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SPECIAL FEATURE: ORIGINAL ARTICLE

Globally-Consistent National Pathways towards Sustainable Food and Land-use Systems

Organic agriculture in a low-emission world: exploring combined measures to deliver a sustainable food system in Sweden

Shyam Basnet[1] · **Amanda Wood**[1] · **Elin Röös**[2] · **Torbjörn Jansson**[2] · **Ingo Fetzer**[1] · **Line Gordon**[1]

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Abstract

In the EU, including Sweden, organic farming is seen as a promising pathway for sustainable production, protecting human health and animal welfare, and conserving the environment. Despite positive developments in recent decades, expanding organic farming to the Swedish national target of 30% of farmland under organic production remains challenging. In this study, we developed two scenarios to evaluate the role of organic farming in the broader context of Swedish food systems: (i) baseline trend scenario (*Base*), and (ii) sustainable food system scenario (*Sust*). *Base* describes a future where organic farming is implemented alongside the current consumption, production and waste patterns, while *Sust* describes a future where organic farming is implemented alongside a range of sustainable food system initiatives. These scenarios are coupled with several variants of organic area: (i) current 20% organic area, (ii) the national target of 30% organic area by 2030, and (iii) 50% organic area by 2050 for *Sust*. We applied the 'FABLE (Food, Agriculture, Biodiversity, Land-use and Energy) Calculator' to assess the evolution of the Swedish food system from 2000 to 2050 and evaluate land use, emissions and self-sufficiency impacts under these scenarios. Our findings show that expanding organic farming in the *Base* scenarios increases the use of cropland and agricultural emissions by 2050 compared to the 2010 reference year. However, cropland use and emissions are reduced in the *Sust* scenario, due to dietary changes, reduction of food waste and improved agricultural productivity. This implies that there is room for organic farming and the benefits it provides, e.g. the use of fewer inputs and improved animal welfare in a sustainable food system. However, changing towards organic agriculture is only of advantage when combined with transformative strategies to promote environmental sustainability across multiple sections, such as changed consumption, better production and food waste practices.

Keywords Organic farming · FABLE pathway · Sweden

Introduction

One of humanity's greatest challenges will be to produce enough nutritious and healthy food for a growing global population while also securing environmental, social and economic sustainability. The proposed pathways to achieve such a sustainable future are diverse and include dietary shifts, reductions in food loss and waste (FLW) and changes to food production.

One proposed production-side solution is a transformation of the agro-sector to organic farming (FAO 2018). The International Federation of Organic Agriculture Movements (IFOAM) defines organic agriculture as "a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved" (IFOAM 2008). Organic agriculture is based on agroecological practices, such as varied crop rotations, biological diversity, natural predators and organic fertilizers.

Handled by Katya Perez-Guzman, International Institute for Applied Systems Analysis, Austria.

✉ Shyam Basnet
shyam.basnet@su.se

[1] Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

[2] Swedish University of Agricultural Sciences, Uppsala, Sweden

Research shows that organic farming causes lower environmental impacts [energy use, greenhouse gas (GHG) emissions, nutrient pollution] per unit of land (Tuomisto et al. 2012), better soil quality (Meemken and Qaim 2018), improved animal welfare (Vaarst and Alrøe 2012), reduced chemical use (Pekala 2020) and greater profitability for farmers (Reganold and Wachter 2016). However, organic agriculture also produces lower yields, which is a disadvantage when a growing population is to be fed without unacceptable expansion of agricultural land (Reganold and Wachter 2016; Muller et al. 2017; Meemken and Qaim 2018; Seufert 2019). Therefore, organic farming potentially causes higher unit production costs, higher consumer prices and higher land use and related negative environmental impacts (Meemken and Qaim 2018).

In Sweden, the national government has set targets for the amount of agricultural land area under organic production starting in 1994. The first of which was to expand organic farming to 10% of total agricultural land by 2000. This target has recently been increased to 30% by 2030 (Pekala 2020). In line with these targets, organic area in Sweden has nearly tripled in the past 15 years, now covering 611 kha (~20%) of agricultural land, and organic production of milk and beef increased to 17% and 20% of Swedish gross production, respectively (Statistics Sweden 2021).

Sweden also has consumption targets for increasing the demand for organic food. The Green Public Procurement (GPP) act targets 60% of all food procured by the public sector to be organic by 2030 (Swedish Government 2017). However, public sector consumption only represents 4% of total food consumption (Röös et al. 2021). At the local level, municipal governments such as those in Malmö and Södertälje aim for increasing consumption with a complete supply of organic foods to the public sector. Looking beyond the public sector, demand for organic foods has also grown steadily—with an annual growth rate of almost 8% between 2015 and 2018 (EkoWeb 2020). The country is however a net importer of organic foods (European Commission 2010), which can explain in part the efforts made by the national government to expand domestic organic farming.

Several studies have analysed the potential consequences of expanding organic farming (Foley et al. 2011; Reganold and Wachter 2016; Muller et al. 2017; Seufert and Ramankutty 2017; Karlsson and Röös 2019; Smith et al. 2019; Barbieri et al. 2021). Organic farming can be seen as a solution for a cultivated planet to provide healthy food (Foley et al. 2011). However, many concerns, including the availability of organic fertilizers, such as manure, compost and green biomass, and the total land area required, remain unresolved. Several studies show that a combination of changes in various parts of the food system, including dietary change, productivity improvement and FLW reduction, are needed to reach environmental targets (Bryngelsson et al. 2016; Röös et al. 2017, 2022; Bowles et al. 2019; García-Oliveira et al. 2020).

In this paper, we also take a food system approach to look at production and consumption of organic food in Sweden. Under the aim of achieving 30% organic agriculture area, as set out by the National Food Strategy target, we ask the following questions: What are the environmental and economic consequences of expanding organic farming? What other modifications to the food system are necessary to improve the sustainability of organic production? In this way, we contribute to the idea that argues that organic agriculture will likely to expand, but in combination with other food system changes.

We use the Swedish food system as a case study to explore these questions. Sweden, like many countries, faces several major food system challenges. The current dietary pattern includes substantial amounts of animal products and processed foods (FAO 2019). Moberg et al. (2020) showed that the average Swedish diet transgresses five out of six food system planetary boundaries, thus showing a high global impact on many relevant Earth system processes. The National Food Strategy has recently highlighted organic production and consumption on the political agenda as one solution to supply healthier foods and to improve environmental sustainability (Swedish Government 2017).

In this study, we construct several scenarios that differ regarding (i) the national target for the area of organic cropland, and (ii) whether or not there is a shift towards a sustainable food system in terms of dietary shifts, FLW reductions, and increased agricultural productivity. The scenarios are evaluated using a numerical model that allows us to compute a range of sustainability impacts, including GHG emissions and land use, as well as food self-sufficiency. In our analysis, we are able to separate the impact of organic production from that of other food systems interventions that span production, consumption and waste interventions.

Methods

Modelling approach

To model our scenarios, we used a modelling calculation tool developed by the international FABLE (Food, Agriculture, Biodiversity, Land-use and Energy) Consortium. The 'FABLE Calculator' uses a spatio-temporal national simulation approach for articulating sustainable food and land use system pathways in the national context.[1] The 'FABLE Calculator' models the combination of several scenarios

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[1] Details on 'FABLE Calculator' of version 2020 can be found at https://www.abstract-landscapes.com/fable-calculator.

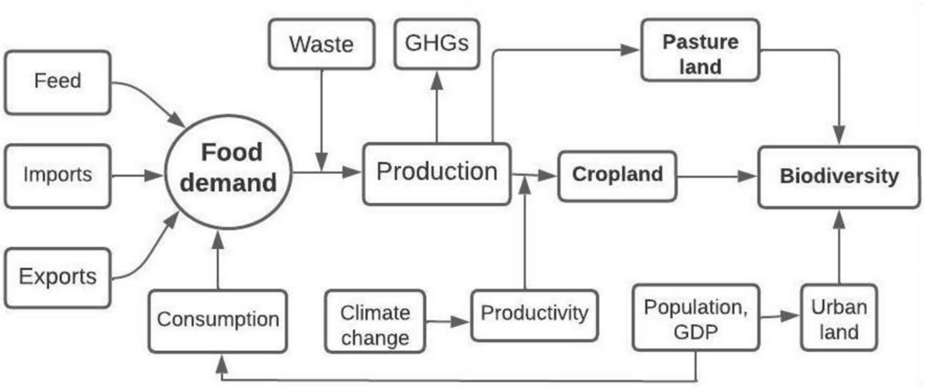

Fig. 1 Schematic diagram of modelling food system (Source: Authors' own)

representing different policies (e.g. National Food Strategy, 2030 Agenda, Green Deal, Farm-to-Fork, EU Biodiversity Strategy, etc.) and changes in the drivers of food systems, such as dietary changes, productivity growth and biodiversity. This calculator also enables the analysis of potential trade-offs in terms of land use, food consumption, trade and GHG emissions for the period 2000–2050 (see Mosnier et al. 2020 for details). An overview of the modelling framework, describing the food and land-use system in the 'FABLE Calculator' is shown in Fig. 1.

As illustrated in Fig. 1, the model is driven by demand (food consumption, exports and animal feed). Consumption in turn is influenced by population growth and affluence. Domestic food production is based on this demand, taking into account food that is imported. Thus, food demand, including food loss and waste, moderates agricultural production. By considering agricultural productivity developments in the context of climate change, this calculator calculates the cropland and semi-natural pastures required for supplying the food demand.

In the modelling process, the 'FABLE Calculator' uses a relatively simple parametric method for estimating food demands, using the caloric intake in kcal/person/year available in FAO Food Balance Sheets (FBS). The model computes the supply of food commodities from domestic production and trade, and maintains a balance between supply and demand for each food commodity.

The model calculates environmental impacts on outcome variables, including cropland use and GHG emissions, as well as food self-sufficiency due to changing food demand as a result of dietary shift, FLW and domestic food production. The cropland use and freshwater consumption are reported based on their annual domestic production requirements. The GHG emissions are cumulative emissions from agricultural production and changes in land use at a national level. We calculated GHG emissions using emission factors applied to crop harvest areas and animal herd size. Effect on biodiversity is estimated by the national area of semi-natural pastures and other natural lands in protected areas (PAs) (see Mosnier et al. 2019, 2020 for further details).

Organic production

In the 'FABLE Calculator', organic production differs from conventional farming with respect to yields, application of agricultural inputs, such as synthetic fertilizers and plant protection materials, and livestock stocking density. In our scenarios, yield differences were determined using the data available in the Swedish Board of Agriculture (Jordbruksverket 2006, 2022a) (see Appendix 3 for details). The higher yield gaps were observed for some of the major cereal crops, such as wheat, barley and rye, in the range of 38–41%. Pulses (e.g. peas and beans) and temporary grasses have the lowest yield differences, ranging from 14 to 24% (see Table SI_1 on Supplementary Information for details). However, these differences can vary depending on crop types, geographical locations, soil quality and available inputs, such as irrigation, green manure and compost.

In terms of applying mineral fertilizers and chemical pesticides, we assumed a 100% reduction in organic agriculture. The application of agro-ecological practices, such as biofertilizers, organic fertilization, crop rotation and intercropping with legumes and manure from animals consuming only organic fodder, is considered the source of soil nutrients for organic farming. To integrate organic agriculture into the 'FABLE Calculator', the total organic area required to achieve the scenario target of 30% or 50% of total agricultural land[2] is explicitly defined in the model. Aggregated areas for organic crops are then allocated between different crops (e.g. organic wheat and organic barley shown in Fig. 2) in proportion to their share of total cropland. The organic harvest is supplied to the market for domestic consumption, and the remaining food demand comes from conventional

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[2] As most fallow land was retained as part of the set-aside program, we fixed it constant at the 2010 level.

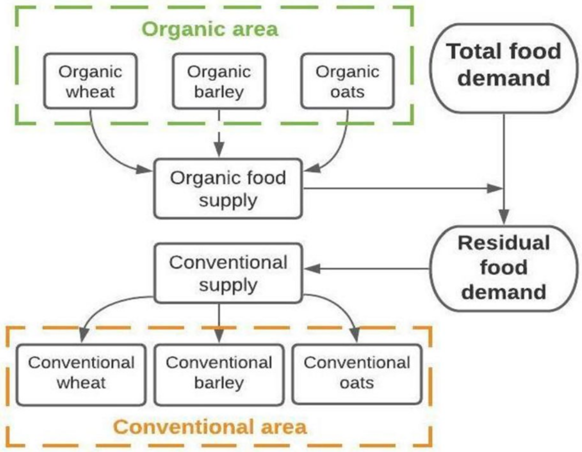

Fig. 2 Modelling framework to conventional and organic food supply

production. Based on the productivity developments, the model calculates the total conventional areas required to produce residual food demand.[3] Thus, the model considers conventional and organic crops to be grown separately, such as conventional wheat and organic wheat, and their aggregation is reported as cropland use.

For organic livestock farming, we considered milk and beef production. We assumed a 15% lower stocking density for organically grown cattle (Finch et al. 2014), leading to 2.97 grazing livestock unit per hectare of pastureland. These cattle have 15% more exposure to grazing and consume 40% less concentrate feed (Gaudaré et al. 2021; Länsstyrelsen 2021a, b) (see Appendix 3 for details). Likewise, feed used in organic animal husbandry was assumed to be based on feed ingredients of exclusively organic origin. For example, organic rapeseed meal and organic grasses (e.g. clover leys) are fed to the livestock that produce organic milk and beef. In line with the target for organic agricultural land, we have also increased the targets for organic grasslands and organic dairy and beef production to 30% or 50% for the associated scenarios. As the current share of organic agricultural land is almost equivalent to the share of organic milk and beef production, we have assumed that manure from organically managed animals would provide sufficient soil nutrients for organic farming.

Model variables and data sources

Food production

We considered yearly data on crop production, livestock farming and crop acreages from the Food and Agriculture Organization of the United Nations (FAO) for the period 2000–2015 (FAO 2019). These data are originally supplied by the Swedish Board of Agriculture, but they are harmonized in FAOSTAT with the FBS on food consumption, trade, feed, processing and other non-food purposes. The missing information on cultivated areas for organic crops was directly collected from the Swedish Board of Agriculture (Statistics Sweden 2021).

This study excludes FBS items with small quantities (e.g. spices) or items not considered food (e.g. alcohol). Most of the FBS items are reported in terms of primary equivalents, i.e. the quantity of raw products. For example, wheat products (e.g. wheat flour and bread) are reported in terms of raw wheat required for their production. For oilseeds crops, we accounted for the link between oil and cake (co-product) using processing coefficients. The same rule applies to beef and milk production of the dairy animals. At present, the 'FABLE Calculator' contains 15 aggregates of agri-food products, including 9 plants and 6 animal aggregates (see Appendix 1 for details).

Food consumption

Information on dietary intake is used to calculate per capita consumption of food items. The calorie content of food products was also obtained from the FAOSTAT (FAO 2019). For defining the current diet, we collected the per capita food intake of various food commodities available for 2017. We selected this year to harmonize with the productivity and trade developments.

Food waste

To account for food waste for each food products, we collected their shares at the supermarket, retail and household level reported in 2010 (FAO 2011). About 25% of the harvested cereal grains was recorded as food waste at the household level, while only 2% was recorded in supermarkets. For fruits and vegetables, food waste was reported at 19% in households and 10% in supermarkets. For details on food waste, see Appendix 2.

Food trade

We collected exports and imports of raw food commodities from FAOSTAT. FAOSTAT transforms processed products

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[3] We refer the residual food demand to the rest of the food demand after the supply of organic food.

into raw product equivalents and reports the aggregate volume of traded raw items.

Feed requirements

National accounts on animal feed were not detailed, often aggregated, and sometimes lacking for a few ingredients. For example, national statistics represent only the amounts sold by the feed industry, but do not record the amounts of feed used on farms. We collected estimated data on feed requirements from Cederberg et al. (2009) and updated with the farm survey data in Västra Götaland County of Sweden (Länsstyrelsen 2021a, b). Complementary data were collected from Herrero et al. (2013), which were calculated based on the weighted average of production systems.

Land use

We collected information on land use in agriculture, forestry, semi-natural pastures and other land types such as urban areas from the FAOSTAT (FAO 2019). The data on cropland use for conventional and organic crop harvests were obtained from the Swedish Board of Agriculture (Jordbruksverket 2022b).

Protected areas

Data on nationally designated Protected Areas (PAs) were collected from the World Database on Protected Areas (UNEP–WCMC and IUCN 2019). These data were available in various land cover classes, such as cultivated land, grasslands, shrubs with tree mosaic and herbaceous vegetation, and urban areas. We aggregated these land cover classes into five land-use categories, namely cropland, forest, pastureland, urban areas and other lands, and excluded water and snow-covered land. This dataset is used to calculate the coverage of PAs for each ecoregion. In Sweden, we have a total of 4 ecoregions, namely Baltic and Sarmatic mixed forests, and Scandinavian taiga and Montane Birch forests. Currently, the PAs occupy 15% of the total terrestrial area, with extensive forest cover. This study focused on the expansion of the network of PAs into forest and other types of land covered with (semi-)natural vegetation. The PAs was assumed to provide habitat for flora and fauna for the conservation and restoration of biodiversity.

Bioenergy production

The present study also assumes an increased demand for agricultural commodities in bioenergy production. We collected estimates of demand for crop products, such as wheat, maize, sugar beet and rapeseed, and of bioenergy production from the OECD (Organization for Economic Co-operation and Development) (OECD/FAO 2019). They are estimated by the OECD-AGLINK model, based on the unit requirement of these crop products for ethanol and biodiesel production.[4] In 2010, Sweden's biofuel production used 8.5 k tons of wheat, 13.9 k tons of maize, and 189.6 k tons of rapeseed oil and 1.5 k tons of sugar beet (FAO 2019). In the sustainable food system scenarios, we assumed moderate growth in biofuel supply from agriculture.

Emission factors

The emission factors for crop harvest areas were collected from the FAO country database for Swedish agriculture (FAO 2019). These data include emissions of nitrous oxide (N_2O) and carbon dioxide (CO_2) from energy use, synthetic fertilizer application and crop residue management. For organic farming, the emission factors per unit of output are collected from Smith et al. (2019) and converted them into emissions per unit area using the organic yields of Statistics Sweden (2021).[5] For some crops (e.g. oats, potatoes and onions), the emission factors per unit of output (CO_{2e} tonne^{-1}) are slightly higher in the organic production system, but for some others (e.g. wheat, barley, rye, triticale, milk and beef) they are lower in organic production (Smith et al. 2019). Lower yield and nutrient leaching are the major causes of emissions in the organic production system. The emission factors for the livestock sector are collected from Cederberg et al. (2009), supplemented by Herrero et al. (2013). This information includes emissions of N_2O and methane (CH_4) from enteric fermentation and livestock manure. The carbon stock in forest biomass is obtained from the FAO database (FAO 2019). For cropland and pasture, we collected emission factors from Lindgren and Lundblad (2014). We assume a biomass carbon stock in other land cover types equivalent to 30% of the forest biomass carbon stock following recommendations by Mosnier et al. (2019).[6] Information on the CO_2 savings of biofuels relative to fossil fuels is collected from RFA (2008). The emission factors and the sequestration changes with land use and land-use changes are used to compute GHG emissions across all scenarios (see Table SI.2 on Supplementary Information for details on emission factors).

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[4] The model adopted the climate change mitigation scenario, namely 2-degree scenario (2DS), developed by the International Energy Agency (IEA). This scenario assumes a 50% probability of limiting future global average temperature to an increase of 2 °C by 2100 (OECD 2019).

[5] There are no emissions of synthetic fertilizers from organic farming. Emissions from cattle manure are accounted for under the heading 'livestock sector emissions'.

[6] The FABLE Consortium made this assumption due to the lack of reliable national information.

Climate change

Representative Concentration Paths (RCPs) are the most recent atmospheric concentration scenarios adopted by the Intergovernmental Panel on Climate Change (IPCC) for the fifth assessment report in 2014. This study assumes the RCP2.6 scenario (see Appendix 3 for more information), which can reduce crop yields in Sweden by 1.4% by 2050 from 2010 level. As changes in the effect of CO_2 fertilization over time have yet to be fully explored (Wang et al. 2020), we have excluded the fertilization effect on measuring the environmental impacts.

Demographics

Historical observations on population, gender composition and age structure were collected from UN (2017). In this study, we adopted the Shared Socioeconomic Pathway (SSP) that represents the low challenges in climate change mitigation and adaptation: SSP1. In the Swedish context, the SSP1 projects the national population to reach 12.97 million by 2050 (see Appendix 3 for details).

Scenario development

We developed two sets of scenarios that we call *baseline scenarios* and *sustainable food system scenarios.* Within each of those sets, we varied the target level for organic cropland area. Moreover, we ran additional computations to explore the individual and combined contribution of various changes to food production, consumption and waste to sustainability.

There are two *baseline scenarios*: *Base20* corresponds to organic farming remaining at the current 20% of total agricultural land. In *Base30,* we explore the impacts of pursuing organic agriculture as the only sustainability strategy. Thus, we include the expansion of organic agriculture in line with the current government target to reach 30% organic area by 2030, and no further expansion beyond that point.

In both baseline scenarios, we assume a continuation of historical trends in population, GDP growth, food production, consumption, food waste, trade and land-use. For most parameters, a reference year of 2010 was used, because in the numerical model (described below) variables such as protected areas, animal feed requirements, FLW and agricultural inputs in biofuel production were available for 2010. However, we used a base year of 2017 to account for per capita consumption, as this was the latest information available at the FAO Food Balance Sheets (FBS). We also used the same reference year for food imports and exports, because these were the most recent agricultural trade data (Statistics Sweden 2021). Previous studies (e.g. Jonasson 2018; Naturvårdsverket 2019; Wirsenius 2019) also used 2017 as base year for developing scenarios for computing GHG emissions from food production and consumption in Sweden.

Finally, we assumed that Sweden meets its commitment to the Convention on Biological Diversity, thus expanded the protected areas (PAs) to 30% of terrestrial land and inland waters by 2030. In contrast, we assumed low ambitions to reduce the climate impacts of agriculture, given the current lack of political will. More scenario details are available in Appendix 3.

Sustainable food system scenarios

This set of scenarios explores various targets for organic production in combination with a food systems approach to improving sustainability. The changes, compared to the baseline trends, included in all these scenarios are (1) a shift towards more a sustainable diet, (2) reduction in FLW and (3) improved crop and livestock productivity. The shifts towards a more sustainable diet were made in consultation with relevant public sector agencies. The dietary shifts included a decrease in animal source foods (red meat, poultry, eggs and dairy) and an increase in vegetables, root vegetables, legumes and temperate fruits (see Appendix 3 for details). FLW was halved across the value chain, in line with the Sustainable Development Goal Target 12.3 (Flanagan et al. 2019).

Productivity shifts for crops and livestock were based on expected yield growth. We calculated annual yield growth in Sweden with recently available data in the Swedish Board of Agriculture (Jordbruksverket 2006, 2022a) from 2000 to 2010 at − 1.3% to 5.1%, depending on the products. The lowest growth was recorded for rye and the highest for potatoes. For the baseline scenarios—*Base20* and *Base30*, we truncated negative growth to zero to avoid a declining trend and higher growth to 1.5% to curb exponential growth in long-term yields. Jonasson (2018) also predicted similar yield growth of 0.5% per year for cereals, 1% per year for milk and eggs and 1.5% per year for pork until 2045. As in Clark et al. (2020), we assumed that the yields are 50% higher than the maximum yield observed in the period 2000–2010. This equates to approximately 1% yield growth per year up to 2050 (see Appendix 3 for details).

In addition to local production, the Swedish National Food Strategy 2016/2017 also promotes the consumption and exports of Swedish food, including organic products. In the sustainability scenarios, we assumed a 30% increase in food exports from 2017 to 2030.[7] The amount of imports

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[7] Based on personal communication with the Swedish Board of Agriculture and the Swedish Trade agencies, we assumed moderate export growth with a 30% increase between 2017 and 2050. It applies to all products exported in 2017. We have no trade for organic foods, as we lack historical observations on their trade.

Table 1 Major variables differ across scenarios

Variables	Baseline scenario		Sustainable food system scenario		
	Base20	Base30	Sust20	Sust30	Sust50
Organic agricultural land	20%	30%	20%	30%	50%
Crop and livestock yield	Business-as-usual trend		Moderate growth		
Livestock stocking	No change in permanent pasture		15% fewer livestock on pasture		
Food loss and waste	No change in the current state		50% reduction by 2050		
Imports	Stable at the 2017 levels		Reduce imports		
Exports	No changes in trade policy		30% increase from 2017 levels		
Dietary composition	Current dietary intake		More intake of plant-based foods		
Biofuels and bioenergy	Stable demand as 2010		Moderate growth		
Biodiversity	PAs in 17% of land by 2030		PAs in 30% of land by 2030		

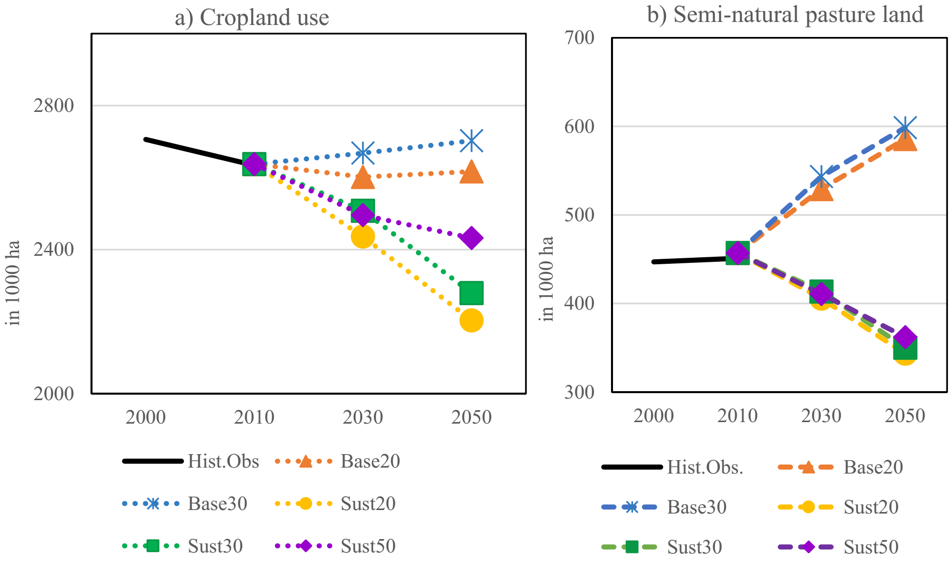

Fig. 3 Land use in simulation scenarios

depends on consumer preferences for the diet, population growth, domestic supply and other factors. The sustainability scenarios are coupled with an import development adapted to dietary transition. In recent years, the trend is a decline in beef consumption combined with a slight increase in domestic beef production. If this trend continues, there will be even smaller share of beef imports in consumption. As the study diet was designed to reduce beef consumption, we also assumed to reduce beef imports (see Appendix 3 for details).

To explore the role of organic agriculture as part of the mix of sustainability solutions, we created three variations of the sustainability scenario as:

(i) we test only the sustainability measures detailed above, with the current 20% organic acreage (hereafter referred to as "*Sust20*").

(ii) we increase the current target linearly to 30% organic agricultural land by 2030 (hereafter referred to as "*Sust30*").

(iii) we extend the growth of organic agriculture linearly from 30% in 2030 to 50% in 2050 (hereafter referred to as "*Sust50*").

Given that the National Food Strategy 2016/2017 is already in place to implement transformative actions towards a sustainable food system, we assumed that the 2050 target of 50% organic agricultural land in the baseline scenarios (e.g. current level of per capita consumption) would be less probable case.

Table 1 summarizes the descriptions of the variants of baseline and sustainable food system scenarios.

Results

This section presents the outcomes of the baseline and sustainability scenarios with variations in the area of organic agricultural land. We describe the impacts of each scenario

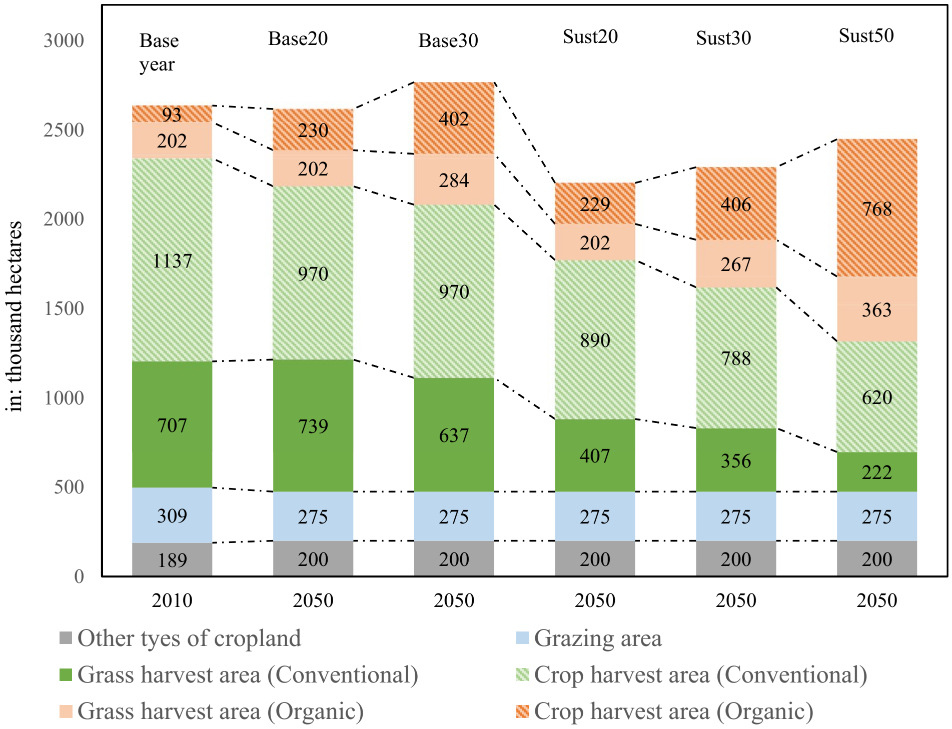

Fig. 4 Changes in cropland use across scenarios

on cropland and pasture land use, agricultural emissions and food self-sufficiency.

Agricultural land use

Projected cropland area includes both conventional and organic areas for crop and livestock production. The baseline scenario (*Base20*), which assumes 20% organic agricultural land (i.e. current organic area), projects a cropland area of 2.61 million hectares by 2030, which is slightly (− 1.4%) lower than the 2010 reference year (2.64 million hectares according to Statistics Sweden 2021) (see *Base20* in Fig. 3a). In 2050, cropland area remains relatively close to the 2010 reference year (2.63 million hectares). In this scenario, food demand increases as population grows, but crop yield improvements prevent a larger land use expansion.

In the *Base30* scenario, which assumes the expansion of organic farming to 30% of the utilized agricultural area (UAA) by 2030, requires 2.71 million hectares of cropland by 2050. This is 3.1% higher than the projected cropland in the *Base20* scenario and the difference is due to the expansion of organic agricultural land. As the sustainability measures such as dietary transition, reducing FLW and improving agricultural productivity, are adopted in the *Sust30* scenario, cropland area decreases to 2.28 million hectares in 2050 (see Fig. 3a). This is about 16% less cropland requirement than the *Base30* scenario. This is mainly attributed to the dietary transition, which can alone reduce the cropland use by 9.7%, followed by productivity growth and FLW reduction. The lowest land use is found in *Sust20*, where there is no expansion of organic area and the sustainable food system changes are included.

With regard to the use of semi-natural pastures, the baseline and sustainability scenarios have divergence effects. In the baseline scenarios, including *Base20* and *Base30*, the use of pastures is estimated to increase to 586 kha (in *Base20*) and 599 kha (in *Base30*) in 2050, which are 28% and 31% higher than the 2010 level, respectively. In 2010, the use of semi-natural pastures for livestock grazing was reported to 457 kha (Statistics Sweden 2021). The baseline scenarios (*Base20* and *Base30*) assume constant per capita consumption of the current Swedish diet available at FAO (2019) for the period 2020–2050. As the current diet contains relatively larger shares of animal origin products, such as beef, pork and milk, the growing population would require more supply of these foods, leading to increase in animal herd sizes. This has a positive impact, as cattle grazing would help maintain semi-natural pastures that are rich in biodiversity. In Sweden, undergrazing and abandonment of semi-natural pastures is the predominant problem (Kumm 2003). To preserve these pastures, Swedish farmers receive an agri-environmental payment under the EU's Common Agricultural Policy for regular grazing. However, an increase in livestock would also release more GHGs and could have adverse effects on the environment. The sustainability scenarios, including *Sust20*, *Sust30* and *Sust50*, use less pasture land for grazing, as the livestock production are expected to decrease with the reduced consumption of animal products. In the same

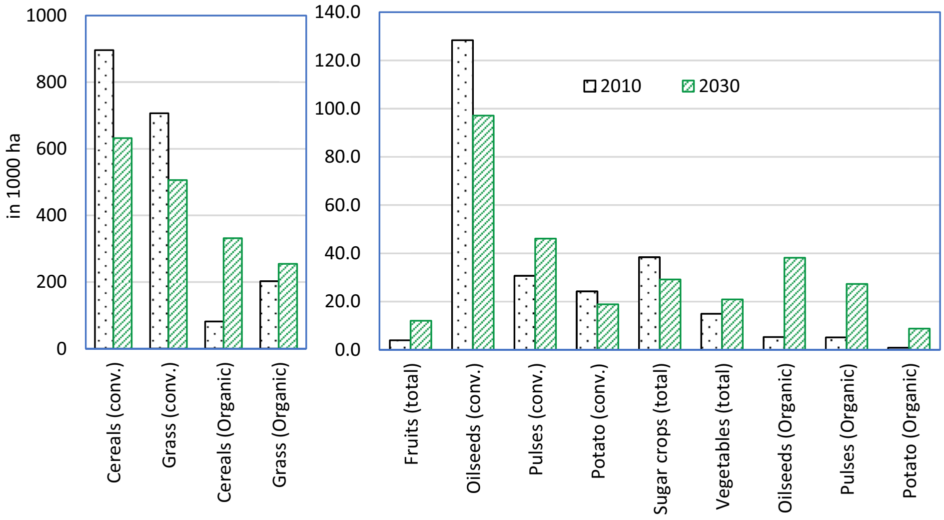

Fig. 5 Changes in crop acreage in the *Sust30*

way, production capacities, such as agroclimatic conditions and biophysical properties, can affect food supply and consumption patterns, while food tends to be locally produced. In the sustainability scenarios—*Sust20*, *Sust30* and *Sust50*, changes in cereals harvest area and grass cultivation are largely responsible for reduction in cropland use in 2030 and 2050 (Fig. 4). Altogether, these crops (cereals and temporary grasses) explain 54% of the changes in cropland between 2010 and 2050, due to increase in their productivities. Substantial share in the reduction of crop harvest area (52%) is attributed to decrease in the planted areas of temporary grasses (e.g. clover). The dietary transition in the sustainability scenarios reduces demand for animal products, which reduces the livestock production activities (e.g. cultivation of grasses). During this period, areas under organic crops, including cereals, pulses and temporary grasses, is increased by 1.2 times of the 2010 level in the *Sust30* scenario and it is extended to 3.8 times in the *Sust50* scenario. In these scenarios, some of the conventional areas are converted to organic production, while a small share of the conventional crop harvest area is abandoned by agriculture. The conventional crop harvest areas are reduced by 24% and 55% of the 2010 level in the *Sust30* and *Sust50* scenario by 2050. In 2050, the organic crop production area is expanded to 768 kha, while it is shrunk to 620 kha in conventional farming (see Fig. 4). Due to reduced feed demand, the cultivation of temporary grasses is also decreased over the same period.

In the sustainability scenarios, the cultivated areas of fruits, vegetables and pulses are expected to increase for both conventional and organic production. In the *Sust30* scenario, the cultivated areas for fruits can increase to 12 kha in 2030, which is 3 times higher than the 2010 level (see Fig. 5). This is particularly observed with apples and other temperate fruits. In Sweden, tomatoes, onions, cabbage, carrots and lettuce are commonly grown vegetables, although they account for only 0.75% of total arable land, i.e. around 15 kha in 2010. Because of more consumption of vegetables, the *Sust30* scenario increases their cultivation to 21 kha in 2030, which is 40% higher than the 2010 level (see Fig. 5). Likewise, the cultivated areas of leguminous crops, such as peas and beans, are expected to increase in the sustainability scenarios. The cultivated areas for these crops were reported to 36 kha in 2010, which is expected to increase to 73 kha in 2030 in the *Sust30* scenario. The total use of cropland for conventional and organic production of oilseed crops and temporary grasses decreases noticeably between 2010 and 2050.

Emissions

We calculated emissions and removals from agricultural production, land use changes and biofuel savings by pairing their emission intensities. In the present study, we have estimated the agricultural emissions to 5.60 MtCO2e in 2030, and reach 5.55 MtCO2e in 2050 in the *Base20* scenario (Fig. 6a), which are 1% and 5% higher than the estimates by FAO (2018).[8] The differences in the absolute emission estimates are due to differences in model assumptions, such as expansion of organic farming, yield improvement, dietary transition and SSP pathways. Note that we have estimated a decreasing trend in agricultural emissions after 2030 that is possible thanks to yield increases even though we have a constant per capita consumption and a growing population.

The expansion of organic farming in the *Base30* scenario would further increase the GHG emissions to 5.65 MtCO2eq in 2050 (see *Base30* in Fig. 6a), which is merely

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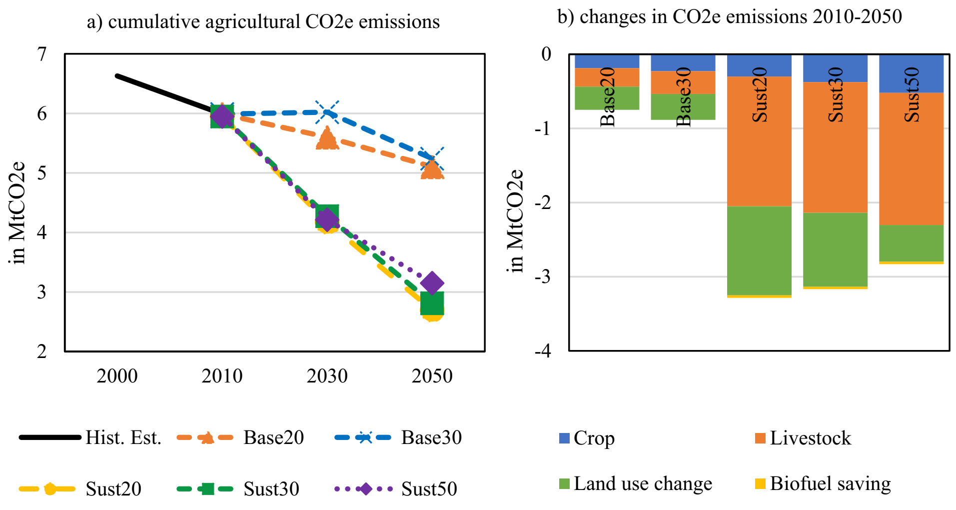
[8] FAO (2018) estimated the CO2e emissions for Swedish agriculture to be 5.57 MtCO2e by 2030 and 5.30 MtCO2e by 2050.

Fig. 6 Emissions in the food production system



1.7% higher than the *Base20* scenario. In the *Base30* scenario, the livestock sector is the largest source of emissions (4.08 MtCO2e/year in 2050), while biofuel serves as a sink (− 0.41 MtCO2e/year). In the *Base30* scenario, we observe an increase in GHG emissions in the agriculture sector by 0.44 MtCO2e between 2010 and 2050 (see Fig. 6b). The land-use changes to shrubland and other vegetations were the removals of GHG emissions.

The sustainability scenarios, including *Sust20*, *Sust30* and *Sust50*, lead to a 30–40% reduction in the net agricultural emissions by 2050, comparing to the 2010 level (Fig. 6a). Assuming that the three sustainability measures—dietary shifts, reducing FLW and improving productivity, are progressively adopted so as to be fully adopted by 2050, the GHG emissions from crop and livestock production can decrease to 4.03 MtCO2e in 2050, which is 34% lower than the 2010 level (see *Sust20* in Fig. 6a). Due to the adoption of the sustainability measures, even if we expand the current organic acreages to 30% of the UAA, i.e. in the *Sust30* scenario, the GHG emissions can still reduce by 45% in 2050, comparing to the *Base30* scenario. This shows that the food system approach can provide space for expanding organic farming with reduced emissions. However, it requires the adoption of these sustainability measures—dietary shifts, FLW reduction and productivity improvement. The complete adoption of these measures would even provide a leeway for the expansion of organic farming up to 50% by 2050, without exceeding the emissions estimates in the *Base20* scenario (see *Sust50* in Fig. 7). The decrease in GHG emissions is primarily attributable to lower animal production, especially pork and beef, and regeneration of natural vegetation.

Food self-sufficiency

The concept of food self-sufficiency describes the degree to which a country can meet its food demand with domestic production. This implies that self-sufficiency is mainly influenced by the consumption pattern and the volume of domestic production. We expect improved food self-sufficiency as we move towards a sustainable food system. As can be seen the horizontal bars approaching to the vertical dashed line in Fig. 8a, *Sust30* can improve self-sufficiency ratios for some food commodities, such as cereals, fruits, vegetables, milk, beef, pork and eggs over the 2010–2050 period. For cereal grains, food self-sufficiency is expected to increase, due to higher domestic production (see Fig. 8b). In case of animal origin products, such as milk, beef and pork, their self-sufficiencies can improve by 2050 (see *Sust30* in Fig. 8a) with the reduction in their imports, which has been largely affected by their reduced consumption (see Fig. 8b). On overall, the self-sufficiency ratios for most of the food commodities are expected to improve in the sustainability scenarios, compared to the baseline scenarios.

Within the sustainability scenarios—*Sust20*, *Sust30* and *Sust50*, the self-sufficiency ratios for most food

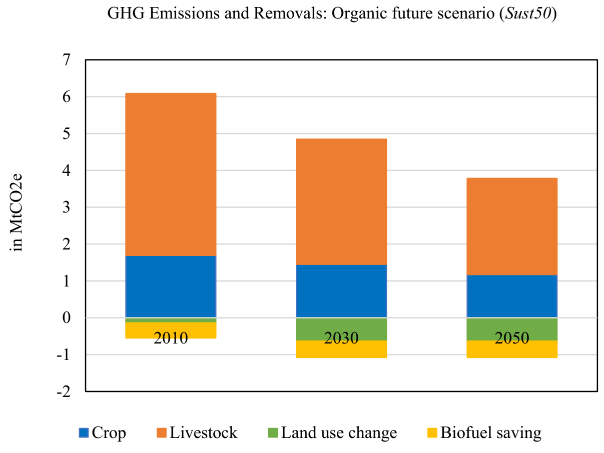
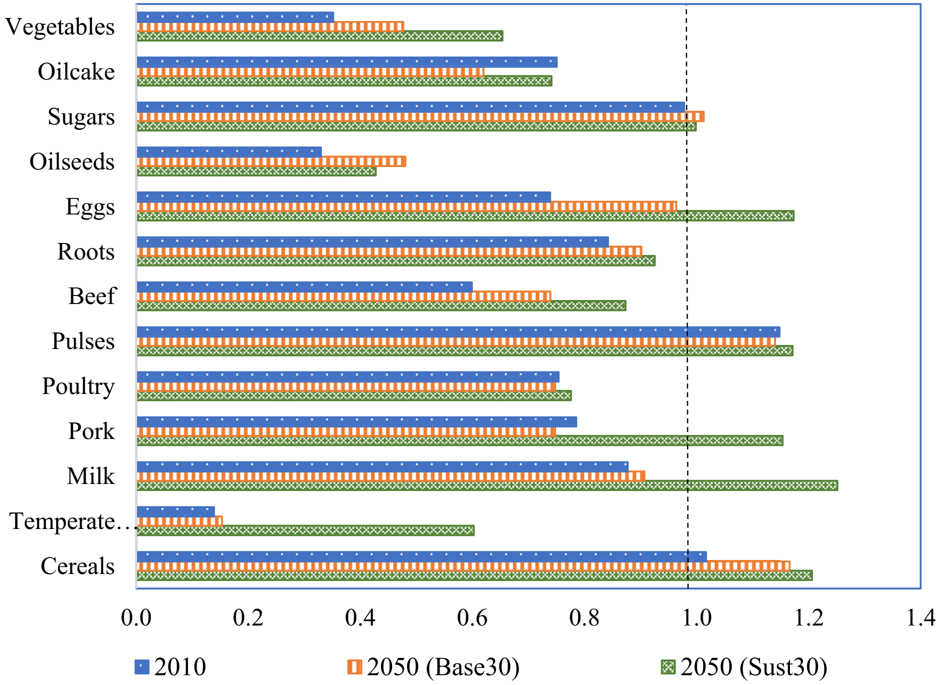


Fig. 7 GHG emissions and removals: organic future scenario (*Sust50*)

(a) food self-sufficiency ratios



b) food demand and supply in 2050 (Sust30)

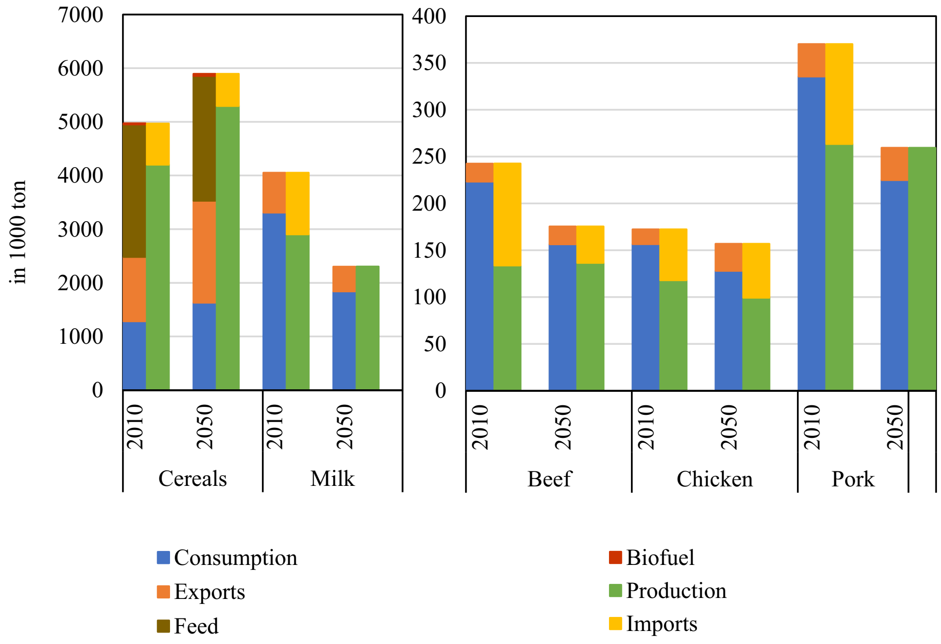


Fig. 8 Food self-sufficiency with their demand and supply in 2050 (*Sust30*). **a** Food self-sufficiency ratios. **b** Food demand and supply in 2050 (Sust30). Note: In **b**, the first bar represents demand for consumption, exports, feed and biofuels, while the second bar shows supply by production and imports

commodities would remain unchanged with increased adoption of organic farming. Aggregate domestic production does not change remarkably between these sustainability scenarios. Rather, it would change the shares of the organic and conventional area. However, when comparing the sustainability and baseline scenarios, we see that implementing sustainability measures would significantly affect the food self-sufficiency ratios (as seen in *Base30* and *Sust30* in Fig. 8a). This is mainly motivated by three sustainability measures—dietary change, reducing FLW and improving yields.

Discussion

Agricultural land use

In the baseline scenarios (i.e. adopting no sustainability strategies), the expansion of organic area would require more cropland. Thus, this study confirms earlier results that expanding organic farming would require more cropland (Reganold and Wachter 2016; Muller et al. 2017; Seufert and Ramankutty 2017; Karlsson and Röös 2019). We find an increased use of cropland in Sweden already in the baseline scenarios, if the current per capita food consumption remains unchanged, and achieving the 30% target requires expanding the cultivated agricultural land beyond the 2010 reference year (2.64 million hectares in 2010; Statistics Sweden 2021). Previous studies (e.g. Erb et al. 2016; Muller et al. 2017; Barbieri et al. 2021) also argue that organic farming alone cannot feed the growing population and poses a threat to forests and grasslands, if extended worldwide.

In contrast, our sustainable food system scenarios suggest that dietary shifts combined with food waste reductions can significantly reduce cropland use, leaving room for organic farming to expand. In such a food system, it would be possible to expand organic farming to 50% of the UAA by 2050, without increasing the cumulative use of cropland. Previous studies (Röös et al. 2017; Springmann et al. 2018; Clark et al. 2020) have shown similar results of reduced cropland use through various mitigation strategies. Röös et al. (2017) also argue for improving the food system, in particular dietary transition, reducing FLW and increasing productivity, to feed the growing population with the currently available arable land. Along with these strategies, Karlsson and Röös (2019) also suggested reducing food-feed competition, to increase significantly the share of organic production in Sweden. In the present study, we also considered more exposure of livestock to grazing and feeding less concentrate grains as the efforts to strengthen the sustainability scenarios.

The baseline scenarios project increased use of semi-natural pastures for livestock grazing, as a result of increased animal herd size. However, expansion of pasture land will require policy incentives, and thus it is more likely that stocking density just increases. That would not be ideal, since intensive grazing on semi-natural pastures can have adverse effects on flora and fauna diversity (Kleijn and Sutherland 2003). On the other hand, in the sustainability scenarios, we see less semi-natural pasture land use, but also lower livestock stocking densities. This presents a bit of a trade-off, in that remaining pasture land might be better preserved with lower stocking densities, but we would also lose pastures where many red listed species live. Previous studies have shown that low levels of cattle grazing is desirable for biodiversity, given that many red listed species have evolved to live in such pastures (Waldén and Lindborg 2016; Nilsson et al. 2013).

Emissions

The increased agricultural production in the baseline scenarios would release more GHGs. Expanding organic farming in this scenario releases somewhat more GHG emissions, as emission savings from reduced fertilizer application in organic production are offset by increased emissions from land use. Historically, GHG emissions from the agriculture sector in Sweden were reduced between 1990 and 2018 despite a strong expansion of organic production (Swedish Environmental Protection Agency 2019; Ritchie and Roser 2020). That reduction was explained by a reduction in the number of animals (mainly dairy cows and hogs), improved manure management practices, less use of nitrogen-based mineral fertilizers and reduced crop acreage (Swedish Environmental Protection Agency 2019). However, not all of those developments continue in our baseline, such as manure management practices.

The sustainability scenarios demonstrate the potential for reducing GHG emissions from agriculture in Sweden. The decrease in GHG emissions is primarily attributable to lower animal production and reduction in land use. Assuming that the strategies to reduce unhealthy food consumption (dietary transition) and FLW, are progressively adopted so as to be fully adopted by 2050, we find a 55% reduction in GHG emissions from 2010 to 2050. This is broadly in line with previous research that has identified dietary shifts as a key lever to reduce emissions (Tukker et al. 2011; Tilman and Clark 2014; Springmann et al. 2018; Clark et al. 2020). Increasing the share of organic production within the sustainability scenarios increases emissions compared to maintaining current levels of organics because of increased crop acreage and livestock farming. Nevertheless, even after expansion of organically cropped areas to 30% in 2030 and 50% in 2050, the emissions would still be lower than in the business-as-usual scenario.

In the Nationally Determined Commitments (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC), Sweden has committed to reduce GHG emissions by 40% by 2030 compared to 1990 from energy, industrial processes, agriculture, forestry and other land use (EU 2015), and zero net GHG emissions by 2045. In the light of our results, it is difficult to see how a strong expansion of organically farmed area could be reconciled with those climate ambitions unless combined with dietary changes, improving productivity and reducing FLW.

Food self-sufficiency

In the National Food Strategy 2016/2017, the government emphasized for improving food self-sufficiency by increasing domestic food production (Swedish Government 2017). This includes improving agricultural productivity, dietary shifts to plant-based foods, and promotion of organic farming. About half of the Swedish food consumption is produced domestically, accounting for 55–60% of food self-sufficiency, down from 75% in 1988 (LRF 2021). The sustainability scenarios improve the self-sufficiency ratios for most of the food commodities in 2050 for most products. The food self-sufficiency can improve either by increasing domestic production or reducing consumption. In case of plant-based foods such as cereals, pulses and potato, the self-sufficiency ratios are improved by increased domestic production, whereas for animal products, reduced demand associated with dietary shifts is the main driver. Therefore, our results are consistent with previous studies (Beltran-Pea et al. 2020), finding that the food self-sufficiency ratios can improve in the sustainability scenarios combining a low-carbon diet, improving productivity and reducing FLW.

The expansion of organic farming would have no significant impact on cumulative domestic production. The new entrants in organic farming were initially practitioners of the conventional production system. Their transition to organic farming would only change the mode of production and use more cropland to compensate for lower organic yields. Consequently, food self-sufficiency ratios would not be very different as organic farming expands. The promotion of organic farming together with the adoption of sustainability measures may motivate consumers to demand more local foods, which would improve food self-sufficiency.

Study limitations and contributions

This is modelling study that explores an uncertain future. The results may deviate from other studies for several reasons, such as availability of input data, model structure and uncertainties in scenario representations. All of our calculations are based on the FAO food balance sheets, which record the food availability. Thus, the model results may contain differences in the level of food consumption compared to other studies. Blue foods, including fish and other sea foods, have been considered only to calculate calorie intake, but the model excludes aquaculture on the production side. For GDP and population growth, we considered the SSP1 scenario as a sustainable path to long-term economic growth and demographic change. Deviation from this scenario may have a moderate impact on the outcomes of the pathway.

Lastly, the ‘FABLE Calculator’ is an input–output model, representing the AFOLU sectors relevant to food and land-use systems, and does not represent the entire economy of the country. As a result, this model does not account for knock-on effects in other sectors of the economy. Medium-level trade scenarios have been assumed to be less sensitive to economic growth and climate change outside of Sweden. Despite uncertainties and limitations, our study indicates that organic farming can be part of a food system with increased protection of natural resources and animal welfare if combined with mitigation measures such as dietary shift, reducing FLW and improving productivity. The latter measures provide some leeway to expand organic farming without exceeding the current state of cropland use and GHG emissions. Previous studies (Erb et al. 2016; Muller et al. 2017; Springmann et al. 2018; Conijn et al. 2018; Barbieri et al. 2021) also suggested these triple actions to operate the food system in the safe space of planetary boundaries.

We expect that this study helps policymakers identify potential constraints and opportunities for the expansion of organic agriculture in Sweden. In particular, our results would support a further expansion to Sweden’s national organic production target, so long as it is part of a package of food system strategies. This study could also become relevant for other EU countries, as the EU’s Farm-to-Fork strategy under the Green Deal policy also aims to expand organic agriculture.

Conclusions

This study showed that the expansion of organic farming towards the National Food Strategy goal may require more cropland and result in higher GHG emissions in the baseline scenarios. However, it would be possible to expand organic agriculture on available farmland if the current Swedish diet (defined by FAO consumption data) is transformed to a low-carbon diet, yield increased by 50%, and FLW reduced by 50%. These sustainability measures can greatly reduce the expansion of cultivated land into natural habitats and semi-natural pastures. The adoption of these sustainability measures with lower livestock stocking densities can reduce the current intensive grazing on semi-natural pasture land.

Integrating the sustainable measures in the food system is critical to reduce food demand and to increase the production efficiency of cropland per unit of organic production. However, none of the individual strategies alone can reduce the conventional cropland and allows for the expansion of organic farming. Policy incentives for transforming the broader food system are thus necessary to contribute to achieving the national food policy goal of expanding organic agriculture without other negative environmental consequences. As the ‘FABLE Calculator’ can be tailored to the national context by including open access data on national food balances, agricultural production and land use trends, this study can be extended to other countries in the EU. Such study can identify the constraints and opportunities of expanding organic farming in different places, as a part of the EU's F2F strategy, and evaluate the potential implications for food security in the global context.

Appendix 1: Details of the agri-food aggregates in the model

Animal products	Plant-based products	
Bovine meat Milk Eggs Pork meat Poultry meat Other ruminant meat	Cereal grains (rice, maize, wheat, oats, barley, rye, triticale, sorghum, millet and other cereals) Pulses (peas, beans, groundnut, nuts and other pulses) Fruits (apple, banana, grape, lemon, orange, other citrus, coconut, date, grapefruit, pineapple, plantain and other fruits), Vegetables (tomato, onion, olive, piment, other vegetables) Oil crops (rapeseeds, soybeans, sunflower, sesame, cotton and other oilseed crops) Root tuber crops (potato, cassava, yams, sweet potato and other tuber crops) Sugar crops (sugar beet, sugarcane) Beverages and spices (coffee, tea, tobacco, clove, cocoa, pepper and other spices)	Grass (temporary pastures)

Appendix 2: Food waste situation in 2010, by food product

Source: FAO (2011)

	Beef (%)	Poultry (%)	Fish (%)	Milk (%)	Fruits and vegetables (%)	Grains (%)	Nuts (%)	Pulses (%)	Vegetable oils (%)	Roots (%)
Supermarket retail	4	4	9	1	10	2	1	1	1	7
Consumption	11	11	11	7	19	25	4	4	4	17

Unit: % of total quantity

Appendix 3: Underlying assumptions for baseline and sustainable food system scenarios

Instrument	Baseline scenarios	Sustainable food system scenarios
Crop productivity for the key crops in the country (in t/ha)	Medium pace of crop yield growth, the current business-as-usual trend. By 2050, yield of major crops increases as below while that for other crops remains the same: *Conventional production system:* 8.4 t/ha for wheat [5.4 t/ha] 5.3 t/ha for barley [4.1 t/ha] 4.8 t/ha for oats [3.5 t/ha] 6.7 t/ha for rye [4.9 t/ha] 3.6 t/ha for peas [2.6 t/ha] 19.3 t/ha for apple [15.7 t/ha] 39.5 t/ha for potato [30.1 t/ha] 68.3 t/ha for sugar beet [50.3 t/ha] 3.2 t/ha for rapeseed [2.5 t/ha] 26.2 t/ha for vegetables [18.8 t/ha] Note: Brackets are for 2010 yields *Organic production system:* 3.7 t/ha for wheat [2.7 t/ha] 2.3 t/ha for barley [2.2 t/ha] 2.2 t/ha for oats [2.1 t/ha] 3.6 t/ha for rye [2.2 t/ha] 2.2 t/ha for peas [1.8 t/ha] 2.61 t/ha for beans [2.0 t/ha] 19.9 t/ha for potato [14.9 t/ha] 1.2 t/ha for rapeseed [0.8 t/ha] Source: Observations in 2000–2010 were collected from Jordbruksverket (2006, 2022a) and FAO (2019) Projected yields were calculated based on scenario definition	Crop yields improve more moderately, equivalent to 50% of the maximum yields observed in 2000–2010. By 2050, yield of major crops increases as below: *Conventional production system:* 8.7 t/ha for wheat 6.1 t/ha for barley 5.4 t/ha for oats 7.6 t/ha for rye 4.0 t/ha for peas 23.1 t/ha for apple 45.9 t/ha for potato 75.4 t/ha for sugar beet 3.7 t/ha for rapeseed 29.8 t/ha for vegetables *Organic production system:* 4.6 t/ha for wheat 3.3 t/ha for barley 3.2 t/ha for oats 4.6 tha for rye 2.8 t/ha for peas 2.95 t/ha for beans 22.4 t/ha for potato 1.5 t/ha for rapeseed Source: Authors' calculation with a 50% higher of maximum yields observed in 2000–2010
Livestock productivity for the key livestock products in the country (in t/head)	The current trend growth is assumed. By 2050, livestock production reaches: *Conventional production system:* 99 kg/head for beef [86 kg/head] 27 kg/head for chicken [20 kg/head] 61 kg/head for eggs [50.5 kg/head] 9.6 t/head for milk [7.4 t/head] 221 kg/head for pork [168 kg/head] Note: Brackets are for 2010 yields *Organic production system:* 97 kg/head for beef [86 kg/head] 8.8 t/head for milk [7.4 t/head] Source: Observations in 2000–2010 were collected from FAO (2019) and Statistics Sweden (2021). Projected yields were calculated based on scenario definition	Moderate growth is favoured for the low-GHG production system. By 2050, livestock production reaches: *Conventional production system:* 129 kg/head for beef 28 kg/head for chicken 76 kg/head for eggs 12.1 t/head for milk 228 kg/head for pork *Organic production system:* 126 kg/head for beef 11.1 t/head for milk Source: Authors' calculation based on yield growth assumptions by 50% of maximum yields observed in 2000–2010
Pasture stocking rate (animal units/ha pasture)	No change in the management of the permanent pasture area Average ruminant livestock stocking density is 3.49 livestock units/ha pasture land	Less grazing livestock id expected on the pasture. Ruminant stocking density reduced by 15% to 2.97 livestock units/ha of pasture
Post-harvest losses	No change in the current state of post-harvest losses. Constant share of losses in post-harvest handling after 2010	Halve the post-harvest losses by 2050 compared to 2010 base year. Regulatory frameworks, R&D, and investment for improved storage and processing

Instrument	Baseline scenarios	Sustainable food system scenarios
Trade Share of consumption which is imported for key imported products (%)	No policy changes, stable imports of the 2017 levels remain by 2050 for major food commodities. For production feasible commodities, the import shares of total consumption reduce: Up to 15% for pork, milk, chicken, eggs, potato and rapeseeds 25% for beef and mutton 35–50% for apple, beans and other fruits and oilseeds 60–100% for tropical fruits, vegetables, cereals, and soybeans Source: Authors' calculation based on scenario definition	Change in consumption and increase national production reduce imports. By 2050, the import shares reduce: Up to 15% for chicken, mutton, tropical fruits and cereals 25% for other fruits and vegetables, oilseeds 35–45% for apple, tomato, potato, rapeseeds 60–100% for beef, pork, milk and beans Source: Authors' calculation
Evolution of exports for key exported products (1000 tons)	No major changes in trade policy. Stable exports of the 2017 levels by 2050 as: 446 k tons of barley 706 k tons of wheat 270 k tons of oats 56 k tons of rye 47 k tons of peas 47 k tons of sugar beet Source: FAO (2019)	No major changes in trade policy, increase exports by 30% of the 2017 levels by 2050 as follows: 556 k tons of barley 917 k tons of wheat 351 k tons of oats 73 k tons of rye 61 k tons of peas 47 k tons of sugar beet Source: Authors' own based on scenario definition
Food: Average dietary composition (daily kcal per commodity group)	Current dietary intake in Sweden, according to FAO statistics for 2017. By 2050, the average daily calorie consumption reaches to 2875 kcal and is: 300 g/cap/day for cereals 470 g/cap/day for dairy milk 20 g/cap/day for vegetable oils 92 g/cap/day for added sugars 154 g/cap/day for red meat (pork and beef) 395 g/cap/day for fruits and vegetables 135 g/cap/day for fish and poultry 34 g/cap/day for eggs 16 g/cap/day for pulses and nuts 144 g/cap/day for roots 10 g/cap/day for animal fat Source: FAO (2019)	More sustainable and healthy diets. Livestock products' share decreases with more consumption of plant-based foods such as fruits, vegetables, pulses, and nuts By 2050, the average daily calorie consumption/cap reaches to 2663 kcal and is: 300 g/cap/day for cereals 400 g/cap/day for dairy milk 21 g/cap/day for vegetable oils 31 g/cap/day for added sugars 91 g/cap/day for red meat (pork and beef) 625 g/cap/day for fruits and vegetables 116 g/cap/day for fish and poultry 17 g/cap/day for eggs 87 g/cap/day for pulses and nuts 200 g/cap/day for roots 2 g/cap/day for animal fat Source: based on conversations with stakeholders from the public sectors
Share of food consumption which is wasted at the household level (%)	No change in the current state of food loss and waste. Constant share of food waste after 2010	Regulatory frameworks, R&D and investment for improved storage and processing, and consumer awareness drastically reduce food loss and waste in 2050 by 50% compared to the share in 2010. However, a breakthrough in technology may be required for a 50% reduction in food loss and waste (Searchinger et al. 2018)
Biofuels: Targets on biofuel and/or other bioenergy use	Assume a no change (stable biofuel demand as 2010)	OECD-AGLINK Scenario, moderate growth in the supply of biofuels from agriculture. By 2050, biofuel production accounts for: 4109 kt of wheat production 4107 kt of corn production 12,187 kt of sugar beet production 8854 kt of rapeseed production
Biodiversity: Protected areas (% of total land)	Better management of PAs. PAs are extended to 17% of terrestrial and inland water by 2030 and remain stable afterward	Protected areas are extended to 30% of terrestrial land by 2030 and remain stable afterward. These additional areas are protected to make them unavailable for agricultural expansion

Instrument	Baseline scenarios	Sustainable food system scenarios
Population	SSP1: Incentives to influence demographics in the direction which is supposed to improve the sustainability of the system. 12.8 million population is projected	
GDP growth	SSP1: Medium level of economic growth with a focus on environment sustainability and resource efficiency	
Land constraints on agricultural expansion	Free expansion of productive land under the total land boundary. No constraint on the expansion of agricultural land outside beyond existing protected areas and under the total land boundary	
Afforestation	No active afforestation. 28 million ha forest areas will be maintained by 2050	
Climate change: Crop model and climate change scenario	By 2100, global GHG concentration leads to a radiative forcing level of 2.6 W/m^2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilization effect	

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Data availability Data were derived from the FAOSTAT Statistical Database, available at https://www.fao.org/faostat/en/#home. Additional information was collected from the Swedish Board of Agriculture available in the public domain: Statistical Database at https://jordbruksverket.se/om-jordbruksverket/jordbruksverketsofficiella-statistik/statistikdatabasen.

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