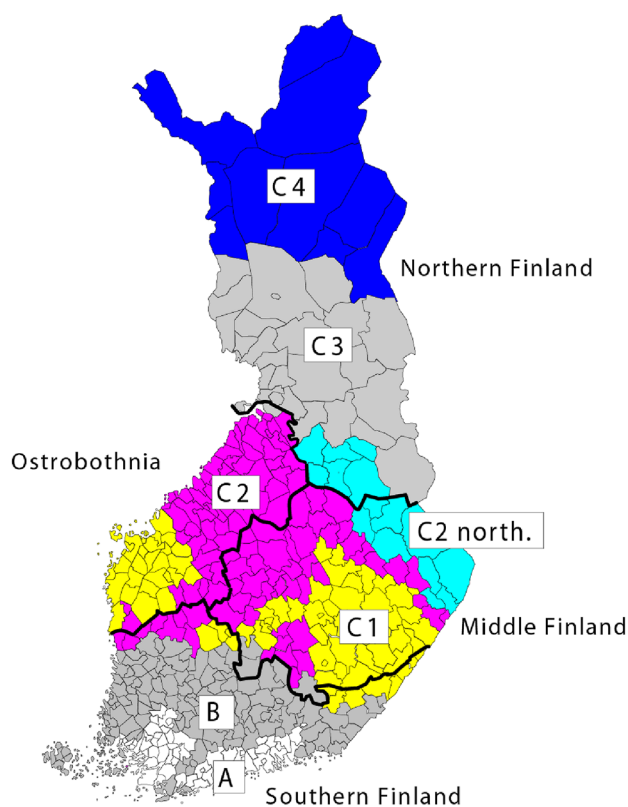
Main areas and support regions

Fig. 2 Regional disaggregation of DREMFIA sector model

Finland and Ostrobothnia region, whilst dairy and beef, as well as related feed crop production, are the dominant production lines in Middle and Northern Finland. Products and intermediate products may be transported between the regions at certain transportation costs.

DREMFIA is a dynamic recursive model for simulating agricultural production and markets from 1995 up to 2050 (Lehtonen 2001, 2004). The underlying hypothesis in the model is that in competitive markets, producers engage in profit maximising behaviour and consumers engage in utility maximising behaviour. Decreasing marginal utility of consumers and increasing marginal cost per unit produced in terms of quantity lead to equilibrium market prices that are equal to the marginal cost of production in competitive markets. Each region specialises in products and production lines that yield the greatest relative profitability considering the profitability of production in other regions and consumer demand. This means that total use of different production resources, including farmland, in different regions is optimised to maximise sectoral welfare, taking into account differences in resource quality, technology, costs of production inputs and transportation costs.

Sector models of agriculture simulating competitive markets under fixed resources and production technology have long been common tools in agricultural economics (McCarl and Spreen 1980). Farmland resources are typically assumed to be fixed, whilst quasi-fixed inputs, such as buildings and machinery, typically have a lifespan of 10–30 years. Available farmland is assumed a fixed resource per region in DREMFIA. Peatlands are considered as shares of available farmland per region, based on Kekkonen et al. (2019).

The DREMFIA model consists of two main parts: (1) a technology diffusion model that determines sector-level investments in different production technologies; (2) an optimisation routine simulating annual production decisions (within the limits of fixed factors) and price changes, i.e. supply and demand reactions, by maximising producer and consumer surplus subject to regional product balance and resource (land and capital) constraints (Fig. 3).

Production activities include several different animals, hectares under different crops and set-aside, feed diet composition, chemical and manure fertiliser use, and the resulting crop yield level. DREMFIA excludes horticulture, lambs, reindeers, horses, and fur animals which, however, are minor in terms of GHG emissions. In a dynamic recursive model, parts (1) and (2) are coupled and interact so that (changed) prices from the market-simulating optimisation model enter the technology diffusion model, representing endogenous sector-level investments in each region (Lehtonen 2004), and changes in animal production capacities of different techniques enter the market model in the following year. Technical change and investments, implying evolution of farm size distribution and production capital in different regions, are modelled as a process of technology diffusion, as described by Soete and Turner (1984). The endogenous evolution of farm size structure and technology is important in simulating regional shifts in production due to policy or demand changes, influencing the capacity of different regions to increase or decrease production.

Foreign trade and demand in DREMFIA

DREMFIA includes foreign trade activities, using the Armington assumption (Armington 1969). Imported and domestic products are imperfect substitutes, i.e. endogenous prices of domestic and imported products are dependent. This means that the demand functions of domestic and imported products are coupled through substitution elasticities. Exogenously given EU prices influence domestic prices, but domestic prices may be different from EU prices, depending on the balance between supply and demand in domestic markets. For example, decreasing domestic supply may drive up domestic prices slightly even if EU prices were stable, because consumers do not see imported products,

Fig. 3 Basic structure of the DREMFIA sector model
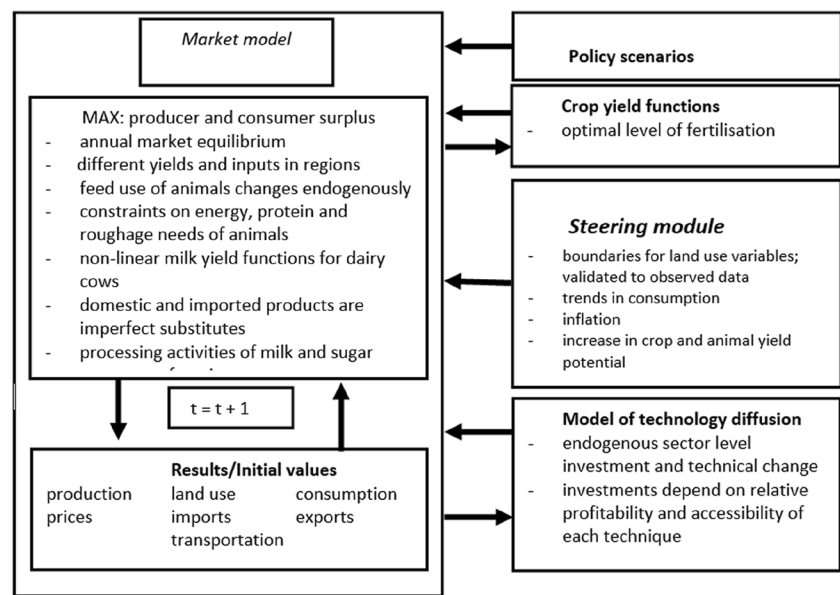
especially beef, and many dairy products, as perfect substitutes to domestic ones.

Changes in total demand per capita of different food products over time is driven by exogenous demand trends in the model. However, the model is free to decide the level of domestic production in all regions, and imports and exports. Domestic and foreign products as more or less imperfect substitutes (Lehtonen 2001). The parameters of the Armington-based demand system, commonly used in economic equilibrium models, include price elasticity of demand and substitution elasticity between domestic and imported products. The substitution elasticities have been adjusted in the model calibration so that the domestic prices, dependent on exogenous EU price level in the model and the domestic consumption of domestic and imported foods, are very close to the observed statistical values from 1995 to 2020, especially in the most recent years. Hence, the future food demand scenarios, assumed to be driven by consumers' values and preferences, are given as exogenous parameters to the model.

Production functions and use of inputs

The use of variable inputs, such as fertilisers and feedstuffs, is dependent on agricultural product prices and fertiliser prices through production functions. The nutrients from animal manure are explicitly taken into account in the economic model. Feeding of animals may change in the short term within certain bounds imposed by fixed production factors and animal biology, provided that nutrition requirements, such as energy, protein, phosphorous, and roughage needs, are fulfilled. Specific production functions are used

to model the dependency between the average milk yield of dairy cows and the amount of grain-based feedstuffs used in feeding. The yield of dairy cows, which increases appr. at 1% rate annually due to genetic improvements in the dairy cattle herd, responds to changes in the prices of milk and feedstuffs.

Validation

The validation of the DREMFIA model is carried out in four main steps, given briefly below. Validation is based on statistical data, input use data from a "typical farm" along with expert judgement (Lehtonen 2001, 2015; Lehtonen and Niemi 2018). Calibration, i.e. adjustments of some parameters difficult to be estimated from empirical data material, is needed to reach the realised level of total production and domestic prices. First, given EU level prices, observed domestic prices, and realised import volumes, the substitution elasticities of the Armington-based demand system in the model are adjusted to reach observed prices and import volumes. Second, the parameters of specific investment models for dairy farm size are adjusted to replicate the observed evolution of dairy farm size structure from 1995 to 2019. Third, milk yield function of dairy cows, validated earlier from research datasets, was slightly adjusted to replicate the realised milk yields of dairy cows. Fertiliser use and crop yields have been validated using empirically estimated crop yield response functions and statistics of regional crop yields, fertiliser use as well as prices of crops and fertilisers at the national level. Fourth, some residual costs of different cropping activities have been adjusted to reach the observed overall land use and production levels. More emphasis has

been given on validating the model to match the statistical data from recent years.

The overall DREMFIA model closely replicates ex-post production 1995–2020. The model is built to reach a steady-state equilibrium, long- and medium-term changes in aggregate amounts, and regional location, in a 10- to 15-year period given no further policy changes. The steady-state equilibria found at the whole country level are also due to limited domestic consumption of foodstuffs and the costs of exports. Another reason for steady states in the 10- to 15-year period is the Armington assumption, i.e. the imperfect substitution between domestic and imported products. A more detailed presentation of the model can be found in Lehtonen (2001, 2015). The model validation over the ex-post period is shown in more detail in applications specific to exogenous changes in food consumption (Lehtonen and Irz 2013), agri-environmental policy assessment (Lehtonen and Rankinen 2015), grass clover promotion (Lehtonen and Niskanen 2016), and agricultural policy (Lehtonen and Niemi 2018).

FABLE calculator

Results of DREMFIA were used as the input for the FABLE calculator, which in turn was linked to the trade balancing at the global level between different countries. Without balancing the global exports and imports, the global level analysis carried out by the FABLE consortium (FABLE 2020) would be illogical. This trade balancing was organised by the FABLE secretariat and participated by other FABLE teams (FABLE 2020; Mosnier et al. 2022).

The results from the DREMFIA model—number of animals, land use, crop and animal yields, exports, and imports of agricultural commodities—were given as input to the FABLE calculator in 5-year time-steps since the global trade balancing was done in 2020, 2025, 2030, 2035, 2040, 2045, 2050 (Mosnier et al. 2020). Hence, the exports and imports derived from the DREMFIA model were assigned to several different exporting and importing countries whilst the production volumes in Finland were only slightly changed. FABLE calculator includes all significant agricultural commodities, also production and consumption of vegetables, fruits and nuts which are not included in DREMFIA. Thus the trade balancing provided results on the consumption and imports of nuts and fruits which are little cultivated in Finland. The FABLE calculator was also used in calculating overall land use change including afforestation and reduced use of peatlands in agriculture, and the resulting GHG emissions from the AFOLU sector.

Some specific adjustments and extensions in the FABLE calculator were necessary to incorporate the results of the DREMFIA model: extended feed types to typical Finnish feeds (incl. e.g. oats often used for feed in Finland), feed use efficiency scenarios, i.e.possibility to increase or decrease each required feed per animal over time, extended productivity shifters to product-specific multipliers allowing crop-specific shifts in yields for different cereals; extension of import and export scenarios to product-specific scenarios, and extension to take peatland soil GHG emissions into account based on the coefficients used in national GHG inventory (Statistics Finland 2021; IPCC 2014).

Results

The results presented below are specific to Finland only, and the very small global repercussions of the agricultural changes in Finland are not considered.

In the current trend (CT) scenario, increases in input prices during the 2020s are mostly covered by the increase in nominal prices of agricultural commodities at the global level, but in the case of Finland especially, the increased prices of fertilisers and fossil fuel-based energy imply decreasing profitability of crop production, whilst the profitability of livestock production is little affected. For this reason production of some crops decrease slightly or moderately in CT scenario.

The development of cereals and grass forage production areas, as well as the areas of other crops, is presented in Fig. 4. Cereal area decreases by 100,000 ha, appr. 10%, in CT scenario mainly due to decreased profitability. A small net increase in the cereals yields by 5%, however, implies appr. 5% reduction in the overall cereals production volume. Cereal area decreases by 29% (315,000 ha) during 2020–2050 in the SUST scenario, but the total cereal production volume decreases only appr. 20% due to increased cereals yields (10%). The reason for the large reduction in the area under cereals is the reduced feed demand, and the low real prices implying little incentive to increase cereals exports.

Milk yield per dairy cow increases from 9 t/cow per year up to 10.5 t/cow per year in both scenarios. Consequently, less dairy cows are needed for milk production, and the reduced number of dairy cows (2020: 260,000; 2050: 193,000) result in decreased beef production by 16% already in the CT scenario. The number of suckler cows increases from 62,000 (2020) to 74,000 cows (2050), but this has a small positive effect on the decreasing trend of beef production.

The number of dairy cows decreases from 260,000 (2020) to 121,000 cows up to 2050 in the SUST scenario. This is the joint effect of reduced milk production (− 39%) and increased milk yield per dairy cow. Since the subsidy payments per beef animal decrease by 50% in SUST scenario it

Fig. 4 Land use (1000 ha) for cereals (blue), grassland (green), and other crops (orange) for CT (solid) and SUST (dash) scenarios
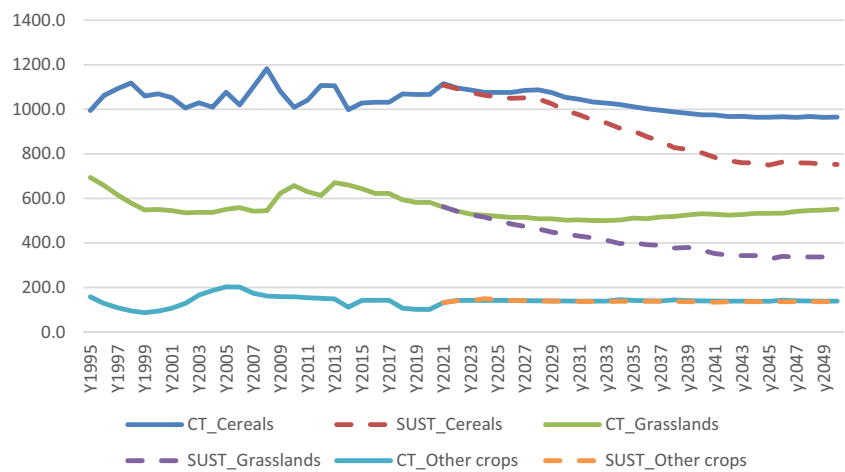
affects negatively the number of suckler cows (2020: 62,000; 2050: 49,000) and indirectly also dairy production.

Total grassland area decreases 5% in the CT scenario despite the larger reduction in the number of total bovine animals, and the small yield increase of grassland production (5–10% depending on the region). Thus, the grassland area decreases relatively less than the need of grass forage feed. This is because of the agri-environmental payments for extensive grassland production in the current EU CAP is assumed unchanged in the CT scenario. However, the total grassland area in the SUST scenario decreases as much as 50% (− 290,000 ha) because of the large reduction of beef production (− 53%) and milk production (− 39%) 2020–2050. Extra subsidy payments for extensive grasslands are not sufficient to maintain grassland areas and they decrease because of reduced feed demand and increased yield of grass forage (10–20% depending on the region) in the SUST scenario.

Remarkably, areas under other crops, (e.g. potatoes, sugarbeet, oilseeds, grain legumes) are almost the same in the CT and SUST scenarios, even if the demand for these crops increase, e.g. the demand for grain legumes for food increase by 500% in the SUST scenario (Fig. 4). This is because the potato, plant oil, and sugar consumption is little affected by the diet change in the SUST scenario, and

because cultivating grain legumes for feed is reduced by 45% in the SUST scenario (Table 2). Consequently, the increased cultivation of grain legumes for food does not result in any significant increase in the area of grain legumes, in total, whilst the quantity of grain legumes production increases by appr. 30% due to an increase of yields by 30% in SUST scenario 2020–2050 (Fig. 4).

Changes in exports and imports

Significant adjustments in imports to Finland, were made only for seven commodities in global trade balancing procedure, as shown in Fig. 5. In the CT scenario, the trade balancing (weak global supply) resulted in reduced 2050 imports of vegetables, apples, and rapeseed from the initial levels suggested by the CT food diet (Fig. 5). The reduced 2050 imports were then balanced by slightly decreased domestic consumption and increased domestic production (shown in Fig. 5), to keep supply and demand in balance. For example, production volumes of vegetables and apples are significantly increased because of the reduced imports to meet domestic demand. However, imports of nuts and fruits, little cultivated in Finland due to climatic constraints, were

Table 2 Summary of agricultural production changes 2020–2050 in current trends and sustainability scenarios

| Current trends (CT)	Sustainability (SUST)
Beef − 16%, pork − 12%, poultry − 3% Dairy milk − 4%, cereals − 10%, oilseeds + 5%	Beef − 47%, pork − 54%, poultry − 31% Dairy milk − 39% Oats − 35%, barley − 19%, wheat − 15%, peas for food + 250% (for feed − 45%), oilseeds + 5%
100 kha (− 4%) less land needed in agriculture	530 kha (− 23%) less land needed in agriculture
No afforestation	0.20 Mha afforested
GHG: − 5% (13.3 Mt CO_2eq.—> 12.6 Mt CO_2eq.)	GHG: − 46% (13.3 Mt CO_2eq.—> 7.2 Mt CO_2eq.)
Farm income: − 11%	Farm income: − 19%
Share of organic soil on cropland: 10.5%	Share of organic soil on cropland: 7.9%
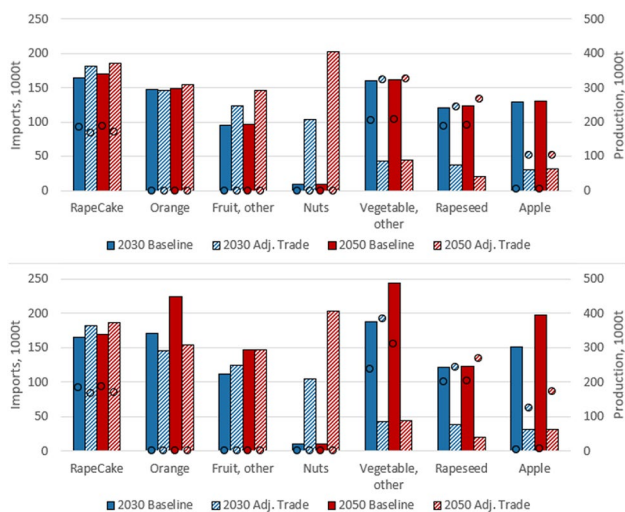
Fig. 5 Adjustments in imports of the main imported agricultural commodities in the CT (upper figure) and SUST (lower figure) scenarios. Bars depict the imports and circles domestic production. Note that 'Baseline' refers to the initial import volume derived in national level DREMFIA model and supplied in FABLE calculator in the CT/SUST scenario, and 'Adj. Trade' refers to adjusted trade volume after global trade balancing

increased significantly in the trade balancing because of the strong global supply.

Similar, but not identical, trade adjustments were made in the SUST scenario, where the dietary shift towards plant-based foods implies higher initial import levels than in the CT scenario. The global market then supplies higher import volumes of vegetables, apples and nuts in the SUST scenario than in the CT scenario. However, only the import volume of oranges is clearly higher in the SUST scenario than in the CT scenario, 2050. It is remarkable that whilst domestic demand of vegetables, fruits, oilseed products and nuts is higher in the SUST scenario than in the CT scenario. balancing procedure provides only little more imports of these products in the SUST scenario. This is an indication that global demand for these products increases in the SUST scenario. This may provide opportunities for domestic production for vegetable and oilseed products, whilst nuts and oranges are difficult to be produced domestically due to climatic conditions.

Self-sufficiency

Under the current trends pathway, it is projected that Finland would be self-sufficient in cereals, eggs, and dairy in 2050, and almost self-sufficient in poultry, roots, and tubers. Self-sufficiency is decreasing in beef but increasing slightly only in oilseeds. Self-sufficiency is staying constant with the other products from 2020 to 2050. The product groups

for which Finland depends on the most on imports to satisfy internal consumption are fruits, vegetables, nuts, and pulses. This dependency will remain rather stable in the CT scenario until 2050, despite some farm subsidies paid for grain legumes, and despite increased yields of grain legumes from their low initial levels.

Under the Sustainable pathway, by 2050, Finland remains self-sufficient in cereals, eggs, and dairy, and almost self-sufficient in poultry, roots, and tubers, as in the current trends pathway. However, Finland would be less self-sufficient in pulses and nuts because of increasing consumption and unfavourable climatic conditions to grow these crops.

GHG emissions

GHG emissions decrease little (− 5%) in CT scenario but very significantly in the SUST scenario (− 46%) 2020–2050 for four main reasons. First, due to the decreases in dairy and beef consumption and production and the following decreases in feed production, 200,000 ha of old cropland is afforested. As much as 90,000 ha of organic soils is afforested by 2050, reducing soil GHG emissions from agriculture by 2.25 Mt CO_2eq. between 2020 and 2050. The share of organic soils on agricultural land decreases from 10.5 to 7.9%. Second, significantly fewer nitrogen fertilisers, both chemical nitrogen fertiliser and livestock manure, are applied. Thus, NO_2 emissions from soils and CO_2 emissions from mineral soils are reduced. Third, afforestation of mineral soils, appr. 110,000 ha, leads to gradually increasing carbon sequestration up to 2050. Carbon sequestration achieved through afforesting farmland will increase after 2050, since the accumulation of C stock in wood and litter input to the soil will increase when the trees grow larger. This is not considered in the GHG emission calculation extending up to 2050 only. Fourth, since beef production (− 53%) and milk production (− 39%) are both reduced in the SUST pathway 2020–2050, methane emissions from bovine animals decrease by appr. 40% (− 0.8 Mt CO_2eq.). This is 5% reduction of the total GHG emissions of agriculture, whilst the GHG emission reductions from decreased chemical and manure fertilisation is more significant.

Farm income

Total farm income for basic agriculture (excluding horticulture), calculated in the DREMFIA model, will decrease as much as 19% in the SUST scenario whilst the input price inflation and a small reduction in production lead to an 11% reduction in farm income in the CT scenario. There has been a strong decrease in total farm income by > 50% whilst the number of farms decreased by 40% in Finland

during 2000–2019 (Luke 2021). From this perspective, the 11% reduction in farm income, or even 19% reduction in the SUST scenario, is not dramatic. The farm income reduction in the SUST scenario is mainly because of decreased volume of meat and dairy production, and partly because of fewer CAP pillar 1 area payments (− 20%). Increasing grain legumes (promoted by a small subsidy paid per ha) and oats for food due to diet change implies a small increase in the production of these crops and provides much less income than the income lost from reduced livestock production. Gradually increasing crop yields in the SUST scenario provide some income gain due to more efficient production implying less land and field working needed per tonne of harvested crop. However, the farm income in the SUST scenario does not include any compensations for farmers, in net terms, for afforestation of peatlands or mineral soils. It is assumed that farmers are only paid the cost of afforestation and thus no compensation for lost farm income because of decreased agricultural production is paid.

Discussion

The outcomes of the two pathways, current trends and sustainable, clearly show that moderate—but not drastic—changes in diets, productivity, food trade, and land use may decrease agricultural GHG emissions very significantly, e.g. 46% (− 6.1 Mt CO_2eq.) by 2050, as calculated in this study. The key driving forces in this development facilitating GHG emission reductions are diet changes (reduced consumption livestock products and increased consumption of plant-based foods), increased crop yields and related changes in land use, as well as incentives for afforestation and GHG abatements from peatlands. If decreased demand for livestock products is coupled to decreasing farm subsidy payments, which partly maintain current land use and crop production levels, some land is freed up from agriculture to carbon sequestration. It is remarkable that afforesting 90,000 ha of peatlands could provide − 2.25 Mt CO_2eq. GHG emission reduction, three times more than the GHG reduction from reduced enteric fermentation of bovine animals (appr. 0.75 Mt CO_2eq.). Hence, the incentives for afforesting peatlands no longer used in agriculture play a key role in GHG mitigation. Still the diet change and higher yields of crops are the main drivers which make land use measures possible, or at least more applicable.

The food diet change in the SUST scenario means replacing animal-based protein with plant proteins in a large scale. Since production of plant proteins and fruits is particularly challenging in northern latitudes, increased imports of these commodities is likely in scenarios and futures like SUST. The results from global trade balancing suggest that imports of e.g. vegetables, rapeseeds, and apples could be reduced

due to increasing global demand. This could provide opportunities for domestic producers. However, the results from global trade adjustments should be considered preliminary, though novel since using this kind of trade adjustment procedure is relatively new.

Improved productivity, achieved due to successful adaptation to climate change, benefits farm incomes, food security and possibilities for GHG abatement. Increasing productivity through adaptation to climate change and advanced farm management is not easily achieved. It requires improved utilisation of production inputs. This, in turn, requires improved quality of agricultural soils (e.g. water retention and soil pH), improved crop protection, and crop rotation, which may also improve biodiversity, resilience and productivity at the farm level (Rosa-Schleich et al. 2019). Diversified crop production is also driven by food diet changes towards plant-based eating. Reduced cereal dominance, increased protein crops and fruits and vegetable production could diversify land use both at the farm and regional scale.

Considering food security and risks of producing plant-based proteins in northern conditions, large-scale, efficient, and productive livestock farms and related production chains are also needed in the future as the consumption of livestock products is unlikely to decrease rapidly. In the scenarios of this study, 50–70% of current demand and production of livestock products may remain up to the year 2050. Animal products have clear advantages in human nutrition, especially for children and elderly people, because of, for example, iron, zinc, vitamins B12 and D, as well as calcium and selenium, all of which are not easily obtained from purely vegetarian or vegan diets (Valsta et al. 2018). However, decreasing the consumption of animal-based foods would have positive health effects for many people since high cholesterol and blood pressure as well as cardiovascular diseases are common and often linked to high saturated fat intake in Finland (Valsta et al. 2018; Koponen et al. 2018).

This study shows that farmers will lose income due to diet changes where livestock products are replaced by plant-based proteins which are processed to food products outside farms. Hence, such diet changes result in the shift of value added away from farms. In addition, part of the plant proteins, e.g. nuts, substituting livestock products, is difficult to be cultivated in Finland and thus nuts are imported. Furthermore, peas and beans yields are relatively low in Finland, and their quality is highly variable (Peltonen-Sainio et al. 2013). Shifting from livestock to plant protein production seems to be a bad deal from a farmer's perspective. This is the situation especially in northern regions with harsh climatic conditions. Changes in farm incomes and rural livelihood are likely to be different in different regions.

This analysis does not consider the change in the total value of food for consumers, and further analysis is required for that. We have also not been able calculate changes in

public budgets and net value for agricultural sector in detail since additional research is needed to quantify the costs of climate change adaptation aimed for significant crop yield changes, or to quantify costs of afforestation or abandonment of low-productive agricultural peatlands. Some currently existing farm subsidies are assumed to be reduced in SUST scenario and these resources could be used for specific climate change adaptation and mitigation actions.

One of the major shortcomings of this study is that the same OECD-FAO 2021 EU price forecasts were used in both CT (RCP6.0 climate scenario) and SUST (RCP 2.6) scenario. This is probably not a realistic assumption since the climate conditions for agriculture are different globally in these scenarios. Hence, the differences in farm incomes between the scenarios should be considered preliminary and possibly weak results. Global agricultural market and trade models, capable of calculating some estimates on the difference between prices in different scenarios, were not available for this study.

It is necessary to study what might be the future options for farmers if the demand for livestock product decreases. Alternative sources of living and farm livelihoods might be available outside agriculture, e.g. in renewable energy production or other activities dependent on land availability. An alternative use for farmland is a significant resource economic issue because of deposit values. The value of farmland is usually significantly higher than the value of forest land. Hence, the scenarios such as SUST involve several societal issues and challenges especially in northern regions with limited viable options for farming and food production.

Despite such challenges, the SUST scenario provides one avenue for a more sustainable future of Finnish agriculture and food sector: 46% reductions in agricultural GHG emissions 2020–2050, improved crop productivity and reduced need for farmland due to successful adaptation to climate change, and improved human nutrition due to plant-based foods replacing current high consumption of livestock-based foods. Even though farm income in SUST scenario is slightly less than the farm income in Current Trends-scenario, alternative uses of farmland, or other income compensations could be developed to balance the negative societal effects in rural areas. Income compensations could be well-grounded and motivated since the costs of GHG emissions reductions from peatlands may be low (Purola and Lehtonen 2022; Maanavilja et al. 2021) and lower than, e.g. the realised prices of tradable CO_2-permit prices in the EU during 2020–2021 (€50–70/t CO_2eq.) (Ember 2022).This study did not consider which incentives—taxes or subsidies, or both—could be sufficient to realise the land use change.

Whilst Saarinen et al. (2020) found fully vegan diets most potential for GHG reductions, even as high as 39% in terms of carbon footprint of food, SUST scenario shows 46% reduction in GHG emissions 2020–2050, possible without totally abandoning livestock-based products in human nutrition. This is possible if abandonment and afforestation of low-productive peatlands and mineral soils, and if successful climate change adaptation results in crop yield gains reducing the area needed for agriculture. Considering the difficulties and challenges in producing plant proteins in Finnish climate conditions (even under climate change), domestic production of both plant proteins and livestock products in SUST scenario might be more appealing for national decision makers and farming communities, considering food security and rural livelihoods, than e.g. fully vegan futures. Since the diet change, changes in productivity, agricultural production, and land use are not drastic but rather moderate in the SUST scenario in the long term, the calculated GHG emission reductions might be possible to be reached.

This study, showing 46% reductions in GHG emissions 2020–2050, can be compared to the climate roadmap of Finnish agricultural producers (Lehtonen et al. 2020), assuming minimal diet change, found 29% reductions possible up to 2035 and 38% reduction up to 2050, if very large-scale mitigation measures were applied on peatlands. Hence, the SUST scenario provides another scenario and future avenue, which is not based on either very large diet change or highly ambitious plan for land use change, for food and agriculture in Finland. More research and analysis is necessary to support decision making and developing policy measures related to GHG emission reductions and sustainable agriculture. It seems necessary to develop several alternative sustainability scenarios with different balance of the drivers of change.

Conclusion

Our results suggest that food diet changes, if coupled to increased crop yields and significant land use change, may together contribute to 46% reduction in AFOLU emissions in Finland by 2050. The key drivers to launch this kind of change are (1) more climate-, environment-, and health-conscious consumer behaviours; (2) 10–15% higher crop yields due to successful adaptation to climate change; (3) land use policies incentivising changed management of peatlands and afforestation of mineral soils not needed in feed production for livestock. To obtain higher than 40% GHG emission reductions, all people don't need to become vegans, but many must halve their consumption of livestock products from their high levels. How plant-based proteins could replace livestock-based food in diets is a very essential topic to be studied, considering national context and food traditions. Increased diversity of protein sources could enable reduction of livestock, farmland area and GHG emissions.

However, much depends if there is a true opportunity for consumers to take the necessary actions to effectively

realise diet changes, and if there are incentives for farmers and their stakeholders to seize the opportunity for productivity developments and land use changes analysed in this paper. This requires investments in agricultural research and development, not least in plant and animal breeding and crop protection (e.g. integrated pest management) under climate change, land use management esp. at peatland soils, and different carbon sequestration options on mineral soils. To realise the required large-scale changes in agriculture, economic incentives for change are pivotal. Productivity does not increase without effort. All the costs linked to this or other large-scale changes in agriculture were not analysed in detail in this study.

The results of this study suggest decreasing farm incomes in Finland in more sustainable pathways, despite productivity gains. There is a challenge how to motivate and incentivise farmers for taking necessary actions to reach the low carbon sustainable path outlined in this study. Farmers need sufficient incentives for implementing the land use changes and other means of decreasing GHG emissions. For example, lost farm subsidies due to afforestation, idling or re-wetting peatlands, and resulting reduced incomes should be compensated, at least partly, for farmers. They need to find profitable and feasible alternatives for current farming. Most likely, many farmers in less favoured regions will not be able to shift from livestock production to plant protein production due to low yields and high yield and quality risks. Furthermore, such a change is likely to shift value added away from farms to other actors of the food chain since peas and beans are produced at relatively low prices and most of the value is created in food processing outside farms.

Launching transitions to sustainable low carbon paths in agriculture and food requires studying and analysing the long-run implications of alternative development paths. Sustainability transitions in agri-food sector pose big challenges for research, policymakers and for the society at large. Whilst our main contribution is including explicit climate change adaptation and global trade perspectives in sustainable pathways of Finnish agriculture, we also found some gaps and weak points to be improved in the analysis. They are related to crop-specific climate change adaptations and related costs, feasibility and costs of afforestation, and feasibility of policy measures incentivising GHG reductions. Research, especially after such improvements, can contribute in analysing the effects of alternative policy measures in long-term pathways, and in developing several alternative, quantitative sustainability scenarios including production, land use, GHG emission and income changes, with different balance of the drivers of change and policy measures in different scenarios, then to be considered by decision-makers.

Declarations

Conflict of interest Authors declare no conflict of interest.

References

Allais O, Bertail P, Nichèle V (2010) The effects of a fat tax on French households' purchases: a nutritional approach. Am J Agric Econ 92: 228–245. https://www.jstor.org/stable/40647979

Armington P (1969) A theory of demand for products distinguished by place of production. IMF Staff Pap 16:159–178

Blandford D, Hassapoyannes K (2018) The role of agriculture in global GHG mitigation. OECD Food, Agriculture and Fisheries Papers, No. 112, OECD Publishing, Paris. https://doi.org/10.1787/da017ae2-en

Ember (2022). The latest data on EU ETS carbon prices. https://ember-climate.org/data/data-tools/carbon-price-viewer/. Accessed 18 May 2022

FABLE (2020) Pathways to Sustainable Land-Use and Food Systems. 2020 Report of the FABLE Consortium. Laxenburg and Paris: International Institute for Applied Systems Analysis (IIASA) and Sustainable Development Solutions Network (SDSN). https://doi.org/10.22022/ESM/12-2020.16896

Government of Finland (2019) Inclusive and competent Finland: a socially, economically and ecologically sustainable society. Programme of Prime Minister Antti Rinne's Government, pp 230. Retrieved from Finnish Government website: https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/161664/Inclusive%20and%20competent%20Finland_2019_WEB.pdf?sequence=7&isAllowed=y. Accessed 17 Sept 2022

Hakala K, Hannukkala A, Huusela-Veistola E, Jalli M, Peltonen-Sainio P (2011) Pests and diseases in a changing climate a major challenge for Finnish crop production. Agric Food Sci 20(19):3–14

Höglind M, Thorsen SM, Semenov MA (2013) Assessing uncertainties in impact of climate change on grass production in Northern Europe using ensembles of global climate models. Agric for Meteorol 170:103–113

IPCC (2014) 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. Hiraishi T, Krug T, Tanabe K, Srivastava N, Baasansuren J, Fukuda M, Troxler TG (eds)

Kässi P, Känkänen H, Niskanen O, Lehtonen H, Höglind M (2015) Farm level approach to manage grass yield variation under climate change in Finland and north-western Russia. Biosyst Eng 140:11–22. https://doi.org/10.1016/j.biosystemseng.2015.08.006

Kekkonen H, Ojanen H, Haakana M, Latukka A (2019) Mapping of cultivated organic soils for targeting greenhouse gas mitigation. Carbon Manag 10:115–126. https://doi.org/10.1080/17583004.2018.1557990

Koljonen T, Aakkula J, Honkatukia J, Soimakallio S, Haakana M, Hirvelä H, Tuomainen T (2020) Hiilineutraali Suomi 2035—Skenaariot ja vaikutusarviot. https://doi.org/10.32040/2242-122X.2020.T366

Koponen P, Borodulin K, Lundqvist A, Sääksjärvi K, Koskinen S (2018) Terveys, toimintakyky ja hyvinvointi Suomessa: FinTerveys 2017-tutkimus. http://www.julkari.fi/handle/10024/136223. Accessed 19 Sept 2022

Lehtonen H (2001) Principles, structure and application of dynamic regional sector model of Finnish agriculture. Academic dissertation. Systems Analysis Laboratory, Helsinki University of Technology. Publications 98. Agrifood Research Finland, Economic Research (MTTL). Helsinki. http://lib.tkk.fi/Diss/2001/isbn9512256894/. Accessed 19 Sept 2022

Lehtonen H (2004) Impacts of de-coupling agricultural support on dairy investments and milk production volume in Finland. Acta Agric Scand Sect C Econ 1:46–62

Lehtonen H (2015) Evaluating adaptation and the production development of Finnish agriculture in climate and global change. Agric Food Sci 24(3):219–234. https://doi.org/10.23986/afsci.51080

Lehtonen H, Irz X (2013) Impacts of reducing red meat consumption on agricultural production in Finland. Agric Food Sci 22:356–370 http://ojs.tsv.fi/index.php/AFS/article/view/8007/6412

Lehtonen H, Niemi JS (2018) Effects of reducing EU agricultural support payments on production and farm income in Finland. Agric Food Sci 27(2):124–137. https://doi.org/10.23986/afsci.67673

Lehtonen H, Niskanen O (2016) Promoting clover-grass: implications for agricultural land use in Finland. Land Use Policy 59:310–319. https://doi.org/10.1016/j.landusepol.2016.09.005

Lehtonen H, Rankinen K (2015) Impacts of agri-environmental policy on land use and nitrogen leaching in Finland. Environ Sci Policy 50:130–144. https://doi.org/10.1016/j.envsci.2015.02.001

Lehtonen H, Niskanen O, Karhula T, Jansik C (2017) Maatalouden rakennekehitys ja investointitarve vuoteen 2030. Markkinaskenaarioiden vaikutus maatalouden tuotantorakenteeseen (an English abstract: "Structural change and investment needs in Finnish agriculture by 2030") (No. 19/2017; p 59). http://urn.fi/URN:ISBN:978-952-326-383-3. Accessed 19 Sept 2022

Lehtonen H, Palosuo T, Korhonen P, Liu X (2018) Higher crop yield levels in the North Savo Region—means and challenges indicated by farmers and their close stakeholders. Agriculture 8:1–14

Lehtonen H, Saarnio S, Rantala J, Luostarinen S, Maanavilja L, Heikkinen J, Soini K, Aakkula J, Jallinoja M, Rasi S, Niemi J (2020) Maatalouden ilmastotiekartta—Tiekartta kasvihuonekaasupäästöjen vähentämiseen Suomen maataloudessa. 131 s. ISBN 978-952-9733-54-5. Includes an English abstract (4p.). Maa- ja

metsätaloustuottajain Keskusliitto MTK ry. Helsinki. http://urn.fi/URN:NBN:fi-fe2020082161330. Accessed 19 Sept 2022

Luke (2021) Luke Economydoctor database. www.luke.fi/economydoctor Referenced Nov 15 2021

Maanavilja L, Tuomainen T, Aakkula J, Haakana M, Heikkinen J, Hirvelä H, Kilpeläinen H, Koikkalainen K, Kärkkäinen L, Lehtonen H, Miettinen A, Mutanen A, Myllykangas J-P, Ollila P, Viitanen J, Vikfors S, Wall A (2021) Hiilineutraali Suomi 2035: Maankäyttö- ja maataloussektorin skenaariot. Valtioneuvoston selvitys- ja tutkimustoiminnan julkaisusarja 2021 63: 102 s. http://urn.fi/URN:ISBN:978-952-383-263-3

McCarl BA, Spreen TH (1980) Price endogenous mathematical programming as a tool for sector analysis. Am J Agric Econ 1980:88–102

Ministry of Agriculture and Forestry (2021) Government approves Finland's CAP Strategic Plan -proposal submitted to European Commission. Press release of the Ministry of Agriculture and Forestry December 16 2021. https://mmm.fi/-/hallitus-hyvaksyi-suomen-cap-suunnitelman-esitys-lahtee-euroopan-komission-kasittelyyn?languageId=en_US. Accessed 19 Sept 2022

Mosnier A, Penescu L, Perez Guzman K, Steinhauser J, Thomson M, Douzal C, Poncet J (2020) FABLE Calculator 2020 update. International Institute for Applied Systems Analysis (IIASA) and Sustainable Development Solutions Network (SDSN), Laxenburg, Austria. https://doi.org/10.22022/ESM/12-2020.16934. Accessed 17 Sept 2022

Mosnier A, Schmidt-Traub G, Obersteiner M, .& Wang, X (2022) (this special issue) How to reconcile diverse national food and land-use priorities with global sustainability?

OECD-FAO (2020) OECD-FAO Agricultural Outlook 2020–2029. https://doi.org/10.1787/1112c23b-en

Palosuo T, Hoffmann MP, Rötter RP, Lehtonen H (2021) Sustainable intensification of crop production under alternative future changes in climate and technology: the case of the North Savo region. Agric Syst 190:103135. https://doi.org/10.1016/j.agsy.2021.103135

Peltonen-Sainio P, Hannukkala A, Huusela-Veistola E, Voutila L, Niemi J, Valaja J, Hakala K (2013) Potential and realities of enhancing rapeseed- and grain legume-based protein production in a northern climate. J Agric Sci 151(3):303–321. https://doi.org/10.1017/S002185961200038X

Purola T, Lehtonen H (2022) Farm-level effects of emissions tax and adjustable drainage on peatlands. Environ Manag. https://doi.org/10.1007/s00267-021-01543-1

Roe S, Streck C, Obersteiner M, Frank S, Lawrence D (2019) Contribution of the land sector to a 1.5 °C world. Nat Clim Change 9(11):817–828. https://doi.org/10.1038/s41558-019-0591-9

Rosa-Schleich J, Loos J, Mußhof O, Tscharntke T (2019) Ecological-economic trade-offs of diversifed farming systems—a review. Ecol Econ 160:251–263. https://doi.org/10.1016/j.ecolecon.2019.03.002

Saarinen M, Knuuttila M, Lehtonen H, Niemi J, Regina K, Rikkonen P, Varho V, Kaljonen M, Mattila T, Seppälä J (2020) A controlled dietary change could produce climate benefits, improve nutrition and maintain Finnish agriculture. Article Series of Government's analysis, assessment and research activities 12/2020. https://tietokayttoon.fi/julkaisu?pubid=34401. Accessed 19 Sept 2022

Smed S, Scarborough P, Rayner M, Jensen J (2016) The effects of the Danish saturated fat tax on food and nutrient intake and modelled health outcomes: an econometric and comparative risk assessment evaluation. Eur J Clin Nutr 70: 681–686. https://pubmed.ncbi.nlm.nih.gov/27071513/

Soete L, Turner R (1984) Technology diffusion and the rate of technical change. Econ J 94:612–623

Statistics Finland (2021) Greenhouse gas emissions in Finland 1990 to 2019—National Inventory Report under the UNFCCC and the Kyoto Protocol. Helsinki: Statistics Finland. Available on the Internet: https://www.stat.fi/static/media/uploads/tup/khkinv/fi_nir_eu_2019_2021-03-15.pdf

Tao F, Rötter RP, Palosuo T, Höhn J, Peltonen-Sainio P, Rajala A, Salo T (2015) Assessing climate effects on wheat yield and water use in Finland using a super-ensemble-based probabilistic approach. Clim Res 65:23–37. https://doi.org/10.3354/cr01318

Tiffin R, Arnoult M (2011) The public health impacts of a fat tax. Eur J Clin Nutr 65: 427–433. https://pubmed.ncbi.nlm.nih.gov/21245880/

Valsta L, Kaartinen N, Tapanainen H, Männistö S, Sääksjärvi K (eds) (2018) Ravitsemus Suomessa—FinRavinto 2017—tutkimus [Nutrition in Finland—The National FinDiet 2017 Survey]. http://www.julkari.fi/handle/10024/137433

van Gastelen S, Dijkstra J, Jeroen Z, Heck ML, Kindermann M, Klop A, de Mol R, Rijnders D, Walker N, Bannink A (2022) Methane mitigation potential of 3-nitrooxypropanol in lactating cows is influenced by basal diet composition. J Dairy Sci 105:4064–4082. https://doi.org/10.3168/jds.2021-20782

Wanner N, Cafiero C, Troubat N, Conforti P (2014) Refinements to the FAO methodology for estimating the prevalence of undernourishment indicator. ESS Working Paper No. 14-05. http://www.fao.org/3/a-i4046e.pdf

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Murray CJL (2019) Food in the anthropocene: the EAT—Lancet Commission on healthy diets from sustainable food systems. Lancet 393(10170):447–492. https://doi.org/10.1016/S0140-6736(18)31788-4