Agroecological practices in combination with healthy diets can help meet EU food system policy targets

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Abstract:

Agroecology has been proposed as a strategy to improve food system sustainability, but has also been criticised for using land inefficiently. We compared five explorative storylines, developed in a stakeholder process, for future food systems in the EU to 2050. We modelled a range of biophysical (*e.g.,* land use and food production), environmental (*e.g.*, greenhouse gas emissions) and social indicators, and potential for regional food self-sufficiency, and investigated the economic policy needed to reach these futures by 2050. Two contrasting storylines for upscaling agroecological practices emerged. In one, agroecology was implemented to produce high-value products serving high-income consumers through trade but, despite 40% of agricultural area being under organic management, only two out of eight EU environmental policy targets were met. As diets followed current trends in this storyline, there were few improvements in environmental

indicators compared with the current situation, despite large-scale implementation of agroecological farming practices. This suggests that large-scale implementation of agroecological practices without concurrent changes on the demand side could aggravate existing environmental pressures. However, our second agroecological storyline showed that if large-scale diffusion of agroecological farming practices were implemented alongside drastic dietary change and waste reductions, major improvements on environmental indicators could be achieved and all relevant EU policy targets met. An alternative storyline comprising sustainable intensification in combination with dietary change and waste reductions was efficient in meeting targets related to climate, biodiversity, ammonia emissions, and use of antibiotics, but did not meet targets for reductions in pesticide and fertiliser use. These results confirm the importance of dietary change for food system climate mitigation. Economic modelling showed a need for drastic changes in consumer preferences towards more plant-based, agroecological and local foods, and for improvements in technology, for these storylines to be realised, as very high taxes and tariffs would otherwise be needed.

1. Introduction

Agroecology as a strategy to improve food system sustainability has been proposed by major influential institutions (FAO 2018a; IPCC 2019; HLPE 2019). Within the European Union (EU), both the Farm-to-Fork strategy (EC 2020a) and the Biodiversity Strategy (EC 2020b) also highlight the importance of agroecological approaches. Agroecological farming practices include crop-livestock integration, low-input management, reliance on local resources and diversification (Altieri & Rosset 1996). Despite recent attempts to define and describe it more closely (FAO 2018b; Wezel *et al.* 2020), agroecology comes in many forms and context-specific implementations (Bezner Kerr *et al.* 2021; Lampkin *et al.* 2020; Gallardo-López *et al.* 2018). It can be interpreted as a science, a social movement and a set of practices (Wezel & Soldat 2009). The current EU regulation on organic production (EU 2018) is an example of a formalised implementation of farming based on agroecological practices that has had some success. However, implementation rates have been modest; the average proportion of land under organic practices in the EU in 2019 was only 8.5% (ranging from approximately 0.5% in Malta to 25% in Austria) (Eurostat 2021).

However, agroecology and organic production systems have also been criticised for being non-viable on a large scale (Connor & Mínguez 2012; Connor 2018; Smith *et al.* 2019). This is because agroecological farming systems are more land-demanding due to lower yields and the common practice to 'grow' nitrogen (N) using leguminous crops, rather than relying on externally supplied N in the form of synthetic fertilisers. Fuchs *et al.* (2020) highlighted the risk of greening EU agriculture using agroecology, suggesting that this might displace production elsewhere, leading to increased impacts in other world regions. Nevertheless, Muller *et al.* (2017) demonstrated that organic production on a global scale can be feasible in terms of land availability *if* coupled with demand-side mitigation options, including dietary change and waste reduction. Other studies have confirmed these findings, *e.g.* Erb *et al.* (2016) and Theurl *et al.* (2020) found that many options exist to meet global food demands by 2050 without deforestation, even with low crop yields. Billen *et al.* (2021) looked at Europe specifically and demonstrated that implementing agroecological practices in combination with dietary change can feed the projected European population by 2050, while halving current N losses to the environment. Studies like these are useful as they show the 'option space' available, especially regarding the feasibility of upscaling agroecological farming practices, and highlight the need for demand-side changes and for external N inputs. However, they only consider biophysical factors and disregard socio-economic aspects. Moreover, the interplay between socio-economic drivers and social desirability is beyond the scope of biophysical modelling studies.

Scenario development and other foresight activities provide a structured way of thinking about the future and can enable effective decision making (Wiebe *et al.* 2018). Scenarios are descriptions of plausible and possible futures that help investigate outcomes of different actions implemented today or in the future. Engaging stakeholders in scenario development can increase the relevance and salience of future scenarios and bring in aspects of social desirability (Kok *et al.* 2007). There have been a number of scenario development initiatives covering the food system (https://www.foresight4food.net/ provides a compilation; see also Zurek *et al.* 2021). To name a few, FAO (2018a) presents three influential global scenarios (Business As Usual, Towards Sustainability, and Stratified Societies), which describe different future developments in terms of food production and consumption in different regions of the world. Mora *et al.* (2020) developed global scenarios with particular focus on nutrition and health, while Mitter *et al.* (2020) developed five qualitative storylines for EU agriculture building on the Shared Socio-economic Pathways (SSPs) (Riahi *et al.* 2017) in close cooperation with stakeholders.

Few previous scenario studies have dealt specifically with agroecology. An exception is the study by Karlsson *et al.* (2018), who together with stakeholders designed a future food vision based on organic farming for the Nordic countries and modelled the outcomes of this vision in terms of land and energy use, greenhouse gases (GHG), foods produced, and N and phosphorus (P) flows (Karlsson & Röös 2019). On the European level, Poux & Aubert (2018) developed and modelled a scenario in which dietary change allowed for reduced yields and thus widespread implementation of agroecology, which reduced GHG emissions by 40% while maintaining export capacity, conserving natural resources and restoring biodiversity. As agroecology is now being promoted at EU level (EC 2020a; CoR 2021) and by individual member states (*e.g.* the Swedish Food Strategy; GOS 2017) and by a range of non-government organisations (Food, Farming & Countryside Commission, 2021), it is important to further investigate possible future consequences of large-scale implementation of agroecology.

In this paper, we present five explorative qualitative storylines, developed in a stakeholder process, for future development of food systems in the EU to 2050. For each scenario, we used two biophysical mass-flow and nutrient models to model outcomes in terms of land use, food production, a range of environmental and social indicators and potential for regional food self-sufficiency, and compared these outcomes to relevant EU-level policy targets. The biophysical models follow thermodynamic principles and do not pursue optimization routines based on economic reasoning, and hence are able to model the environmental implications of counterfactual scenarios, which are far from current economic equilibriums. Based on the physical outcomes of the five storylines, we then considered the type of economic policy needed to achieve these futures by 2050. The overall aim of the work was to provide policy-relevant information on the environmental and economic effects of applying agroecological practices on a large scale. The study makes a novel contribution to current food system scenario research by integrating qualitative agroecologically focused storylines with biophysical and macroeconomic modelling.

The remainder of this paper is divided into five parts, describing: development of the five qualitative storylines (section 2), biophysical modelling to determine the impacts of the storylines at the global, EU (here the EU25 excluding Malta and Cyprus but including the United Kingdom), country and NUTS2-region scale (section 3), benchmarking of results against current policy targets (section 4), and macroeconomic modelling to identify the economic policies needed to achieve the biophysical outcomes (section 5). Finally, we discuss our findings in section 6.

2. Storylines

2.1 Development of storylines

Storylines formed the qualitative context (*i.e.* narrative) in which quantitative outcomes from our modelling work should be interpreted. Storylines need to be salient (*i.e.* relevant to the policy question and stakeholders), explore a range of plausible futures, credible (*i.e.* scientifically sound and consistent) and legitimate (*i.e.* societally accepted and transparent) (Pérez-Soba & Maas 2015; Rounsevell & Metzger 2010). To ensure that our storylines met these criteria, they were developed in an iterative and transparent manner in a process involving a wide range of EU-level and local stakeholders and project partners, representing knowledge and views from 13 EU member states, Switzerland and the UK (see Röös *et al.* (2021) for details). The well-established matrix approach (Rounsevell & Metzger 2010) was applied to create the storylines. In this approach, two major uncertainties concerning the system under study are identified and drawn out along two axes, forming a scenario cross. The axes create four quadrants, in which storylines consistent with the characteristics of the axes are developed. The axes used here were: 1) the level of implementation of agroecological farming practices, and 2) localisation of the food system (*i.e.* level of trade within the EU and globally) (Fig. 1). These emerged in stakeholder workshops as key uncertainties and drivers of development of the EU food system. The storylines were drafted by the authors and discussed and refined during stakeholder workshops and through written feedback (Röös *et al.* 2021).

Five storylines for the year 2050 emerged (Fig. 1). *Business-as-usual* extended the dynamics and critical aspects of current agri-food systems into the future, while *Agroecology-for-exports* depicted a future in which policy and market actors promote the agroecological approach as a marketing strategy. In the third quadrant of the scenario cross, two storylines arose. Both were based on more localised food systems being given priority over agroecological farming practices, but for different reasons. In *Localisation-for-protectionism*, rising nationalism and protectionism demanded further re-nationalisation of agricultural production and policies, while in *Localisation-for-sustainability* the ambition was to increase food system sustainability by cutting food miles and diversifying local production systems. Finally, *Local-agroecological-food-systems* reflected implementation of more advanced stages of agroecological transition, called 're-design'. While the *Localisation-for-sustainability* storyline relied more on the route of ‘sustainable intensification’ and advanced technology for achieving sustainability, *Local-agroecological-food-systems* differed by embracing ‘strong’ agroecological practices. Strong agroecological practices in this context are biodiversity-based solutions that require a re-design of current farming systems, in contrast to weak practices which are mainly limited to improved efficiency and precision in the use of inputs and replacing synthetic chemicals with organic variants (Guisepelli *et al.* 2018; Prazan & Aalders 2019). Summaries of the storylines are given in section 2.2 and the full storylines can be found in the Supplementary Material S1.

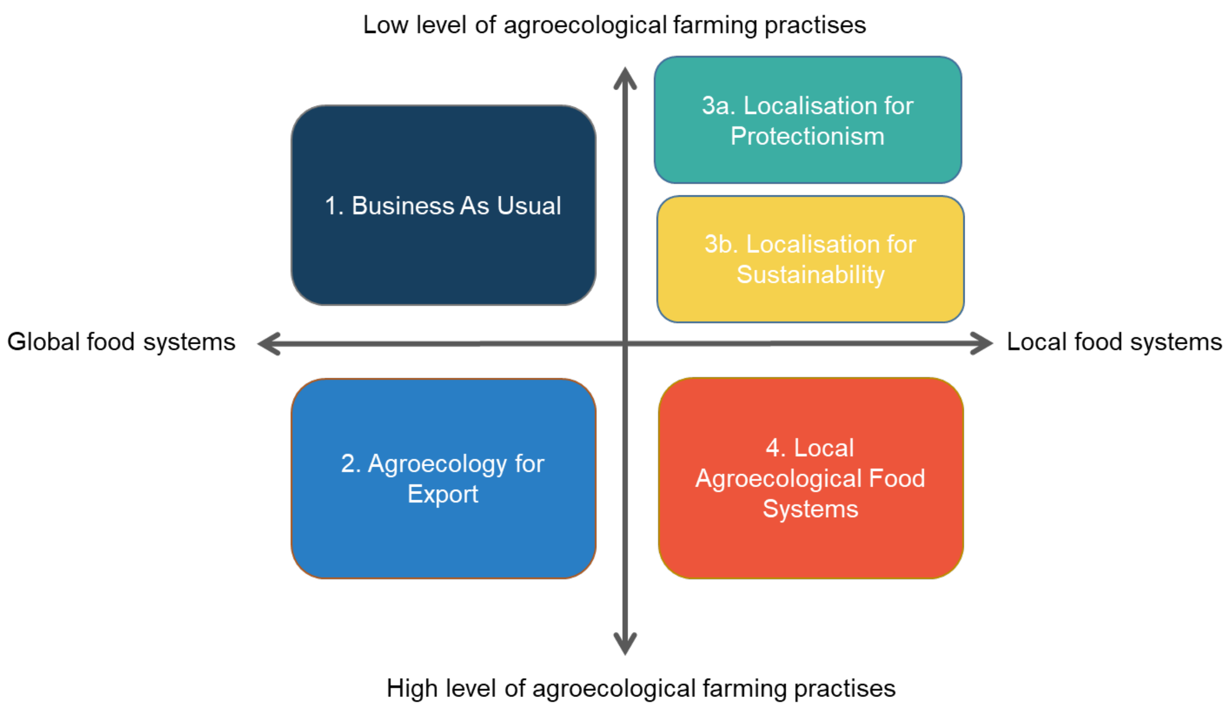

Fig. 1. *Scenario cross and the five storylines developed in this study.*

2.2 Storylines

2.2.1. Storyline 1: Business-as-usual

Business-as-usual describes a future in which globalisation of the EU food system continues and implementation of agroecology is low. Farmers are incentivised to produce commodities at the lowest possible cost, with corresponding effects on specialisation and benefiting from economies-of-scale, but at the expense of the environment. Trade increases among EU member states and between the EU and global markets, and specialisation of production in different regions continues. A few multinational food industries and retailers dominate the global food market. On a global level, there is weak cooperation between international and national institutions, the private sector and civil society. The structure of the EU agricultural policy remains similar to the current Common Agricultural Policy (CAP) and continues to drive agricultural production towards specialised, large-scale and export-oriented agricultural production. Although the CAP includes support for *e.g.* organic production and other agroecological practices, there is large variation in the implementation rate of such policies between countries and efforts are uncoordinated. Although there is an ambition at the EU level for more agroecological practices, these are only half-heartedly supported by most national governments. There is weak or no policy targeting demand (*e.g.* consumption taxes, labelling, nudging *etc.*) in EU member states. Production trends continue according to current trends, with slight decreases in agricultural area and increases in cereal, poultry, dairy, and intensive beef production. Food waste levels remain similar to current levels or decrease somewhat in countries in which waste reduction policies are implemented. Diets are not substantially changed, but follow current trends.

2.2.2. Storyline 2: Agroecology-for-exports

In the *Agroecology-for-exports* future, the focus is on competitive markets, innovation and participatory societies, with the goal of achieving sustainable development through rapid technological progress and diffusion. Integration of global markets continues, leading to high levels of international trade. The increased global wealth leads to the adoption of resource- and energy-demanding lifestyles by the growing global middle-class, as developing countries follow the resource- and fossil energy-demanding development in industrialised countries. Food systems, like other sectors, have become increasingly globalised, with high trade both within the EU and across the globe. In the EU specifically, strong support and investment in organic farming, following the goals set up in the Farm-to-Fork Strategy (EC 2020a), have led to a large increase in land managed with (weak) agroecological practices. Although the initial ambition in the Farm-to-Fork Strategy was to promote organic production to reduce environmental pressures, the main driver has gradually changed to using agroecological approaches (in this future interpreted as organic farming) as a means to produce high-value foods for trade between EU member states, but also for exports to the newly affluent economies with a rapidly growing upper and middle class. The focus is on banning the use of pesticides in organic production, to prevent potential negative effects on human health. Most agroecological farming systems resemble current mainstream organic practices and tend to be of the 'substitution' rather than the 're-design' variant. Eating patterns develop according to current projections, staying rich in meat and other resource-intensive food products. A highly segmented food market is evident in this storyline, in which agroecological products are consumed by the highly educated segment of the population and exported outside the EU, while the majority consume conventional low-quality food. Food waste levels remain similar to current levels or decrease somewhat in countries where waste reduction policies are implemented.

2.2.3. Storyline 3a: Localisation-for-protectionism

The *Localisation-for-protectionism* storyline reflects a development in which nationally or locally produced foods, regardless of production methods, are prioritised in the EU. Investment in agroecological farming systems is low. Global trade wars, recurring pandemics starting with the COVID-19 situation in 2020 and global political tendencies for less international cooperation and increased competition between regions strengthen belief in the importance of self-sufficiency in food supply. In the wake of this, some EU member states have put policies in place to promote more national food production, based on arguments like supporting local farmers and/or reducing the dependency on imported foods, *e.g.* in preparedness for supply interruptions due to conflicts or trade wars. Member states keep agriculture strongly protected and financially supported. Member states manage to keep up with international competition mainly through protective trade policy, but also through consumer demand for domestic products. On the demand side, most countries implement policies to promote consumption of local foods. There are increasing numbers of publicly funded projects and initiatives to support local production, including labelling schemes and policies to support short supply chains. In terms of agricultural production in the EU, the focus is on increased output of bulk commodities and continued growth of the agricultural sector, primarily to supply member state populations. Local production is prioritised over implementing agroecological practices or other more sustainable ways of farming, which are often seen as inefficient use of land. Major investments in local food processing facilities, locally adapted machinery and production of agricultural inputs such as fertilisers, pesticides and machinery have been made in many countries to enable local food systems. Most citizens continue to eat a highly environmentally impacting diet, with high levels of animal products, as there are few consumer side policies in place to steer consumption in a different direction and as investment and support for intensive livestock production continue. Food waste decreases slightly due to somewhat higher food prices.

2.2.4. Storyline 3b: Localisation-for-sustainability

In the *Localisation-for-sustainability* storyline, local food systems do not arise for reasons of nationalism and protectionism, but rather as an outcome of a deliberate policy goal of creating sustainable and resilient food systems. Supporting local food production to sustain and develop rural communities is an important socio-economic sustainability goal that is given high priority in this narrative. The main difference between this and the *Local-agroecological-food-system* storyline (see section 2.2.5 and S1.5), which also includes a transition to local food systems, is that *Local-agroecological-food-systems* has a strong focus on agroecological food systems, including more ’nature’-based practices and re-design of agricultural systems. *Localisation-for-sustainability* focuses on the localisation aspects and relies more on technical solutions to achieve sustainability, i.e. it is more aligned with the ‘sustainable intensification’ perspective of agriculture (Godfray 2015). For example, in this storyline, using mineral N fertilisers produced using renewable energy would be seen as a sustainable practice. In line with the sustainable intensification perspective, further deforestation or cultivation of grassland is heavily regulated in this storyline. Agroecological practices have not increased from current levels and are dominated by weak practices. A prerequisite for ‘pursuit of a sustainable and resilient localised food systems’ is a shift in diets to increased seasonality, determined by local availability of foods. Depending on location, eating patterns in the EU then stratify. In southern Europe, climate change-induced droughts drive up the price of crops and the economic viability of feeding cereals to livestock diminishes, so diets become mainly plant-based, i.e. vegan and vegetarian diets become the norm. In northern Europe, the variation in climate conditions increases markedly, making the availability of fruits, vegetables, and cereals more volatile. Increased use (and dependence) on low-cost grazing on marginal lands makes milk and ruminant meat more abundantly available, however. Additionally, rapid technological advances introduce an array of novel food products, stemming from sources with low environmental impact.

2.2.5. Storyline 4: Local-agroecological-food-systems

A rapid increase in climate and environmental concerns among large population groups in the EU and fierce campaigning for stricter policies to prevent climate and environmental breakdown drive change in the *Local-agroecological-food-systems* storyline. This integrated approach to EU food security presented in the Farm-to-Fork Strategy (EC 2020a), rather than the silo approach of separate agricultural, environmental and health policies, has been largely adopted by most member states by 2028. The strategy's high ambitions for organic farming (goal of 25% of total farmland in 2030) spurs investment and interest in agroecological transitions. Different types of alternative food systems expand rapidly, including different types of community-supported agriculture and short supply chain/direct sales online systems. The CAP is now handled under the umbrella of the integrated food policy and has radically changed by 2050. Most importantly, support for industrial livestock holdings has been abolished and major investments have gone into improving the productivity of smaller agroecological farms and supporting transition to agroecological farming. Greater consumer awareness is achieved by coherent marketing campaigns and dissemination of clear, accurate and complete information about the benefits of agroecological production systems for society. By 2050, on average across member states, 20-50% of land is farmed with strong agroecological practices, serving mostly local markets. Industrial pig and poultry holdings have drastically decreased, as consumer support for such systems has been heavily reduced by increased awareness of animal welfare, antibiotic resistance and risks of zoonosis. Ruminant populations are not affected to the same extent, as these can be incorporated into agroecological farming systems more easily. However, many intensive ruminant production systems are re-designed to be grass-based, with animal numbers adjusted to local land availability. The concept of locally adapted agroecological food systems in this storyline also involves striving for more healthy and sustainable consumption patterns. This includes a view that excess intake of “unnecessary” foods, excess consumption of livestock products, especially from animal species consuming human-edible feed (*i.e.* pigs and poultry), and excess intake of food in general is a waste and should be prevented by powerful policy measures. As a result of the action put in place in many areas on production, consumption and waste reduction, diets are drastically changed to more sustainable, mainly plant-based, diets, although in some countries where consumption of ruminant products is currently low, the consumption of beef and dairy from grass-based systems is increased, replacing some of the monogastric products.

3. Biophysical modelling

3.1 Biophysical models

We used two biophysical mass- and nutrient-flow models, BioBaM (version BioBaM-GHG 2.0; Kalt *et al.* 2021; Muller *et al.* 2020) and SOLm (Muller *et al.* 2017; 2020; Röös *et al.* 2021), to model the biophysical outcomes and some socioeconomic indicators of the different storylines. The model outputs include: (1) area of agricultural land used in different regions, (2) amounts of crop and livestock biomass produced in different regions to meet demand, (3) 'potential land feasibility', (4) the N deficit, thus addressing the challenge of potential N undersupply in agroecological systems (Connor 2018; Barbieri et al. 2021; Morais et al. 2021), (5) GHG emissions from agricultural production, including energy use, production of inputs and land use change, (6) biodiversity pressures, (7) the net trade between EU regions and member states and rest of the world (RoW), (8) producer value, labour use and labour productivity, and (9) animal welfare. The models were calibrated with data on land availability and yields from FAO (2020), Eurostat (2021) and the Common Agricultural Policy Regionalised Impact (CAPRI) model (Britz & Witzke 2015; Kempen & Witzke 2018). The baseline reflected the situation in 2012, and thus consisted of a mix of conventional and organic systems in a region, *i.e.* the yields per NUTS2 region were the average yields for organic and conventional systems combined. This baseline was chosen for consistency across the different data sources that were used as input to the models, *e.g.* grassland areas and yields, the CAPRI data on livestock diets. The latest FAO (2018a) scenarios were used as the starting point and further geographical detail was added for the EU, including agroecological practices. For developments in the RoW, we used input data and factors for the business-as-usual scenario from FAO (2018a), complemented with data from Erb *et al.* (2016) and Kalt *et al.*

(2021). For simplicity, developments in RoW were held constant in the modelling across all storylines. Hence, we investigated the consequences of different developments in the EU in a context in which RoW followed the business-as-usual scenario in FAO (2018a), meaning that preferences and values of consumers and policy makers in the rest of the world remain unchanged even if these change drastically in the EU.

In BioBaM, the EU is divided into 227 regions (NUTS2), thus enabling detailed spatial assessment and integration of land use change-induced impacts resulting from changes in production (*e.g.* use of agroecological practices or changes in food demand). BioBaM calculates changes in the flows of biomass from cropland and grassland and induced land use changes based on exogenously set population dynamics and diets (here following the storylines). When land is freed up as a result of decreased demand or increased productivity, it is assumed to revert to vegetation regrowth native to the region, leading to 'nature-based' carbon sequestration (Kreidenweis *et al.* 2016; Griscom *et al.* 2017).

In this study, potential land feasibility was calculated as the ratio between the area of land needed to supply demand in a region, using local yields and livestock efficiencies to determine the land demand, and the available land in that region considering allowed expansion of cropland according to the different storylines (section 3.2.1) (Table 1). The ratio is calculated separately for cropland and grassland, with the lower value determining the potential land feasibility (Kalt *et al.* 2021). That is, when calculating the potential land feasibility, what is currently grown in the region is not considered, but rather the BioBaM model looks at whether the local demand for food could potentially be satisfied by local production. Biodiversity pressures are captured by three different indicators: (i) total biomass appropriation, defined as the harvested biomass as a share of the potential net primary production (Haberl *et al.* 2007b), (ii) grazing pressure, *i.e.* grazing harvest as a percentage of the current vegetation (Petz *et al.* 2014), and (iii) heterogeneity of agricultural land use as captured by the Shannon index, a proxy for the supportive capacity of agroecosystems to host biodiversity (Mayer *et al.* 2021).

The SOLm model follows a similar approach, but relies on more detailed modelling of agronomic aspects of production systems (*e.g.* for animal production systems with herd structures and correspondingly differentiated feed supply, nutrient excretion and emissions) (Muller *et al.* 2017; 2020; Röös *et al.* 2021). We used SOLm to complement the outputs from BioBaM with results on: (i) additional indicators of resource use (use of energy, pesticides and irrigation water), (ii) additional environmental indicators (N surplus, water scarcity and ammonia emissions), and (iii) socio-economic indicators (use of antibiotics in livestock production, labour use, producer value and labour productivity). Producer value is derived using the production quantities and the per unit primary product producer prices as provided by FAO (2020), reflecting farm-gate prices received by the farmers. SOLm also captures trade flows, which we used as inputs in macroeconomic modelling. Being a biophysical model, trade flows in SOLm are derived from trade flows as provided by the data for the baseline year; exports from each country then being adapted proportionally to changes in domestic production and source regions for imports being adjusted according to the trade clusters in the scenarios. The drawback of this approach is that it is not driven by market dynamics, which could allow us to derive prices directly, the advantage is that it is close to the baseline in relative trade-patterns and thus captures country specific aspects that are mirrored in these. The N surplus indicator captures the difference between total N inputs (mineral fertiliser, manure production, other organic fertilisers, biological fixation and deposition) and outputs (N in crop and grassland biomass) from the agricultural production systems according to the OECD N balance (OECD 2019).

Other land uses (*e.g.* for fibre and biofuels), population and emission factors for energy use were held constant across the five storylines. Other land uses were set according to the FAO commodity balances as in 2012 (FAO, 2018a), population was assumed to follow a medium projection for population development (Fricko *et al.* 2017) and emissions from energy use corresponded to current levels (for emission factors used in BioBaM, see Kalt *et al.* (2021) and Muller *et al.* (2020)).

3.2 Parameterisation of the biophysical models

This section describes how the qualitative storylines were translated into concrete numeral input to the models (see Table 1 for a summary).

3.2.1 Cropping

The storylines differed in terms of how and to what extent agroecological farming practices were implemented. In *Business-as-usual*, *Localisation-for-protectionism* and *Localisation-for-sustainability,* it was assumed that there was no change in the diffusion of such practices from the baseline, *i.e.* implementation of agroecological practices reflected the situation in 2012. In *Agroecology-for-exports*, 75% of fruits, vegetables and nuts for the EU market were assumed to be produced using organic practices, while 100% of fruits, vegetables and nuts for export to RoW were assumed to be organic (grown on surplus land not needed for supplying the EU food demand). For all other crops, organic practices were assumed to be used on 20% of available land in this storyline. For *Local-agroecological-food-systems*, a diffusion rate of agroecological practices of 50% for all crops in 2050 was assumed.

A yearly increase in conventional crop yields following FAO (2018a) was assumed. These yield changes accounted for expected negative impacts on yields from climate change. We implemented weak agroecological practices as organic farming, assuming yield gaps based on Ponisio *et al.* (2015). In addition, in organic crop rotations, legumes were assumed to be included every four years to supply nitrogen. A smaller yield gap, 50% of the gap in Ponisio *et al.* (2015), was assumed for strong agroecological practices, as we assumed these to allow for external N fertiliser additions, such as mineral fertilisers, in cases where legumes (grown every four years) do not provide the amounts of N needed.

The storylines also differed in the extent to which cropland was allowed to expand into grassland (with no expansion into forest allowed in any of the storylines) in cases where the available 2012 domestic cropland was not sufficient to cover demand. In *Business-as-usual,* cropland was allowed to expand by up to 20% compared with the 2012 cropland extent in each region (if sufficient grassland suitable for cropping was available). In *Agroecology-for-export* and *Localisation-for-protectionism*, cropland was allowed to expand by up to 70% if enough land suitable for cropping (*i.e.* highly productive grassland) was available in the region, in accordance with the focus on increased agricultural production and de-emphasised environmental concerns. However, in *Agroecology-for-export*, expansion was only allowed to cover demand in Europe and not to provide additional commodities for export. In *Localisation-for-sustainability* and *Local-agroecological-food-systems*, no expansion of cropland was allowed.

Table 1. Model inputs used in biophysical modelling of the different storylines

	1. Business-as-usual	2. Agroecology-for-exports	3a. Localisation-for-protectionism	3b. Localisation-for-sustainability	4. Local-agroecological-food-systems
CROPPING					
Share of land under agroecological practices	As in 2012 (5.7% in organic production on average)	75/100%[a] of high-value crops (fruits, veg, nuts), 20% for all other crops	As in 2012	As in 2012	50% of cropland under agroecological practices (all crops equally)
Crop yields conventional	FAOSTAT 2012 with productivity increases [b]				
Crop yields agroecology	NA	Organic yields. i.e. yield gaps according to Ponisio *et al.* (2015)	NA	NA	Agroecological yields, *i.e.* 50% of the Ponisio *et al.* (2015) yield gap
Nitrogen supply	Synthetic fertilisers	Biological fixation (legumes every fourth year)	Synthetic fertilisers	Synthetic fertilisers	Biological fixation (legumes every fourth year) complemented with synthetic fertilisers
Cropland expansion	Maximum 20% expansion, if suitable land available	Maximum 70% expansion, if suitable land available	Maximum 70% expansion, if suitable land available	Not allowed	Not allowed
LIVESTOCK					
Livestock diets	As in 2012 CAPRI (EU), Herrero *et al.* (2013) for RoW with yearly productivity improvements	'Intermediate' ruminant production; 10% reduction in efficiency for monogastrics on average	As in 2012	As in 2012	Ruminant diets entirely grass-based, 10% reduction in efficiency for monogastrics on average
Distribution of livestock	According to current patterns	According to cropland and grassland availability across the EU	According to cropland and grassland availability within the country	According to cropland and grassland availability within the country	According to cropland and grassland availability within the country
Maximum grazing intensity	Max. sustainable level (Erb *et al.* 2016)	Max. sustainable level (Erb *et al.* 2016)	+10% from Business-as-usual	-10% from Business-as-usual	-20% from Business-as-usual

DIETS AND WASTE					
Dietary patterns	FAO BAU projection[c]	FAO BAU projection[c]	FAO BAU projection[c]	Strict average EAT-*Lancet* diet[d]	EAT-*Lancet* diet[d] with higher share of beef and dairy
Ruminant / monogastric meat	As in FAO BAU projection	As in FAO BAU projection	As in FAO BAU projection	Strictly according to the EAT-*Lancet* diet (d)	50% of monogastric meat in the EAT-*Lancet* diet (d) replaced with ruminant meat and dairy
Waste levels	As in 2012	As in 2012	Reduced by 15%	Reduced by 50%	Reduced by 50%
TRADE					
Trade clusters	Global trade, no restriction	EU-trade first, then RoW	Country wide trade first, then EU then RoW	Country wide trade first, then EU then RoW	Country wide trade first, then EU then RoW

[a]75% for the EU market, 100% for exports.
[b]FAO 2018a; Table S2.1.
[c]FAO 2018a; Business-as-usual scenario.
[d]Willett *et al.* 2019.

3.2.2 Livestock production

Livestock diets from CAPRI were assumed for the EU (Britz & Witzke 2015), and livestock diets from Herrero *et al.* (2013) for RoW. Annual efficiency gains of 0.1% for the Global North and 0.24% for the Global South were assumed for all livestock species (Fricko *et al.* 2017). These livestock diets were used for *Business-as-usual, Localisation-for-protectionism* and *Localisation-for-sustainability*.

In *Agroecology-for-exports*, the mix of conventional and organic ruminant production was modelled as an 'intermediate intensity' production system in which the amount of feed produced from cropland was heavily reduced (by between 46% and 96% across countries). In *Local-agroecological-food-systems*, ruminants were assumed to be entirely grass-fed. For both these storylines, it was assumed that conventional systems still dominated production of monogastric animals, but that agroecological practices with lower feed conversion ratios increased slightly (modelled as an overall reduction in feed conversion ratio for monogastrics of 10% in both cases).

For *Business-as-usual*, livestock production was distributed spatially according to current patterns and scaled linearly with demand. For the three storylines based on localisation, livestock production was re-distributed across the country based on the availability of cropland and grassland. For example, if ruminant production in a region needed to increase due to an increase in demand for meat and dairy and no further grassland was available in that region, ruminant production was moved to another region within the country with grassland available, and similarly for cropland and monogastric production. For *Agroecology-for-export*, following its emphasis on trade, redistribution of livestock production across the whole of the EU was assumed. Grazing intensities were assumed to remain below maximum sustainable thresholds (Kalt *et al.* 2021; Erb *et al.* 2016; Haberl *et al.* 2007a) in *Business-as-usual* and *Agroecology-for-export*. In *Localisation-for-protectionism*, grazing was allowed to intensify to deliver more local foods, while in *Localisation-for-sustainability* and even more so in *Local-agroecological-food-systems*, maximum grazing intensity was reduced to protect biodiversity.

3.2.3 Diets and waste

In *Business-as-usual*, *Agroecology-for-exports* and *Local-for-protectionism*, the diets followed FAO (2018a) per country business-as-usual projections, *i.e.* they only changed slightly from 2012 diets. In *Local-for-sustainability* and *Local-agroecological-food-systems*, due to their sustainability focus, diets were assumed to change drastically to align with the EAT-*Lancet* reference diet, defined as a healthy diet whose environmental impacts have the potential to stay within planetary boundaries (Willett *et al.* 2019). The major food groups (grains, vegetables *etc.*) were assumed to be the same as in EAT-*Lancet* in all countries, but type of *e.g.* grains and vegetables depended on what was historically (2012) grown in the region. In *Local-for-sustainability*, the amount of foods followed EAT-*Lancet* strictly, while in *Local-agroecological-food-systems*, 50% of monogastric meat was replaced by ruminant meat and dairy, reflecting the role of ruminants in making use of grassland (van Selm *et al.* 2022). See Fig. S3.1 and Table S3.1 for percentage changes in consumption of the major food groups.

In the two sustainability-focused storylines, *Local-for-sustainability* and *Local-agroecological-food-systems*, food waste and losses were reduced by 50%. In *Local-for-protectionism*, food waste and losses were reduced by 15%, while in the other two storylines they remained at current levels.

3.2.4 Trade

In *Business-as-usual*, we assumed that the crop production shares of each country remained similar to the base year. In cases in which the 2012 land availability was not sufficient to meet local demand, commodities to supply the EU with food were assumed to be sourced from any country globally with unused cropland available. Thus, if there are global increases in cereal consumption (and thus production to cover this consumption), the EU was also assumed to increase total production in regions with land available. However, for livestock production, the EU was assumed to produce only the animal products needed in RoW that could not be produced beyond the EU without land expansion. This assumption was applied across storylines and, since production and consumption in RoW were kept the same across storylines, net exports (*i.e.* the global deficit) of animal products were the same for all storylines.

In *Agroecology-for-exports*, deficits in EU regions were assumed to be covered by production within the EU in the first instance. If EU regions had spare cropland after meeting local demand, they were assumed to utilise this land for production of export goods (fruits, vegetables and nuts) using organic practices. These exports of organic products from the EU did not replace other production in RoW, as these products were considered luxury crops consumed in addition to projected consumption. In the three localisation storylines, supply from within the respective country was prioritised over imports from other countries. Deficits in regions beyond the EU (as a result of decreased exports from the EU) were first covered by surplus production in RoW. If these RoW regions could not provide sufficient biomass, EU regions were assumed to produce for export.

3.3 Results from biophysical modelling

3.3.1 Land use

In all storylines, including those in which livestock consumption and food waste levels stayed high (according to current trends), the use of cropland and grazing land was reduced as a result of increases in yields and livestock productivity and land was freed up for vegetation regrowth (Fig. 2a; Table S3.1). However, in *Agroecology-for-exports* this effect was minor, as surplus land, *i.e.* land available after meeting EU demand, was used to produce for export. Most land was freed up in *Localisation-for-sustainability*, with 29% of cropland and 72% of grazing land used in 2012 released for other uses as a result of drastic changes to diets and waste. In *Local-agroecological-food-systems* this effect was not as strong, as this storyline favoured ruminant livestock, which are more land-demanding, over monogastrics and only 13% of grazing land was freed up. However, grazing in this storyline was extensive and, despite its large-scale use of land, it could be beneficial for biodiversity (Dumont *et al.* 2009).

Localisation-for-protectionism gave similar results in terms of land use as *Business-as-usual*, because diets were the same across these storylines (Fig. 2a). However, slightly more land was freed up in *Localisation-for-protectionism* as livestock were distributed within the country, grazing was intensified and waste was slightly reduced compared with *Business-as-usual* (Table 1). Under the assumption of demand in RoW developing according to business as usual in all cases, decreases in exports from the EU increased production in RoW, and hence use of agricultural land. For all storylines, cropland use outside the EU increased by 9-17% (Table S3.1). However, global grazing land decreased by approximately 13% as a result of ruminant livestock productivity increases.

Thus despite the need for more cropland abroad, the need for total agricultural land globally decreased by 5-7% (Table S3.1).

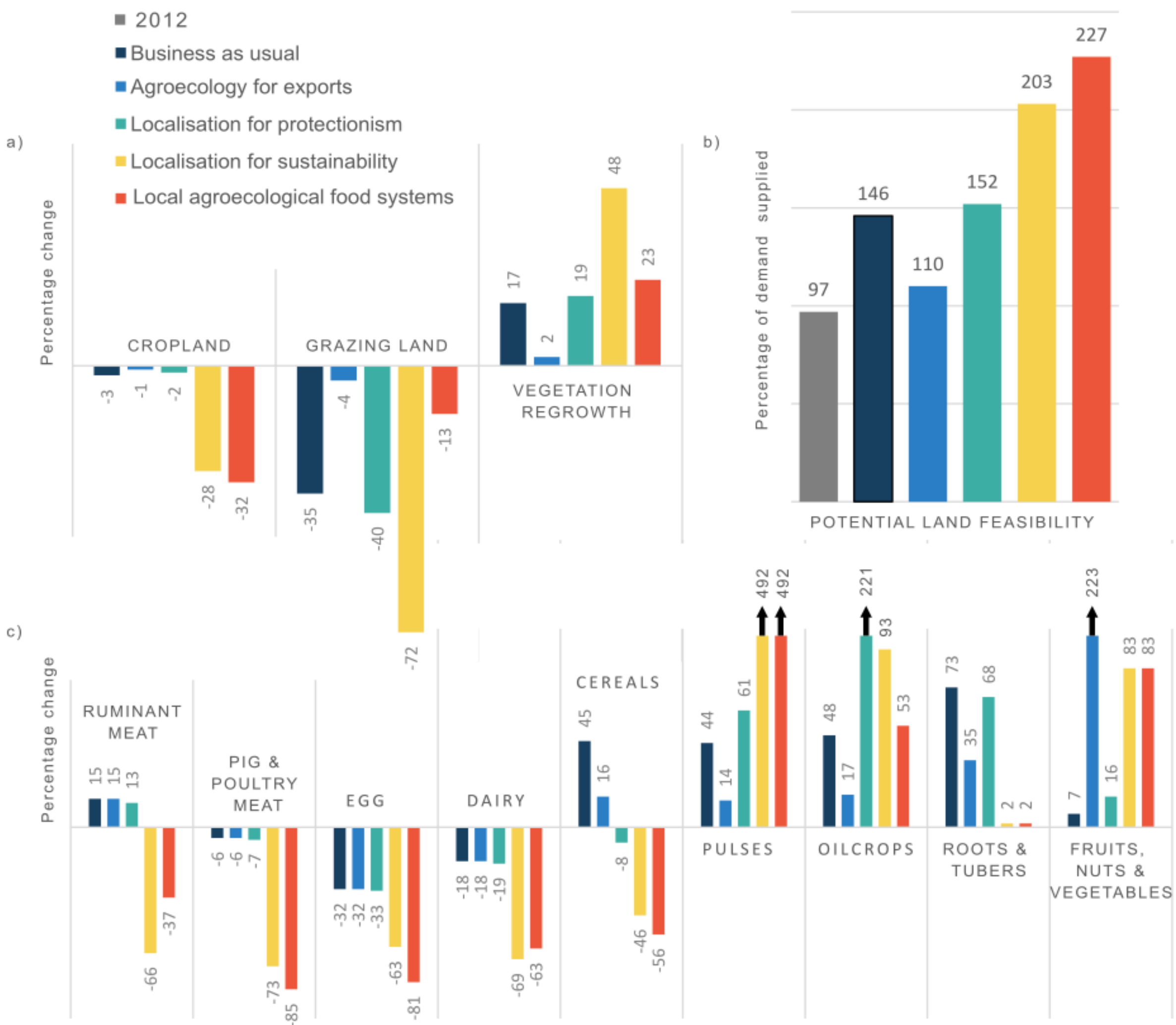

Fig. 2. *(a) Percentage change in cropland and grazing land and percentage of total agricultural land available for vegetation regrowth across scenarios, (b) potential land feasibility in the European Union (EU), i.e. the extent to which available agricultural land in 2012 can theoretically support local demand, and (c) percentage change in EU production of a number of main commodities in the different scenarios.*

3.3.2 Food production

Ruminant meat production in the EU increased by 13-15% in the storylines in which diets developed according to projected trends (*Business-as-Usual, Agroecology-for-exports* and *Localisation-for-protectionism*), driven by increases in demand within the EU and RoW. Production of monogastric meat, egg and dairy declined (by 6-7%, 32-33% and 18-19%, respectively) in these three storylines, due to reductions in exports, with more global production taking place in RoW (Fig. 2c). Production volumes were somewhat lower in *Localisation-for-protectionism*, due to slightly decreased food waste (15%) (Table 1). There were drastic reductions in livestock production in the two storylines in which diets changed to align with the EAT-*Lancet* diet (*Localisation-for-sustainability* and *Local-agroecological food systems*). Ruminant meat production decreased by 66% in the *Localisation-for-sustainability*, but by considerably less in *Local-agroecological food systems* (37%), where 50% of monogastric products were replaced with ruminant products.

Production of most crops increased in all storylines. However, for storylines in which diets aligned with the EAT-*Lancet* diet, production of cereals decreased as a consequence of decreased demand for feed for monogastrics. In *Business-As-Usual,* production of cereals increased by 45%, oil crops by 48%, roots and tubers by 73% and fruits and vegetables by 9% (Fig. 2c). Holding country-level production shares constant at 2012 levels when global demand increased meant that production was scaled up for all crops in all regions until there was no more available land. Hence, production in the EU expanded beyond the EU demand to also supply increased amounts to RoW. There were drastic increases in pulses (almost 500% corresponding to approximately 8% of cropland) in the storylines in which diets aligned with the EAT-*Lancet* diet, as plant protein replaced animal protein.

Large increases in production of oil crops were also seen for storylines in which food production was localised (*Localisation-for-protectionism*, *Localisation-for-sustainability* and *Local-agroecological food systems*), as the EU currently imports large amounts of oil crops. Hence in a future relying on local production, substantially more oil crops would have to be grown in the EU, using up to almost a fourth of cropland. This presents a major challenge in terms of the availability of land to grow *e.g*. rapeseed in reasonable rotations to avoid plant pests and diseases (Bajželj *et al.* 2021). In *Agroecology-for-exports*, production of fruits, vegetables and nuts increased substantially (223%) following the strategy of using excess land for exporting high-value organic products. In *Localisation-for-sustainability* and *Local-agroecological-food-systems,* production of these crops also increased substantially (83%), following a doubling in EU consumption (Fig. S3.1). The way in which production of animal products and crops changed for different member states is shown in Table S5.1 and S5.2, respectively.

3.3.3 Potential land feasibility

The potential land feasibility (the ratio between the area of land needed to supply demand in a region and the available land in that region considering allowed expansion of cropland; section 3.1) of regions and countries in the EU depended on cropland and grassland availability and on diets, which determined the demand for food and feed. In 2012, the availability of land in the EU was close to matching the area of land needed to meet the EU population biomass demand, as the potential land feasibility was 97% (Fig. 2b).

At the aggregated EU level and for all storylines, potential land feasibility was higher than in 2012 due to productivity gains and/or changes in diets, while the population in the EU remained nearly constant. In *Business-As-Usual*, potential land feasibility was nearly 146%, due to yield and livestock productivity increases. In *Agroecology-for-exports* it was a little lower (110%), due to a 20% implementation rate of agroecological farming practices, and hence lower yields. Potential land feasibility in *Localisation-for-protectionism* was similar (152%) to that in *Business-as-usual*, as in both these storylines there were no drastic dietary changes but increases in yields and livestock productivity (Fig. 2b). However, in *Localisation-for-protectionism*, grazing intensity increased (*i.e.* more ruminant meat and milk could be produced from grazing land) and food waste was slightly reduced, so potential land feasibility increased for most countries. In *Localisation-for-sustainability* and *Local-agroecological-food-systems*, potential land feasibility was highest among all storylines (203% and 227% respectively), because of drastically reduced biomass demand from aligning EU diets with the EAT-*Lancet* diet. In these storylines, extensification of grazing land, and hence a reduction in food produced from this land, was feasible without impairing potential land feasibility.

On a national level, in 2012 only 11 out of the 26 member states assessed had sufficient land to potentially support national demand, with potential land feasibility ranging from 36% for Portugal to 217% for Denmark (Table S6.1). With increases in productivity, land feasibility increased for all member states in all storylines except *Agroecology-for-exports*. However, in *Business-as-usual* eight member states still did not achieve land feasibility and in *Localisation-for-protectionism* it was not achieved by six member states. In *Localisation-for-protectionism*, potential land feasibility was 44% higher than in *Business-as-usual* for some countries (Croatia, Ireland and Slovenia) due to reduced food waste, higher cropland expansion allowance and higher grazing intensity (Table S6.1).

For the two storylines based on futures with more localised food systems and drastically changed diets (*Localisation-for-sustainability* and *Local-agroecological-food-systems*), all but four countries (Belgium, the Netherlands, Portugal, the UK) achieved land feasibility. For *Agroecology-for-exports*, potential land feasibility showed very varying results for different countries (Table S6.1). For some countries, *e.g.* Denmark, Germany and Sweden, there were drastic reductions in potential land feasibility due to higher shares of agroecological crop production and a shift away from concentrate feeds towards by-products and grass for ruminants. Since diets remained comparable to current levels, meeting this demand required more land which, ceteris paribus, reduced potential land feasibility. Potential land feasibility was substantially higher than in *Business-as-usual* only for countries such as Ireland, due to shifts in ruminant diets towards more grass-based feed and thus less fodder demand from cropland. The potential land feasibility at the sub-national scale (NUTS2) is shown in Fig. 3.

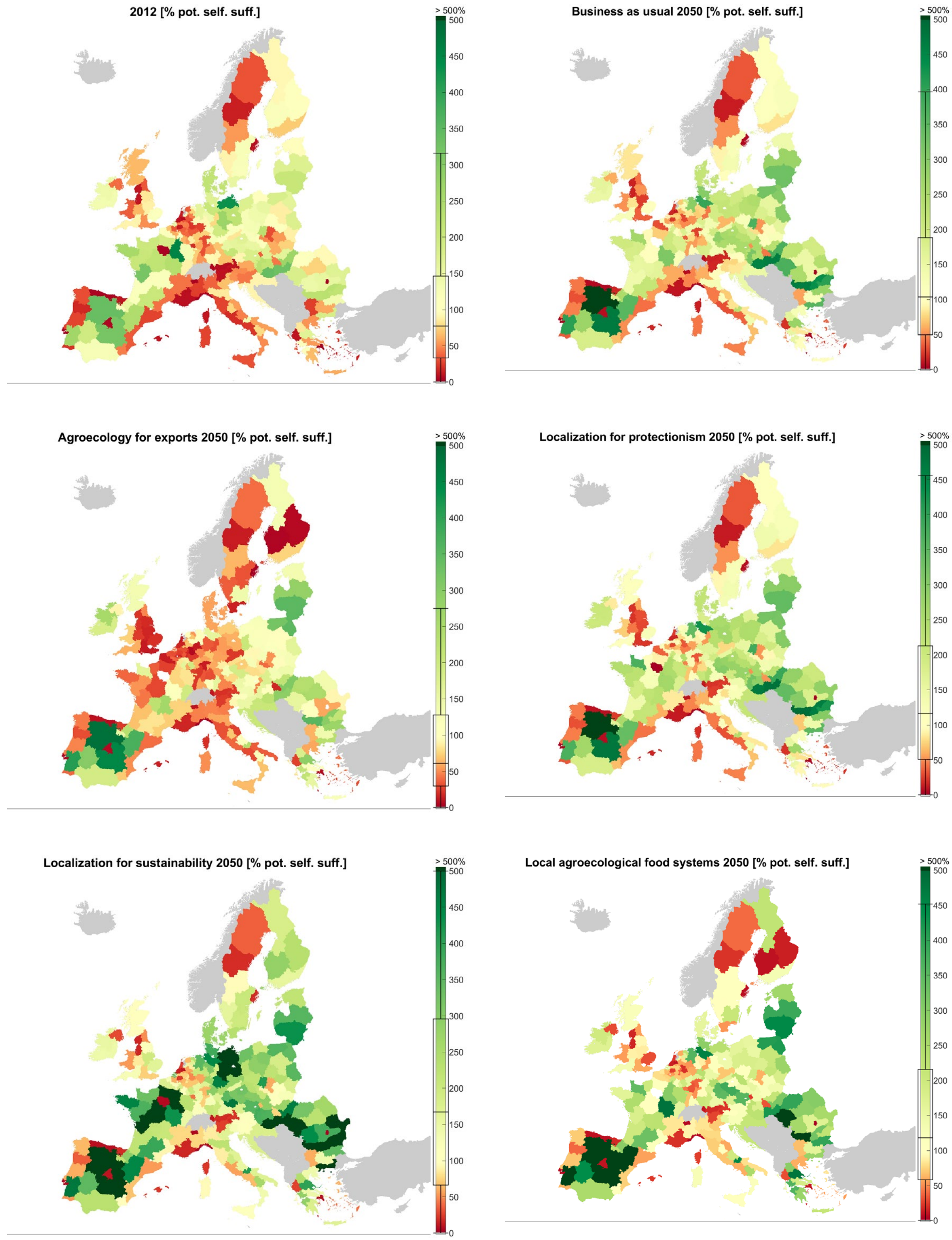

Fig. 3. *Potential land feasibility (the ratio between the area of land needed to supply demand in a region and the available land in that region considering allowed expansion of cropland) in sub-regions (NUTS2) across the different storylines.*

3.3.4 Environmental impact

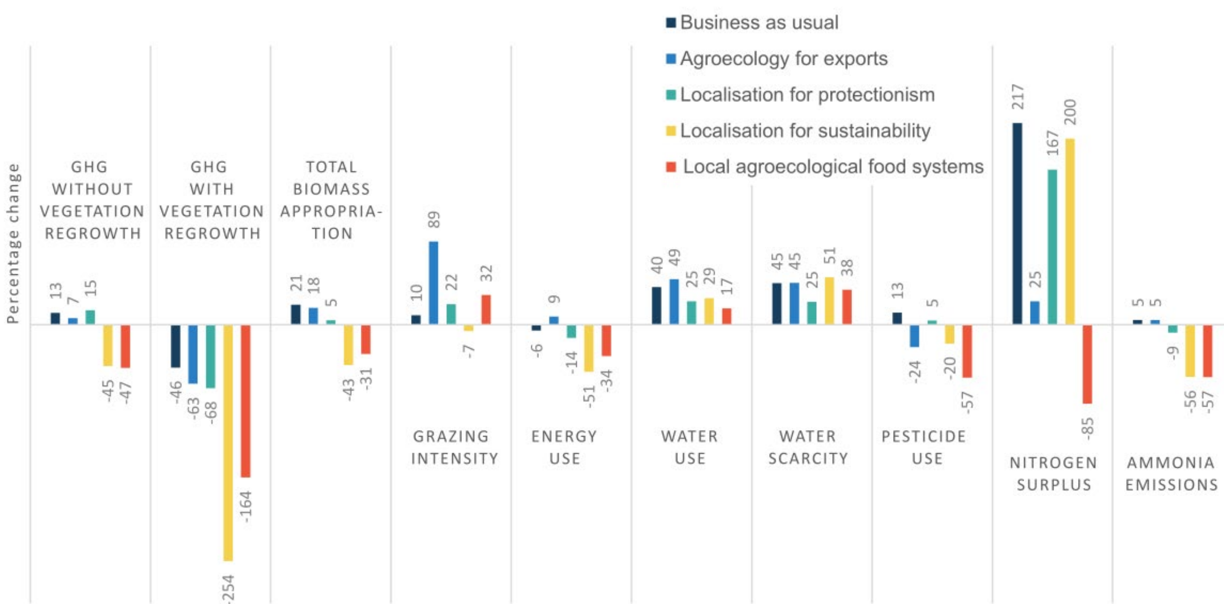

Fig. 4. *Environmental impacts of the storylines in relation to the baseline year 2012.*

For all storylines in which diets did not change substantially, GHG emissions increased somewhat (to 588 Mt CO_2e for *Business-as-usual*, 558 Mt CO_2e for *Agroecology-for-exports* and 603 Mt CO_2e for *Localisation-for-protectionism*, from 522 Mt CO_2e in 2012; Fig. S7.1). In *Localisation-for-sustainability* and *Local-agroecological-food-systems,* emissions were drastically reduced, to 290 and 279 Mt CO_2e, respectively, due to reductions in overall demand and hence lower production volumes. Vegetation regrowth on freed land enabled carbon sequestration so that 52%, 66% and 72% of emissions were offset in *Business-as-usual, Agroecology-for-exports* and *Localisation-for-protectionism*, respectively. In *Localisation-for-sustainability* and *Local-agroecological-food-systems,* vegetation regrowth made these futures net-negative in terms of

GHG emissions from agriculture (Fig. S7.1). However, under the assumption that food consumption will not deteriorate from current trends of increased demand in RoW and that foregone production in the EU must be replaced by production outside the EU, global emissions still increased from 2012 and were more similar across storylines (Fig. S7.2).

Different cropping patterns across the storylines drove differences in energy use and, to a lesser extent, the share of organic production. Water use and water scarcity increased in all storylines due to increased production of irrigated crops, such as fruits or vegetables (Fig. 2c). The increase in water use was smaller in *Localisation-for-protectionism* than in *Business-as-usual*, explained by reductions in food waste with corresponding lower overall production levels and by the shift in crop production patterns between regions with different water scarcity levels. In *Agroecology-for-exports*, production of irrigation-intensive crops such as fruits, vegetables and nuts explain the higher water use. In *Localisation-for-sustainability* and *Local-agroecological-food-systems*, water use increased due to the need for irrigation of oil crops, pulses, fruit, vegetable and nuts, despite large reductions in overall crop production, which referred here to largely non-irrigated crops (cereals). Water scarcity was determined by location of production. In *Localisation-for-sustainability*, water scarcity was higher than in *Agroecology-for-exports* as the focus on local food led to production of water-demanding crops in water-scarce areas, while in *Agroecology-for-exports* increased production of fruits, vegetables and nuts also increased in places where water was more abundant.

Pesticide use increased somewhat in *Business-as-usual* and *Localisation-for-protectionism* due to higher production volumes. The most important driver of pesticide use was the share of organic production, explaining the decrease in storylines with large shares of agroecological production (*Agroecology-for-exports* and *Local-agroecological-food*-systems). However, pesticide use also decreased in *Localisation-for-sustainability,* as a result of decreased overall production volumes following changes in diet. Regional production patterns also played an important role, *i.e.* whether or not production increases occurred in regions with generally higher pesticide use levels per hectare.

In *Business-as-usual*, increasing intensification continued with yet more N inputs per unit output, a pattern which persisted in all storylines with low shares of agroecological practices. The N surplus was considerably reduced in *Agroecology-for-exports*, due to the higher share of organic production with corresponding reductions in mineral fertiliser use. The effect was even greater in *Local-agroecological-food-systems*, where the high share of agroecological production resulted in an 85% reduction in the N surplus compared with 2012 (Fig. 4). Reductions in ammonia emissions in *Localisation-for-sustainability* and *Local-agroecological-food-systems* resulted from drastic reductions in livestock production in these storylines.

In terms of indicators for impacts on biodiversity, total biomass appropriation followed total production volumes, while grazing intensity showed greater variation across scenarios (Fig. 4). It was highest for *Agroecology-for-exports* as biomass demand remained high (no substantial changes to diets) and ruminant livestock was increasingly grass-fed. Grazing intensity also increased in *Local-agroecological-food*-systems compared with the 2012 level, although meat consumption was reduced drastically. In that storyline the share of ruminant meat was higher, as ruminant products were favoured over monogastric meat, while in *Localisation-for-sustainability* the amounts of meats followed the EAT-*Lancet* reference diet strictly, with more poultry and less ruminant meat, which also decreased the grazing pressure below 2012 levels.

In 2012, most regions showed a medium level of heterogeneity, with lower diversity in the UK in Northern Europe (Fig. 5). In *Business-as-usual* and *Agroecology-for-exports*, the Shannon index decreased, indicating lower heterogeneity, due primarily to further intensification and continuation of the current specialisation in *Business-as-usual*, and to the strong focus on high-value products for exports in *Agroecology-for-exports*. In *Localisation-for-protectionism* and *Localisation-for-sustainability*, heterogeneity increased moderately and more significantly, respectively, compared with 2012. Since domestic demand was the major driver of agricultural production in these two storylines, this led to a more diverse set of crops, increasing the heterogeneity of agricultural production. *Local-agroecological-food-system* showed the most pronounced heterogeneity of all scenarios, reaching an average EU-wide Shannon index of over 70 (Fig. 5).

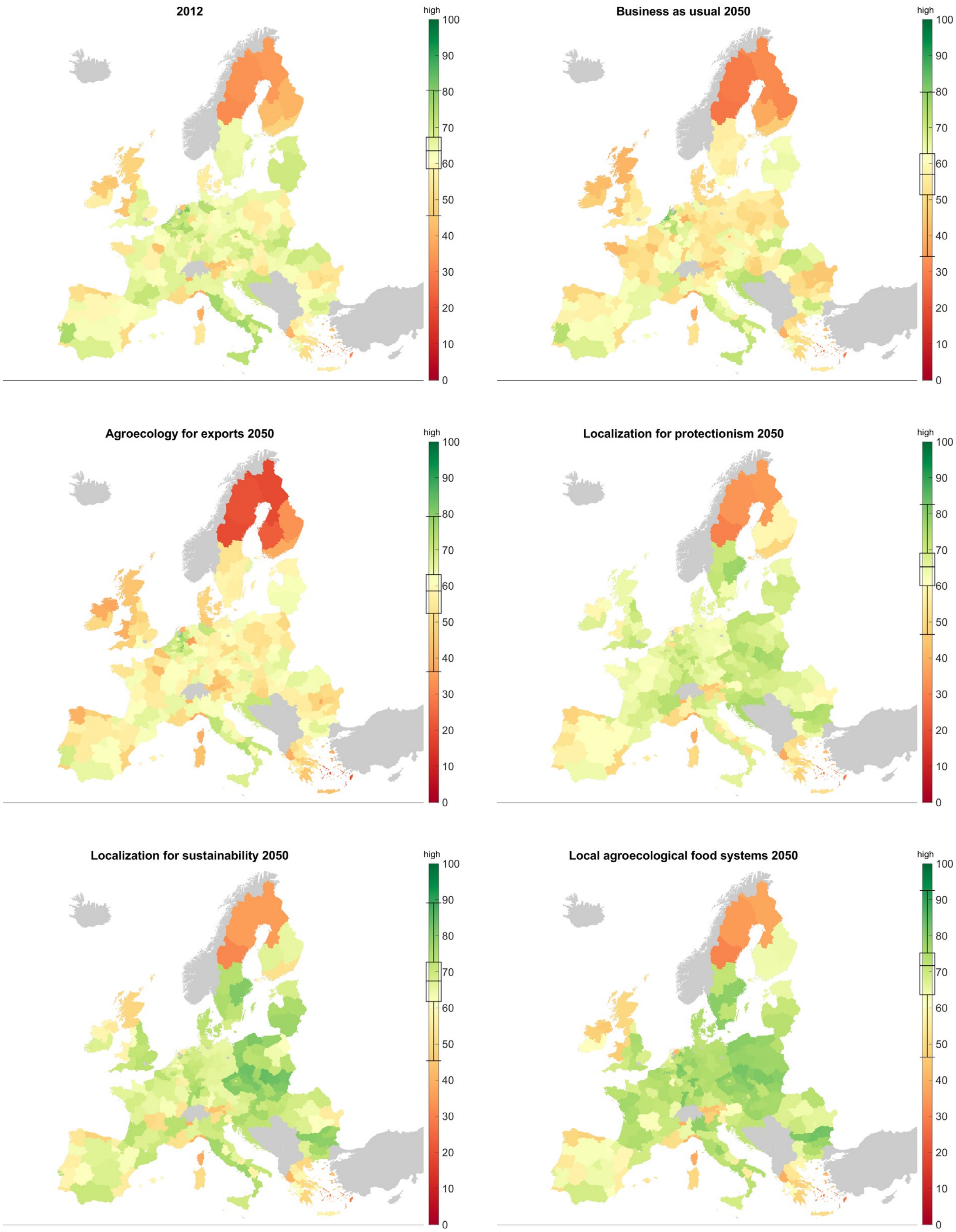
2012
Business as usual 2050
Agroecology for exports 2050
Localization for protectionism 2050
Localization for sustainability 2050
Local agroecological food systems 2050
high
100
90
80
70
60
50
40
30
20
10
0

Fig. 5. *Heterogeneity of agricultural land use per region in the different storylines, calculated as Shannon Index based on 14 agricultural land uses (11 cropland uses, 3 grassland uses). A high score represents high heterogeneity.*

3.3.5 Socio-economic consequences

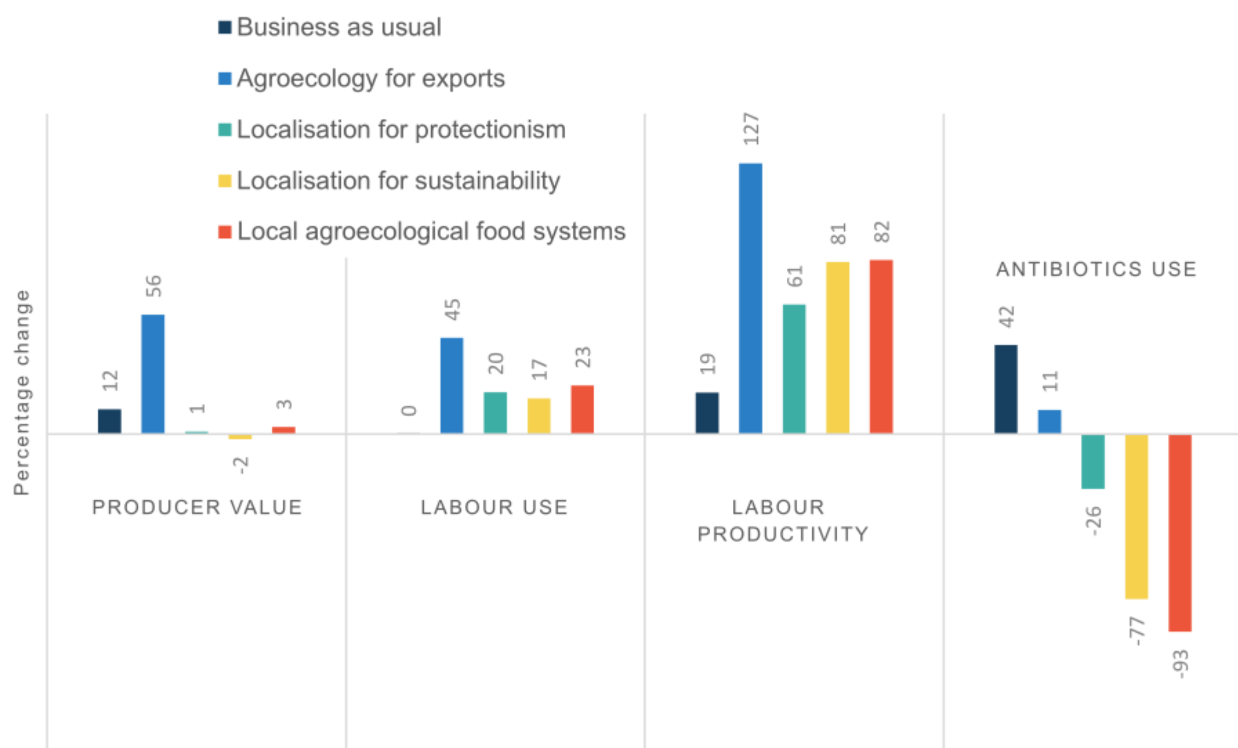

Fig. 6. *Percentage change in socio-economic variables in the different storylines in relation to the baseline year 2012.*

In *Agroecology-for-exports*, the increase in high value and labour intensive products (fruits, vegetables and nuts) led to overall higher producer value and labour use, in such proportions that the labour productivity also increased (Fig. 6). To a small extent in this storyline and to a very pronounced degree in storylines with lower livestock numbers, the labour productivity results were driven by a shift from the livestock to the crop sector. In general, the drop in labour use and producer value in the livestock sector was compensated for by developments in the cropping sector. For antibiotics use, the differences between storylines reflected differences in intensity and animal numbers, given that the indicator was built on a per-head antibiotics use value multiplied by the number of living animals. For example, in *Local-agroecological-food-systems*, the reduction was driven by reduced animal numbers and a shift from more antibiotic-intensive monogastrics to ruminants. Regional differences in intensity and antibiotics use affected the results, with reductions in overall antibiotics use in *Localisation-for-protectionism* explained by livestock production being moved to areas with less intensive livestock rearing. It also has to be emphasised that the antibiotics use index for 2050 does not account for any potential improvement in antibiotics use, *e.g.* in the course of implementation of the Farm to Fork (EC 2020a), or national policies.

4. Benchmarking against policy targets

In order to benchmark the outcomes of the different storylines, we compared the results from the biophysical modelling with established or proposed policy targets (Table 2). For climate change, the EU 2030 Climate Target Plan, set in place in September 2020, established the ambition of the EU to reduce overall GHG emissions to at least 55% below 1990 levels by 2030. The 2030 Climate Target Plan will be amended to the EU Climate Law, which aims for the EU to be climate-neutral by 2050 (EU 2021). In the current climate framework, there are no specific EU or national targets for the reduction in GHG emissions to be achieved in the agricultural sector specifically. Agricultural emissions are accounted for together with emissions from transport, buildings, waste and small industry, under what is called the Effort Sharing Regulation (ESR). The current EU target for 2030 in the ESR sector is a reduction of 30% from 2005 levels, with a proposed updated target of 40% (EC 2021a). For ammonia emissions, the National Emission Ceilings Directive 2016/2284/EU obliges EU member states to reduce their emissions by 19% by 2030 (EU 2016).

Key quantitative commitments in the EU Biodiversity Strategy for 2030 (EC 2020b), against which we benchmarked our results, include: a reduction in the use of pesticides by 50%; management of at least 10% of agricultural area as high-diversity landscape features (which was considered as freed-up land here); at least 25% of agricultural land under organic management; reduced fertiliser use by at least 20%; and planting at least 3 billion trees (we assumed that 1250 trees can be planted on one hectare of freed-up agricultural land and did not consider technical or economic constraints; EC 2021b). In addition to these goals, the EU Farm-to-Fork strategy includes a goal of reducing the use of antimicrobials in livestock production by 50% (EC 2020a).

Table 2. *Scenario outcomes in relation to 2030 policy targets. (Green = target met; dark red = target not met, light red = target not met, but reduction made)*

Policy area	Target	1. Business-as-usual	2. Agroecology-for-exports	3a. Localisation-for-protectionism	3b. Localisation-for-sustain ability	4. Local agro-ecological food-systems
Climate	30%[1] /40%[2] reduction in emissions	+12%	+6.9%	+15%	-44%	-47%
Ammonia	19% reduction at EU level	+5%	+5%	-9%	-20%	-57%
Pesticides	50% reduction in use	+13%	-24%	+5%	-20%	-57%
Organic production	25% of land under organic management	5.7%	40%	5.7%	5.7%	50%[3]
Fertiliser use	20% reduction in use	+64%	+20%	+58%	+11%	-21%
Biodiversity	10% of agricultural land freed	17%	2.4%	19%	48%	23%
Biodiversity/ carbon seq.	Planting of 3 billion trees	47 billion	7 billion	52 billion	133 billion	64 billion
Antimicrobials	Reduced use by 50%	+42%	+11%	-26%	-77%	-93%

[1]Current target (EC 2021a).
[2]Proposed updated target (EC 2021a).
[3]Not organic production in a strict sense according to current regulations, as some synthetic fertilisers are used.

5. Policy measures for realising the scenarios

5.1 Economic model

We investigated how the biophysical allocations in the respective storylines might be achieved through policy interventions, focusing on two aggregated regions: the EU and RoW. The EU was treated as a single region because it is a customs union and has harmonised its economic and trade policies in the agricultural sector via the CAP. Thus we studied how market-based policies (taxes and subsidies on production and consumption, import tariffs) could achieve the outcomes of the biophysical models, *i.e.* quantities produced, consumed and exported in each of the two regions, for each storyline. The model calculated market-based policies assuming no changes in consumer preferences or technology, but in reality such changes shift demand and supply (as detailed in the storylines) which would lessen the need for the policies in some cases. For instance, an increased preference for domestically produced goods would diminish the need for import tariffs.

We used a partial equilibrium model of production, consumption, and trade (Muth 1964) that has been used previously in many prominent studies on how policy interventions affect agricultural markets (Sumner & Wohlgenant 1985; Gardner 1987; Alston *et al.* 1995). For each storyline, the model found policies necessary to deliver farm-gate prices such that farmers produced the quantities stipulated by storyline, and consumer prices such that consumers purchased the stipulated quantities, while allowing for changes in trade flows. For details, see Supplementary Material S8.

The 2050 *Business-as-usual* storyline was taken as a baseline against which the other storylines were compared. We assumed that policies needed to reach 2050 *Business-As-Usual* were similar to the policy regime in 2012 and that technologies and consumer preferences were similar to those in operation today. The ad valorem import tariffs, consumption taxes/subsidies and production taxes/subsidies in each storyline thus represented changes relative to this baseline, expressed as a percentage of the *Business-as-usual* price. Note that a negative tax is the same as a subsidy.

In *Business-as-usual*, the policies that we considered, such as production subsidies and import tariffs, only made up a small part of EU support for farmers. The OECD Producer Support Estimate for the EU, an aggregate measure of transfers from government (CAP support) to producers covering all agricultural production, was 19% of gross farm receipts in 2020 (OECD 2021). Of these transfers, less than one fifth was in the form of price support such as production subsidies and import tariffs, whereas four-fifths were via income support, which does not directly affect commodity prices. However, some sectors such as poultry (28% of gross receipts), and beef and veal (13%) receive significant production subsidies, while others including dairy (32%) and sugar and confectionery (27%) benefit from significant protection through tariffs (WTO 2020).

5.2 Results from macroeconomic modelling

The economic modelling revealed that if the outcomes in the storylines were to be achieved through market-based policy interventions alone, very strong measures would generally be needed (Table 3; Figures S9.1–S9.3). There was generally a need for high import tariffs to encourage local production, combined with production taxes to discourage production and exports. Consumption subsidies, which are positive in each storyline, counteract the negative impact of production taxes on consumption in order to align with the results from the biophysical model.

Table 3. *Policy instruments required to reach 2050 storylines compared to 2050 BAU, average across all food categories*

	Agroecology for exports	Localisation for protectionism	Localisation for sustainability	Local agroecological food systems
Tariff (%)	+53	+58	+33	+56
Consumption subsidy (%)	+13	+39	+1	+6
Production tax (%)	+24	+104	+69	+113

In Table 3, all of the numbers are percentages of the *Business-as-usual* price. For concreteness, assume that the average price of food in *Business-as-usual* is 100 euro per ton, after allowing for the effects of existing policy (*i.e.* any tariffs, consumption subsidies, and production taxes that may exist in this storyline). Then a production tax of +104 indicates that, on top of existing policy, taxes of 104 euro per ton are paid by producers. Assume that in *Business-as-usual* producers are subsidised at a rate of 20 euro per ton. Then the net production tax will be 84 euros per ton.

Regarding the effect of the policy instruments on prices, since we assumed a high price elasticity of supply, changes in farm-gate prices were rather modest, even when the storylines called for large changes in production quantities. On the other hand, changes in consumer prices were much greater due to low elasticities of demand, consistent with existing literature showing the difficulty of shifting food consumption patterns (Powell & Chaloupka 2009; Smed *et al.* 2016).

5.2.1. Agroecology-for-exports

In the *Agroecology-for-exports* storyline, the focus was on competitive markets, albeit with a focus on within-EU trade over trade with RoW, and innovation for sustainable development. There was strong support for organic farming as a means to produce high-value foods (fruit, nuts and vegetables), both for domestic consumption and export. Eating patterns developed according to current projections, staying rich in meat.

In this scenario, substantial increases in import tariffs compared with *Business-as-usual* were required by 2050 (Table 3). The average tariff increase across the 12 food categories was 53%. This was needed as the EU was more self-sufficient in this scenario due to the EU trade cluster, which prioritised production in the EU over imports from RoW. At the same time, consumption subsidies averaging 13% were required, whereas production was subsidised for nuts and vegetables and taxed for all other products (except vegetables) (Fig. S9.3). The production subsidies for nuts and vegetables were needed to enable exports in the scenario, *i.e.* the production subsidies kept the prices competitive on global markets. These subsidies would have to be combined with regulations to ensure organic production methods, which is similar to the payments for organic production that currently exist under the CAP. However, in this scenario we assumed more rapid innovation in these sectors than in *Business-as-usual*, an innovation that should reduce costs and the need for production subsidies.

5.2.2. Localisation-for-protectionism

Localisation-for-protectionism involved protective trade policy and increased consumer demand for domestic products. On the production side, the focus was on increased outputs of bulk commodities and continued growth of the agricultural sector, primarily to supply national populations. The result was a dramatic increase in production of oil crops and a fall in cereal production due to the need to rectify the current situation in which large volumes of oil crops are imported while cereals are exported.

The average tariff increase needed across the 12 food categories was 58% compared with *Business-as-usual*, which was very similar to *Agroecology-for-exports* (Table 3). This calculation assumed unchanged consumer demand, but in the *Localisation-for-protectionism* storyline demand for domestic products increased; the larger this increase, the smaller the need for a tariff. The shift away from imports led to higher food prices in the EU, which encouraged production. However, production taxes were required for all goods, averaging 104% (Table 3). Finally, substantial consumption subsidies were required for most crops (except for cereals, root crops and tubers) if consumers were to maintain the assumed diet despite the higher prices which would otherwise result from the combination of higher tariffs and lower production subsidies, unless preferences for local products drastically changed.

5.2.3. Localisation-for-sustainability

Under *Localisation-for-sustainability*, local food systems arose as an outcome of a deliberate policy goal of creating sustainable and resilient food systems through 'sustainable intensification'. Hence there was no increase in agroecology, but a shift in diets to increased seasonality and local stratification. Rapid technological advancement also introduced an array of novel food products stemming from sources with low environmental impact.

As in the previous storyline, the emphasis on localisation led to a dramatic drop in cereal production and an increase in oil crops. Furthermore, there was a dramatic drop in production and consumption of animal products, due to their replacement with legumes, fruits, vegetables and nuts. In the economic model, these were achieved through large consumption taxes on milk and meat (and to a lesser extent cereals) and large subsidies on most plant-based foods were needed (Fig. S9.2), combined with large taxes on production to prevent production in the EU for international markets (Fig. S9.3). The average import tariff was 33% (Table 3), which was lower than in *Localisation-for-protectionism* because of the consumption taxes for some food categories, but necessary because international producers were also covered by the consumption taxes. With regard to animal products, these measures should be interpreted as a proxy for the large reductions that would be necessary in the prices of alternatives to milk and meat, combined with changes in consumer preferences for these alternative products. For nuts, oil crops, pulses and vegetables (where EU production increased) the reverse occurred, with consumption and production subsidies or levels of taxes increased compared with *Business-as-usual*. With regard to vegetables, consumption subsidies can be interpreted as increased preferences for these goods.

5.2.4. Local-agroecological-food-systems

In the *Local-agroecological-food-systems* storyline, support for industrial livestock holdings was abolished and major investments went into improving the productivity of smaller agroecological farms, as well as marketing agroecological food. Pig and poultry numbers decreased drastically, whereas ruminants were integrated into grass-based farming systems. Finally, diets became much more plant-based.

In terms of aggregate biophysical quantities, this scenario was quite similar to *Localisation-for-sustainability*, but with a large shift to agroecological production practices. If this shift were mandated by policy, it would imply raised costs and could therefore remove the need for a production tax, which (in the absence of the mandate) would be 113% on average (Fig. S9.3), the highest of all storylines. Furthermore, there would be large consumption taxes on cereals, milk, meat and eggs (Fig. S9.2) but, if there were a sufficiently large preference shift away from these goods, such high consumption taxes would not be necessary. As in the previous scenario, the key was a change in preferences for different foodstuffs, such as meat alternatives and vegetables.

6. Discussion and Conclusions

Two contrasting scenarios for upscaling agroecological practices were compared in this study. In the first, *Agroecology-for-exports*, agroecology was assumed to be implemented as a way to produce high-value products serving high-income consumers through trade. On the positive side, this could increase producer value and labour productivity (Fig. 6). However, despite 40% of the agricultural area being under organic management (far exceeding the Farm-to-Fork target of 25%), only two of the eight EU policy targets analysed were achieved (Table 2). As diets, and hence demand, followed current trends in this storyline, there were few improvements in environmental indicators compared with the current situation, despite large-scale implementation of agroecological practices (Fig. 4). Pesticide use decreased, but not enough to reach the target (Table 2). As land freed up through yield and livestock productivity increases was assumed to be used to produce more for export, this was the only storyline in which the biodiversity target to free 10% of agricultural land was not met. Hence, large-scale implementation of agroecological practices, without concurrent changes on the demand side and without regulations in place to prevent land freed up by increases in yield and livestock productivity being used for additional production, environmental pressures could be aggravated.

However, as illustrated by our second storyline with the emphasis on agroecology, *Local-agroecological-food-systems*, large-scale diffusion of agroecological practices alongside drastic dietary change and waste reductions would allow major improvements in environmental indicators to be achieved. This future was the only one considered here that met all relevant EU policy targets (Table 2). In summary, this illustrates that results highly depend on the assumptions employed to characterise agroecology. Sustainable intensification in combination with dietary change and waste reductions, as illustrated by *Localisation-for-sustainability*, was also effective in meeting targets related to climate, biodiversity, ammonia emissions and the use of antibiotics, but did not meet targets for reductions in pesticide and fertiliser use.

The quantitative EU policy targets for biodiversity (Table 2) only account for biodiversity that would benefit from land being freed up from agriculture, and do not consider farmland biodiversity for which organic farming has proven to be beneficial (Tuck *et al.* 2014). One of the drivers behind the higher biodiversity found on organic farmland is greater diversity in land uses, which we measured in this study using the heterogeneity of agricultural land use indicator (Fig. 5). Heterogeneity was greatest in *Local-agroecological-food-systems* as a result of both localisation, *i.e.* producing all types of crops needed for the local population, and more varied crop rotations in agroecological systems due to the need to grow leguminous crops for nitrogen supply.

In agreement with many previous studies, our results showed the importance of dietary change for climate mitigation (Theurl *et al.* 2020; Röös *et al.* 2017; Muller *et al.* 2017; Sun *et al.* 2022; Bowles *et al.* 2019). For both storylines in which diets were aligned with the EAT-*Lancet* reference diet with drastic reductions in total meat consumption (a reduction with 54-71% across member states in *Localisation-for-sustainability* and 62-78% in *Local-agroecological-food-systems*), GHG emissions in the EU almost halved. In addition, the land saving effect of this dietary change enabled a yearly carbon sink through natural vegetation regrowth of between 500-1100 Mt CO_2e, offsetting more than twice or up to four times the agricultural emissions. Similarly, Lee *et al.* (2019) concluded that, without such transformation of the food system, it is unlikely that Europe will be able to play its role in needed large-scale afforestation ambitions. However, competition for land for different uses (*e.g.* food production for export markets, bioenergy production, infrastructure *etc.*) is increasing, so ensuring that freed land is devoted to natural vegetation regrowth would require strong policies and might not be the preferred option when balancing many sustainability aspects.

The need for drastic changes in dietary patterns raised the question of practical feasibility. Our economic analysis showed that consumption taxes on meat of over 70%, in combination with high production taxes and import tariffs, would be needed to achieve the desired outcomes. The need for high taxes to considerably change consumption is in line with previous research on consumption taxes on food (Powell & Chaloupka 2009; Smed et al. 2016). A 70% tax on meat is comparable to excise duties applied in the EU on goods such as cigarettes, which must be set at a rate of at least 60% of the average retail selling price (Directive 2011/64/EU). A 70% meat tax would be similar in magnitude to the Norwegian sugar tax of 8.60 NOK/kg, implemented in 2017. A 70% meat tax would be several times higher than the EU minimum excise duty on petrol (0.359 EUR/litre, Directive 2003/96/EC). However, such high food taxes are scarcely politically feasible in the current situation in the EU, where food production is currently subsidised through the CAP. Although use of consumption taxes on food to mitigate climate impacts from the food system has been suggested and modelled in research (Säll & Gren 2015), such taxes have not entered into the political negotiations. The Farm-to-Fork strategy mentions that: "*EU tax systems should also aim to ensure that the price of different foods reflects their real costs in terms of use of finite natural* *resources, pollution, GHG emissions and other environmental externalities*." (EC 2020a). However, there is no further concrete information on how that should be achieved. An alternative to such high taxes (or perhaps a precondition for their acceptability) would be drastic changes in preferences towards more plant-based, agroecological and local foods, in order for the futures described in the storylines to be realised. It is still highly uncertain whether such changes in consumer preferences can be achieved, although policy could be used to create social tipping points (Nyborg *et al.* 2016). An aspect that could increase the acceptability of food taxes is the health gains that could also come from a transition to more plant based diets (Springmann et al. 2018). Large-scale diffusion of agroecological practices would also require a range of policy and actions from other food system actors, including initiatives that go beyond agricultural production to include processing and retail and develop the demand side (Wezel *et al.* 2018; Lampkin *et al.* 2020; Moschitz *et al.* 2021).

The extent to which the EU food system is localised or based on trade between member states and RoW was identified by our participating stakeholders as a major uncertainty and driver of development in the EU food system. A call for local food systems can come for several reasons. In response to increasing political instability and increased prioritisation of national interests, some EU member states have put in place policies to increase food self-sufficiency (*e.g.* Sweden; GOV 2017). Our results showed that most, but not all, EU countries can feed their population (Table S6.1), so achieving high self-sufficiency is not viable for all member states. There are mixed views and a long-standing debate on the usefulness of policies to support high levels of self-sufficiency. Proponents of such policies stress the importance of supporting domestic food production in order to be less reliant on global markets, but also to build national pride and contribute to rural development, while critics emphasise the high costs and inefficiency that result from making self-sufficiency a priority (Clapp 2017).

Participatory transdisciplinary research on transition of food systems has the potential to stimulate reflexive learning on the relevant plurality of underlying values, perspectives, assumptions and institutional and power structures (Den Boer *et al.* 2021). Participatory scenario development can enable researchers and practitioners to explore new perspectives on future food systems and to "think outside the box" in developing scenarios that are fundamentally different to the current agri-food system (Schwarz *et al.* 2021). This can help scientists to better incorporate a diversity of reflections and practices in their models and facilitate science-policy-society dialogue on the co-benefits and trade-offs, risks and opportunities associated with transition to agroecological food systems.

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Supplementary Material to

"Agroecological practices in combination with healthy diets can help meet EU food system policy targets"

Table of contents:

S1. Complete storylines

The storylines are also published in one of the deliverables of the Uniseco project (Röös *et al.* 2021). They are reproduced here with only editorial changes and some updated statistics. The storylines were designed to be aligned with the well-established Shared Socioeconomic Pathways (SSP) used in e.g. climate modelling (O'Neill *et al.* 2017). Each storyline thus begins with a reference to the global context as described by the scenario in which that storyline plays out.

S1.1. Storyline 1: *Business-as-usual*

Globalised food systems - current level of implementation of agroecological farming practices

Global context

The SSP2 scenario Middle of the Road provided the overall context for this storyline. In the SSP2 scenario, it is assumed that historical social, economic and technological trends are sustained, income growth develops unevenly and there is slow progress towards reaching sustainability goals (O'Neill *et al.* 2017). Technological developments are also modest and only slowly shared with developing countries. Low-income countries continue to experience food and water insecurity. There is a slow decrease in fossil fuel dependency and a growing demand for energy (SSP2).

Food system orientation and policy landscape

Based on this, the *Business-as-usual* storyline describes a future in which globalisation of the EU food system continues.[1] In this system, farmers are incentivised to produce low-value commodities, leading to further specialisation of farming systems and regions. Trade increases both among EU member states and between the EU and global markets; specialisation in production in different regions continues (SSP2). A few multinational food industries and retailers dominate the global food market. Diets and the range of products on offer become increasingly homogeneous, both within the EU and globally. Obesity levels continue to rise, as do associated health problems.

On global level, there is weak cooperation between international and national institutions, the private sector and civil society (SSP2). Access to global markets is slowly opening up for developing countries. The structure of the EU agricultural policy remains similar to the current Common Agriculture Policy (CAP) and continues to drive agriculture production towards specialised, large-scale and export-oriented agricultural production. The EU budget is somewhat decreased due to Brexit, but most member states push for keeping the EU agricultural budget constant and instead decreasing spending in other areas. The CAP structure is similar to that in place today; Pillar 1 has low requirements for greening. Although Pillar 2 includes support for *e.g.*

[1] The organisation of the EU food system in this scenario is well described by the Therond et al. (2017) socio-economic context for farming called "Globalised commodity-based food systems", in which increasingly efficient industrial processes are used to "*produce large amounts of food that are inexpensive, convenient, safe and attractive*".

organic production and other agroecological practices, variation in the implementation rate of such agro-environmental policies is large between countries and efforts are uncoordinated, due to further increasing freedom for member states to allocate CAP money. Although there is an ambition at the EU level for more agroecological practices (cf. the Farm-to-Fork Strategy), these are only half-heartedly supported by most national governments. There is constant discussion on the ability of agroecology to "feed the world" and a push from large multinational agro-chemical and seed companies to implement more industrialised types of agriculture. There is weak or no policy targeting demand in EU member states, such as taxes on unhealthy or high-impacting foods, restriction on advertisements and similar. These have been effectively counteracted by powerful lobbying groups.

Agricultural production and practices

Production trends are assumed to remain similar to the trends described by the EU Agricultural Outlook (EC 2017), which involves:

"• a continuation of current agricultural and trade policies;
• normal agronomic and climatic conditions;
• no market disruption".

In summary, the outlook is as follows: Utilised EU agricultural area will continue to decrease by 0.2% per year, reaching 172 million ha by 2030. Although total sugar consumption decreases by 5% by 2030 because of increased health concerns, total sugar production increases by 12% by 2030, making the EU a net sugar exporter. Cereal production also increases to 341 million tons by 2030, while oilseed production decreases due to decreased demand for biofuels. Production of feed is expected to rise due to increases in poultry, dairy and intensive beef production. Dairy exports to China are expected to increase considerably, with the EU supplying 30% of this increase in dairy products, mainly as cheese and skimmed milk powder. Dairy consumption increases also within the EU, to around 900,000 tons of milk per year, mostly consumed as cheese, other processed dairy products and included in convenience foods. Milk drinking decreases, however. Meat consumption per capita first increases slightly, but then decreases to current levels by 2030. Beef production decreases slightly, while pig meat production increases marginally (consumption in the EU stabilises and exports increase somewhat). Poultry meat production increases by 5% by 2030.

It is assumed in this storyline that the same trends continue beyond 2030 until 2050. Consumer interest in healthier and more sustainably produced foods, including organic foods and locally produced foods, increases somewhat in the EU. However, due to lack of major public investments in, or support for, the implementation of agroecological farming methods, production of these remains close to current levels on average (the share of organic farming area was 8.5% in 2019; EC 2021a) or increases slowly (reaching an average of somewhere between 10-15% of agricultural land in 2050), although with large regional variation. Certified organic products, produced using mainly weak agroecological practices, dominate the output from agroecological farming systems in the EU; these come in the form of high-value products like wine and other alcoholic beverages, fruits and vegetables, cheese and processed meats, jams and juice etc. sold in niche markets to high-income urban citizens, as well as cheaper bulk commodities sold in ordinary supermarkets. Diversity in crops produced in the EU is similar to current levels or somewhat further decreased (following trends in Kummu *et al.* 2020).

Diets and waste

Food waste levels remain similar to current levels or decrease somewhat in countries in which waste reduction policies are implemented. Diets are not substantially changed, but follow current trends.

S1.2. Storyline 2: *Agroecology-for-exports*

Globalised food systems - high level of implementation of agroecological farming practices in the EU

Global context

The SSP 5 scenario, Fossil-fuelled Development – Taking the Highway, formed the basis for this storyline. In this future, the focus is on competitive markets, innovation and participatory societies, with the goal of achieving sustainable development through rapid technological progress and diffusion, including geo-engineering if needed (O'Neill *et al.* 2017). Integration of global markets continues with further removal of trade barriers, including giving access to disadvantaged actors, leading to high levels of international trade. The increased global wealth leads to the adoption of resource- and energy-demanding lifestyles by the growing global middle-class, as developing countries follow the resource- and fossil energy-demanding developments of industrialised countries. There is a belief that the environmental consequences of this can be solved with different types of engineered technical solutions (SSP5). There are low investments in renewable energy, while major investments in fossil energy continue (SSP5).

Food system orientation and policy landscape

In this storyline, food systems, as other sectors, have become increasingly globalised, with high trade both within the EU and across the globe. In the EU specifically, strong support and investment in organic farming following the goals set up in the Farm-to-Fork Strategy launched in 2020 (EC 2020a) have led to a large increase in land managed with (weak) agroecological practices and the total area is somewhere between 20 and 50% by 2050[2]. Although the initial ambition in

[2] An example of this as a plausible future development of EU agriculture is the Swedish food strategy launched in 2017, which suggests increased organic production (the goal for 2030 is 30% of agricultural land), including exports, to increase rural employment and economic growth. There are also examples from Lithuania of tendencies for "industrialisation" of the organic farming sector as new very large players emerge aimed at exports to e.g. China and Australia.

the Farm-to-Fork Strategy was to promote organic production to reduce environmental pressures, the main driver has gradually changed to using agroecological approaches (in this future interpreted as organic farming) as a means to produce high-value foods for trade between EU member states, but also for exports to the newly affluent economies where a rapidly growing upper and middle class (SSP5) is demanding "clean and healthy" foods, especially foods low in pesticide residues. However, there is also increasing awareness among consumers about the risks of industrial livestock production after a series of food-related crises such as zoonosis outbreaks and problems with antibiotic resistance, resulting in demand for organic foods.

Since most commodities are traded on the EU or global markets, which require large-scale production able to deliver stable volumes to large food industries, large-scale farms dominate both conventional and agroecological (here organic) farming in Europe. Infrastructure and other support for local markets are not prioritised, which further drives small-scale farmers out of business. Imports into the EU of cheap bulk commodities, like soy for feed and palm oil, increase, to supply low-price food to large low-income population groups in the EU. Several export-oriented policies and initiatives have been put in place in EU member states in order to meet the consumer demand for "clean and healthy" foods.[3]

Products are sold on global and EU markets under third-party verified certification schemes. Digital technologies (SSP5) have enabled efficient control and management of such certification systems. Increased cooperation on global level to facilitate trade (SSP5) has led to the development of a global standard for organic production, based on mainly weak agroecological principles (input substitution). The focus is on banning pesticides in organic production to prevent potential negative effects on human health. EU Quality Schemes like the PDO (Protected Designation of Origin) and PGI (Protected Geographical Indication) (EC 2021b) have also gained in importance and are increasingly marketed and recognised abroad. Apart from increased investments in export-oriented strategies to market organic products and other 'greener' products, agricultural policy in the EU is similar to that today, with the majority of the money going to uncoupled area-based payments with weak greening requirements. In this future, small-scale agroecological producers have difficulty competing with large companies, which have much greater capacity to invest heavily in promotion of 'greener' products on global markets.

According to several definitions of agroecology, this storyline includes an inherent inconsistency as the concept of agroecology includes consumption of foods produced locally, i.e. large-scale global trade is not part of an agroecological food system. However, as this is a likely development in a context in which investments in weak agroecological practices to produce added-value

[3]See for example the Danish government's investments in export activities related to organic foods. https://www.foedevarestyrelsen.dk/english/SiteCollectionDocuments/Kemi%20og%20foedevarekvalitet/Oekologiplan%20Danmark_English_Print.pdf

products for a global market are prioritised, in combination with free trade policies, this storyline was deemed interesting and valuable.

Agricultural production and practices

Most agroecological farming systems resemble current mainstream organic practices and are of the 'substitution' rather than the 're-design' variant, and policy focuses mainly on the substitution of problematic inputs. It is mostly high-value crops and livestock products that are grown and marked in agroecological systems. For example, the recent strong trends in Spanish exports of organic products such as fruits, vegetables, wine, oil and nuts is supported by the strong boom in demand by consumers from central-northern countries of Europe. In addition, livestock products including milk powder, cheese and processed meat are organic products that are traded to a large extent.

Globally, EU agriculture's large share of land under agroecological practices is an exception, supplying a global niche market. In general, global agriculture, including the remainder of EU agriculture, is dominated by input- and technology-intensive, high-yielding conventional production practices (SSP5). A growing share of food is also produced in entirely industrialised systems that require little or no agricultural land for its feedstock.[4]

Diets and waste

Eating patterns develop according to current projections, staying rich in meat and other resource-intensive food products and unhealthy foods in developed countries, with increasing meat and dairy consumption in developing countries, but with variations between income groups. Policy targeting demand to support healthy or sustainable diets is non-existent. Current developments continue, with low-income populations struggling with diet-related diseases, while the eating patterns of high-income populations improve somewhat, partly due to technological solutions that help individuals maintain a healthy diet. That is, a highly segmented food market is evident in this storyline in which anonymous agroecological products are consumed by the informed well-educated segment of the population and exported outside the EU, while the majority of the population consumes conventional low-quality food. Food waste levels remain similar to current levels or decrease somewhat in countries where waste reduction policies are implemented.

[4] See for example https://solarfoods.fi/#vision

S1.3 Storyline 3a: *Localisation-for-protectionism*

Local food systems - low level of implementation of agroecological practices in the EU

Global context

This scenario plays out in the future described in the SSP 3, Regional Rivalry – A Rocky Road, scenario. The world experiences a rise in nationalism and regional conflicts, which pushes countries to focus on national security issues, including trade barriers, particularly in energy and agricultural markets (O'Neill et al. 2017). Countries aim to reach energy and food security goals within their own nation or region and global cooperation and trade is low (SSP3). The world is separated into several regional blocks of countries that have little exchange between them, which prevents efficient action to meet sustainability goals (SSP3). Meeting environmental sustainability goals has very low priority in this future (SSP3).

Food system orientation and policy landscape

In this storyline, we see a development in which nationally or locally produced foods, regardless of production methods, are prioritised in the EU. Investment in agroecological farming systems is low. The extent to which localisation of food systems is achieved varies between EU member states, based on the suitability of soils and climates to produce different foods and the role of the agricultural sector in different countries, e.g. the extent of exports. In some member states, this development is a direct consequence of a continued rise in nationalism and protectionism. Some countries are experiencing discontent with EU membership and are aiming for greater independence (cf. Brexit). Global trade wars, recurring pandemics starting with the COVID-19 situation in 2020 and global political tendencies for less international cooperation and increased competition between regions (SSP3) strengthen belief in the importance of self-sufficiency in food supply. In the wake of this, some EU member states put policies in place to promote more national food production, based on arguments like supporting local farmers and/or reducing the dependency on imported foods, e.g. to be prepared for cut-off situations due to conflicts or interruptions due to trade wars.[5] In other member states, nationalism is not as pronounced and support for continued EU cooperation (including a large CAP budget) is maintained. However, these countries are also affected by the global political situation and strategies for food production emphasise the need for high levels of self-sufficiency and independence from large food imports. Many countries look to Finland for inspiration. Finland has managed to maintain high market shares for Finnish products due to explicit goals, strategies and policy investments in strengthening the competitiveness of Finnish farming and promotion of Finnish foods (MAFF 2021).

Due to conflicting views on the role of EU institutions in different EU member states, the centrality of the EU CAP and the contrasting re-nationalisation of agricultural policies are heavily debated.

[5] An example from Sweden of a municipality which might abandon its policy to purchase organic food in favour of locally produced and seasonal foods. https://www.sydsvenskan.se/2019-10-28/lunds-kommun-kan-helt-stryka-krav-pa-ekologisk-mat

The EU has continually lost centralised power. There is still a common agricultural policy in 2050, but with a smaller budget, and member states are left to make most decisions on how it is implemented, i.e. EU-level policies are weak. Member states keep agriculture strongly protected and financially supported. Member states manage to overcome international competition due mainly to protective trade policy, but also to consumer demand for domestic products. On the demand side, most countries implement policies to promote consumption of local foods, e.g. requiring that public meals are "based on local traditions" and made from domestically produced commodities, with information campaigns to promote local food. Member states find creative ways to erect inter-EU trade barriers, e.g. referring to health effects etc. There are increasing numbers of publicly funded projects and initiatives to support local production, including labelling schemes[6] and policies to support short supply chains.

Agricultural production and practices

In terms of agricultural production in the EU, the focus is on increased output of bulk commodities and continued growth of the agricultural sector primarily to supply the national population, but also to achieve gains on a growing EU market through exports of surplus to other member states. An indirect effect of more local food systems is higher diversification of food production in most countries, although within countries and at farm level production is still specialised. National/local food is commonly marketed as healthier and more sustainable (and perceived as such by consumers), while concern about negative health or environmental outcomes is in general secondary. Local production is prioritised over implementing agroecological practices or other more sustainable ways of farming, which are often seen as inefficient use of land. The influence of multinational agro-input and food companies remains strong, but their influence has gradually decreased somewhat for a number of reasons. In countries with nationalist influences, for example, people are increasingly suspicious and negative about anything that relies on cooperation across countries and tend to prefer buying from national companies. New national food companies therefore arise, and existing companies are strengthened. Major investments in local food processing facilities, locally adapted machinery and production of agricultural inputs such as fertilisers, pesticides and machinery have been made in many countries to enable local food systems. However, power in the food chain continues to be concentrated to a few large food industries and retailers in each country. There is also increasing interest in local farmers' markets, although the volumes sold via these channels remain small. Due to the focus on national food production and nationalistic trends, local food cultures thrive in many countries.

The implementation of agroecological practices hence remains low or increases only slightly (maximum 15% of total agricultural area [croplands and grasslands] in 2050) to support mainly three group of citizens: 1) those who oppose current nationalist trends and continue to fight relentlessly, but not very successfully, against environmental pollution, 2) those who use nationalist arguments on "saving our national environment", and therefore see interest in

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[6] E.g. http://euskolabel.hazi.eus/es/

agroecology, and 3) rich consumers in and outside the EU. Agroecology is limited to weak agroecological practices, as the focus on high yield prevails in the agricultural discourse. In the EU, there is a strong push to intensify national agricultural production (both in fertile and marginal areas, including grasslands) with the demand for increased food output overruling objectives to reduce environmental pressures. Globally, investment and development within agriculture are slow (SSP3).

Diets and waste

Most citizens continue to eat a highly environmentally impacting diet with high levels of animal products, as there are few consumer side policies in place to steer consumption in a different direction and as investments and support for intensive livestock production continue. Food waste decreases slightly, due to somewhat higher food prices.

S1.4 Storyline 3b: *Localisation-for-sustainability*

Local food systems - low level of implementation of agroecological practices in the EU

Global context

This alternative storyline emerges in the same scenario quadrant (Fig. 1 in the main manuscript) as *Localisation-for-protectionism*, i.e. out of a combination of high localisation of food systems and a low level of implementation of agroecological practices. Compared with the previous scenario, which played out in the SSP3 scenario; Regional Rivalry – A Rocky Road scenario, *Localisation-for-sustainability* plays out in the SSP 1 scenario: Sustainability – Taking the Green Road.[7] In the SSP 1 sustainability scenario, growing evidence of the multi-faceted cost of inequity and environmental breakdown is pushing for the prioritisation of achievement of sustainability goals, with a shift in focus from economic growth towards improvements in well-being, especially in developing countries (O'Neill *et al.* 2017).

Food system orientation and policy landscape

In this storyline, local food systems do not arise for reasons of nationalism and protectionism, but rather as an outcome of a deliberate policy goal of creating sustainable and resilient food systems. Support for local food production to sustain and develop rural communities is an important socio-economic sustainability goal that is given high priority in this narrative, but other advantages with local food production also act as important drivers. These include cutting food miles[8], closing nutrient cycles and avoiding further regional specialisation and concentration of food production, which leads to water stress, loss of soil carbon, the spread of pests and negative outcomes for biodiversity. Thus, within the framework of the CAP (the design of which stays close to the post-

[7]This scenario was added after the third workshop, as several stakeholders had strong opinions on the negative framing of *Localisation-for-protection*. They argued that local food systems could be established without the negative connotations of nationalism.

[8]https://www.euractiv.com/section/agriculture-food/news/sr-agri-local-zero-kilometre-products-start-to-take-spain-by-storm/

2020 version), member states prioritise policies that steer towards local production systems (cf. Finland, which has achieved this to a certain degree within the current CAP system).

At the same time as local food systems are promoted by global, European and national institutions, global agricultural markets are opened to developing countries (SSP1) to promote greater equity. However, due to the promotion of local and regional food systems for achieving sustainability goals, trade volumes are not substantially increased. Mostly high-value specialist cash crops are imported into the EU, e.g. coffee, tea, cocoa, nuts, tropical fruits etc., while the EU is a net exporter of some surpluses, mainly bulk commodities (cereals, legumes, milk powder), but also of some limited amounts of high-value foods (wine, spirits) to regions which do not have enough agricultural land to sustain their populations (e.g. the Middle East), and to regions and consumer groups (e.g. urban middle-class) that can afford and demand these high-value foods. International and EU-internal trade exchanges are both important for increased resilience, as different regions are affected by climate change-aggravated extreme events.

Agricultural practices

The main difference between this storyline and *Local-agroecological-food-system* (section S1.5), which both include a transition to local food systems, is that *Local-agroecological-food-systems* has a strong focus on agroecological food systems, including more 'nature'-based practices and re-design of agricultural systems, while *Localisation-for-sustainability* focuses on the localisation aspects and relies more on technical solutions to reach sustainability, i.e. it is more aligned with the 'sustainable intensification' perspective of agriculture (Godfray 2015). For example, in this storyline, using mineral nitrogen fertilisers produced using renewable energy[9] would be seen as a sustainable practice, while in the *Local-agroecological-food-systems* storyline nitrogen fixation using legumes would be the preferred option. In line with the sustainable intensification perspective, further deforestation or cultivation of grassland is heavily regulated in this storyline. Agroecological practices have not increased from current levels and are dominated by weak practices.

[9] First renewable fertilisers will come on the market in 2022. https://www.yara.com/corporate-releases/yara-and-lantmannen-sign-first-commercial-agreement-for-fossil-free-fertilizers/

Diets and waste

A prerequisite for 'the pursuit of sustainable and resilient localised food systems' is a shift in diets to increased seasonality, determined by local availability of foods. Depending on location, eating patterns in the EU stratify. In southern parts of Europe, climate change-induced droughts drive up prices of crops and the economic viability of feeding cereals to livestock diminishes, so diets become mainly plant-based – vegan and vegetarian diets become the norm. In northern Europe, variation in climate conditions increases markedly, making the availability of fruits, vegetables and cereals volatile. Increased use and dependence on low-cost grazing on marginal lands make milk and ruminant meat more abundantly available, however. Rapid technological advances introduce an array of novel food products stemming from sources with low environmental impact, e.g. synthetic extraction of protein from inedible biomass, insects and lab-cultivated foods, and processing of legumes, cereals and agro-byproducts (e.g. rapeseed cake) into very meat-like steaks, burgers and sausages, often indistinguishable from real meat.

High investments in health and education and an accelerated demographic transition (SSP1) result in larger shares of the global population demanding fresh and seasonal foods, which acts as a positive feedback loop on health. However, supply is dominated by a narrow range of foods such as wheat, maize, rice, tomatoes, apples etc. and few local and/or traditional crop types are cultivated. That is, current trends of reduced nutrient content in globally widespread crops continue, which hampers some of the positive outcomes for health.

S1.5 Storyline 4: *Local-agroecological-food-systems*

Local food systems - high level of implementation of agroecological farming practices in the EU

Global context

This scenario plays out in a global context as laid out in the SSP1 scenario: Sustainability – Taking the Green Road. Here, growing evidence of the multi-faceted cost of inequity and environmental breakdown is pushing for prioritisation of achieving sustainability goals, with a shift in focus from economic growth towards improvements in well-being, especially in developing countries (O'Neill et al. 2017).

Food system orientation and policy landscape

A rapid increase in climate and environmental concerns among large population groups in the EU and fierce campaigning for stricter policies to prevent climate and environmental breakdown drive change in this storyline. The first sign of this development was seen in 2019 with the Friday for Future movements and in the 2019 election to the European parliament, when the green parties increased their mandate by 40%, followed by the new Green Deal. The COVID-19 pandemic helped increase recognition of the importance of rapidly transitioning to resilient food systems. The EU level Farm-to-Fork Strategy (EC 2020a) for a fair, healthy and environmentally friendly food system and the EU Biodiversity Strategy for 2030 (EC 2020b) launched in 2020 are hence given high priority and are successfully implemented at local level in the member states.

Globally, cooperation between national and international institutions is strengthened, and new global institutions arise to reinforce the rule of law and decrease corruption, in order to work effectively towards greater sustainability on the global level (SSP1). This integrated approach to EU food security presented in the Farm-to-Fork Strategy, rather than the silo approach of separate agricultural, environmental and health policies, has been largely adopted by most member states by 2028. The strategy's high ambitions for organic farming (goal of 25% of total farmland in 2030) spur investments and interest in agroecological transitions to overcome multiple problems, including nutrient and chemical pollution, soil erosion and soil carbon loss, high use of antibiotics and poor animal welfare. They also enhance social sustainability by promotion of more small-scale and diverse farming and food production practices. As a consequence of the COVID-19 pandemic, public support for factory livestock farming is heavily decreased due to its role in the development of zoonosis. Different types of alternative food systems are rapidly expanding, including different types of community-supported agriculture and short supply chain/direct sales online systems. To enable more localised food systems, support is also given to the establishment of small-scale processing. International markets are opened up to developing countries, but trade stays limited due to the focus on regional production (SSP1). European farmers are protected from international competition primarily by industry and retail introducing local produce as a base criterion due to consumer demand, but also by the introduction of trade agreements that implement sustainability criteria, e.g. for countries lacking a tax on CO_2 emissions duties on imported goods. In combination with, and actually preceding the changes in policy, many EU member states are experiencing a boom in bottom-up initiatives fostering agroecological farming practices and local food systems. Local town councils and regions play an important role in this by prioritising local foods from agroecological systems in public procurement, providing space for marketing local food and financial support to local initiative – hence showing political leadership towards local and agroecological food systems. In developing countries, yield increases are accomplished thanks to rapid introduction of best practices and effective technologies, alleviating food security challenges in these regions (SSP1).

The CAP is now handled under the umbrella of the integrated food policy and has radically changed by 2050. Most importantly, support for industrial livestock holdings has been abolished and major investments have gone into improving the productivity of smaller agroecological farms and supporting transition to agroecological farming. Results-Based Payment Schemes and such systems expand in most EU member states between 2030 and 2050. Greater consumer awareness is achieved by coherent marketing campaigns and through dissemination of clear, accurate and complete information about the benefits of agroecological production systems for society. Programmes for knowledge transfer among practitioners and producers in rural areas have also been implemented and are available for most farmers in the EU. The investment in agroecology is also used as a strategy to adapt to unavoidable effects of climate change. CAP Pillar 1 support is thus reformed from purely area-based to being based on several sustainability criteria. One important example is recognition of the inefficiency of feeding human-edible crops to livestock, which leads to the implementation of incentives to feed ruminants more grass and forage and causes the rapid rise in poultry production to level off. Intensive pork production also decreases.

Agricultural production and practices

By 2050, on average across member states, 20-50% of land is farmed with strong agroecological practices serving mostly local markets. Industrial pig and poultry holdings have drastically decreased as consumer support for such systems is heavily affected by increased awareness of animal welfare, antibiotic resistance and risk of zoonosis. Ruminant populations are not affected to the same extent, as these can be incorporated into agroecological systems more easily. However, many intensive ruminant production systems are re-designed to be grass-based, with animal numbers adjusted to local land availability. The support for local agroecological production has been easiest to adopt for small-scale family farms, which have thrived in this policy and market environment. Despite the positive development for agroecology, specialised, often large-scale farms, producing using conventional methods, still occupy 50-80% of the land, since economy-of-scale advantages and sunk costs have made it difficult for these farms to transition and since demand for cheap bulk food persists among large parts of the population.

An important success factor of the rapid transition to strong agroecology at a large scale has been food retailers' and industries' commitment and involvement in the new food strategy. Driven initially by consumer demand[10] and as a result of the societal discourse, food industries have started to work actively with farmers to enable the implementation of agroecological schemes and then gradually incorporate this into their company strategies.[11]

Diets and waste

The concept of locally adapted agroecological food systems in this storyline also includes striving for more healthy and sustainable consumption patterns. This includes a view that excess intake of "unnecessary" unhealthy foods (sugar-sweetened foods and beverages), excess consumption of livestock products, especially from animal species consuming human-edible feed (i.e. pigs and poultry) and excess intake of food in general is a waste, and should be prevented by powerful policy measures[12]. Ordinary food waste is reduced by 25-50%, mainly as a result of increased public awareness but also through a range of different policies. The Farm-to-Fork Strategy includes an initiative to make policy targeting demand and production coherently, directing CAP support towards the production of foods desired in a healthy and sustainable diet. In order to

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[10] Example of recent developments of consumers driving change: https://www.politico.com/news/2019/10/10/food-industry-consumer-brands-association-043892

[11] Dairy company Danone is an example of a large multinational company already promoting *agroeco*logy, in that case under the concept of "regenerative agriculture" https://www.danone.com/impact/planet/regenerative-agriculture.html

[12] For example, taxes on unhealthy foods and policies that steer away from using grains for animal feed.

receive CAP funding, EU member states have to develop and implement certain health-promoting policies, such as fiscal and social policies to promote healthy eating. As a result of the action put in place in many areas on production, consumption and waste reduction, diets are drastically changed to more sustainable, mainly plant-based, diets (EAT-*Lancet* diet; see Willett *et al.* 2019), although in some regions substantial amounts of beef and dairy from grass-based systems are included in diets.

S2. Model schemes

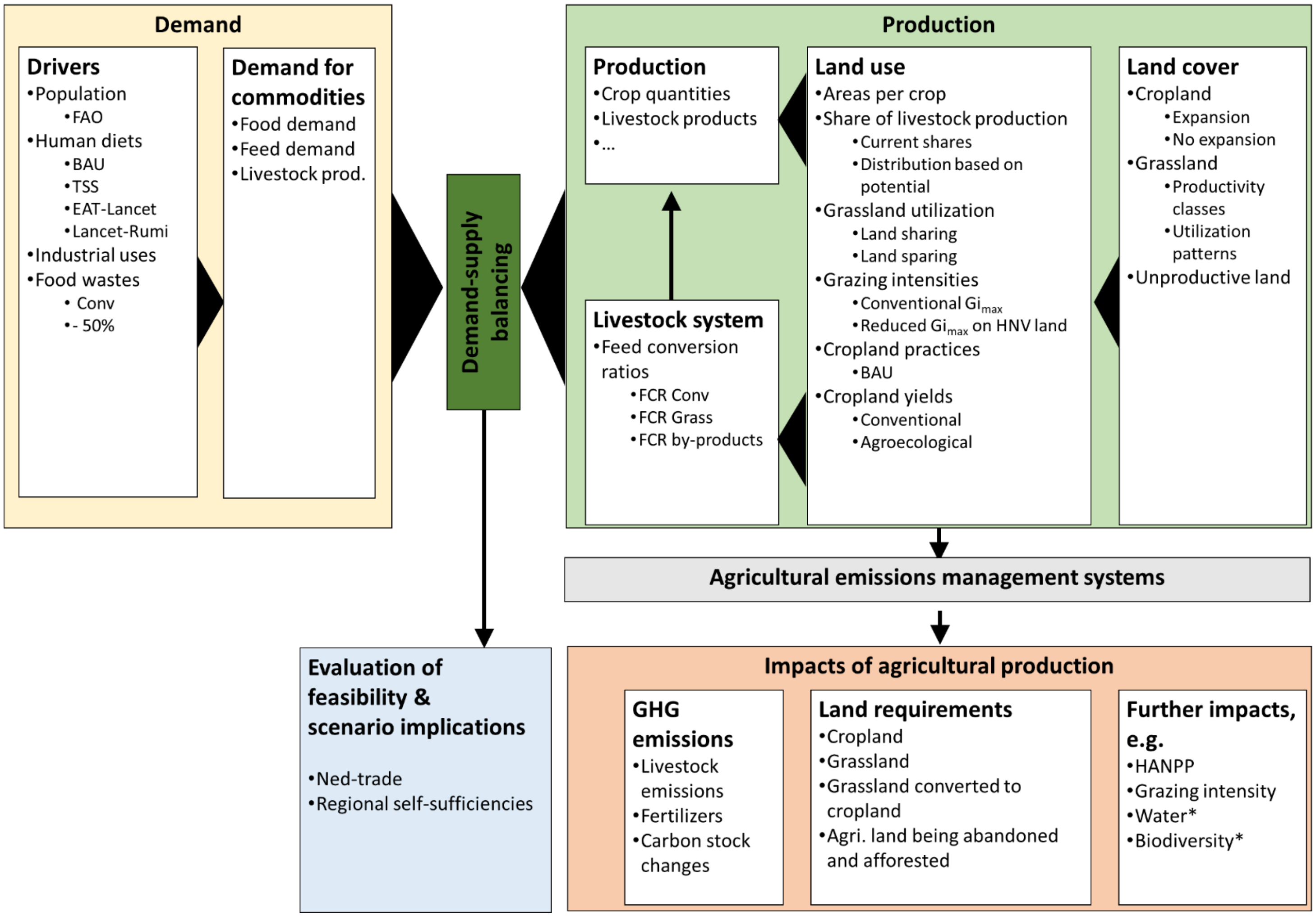

Fig. S2.1. Schematic illustration of the BioBaM model.

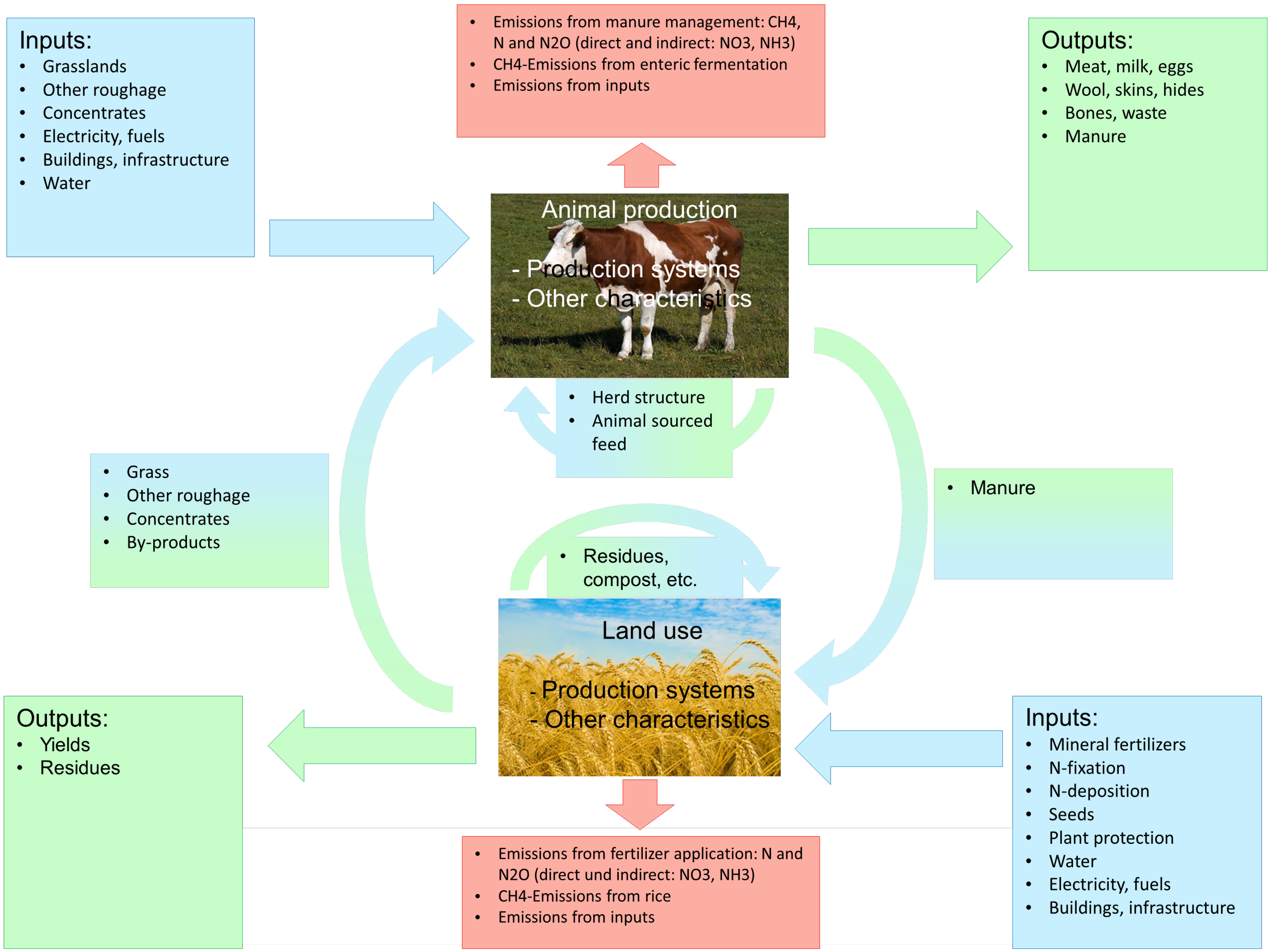

Fig. S2.2. Structure of the agricultural production in SOLm.

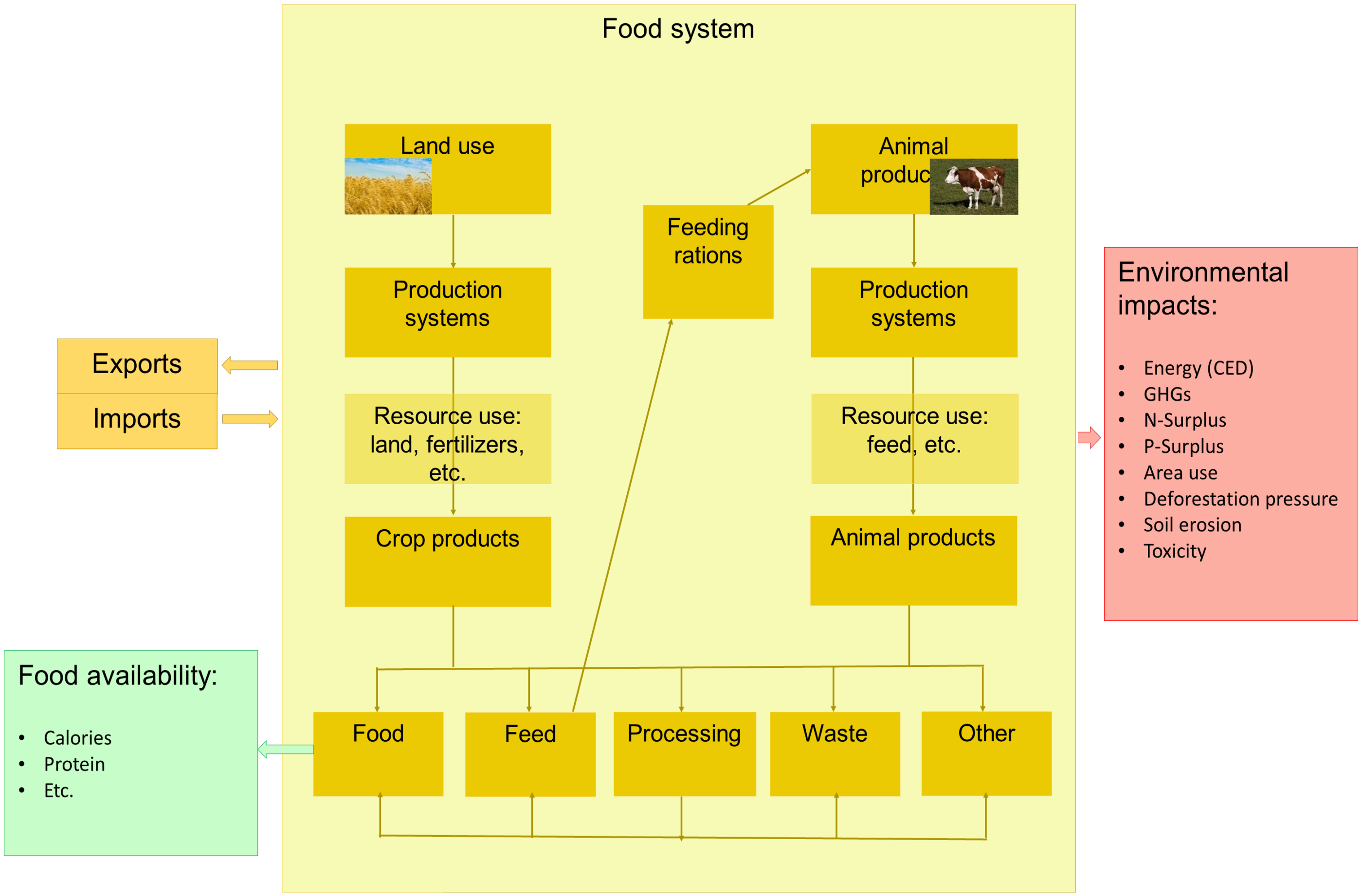

Fig. S2.3. Structure of the food system in SOLm

S3. Diets

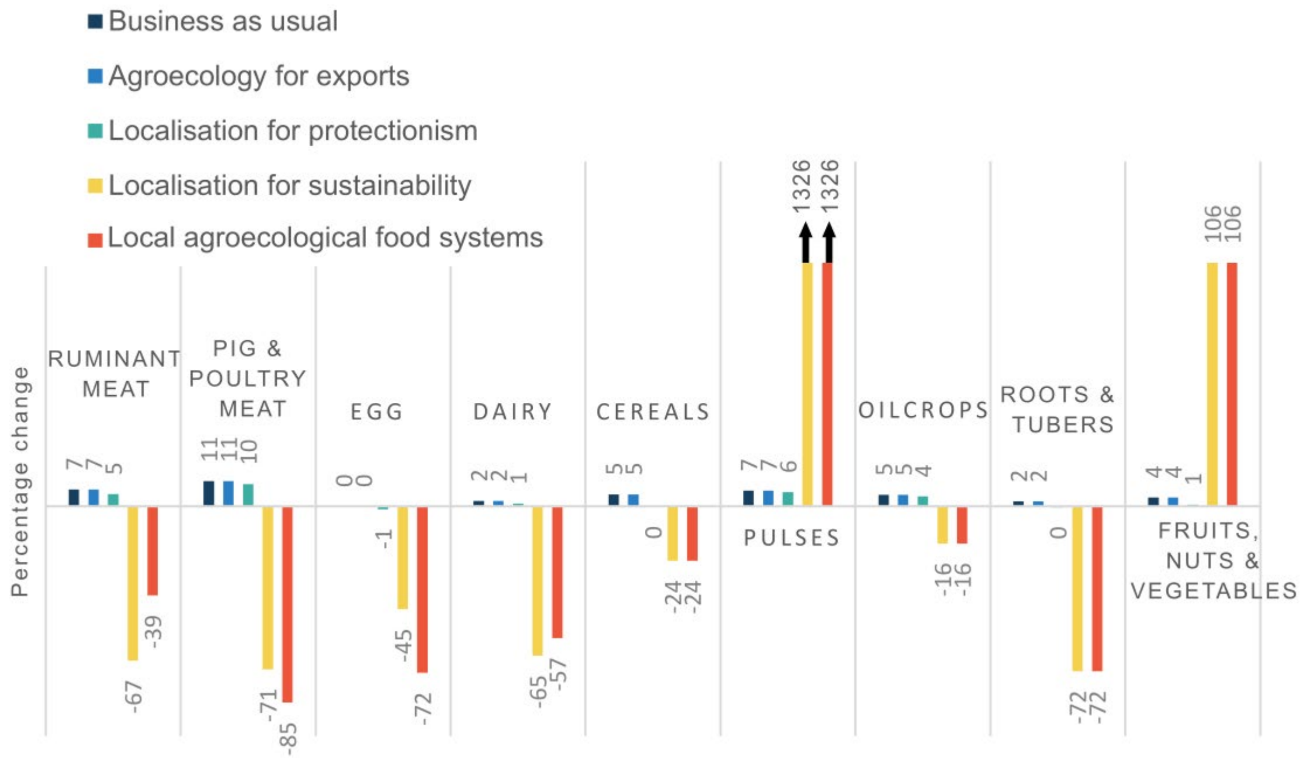

Fig. S3.1. Percentage change in the average EU diet in the different storylines compared with the diet in 2012.

Table S3.1. Percentage change in diets in different countries compared with the diet in 2012

	Business-as-usual and Agroecology-for-exports						Localisation-for-protectionism						Localisation-for-sustainability						Local-agroecological-food-systems					
	Rum. meat	Mono-gastric meat and eggs	Dairy	Cereal	Pulses	Fruits, veg & nuts	Rum. meat	Mono-gastric meat and eggs	Dairy	Cereal	Pulses	Fruits, veg & nuts	Rum. meat	Mono-gastric meat and eggs	Dairy	Cereal	Pulses	Fruits, veg & nuts	Rum. meat	Mono-gastric meat and eggs	Dairy	Cereal	Pulses	Fruits, veg & nuts
Austria	4	7	-1	5	1	3	-2	-1	-1	-5	-1	-3	-67	-72	-68	-14	4645	49	-38	-86	-61	-14	4645	49
Belgium	9	11	-1	7	2	1	-2	-1	-1	-5	-1	-3	-65	-62	-67	-23	1486	131	-35	-81	-59	-23	1486	131
Bulgaria	10	16	2	-1	1	17	-2	-1	-1	-5	-1	-3	-8	-60	-40	-36	1569	277	71	-80	-27	-36	1569	277
Croatia	10	12	2	5	12	8	-2	-1	-1	-5	-1	-3	-55	-62	-62	-19	4765	128	-16	-81	-53	-19	4765	128
Czech Repub	13	14	1	1	20	13	-2	-1	-1	-5	-1	-3	-47	-69	-60	-16	1864	235	-1	-84	-51	-16	1864	235
Denmark	8	9	-1	7	14	3	-2	-1	-1	-5	-1	-3	-76	-59	-64	-28	3561	84	-56	-80	-57	-28	3561	84
Estonia	15	17	1	-5	15	18	-2	-1	-1	-5	-1	-3	-40	-62	-66	-29	659	147	12	-81	-59	-29	659	147
Finland	12	14	0	6	3	3	-2	-1	-1	-5	-1	-3	-69	-64	-80	-16	3176	139	-42	-82	-75	-16	3176	139
France	9	11	3	5	6	2	-2	-1	-1	-5	-1	-3	-79	-66	-68	-24	1927	106	-61	-83	-61	-24	1927	106
Germany	4	6	3	5	4	2	-2	-1	-1	-5	-1	-3	-60	-72	-69	-14	4440	113	-26	-86	-63	-14	4440	113
Greece	7	13	2	7	8	8	-2	-1	-1	-5	-1	-3	-80	-55	-66	-27	693	32	-63	-78	-59	-27	693	32
Hungary	11	12	2	2	18	15	-2	-1	-1	-5	-1	-3	-3	-70	-46	-14	1054	283	80	-85	-34	-14	1054	283
Ireland	5	9	3	5	7	1	-2	-1	-1	-5	-1	-3	-74	-64	-67	-24	1305	80	-51	-82	-60	-24	1305	80
Italy	7	8	3	5	6	2	-2	-1	-1	-5	-1	-3	-76	-67	-67	-38	646	54	-56	-84	-60	-38	646	54
Latvia	19	21	2	-3	20	13	-2	-1	-1	-5	-1	-3	26	-67	-56	-21	82317	215	134	-84	-47	-21	82317	215
Lithuania	16	18	1	-2	7	2	-2	-1	-1	-5	-1	-3	57	-72	-70	-35	1005	252	192	-86	-64	-35	1005	252
Netherlands	9	11	-1	7	7	5	-2	-1	-1	-5	-1	-3	-76	-69	-73	6	2258	52	-55	-84	-67	6	2258	52
Poland	7	9	1	2	13	3	-2	-1	-1	-5	-1	-3	169	-72	-59	-37	1835	225	400	-86	-50	-37	1835	225
Portugal	12	15	3	12	11	2	-2	-1	-1	-5	-1	-3	-67	-70	-59	-27	986	79	-38	-85	-50	-27	986	79
Romania	6	11	2	-1	13	13	-2	-1	-1	-5	-1	-3	-33	-59	-65	-46	1800	147	24	-80	-57	-46	1800	147
Slovakia	14	14	1	0	8	12	-2	-1	-1	-5	-1	-3	-19	-59	-28	-28	2672	237	51	-79	-13	-28	2672	237
Spain	8	11	3	10	0	2	-2	-1	-1	-5	-1	-3	-61	-75	-48	-8	620	125	-27	-87	-36	-8	620	125
Sweden	14	15	0	9	-5	8	-2	-1	-1	-5	-1	-3	-75	-64	-75	-3	2016	93	-53	-82	-70	-3	2016	93
United Kingd	5	9	3	8	13	3	-2	-1	-1	-5	-1	-3	-73	-66	-64	-16	1181	95	-49	-83	-56	-16	1181	95

S4. Land use in different countries across storylines

Table S4.1. Percentage change in land use across countries, the EU (including UK, but excluding Malta and Cyprus) and the rest of the world

	Business as usual			Agroecology for exports			Localisation for protectionism			Localisation for sustainability			Local agroecological food systems		
	Cropland	Graz. land	Veg. reg.	Cropland	Graz. land	Veg. reg.	Cropland	Graz. land	Veg. reg.	Cropland	Graz. land	Veg. reg.	Cropland	Graz. land	Veg. reg.
Austria	6.7	-23.6	13.0	2.8	-17.6	10.4	17.8	-26.8	11.2	-18.2	-82.7	60.1	-18.7	-35.1	29.3
Belgium	-1.7	-23.5	13.2	-11.0	10.0	0.0	28.8	-26.6	0.2	0.0	-81.5	42.7	0.0	0.0	0.0
Bulgaria	5.5	-46.1	16.4	1.0	-11.6	4.4	-12.0	-52.0	28.9	-40.7	-79.5	57.2	-43.1	0.0	24.8
Croatia	7.8	-50.8	35.0	16.4	-6.1	0.0	30.0	-38.1	19.8	-27.5	-82.0	67.3	-32.9	0.0	8.9
Czech Republic	-0.4	-10.1	3.5	0.0	0.0	0.0	-5.9	-31.2	14.0	-32.9	-69.7	44.6	-37.3	0.0	25.4
Denmark	-9.2	-18.8	10.9	-3.1	13.9	0.0	-24.8	-30.1	25.8	-41.5	-89.5	50.4	-40.9	0.0	33.3
Estonia	2.6	-63.6	34.4	0.0	0.0	0.0	5.2	-61.3	32.0	-33.9	-89.5	65.0	-38.8	0.0	17.1
Finland	-14.2	-1.4	9.5	-3.3	5.7	0.0	-4.6	-1.4	3.4	-32.8	-14.1	25.9	-37.3	0.0	23.7
France	-2.9	-20.4	10.2	-0.1	-0.8	0.4	-0.9	-39.0	16.9	-35.3	-71.5	50.5	-37.6	-11.0	26.4
Germany	-1.8	-30.4	11.8	-1.5	-0.1	1.0	-5.7	-40.9	18.0	-34.7	-80.6	50.8	-35.2	-14.4	27.9
Greece	-14.7	-20.8	18.6	0.0	0.0	0.0	2.5	-21.1	12.4	-17.2	-35.5	28.7	-25.1	0.0	9.3
Hungary	-1.0	-66.1	15.9	0.0	-6.9	1.6	-21.7	-68.6	32.5	-43.3	-80.2	51.8	-44.9	0.0	34.6
Ireland	-12.1	-80.7	65.9	0.0	-72.6	56.9	30.6	-80.8	56.7	-22.0	-92.0	76.9	-27.2	-84.1	71.8
Italy	-8.5	-9.5	8.9	-3.7	5.2	0.0	4.8	-11.7	2.0	-7.0	-58.6	28.5	-18.1	0.0	10.5
Latvia	-2.1	-79.2	41.1	0.0	0.0	0.0	-11.4	-79.5	45.8	-45.1	-85.0	65.3	-46.1	-52.4	49.3
Lithuania	-1.5	-81.6	34.0	0.0	0.0	0.0	-19.3	-81.9	44.7	-48.1	-88.9	64.7	-48.3	-73.3	58.5
Luxembourg	-2.2	-57.6	32.1	0.0	0.0	0.0	36.0	-30.6	0.0	-22.8	-87.1	57.6	-32.9	-12.8	22.0
Netherlands	-3.7	-88.2	49.8	-0.6	-12.2	6.9	36.5	-86.2	30.5	0.0	-96.6	52.7	0.0	-54.0	29.4
Poland	3.1	-48.1	11.4	0.0	0.0	0.0	-11.3	-58.9	24.7	-34.8	-77.7	46.9	-37.5	0.0	26.9
Portugal	-10.4	-12.5	11.6	0.0	0.0	0.0	4.3	-12.8	5.1	0.0	-60.5	33.2	0.0	0.0	0.0
Romania	3.9	-35.4	10.3	0.0	-1.8	0.6	-8.6	-47.7	22.7	-44.5	-78.3	56.7	-48.3	-7.0	33.4
Slovakia	-3.1	-72.5	31.7	0.0	0.0	0.0	-0.2	-67.6	27.9	-25.7	-77.8	47.1	-29.9	0.0	17.6
Slovenia	1.7	-48.1	33.7	0.0	0.0	0.0	55.3	-24.4	1.3	-5.3	-87.1	63.4	-12.1	-50.3	39.2
Spain	-6.7	-49.9	27.5	0.2	-0.3	0.1	-7.5	-50.7	28.3	-25.0	-74.5	48.8	-27.8	-0.7	14.8
Sweden	-10.0	-2.6	6.8	-10.0	13.4	0.0	6.6	-8.8	0.0	-15.2	-42.8	27.0	-18.6	0.0	10.6
United Kingdom	4.1	-23.0	13.6	-7.4	-7.4	7.4	41.7	-24.6	1.6	0.0	-75.0	49.0	0.0	-29.0	19.0
EU incl. UK	-2.6	-34.6	16.9	-1.0	-4.0	2.4	-1.9	-39.8	18.9	-28.5	-72.1	48.0	-31.6	-13.0	23.2
Rest of world	9.4	-13.1	7.2	8.7	-12.1	6.6	17.2	-13.0	5.0	17.2	-13.1	5.1	17.2	-13.1	5.1

S5. Food production in different countries across scenarios

Table S5.1. Percentage change in production of animal products across countries, the EU (including UK, but excluding Malta and Cyprus) and the rest of the world

	Business as usual				Agroecology for exports				Localisation for protectionism				Localisation for sustainability				Local agroecological systems			
	Rum. meat	Monog. meat	Egg	Dairy	Rum. meat	Monog. meat	Egg	Dairy	Rum. meat	Monog. meat	Egg	Dairy	Rum. meat	Monog. meat	Egg	Dairy	Rum. meat	Monog. meat	Egg	Dairy
Austria	-22.9	7.8	43.1	-24.2	-22.9	7.8	43.1	-24.2	-24.3	6.6	41.3	-25	-75.3	-71.3	-33.6	-74	-54	-84	-66.8	-68.5
Belgium	-5.7	-50.0	-22.3	0.1	-5.7	-50.0	-22.3	0.1	-7.4	-50.5	-23.3	-1	-69.7	-83.5	-57.4	-60	-44	-91	-78.7	-53.6
Bulgaria	-12.4	46.4	-52.7	-38.3	-12.4	46.4	-52.7	-38.3	-14.0	44.8	-53.3	-39	-27.1	-53.8	-62.1	-62	36	-76	-81.0	-54.9
Croatia	3.7	0.3	-51.0	17.2	3.7	0.3	-51.0	17.2	1.8	-0.8	-51.6	16	-57.3	-69.2	-61.1	-55	-20	-84	-80.6	-45.6
Czech Republic	61.6	42.1	-18.2	-12.5	61.6	42.1	-18.2	-12.5	58.6	40.5	-19.3	-13	-23.7	-64.8	-54.9	-63	42	-82	-77.5	-55.6
Denmark	31.2	-76.7	-34.1	-66.7	31.2	-76.7	-34.1	-66.7	28.8	-76.8	-34.9	-67	-71.2	-85.0	-71.8	-85	-46	-87	-85.9	-83.2
Estonia	-22.2	-9.4	12.0	-60.3	-22.2	-9.4	12.0	-60.3	-23.6	-10.4	10.6	-61	-59.4	-73.2	-34.3	-87	-24	-87	-65.2	-83.8
Finland	52.0	19.1	-27.4	5.6	52.0	19.1	-27.4	5.6	49.2	17.8	-28.3	4	-57.9	-63.0	-48.9	-74	-22	-79	-74.5	-69.8
France	26.5	11.7	-28.4	-26.5	26.5	11.7	-28.4	-26.5	24.3	10.5	-29.3	-27	-74.7	-66.2	-61.7	-76	-54	-81	-79.9	-70.8
Germany	-2.2	-15.4	-13.9	-28.1	-2.2	-15.4	-13.9	-28.1	-4.0	-16.3	-15.0	-29	-62.4	-77.5	-54.6	-76	-30	-87	-77.3	-71.9
Greece	110.2	76.1	-27.4	29.6	110.2	76.1	-27.4	29.6	106.6	74.3	-28.3	28	-49.5	-27.2	-47.2	-51	-18	-56	-72.7	-41.9
Hungary	1.5	-26.5	-62.9	-24.1	1.5	-26.5	-62.9	-24.1	-0.3	-27.3	-63.4	-25	-11.2	-79.9	-80.9	-59	65	-89	-90.4	-50.3
Ireland	-78.3	-3.8	-33.1	-55.6	-78.3	-3.8	-33.1	-55.6	-78.7	-4.9	-34.0	-56	-94.6	-69.5	-49.4	-73	-90	-83	-74.7	-71.3
Italy	114.1	16.6	-29.3	25.0	114.1	16.6	-29.3	25.0	110.2	15.3	-30.2	24	-52.5	-67.0	-63.1	-59	-11	-83	-81.6	-50.2
Latvia	-64.0	37.2	21.7	-61.0	-64.0	37.2	21.7	-61.0	-64.6	35.7	20.2	-61	-62.0	-65.7	-42.6	-83	-29	-83	-71.3	-79.2
Lithuania	-79.0	4.0	-45.5	-59.7	-79.0	4.0	-45.5	-59.7	-79.4	2.9	-46.2	-60	-71.5	-76.3	-72.6	-88	-47	-88	-86.2	-85.5
Luxembourg	-24.3	156.1	1237	-54.7	-25.7	153.2	1220	-55.2	-25.7	153.2	1220	-55	-75.7	-27.8	520.9	-85	-55	-64	210.1	-82.0
Netherlands	29.0	-43.5	-37.4	-56.0	29.0	-43.5	-37.4	-56.0	26.7	-44.1	-38.2	-56	-71.4	-82.3	-73.6	-88	-47	-89	-86.8	-85.3
Poland	-67.2	-15.9	-75.7	-41.5	-67.6	-15.9	-75.8	-37.4	-67.7	-16.8	-76.0	-42	-49.1	-77.8	-78.8	-72	-7	-87	-89.5	-65.5
Portugal	55.4	-15.8	-71.3	196.5	57.3	-15.8	-70.9	115.1	52.4	-16.9	-71.8	193	-51.3	-77.5	-80.0	31	-11	-86	-89.5	16.1
Romania	-26.2	4.8	24.7	-15.1	-26.2	4.8	24.7	-15.1	-27.5	3.6	23.4	-16	-53.4	-63.0	-30.8	-71	-13	-81	-55.6	-64.3
Slovakia	78.9	80.0	43.8	-30.2	78.9	80.0	43.8	-30.2	75.6	78.1	42.0	-31	27.3	-35.5	-30.9	-50	137	-66	-65.4	-39.3
Slovenia	-21.2	12.2	-60.4	-28.7	-22.7	11.0	-61.0	-29.5	-22.7	11.0	-61.0	-30	-74.8	-60.7	-81.6	-76	-53	-79	-90.8	-71.4
Spain	-12.6	-28.7	-41.0	5.7	-12.6	-28.7	-41.0	5.7	-14.2	-29.5	-41.7	5	-68.0	-85.0	-70.7	-40	-40	-92	-85.4	-30.1
Sweden	132.6	100.2	91.2	36.8	132.6	100.2	91.2	36.8	128.4	98.0	88.7	35	-48.3	-34.7	-6.2	-65	-4	-63	-53.1	-57.7
United Kingdom	37.1	113.5	-20.3	31.4	37.1	113.5	-20.3	31.4	34.6	111.2	-21.3	30	-64.4	-33.0	-52.0	-48	-34	-62	-76.0	-38.6
EU (incl. UK)	14.8	-5.6	-32.3	-17.9	14.8	-5.6	-32.3	-17.9	12.7	-6.6	-33.2	-19	-65.8	-72.6	-62.5	-69	-37	-85	-80.9	-63.3
Rest of world	67.2	75.7	3.5	63.1	67.2	75.7	3.5	63.1	67.2	75.7	3.5	63	67.2	75.7	3.5	63	67	76	3.5	63.1

Table S5.2. Percentage change in production of crops across countries, the EU (including UK, but excluding Malta and Cyprus) and the rest of the world

	Business as usual					Agroecology for exports					Localisation for protectionism					Localisation for sustainability					Local agroecological systems				
	Cereals	Pulses	Oilcrops	Roots & tubers	Fruits, veg & nuts	Cereals	Pulses	Oilcrops	Roots & tubers	Fruits, veg & nuts	Cereals	Pulses	Oilcrops	Roots & tubers	Fruits, veg & nuts	Cereals	Pulses	Oilcrops	Roots & tubers	Fruits, veg & nuts	Cereals	Pulses	Oilcrops	Roots & tubers	Fruits, veg & nuts
Austria	70	76	65	76	17	51	52	38	36	190	8	22	421	93	127	-42	605	179	14	199	-52	605	126	12	196
Belgium	59	74	86	99	45	30	-52	66	53	168	29	244	4946	-61	-21	-11	1717	2981	-92	68	-15	1717	2369	-91	79
Bulgaria	58	-5	66	67	0	25	-49	29	48	242	-23	455	-12	593	146	-52	1141	-48	428	268	-62	1141	-67	412	257
Croatia	34	-25	37	46	7	46	-44	48	52	-1	18	428	231	423	59	-49	1460	57	127	104	-64	1460	26	142	105
Czech Republic	53	41	54	65	-36	21	15	21	22	403	-3	150	113	183	150	-43	659	9	62	376	-55	659	-26	66	373
Denmark	36	-36	14	50	-48	5	-46	-13	10	564	-37	133	321	140	198	-57	487	202	92	280	-63	487	164	82	257
Estonia	37	19	19	39	-42	9	4	-6	5	1087	-25	1	178	56	113	-57	113	32	-23	294	-64	113	-38	-20	291
Finland	31	20	20	40	-48	0	-5	-8	3	1101	-24	-29	816	45	83	-53	393	515	41	368	-62	393	383	45	367
France	36	42	39	56	-13	10	19	12	16	242	-22	20	234	154	62	-52	247	79	85	126	-59	247	41	79	122
Germany	72	42	57	95	-15	38	14	24	50	331	0	177	341	82	109	-42	869	153	14	220	-50	869	111	8	211
Greece	16	30	69	47	15	-14	-20	30	9	260	10	52	121	66	-43	-25	751	108	62	-13	-45	751	69	89	-11
Hungary	19	-3	20	27	-16	-8	-27	-8	-7	166	-37	190	26	361	45	-60	563	-28	236	131	-67	563	-48	219	123
Ireland	-12	-30	22	42	-50	-4	-41	32	48	550	6	213	3139	464	212	-55	713	1344	104	260	-63	713	1082	116	263
Italy	49	37	65	65	25	12	-27	26	22	120	-17	59	361	76	-50	-40	735	252	103	-2	-50	735	176	176	1
Latvia	20	7	28	36	-56	-4	-6	2	5	617	-26	128	150	65	117	-59	439	42	-10	208	-66	439	17	-15	193
Lithuania	19	37	21	40	-58	-8	15	-8	3	666	-30	0	109	236	133	-59	81	20	109	219	-66	81	0	92	198
Luxembourg	52	76	95	103	46	37	13	77	77	231	83	279	672	267	32	1	2224	218	130	-3	-20	2224	93	169	0
Netherlands	31	127	93	123	67	4	-44	76	84	320	88	313	34904	-61	18	-4	1890	19232	-86	40	-18	1890	15941	-86	39
Poland	55	52	32	56	8	20	27	1	15	156	-12	108	234	4	26	-50	595	109	-49	139	-61	595	59	-50	134
Portugal	4	47	65	48	4	-24	-46	26	9	120	-10	86	312	-20	-62	-42	958	214	-59	-14	-52	958	161	-53	-2
Romania	47	25	53	51	-1	22	-2	20	32	1180	-5	282	108	110	56	-46	830	21	21	109	-59	830	-12	20	105
Slovakia	40	23	60	58	-29	13	-12	30	27	348	2	204	80	346	125	-36	1083	0	165	354	-46	1083	-33	174	353
Slovenia	54	77	87	85	33	68	49	103	92	115	69	352	1081	174	78	-24	6419	414	-10	88	-42	6419	292	9	93
Spain	33	48	54	46	17	2	17	18	9	104	-2	3	96	155	-39	-43	280	41	97	-5	-56	280	20	98	-6
Sweden	21	24	27	34	-37	-8	-6	-3	-2	304	-30	-13	478	45	83	-51	655	314	28	291	-60	655	243	32	292
United Kingdom	49	75	45	62	-12	32	53	27	41	69	33	-6	338	99	174	-36	437	100	-57	380	-48	437	46	-54	415
EU + UK	45	44	48	73	7	16	14	17	35	223	-8	61	221	68	16	-46	492	93	2	83	-56	492	53	2	83
RoW	56	90	52	44	54	59	91	55	46	59	64	89	42	44	53	64	89	42	44	53	64	89	42	44	53

S6. Potential land feasibility of member states

Table S6.1. Potential land feasibility of member states in 2012 and across the different storylines.

	2012	*Business as usual*	*Agro-ecology for exports*	*Localisation for protectionism*	*Localisation for sustainability*	*Local agro-ecological food systems*
Austria	0.82	1.26	1.43	1.47	1.49	1.47
Belgium	0.43	0.72	0.50	0.79	0.75	0.79
Bulgaria	1.25	2.54	2.56	2.68	3.10	3.14
Croatia	0.91	1.48	2.06	2.13	1.78	2.12
Czech Republic	1.08	1.72	0.84	1.79	2.11	1.63
Denmark	2.17	2.14	0.56	2.18	2.74	1.58
Estonia	0.97	1.44	1.40	1.51	2.18	2.66
Finland	0.95	1.08	0.82	1.09	2.04	1.45
France	1.33	1.65	0.68	1.78	2.36	2.31
Germany	1.05	1.55	0.49	1.40	2.29	1.53
Greece	0.54	0.93	1.16	0.94	1.52	1.85
Hungary	1.96	2.75	1.59	2.80	3.32	1.95
Ireland	1.37	1.40	2.44	2.02	1.46	1.77
Italy	0.43	0.68	0.74	0.69	1.24	1.27
Latvia	1.73	2.78	2.92	2.95	3.57	3.87
Lithuania	2.09	3.37	3.53	3.42	4.33	4.46
Luxembourg	0.56	0.92	0.59	1.11	1.57	1.65
Netherlands	0.38	0.70	0.55	0.82	0.67	0.64
Poland	1.12	1.92	1.25	1.96	2.24	1.96
Portugal	0.36	0.57	0.57	0.57	0.73	0.81
Romania	1.19	2.34	1.35	2.57	3.49	3.39
Slovakia	0.98	1.53	1.68	1.66	1.71	1.93
Slovenia	0.43	0.86	1.48	1.24	1.09	1.23
Spain	0.91	1.35	1.36	1.37	1.79	1.90
Sweden	0.84	0.83	0.46	0.85	1.38	1.14
United Kingdom	0.66	0.83	0.79	1.02	0.90	0.94
EU + UK	0.97	1.42	1.10	1.52	2.03	2.27

S7. Emissions of greenhouse gases from agriculture

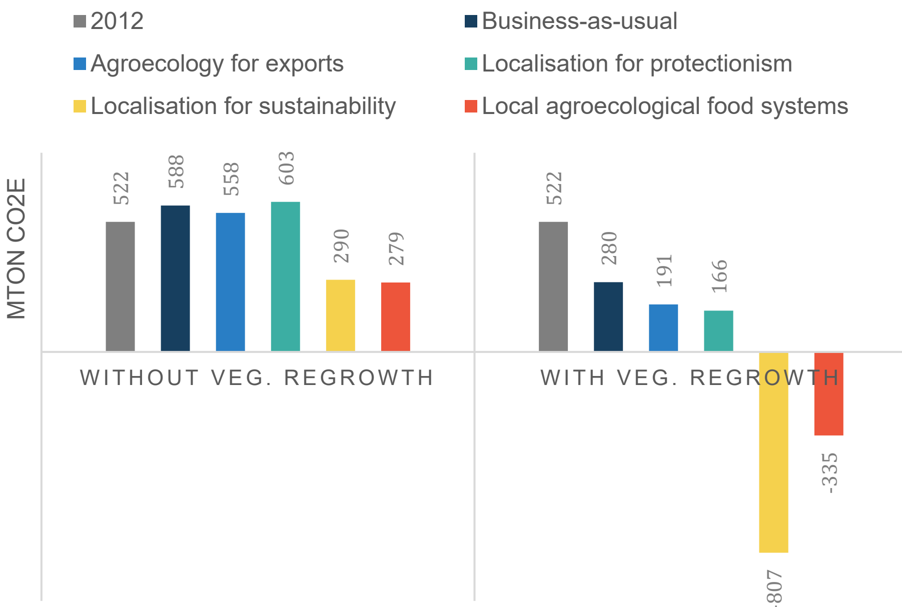

Fig. S7.1. Yearly emissions of greenhouse gases from agriculture in the EU in 2012 and in the different storylines.

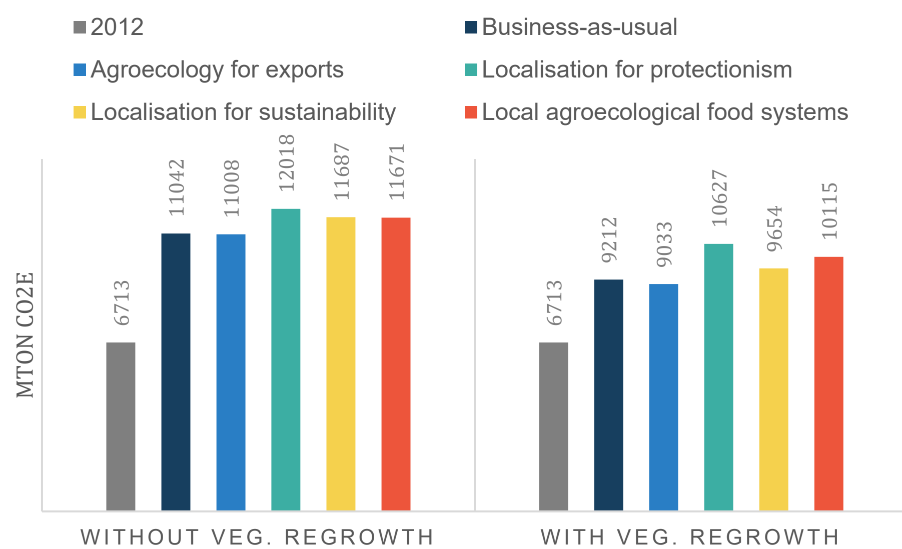

Fig. S7.2. Yearly emissions of greenhouse gases from agriculture globally in 2012 and in the different storylines.

S8. Economic modelling methods

S8.1 Data

Our economic analysis was restricted to tradable agricultural commodities, using the same classification of commodities as in the biophysical models. The economic analysis was carried out separately for 12 commodity groups used in BioBaM and SOLm.

The analysis focused on two aggregated regions: the European Union and the "Rest of the World" (RoW). The EU can be treated as a single region because it is a customs union and has harmonised its economic and trade policies in the agricultural sector via the CAP.

The economic model requires input data on quantities produced, consumed and exported in each of the two regions, which we took from the biophysical models. BioBaM provided the production/consumption data, and SOLm provided the detailed trade flow data. We required these quantity data for the baseline (2050 BAU), as well as for each scenario in 2050.

The economic model requires data on prices of the commodities, which we took from the most recent year of FAOstat. The commodities in the biophysical models are grouped into major food categories, so we had to choose a price for a particular good and country. The choice of price statistics affected the magnitude of the economic welfare and employment results, but not the results for the policies required or the predicted percentage change in prices. The economic model also requires data on the elasticity of supply and demand for each commodity.

As we studied the impacts of different scenarios 30 years from now, we considered the possibility that demand and supply may be less sensitive to price in such a long-run scenario as tastes and technology adapt to changing market conditions. We assumed a supply elasticity equal to 5 for all goods, and a demand elasticity equal to -1 for all goods.

S8.2. Modelling approach

In the analysis, we used a partial equilibrium model of trade called an "equilibrium displacement model". This model was first developed by Muth (1964) and has been used in many studies of international trade, with prominent studies by Sumner and Wohlgenant (1985), Gardner (1987), and Alston *et al.* (1995).

As with any model, the equilibrium displacement model has several advantages and limitations. Attractive properties of equilibrium displacement models are that they need very few inputs, they are flexible and they are tractable enough to allow analytical solutions to be found. Their main drawbacks are that they only model a single market ("partial equilibrium" in the jargon) and do not model the whole economy or complex interactions between markets. As with most models, they are not as trustworthy when studying large deviations from the baseline.

The economic model is a set of equations that defines the interaction between changes in prices, quantities and policy variables in a market. In our case, the market was a particular BioBaM/SOLm food commodity produced, consumed and traded between the EU and RoW. We assumed that both regions produce and consume the good, and that they each produce their own specific variety of the good. The model allows for changes in three policy variables: an EU import tariff, a production subsidy or tax for EU farmers and a consumption subsidy or tax on EU consumers, which are always expressed as a percentage of the price. The policy variables in the economic model are additional to the existing policy instruments already in place under the EU CAP. We did not consider policy changes by RoW.

The model consists of five equations: two equations defining EU and RoW import demand, two equations defining EU and RoW export supply, and an equation specifying that the difference in price between the regions for a good produced in RoW equals the size of the EU import tariff. For example, if the EU applies a tariff on imports from RoW of t percent, the price paid by EU consumers will be t percent higher for the good compared with the price paid by consumers in RoW. Tariffs thus drive a “wedge” between the price in RoW and the price in the EU.

The economic model invokes the so-called Armington assumption, whereby domestically produced food and imported food are assumed to be imperfect substitutes. The elasticity of substitution captures how the relative demand for imports versus domestically-produced goods responds when their relative prices change. Low elasticity of substitution implies that a large change in relative prices would not affect relative demand very much. We assumed an Armington elasticity equal to 5, following Costinot *et al.* (2016). Interactions between the broad categories were not modelled, although these cross-category effects are likely to be small since cross-price demand elasticities are usually a small fraction of the magnitude of own-price demand elasticities.

S8.3 Overview of solution procedure and outputs

We solved the model analytically to find unique solutions for the quantities exported from each region and the prices in each region for its domestically-produced and imported products. The model’s solution for prices and quantities depends on the three policy variables and also on additional parameters such as the elasticities of supply and demand. In a standard economic analysis, one would usually be interested in the impact of a policy change on market quantities and prices. However, in this case the quantities are provided by the biophysical model, and we wanted to know which policies and prices are congruent with the biophysical results with respect to quantities produced, consumed and exported from each region.

It was important that the economic model matched not only the export quantities given by the biophysical model, but also the quantities produced and consumed in each region. We therefore had to "constrain" the economic model's solution for each scenario in order to match not only the traded quantities, but also the production and consumption outcomes.

Antecedents 1 - Expressing demand and supply in log derivative form

Inverse supply as a function of own price P and a production subsidy V per unit produced is:

$$P = S^{-1}(Q_S) - V$$

Inverse demand as a function of own price P and a consumption tax C per unit produced is:

$$P = D^{-1}(Q_D) - C$$

Take differentials:

$$dP = S'(Q_S)dQ_S - dV$$
$$dP = D'(Q_D)dQ_D - dC$$

Use definition of supply elasticity to substitute $S'(Q_S) = (1/\varepsilon)\big(P/(Q_S)\big), D'(Q_D) = (1/\eta)\big(P/(Q_D)\big)$ and rearrange:

$$\big((dQ_S)/(Q_S)\big) = \varepsilon\big((dP)/P\big) + \varepsilon\big((dV)/P\big),$$
$$\big((dQ_D)/(Q_D)\big) = \eta\big((dP)/P\big) + \eta\big((dC)/P\big).$$

Log-differentiated prices quantities are denoted by $EP = dlnP = \big((dP)/P\big)$ and $EQ = dlnQ = \big((dQ)/Q\big)$, respectively.

Log-differentiated per-unit production and consumption subsidies are denoted by $EV = dln(1 + V) = \big((dV)/P\big)$ and $EC = dln(1 + C) = \big((dC)/P\big)$, respectively, the change in the production subsidy or consumption tax rate as a percentage of price.

Antecedents 2 - Log differentials for summed relationships

The economic model must sometimes make assumptions about quantity sums. For example, we assumed that total production of a good equals domestic demand plus exports:

$$Q_S = Q_D + Q_X$$

Express as differential:

$$dQ_S = dQ_D + dQ_X$$

Divide both sides by Q_S:

$$\big((dQ_S)/(Q_S)\big) = \big((dQ_D)/(Q_D)\big)\big((Q_D)/(Q_S)\big) + \big((dQ_X)/(Q_X)\big)\big((Q_X)/(Q_S)\big)$$

Express as shares:

$$EQ_S = (1 - \alpha_X)EQ_D + \alpha_X EQ_X$$

Where $\alpha_X = \big((Q_X)/(Q_S)\big)$. Note that $\big((Q_D)/(Q_S)\big) = \big((Q_S)/(Q_S)\big) - \big((Q_X)/(Q_S)\big) = 1 - \alpha_X$.

Equilibrium displacement model of trade with two products

Basic Setup

Two products and two regions: EU product and RoW product.
Each region produces its own product and consumes domestic and imported varieties, yielding six quantity flows.

Export supply is based on each region's domestic demand and supply elasticities. Superscript (EU or RoW) denotes the product, which differs by country of origin. The EU can subsidise production of its own good by V per unit, and it can levy tariffs t^{RoW} on the imported good. The EU can also subsidise consumption by C per unit.
Price in exporting country or export quantity supplied is denoted by subscript X, price in importing country or import quantity demanded is denoted by subscript M. So the EU pays price P_X^{EU} for its own good, but pays price P_M^{RoW} for the good it imports from RoW.

Import demand and export supply for EU good

Log-differentiated quantity supplied of the EU-produced good is:

$$EQ_S^{EU} = \varepsilon EP_X^{EU} + \varepsilon EV \qquad (1)$$

where EP_X^{EU} is the log-differentiated export price, ε is the own price elasticity of supply and EV is the change in the production subsidy as a share of the price.
Log-differentiated demand for own good in EU is:

$$EQ_D^{EU} = \eta EP_X^{EU} + \eta EC \qquad (2)$$

where η is the own price elasticity of demand and EC is the change in the consumption tax as a share of the price.

RoW import demand for EU good (M denotes imports) is:

$$EQ_M^{EU} = \eta_e EP_M^{EU} \qquad (3)$$

where η_e is the elasticity of demand for imports. Note that we allowed demand elasticity to differ between imports and the domestically-produced goods.

To relate changes in total EU production (EQ_S^{EU}) to changes in domestic demand EQ_D^{EU} and exports EQ_X^{EU}, in log-differentiated terms (see antecedents 2 for more detail), we used the equation:

$$EQ_S^{EU} = (1 - \alpha_X^{EU})EQ_D^{EU} + \alpha_X^{EU}EQ_X^{EU} \quad (4)$$

where α_X^{EU} is the share of EU production that is exported.

Isolate EQ_X^{EU}:

$$EQ_X^{EU} = \left(1/(\alpha_X^{EU})\right)EQ_S^{EU} - \left((1 - \alpha_X^{EU})/(\alpha_X^{EU})\right)EQ_D^{EU} \quad (5)$$

Plug (1) and (2) into (5):

$$EQ_X^{EU} = \left(\left((\varepsilon - \eta)/(\alpha_X^{EU})\right) + \eta\right)EP_X^{EU} + \left(\varepsilon/(\alpha_X^{EU})\right)EV - \eta\left((1 - \alpha_X^{EU})/(\alpha_X^{EU})\right)EC \quad (6)$$

Equation (6) is the EU export supply equation. The quantity of EU exports increases with the price, increases with production subsidies, and increases with taxes on EU-produced goods. If EC is negative, then the policy subsidises consumption of EU-produced goods, and exports decrease.

Import demand and export supply for RoW good

RoW supply and demand (assuming same elasticities as EU):

RoW supply:

$$EQ_S^{RoW} = \varepsilon EP_X^{RoW} \quad (7)$$

RoW demand for own good:

$$EQ_D^{RoW} = \eta EP_X^{RoW} \quad (8)$$

EU import demand for RoW good:

$$EQ_M^{RoW} = \eta_e EP_M^{RoW} \quad (9)$$

RoW export share α_X^{RoW}:

$EQ_S^{RoW} = (1 - \alpha_X^{RoW})EQ_D^{RoW} + \alpha_X^{RoW}EQ_X^{RoW}$Isolate EQ_X^{RoW}:

$$EQ_X^{RoW} = \left(1/(\alpha_X^{RoW})\right)EQ_S^{RoW} - \left((1 - \alpha_X^{RoW})/(\alpha_X^{RoW})\right)EQ_D^{RoW} \quad (10)$$

Plug (7) and (8) into (11):

$$EQ_X^{RoW} = \left(\left((\varepsilon - \eta)/(\alpha_X^{RoW})\right) + \eta\right) EP_X^{RoW} \qquad (11)$$

Equation (11) is the RoW export supply equation.

Market clearing conditions

We defined the market clearing conditions in log-differentiated format:

$$EQ_X^{EU} = EQ_M^{EU}$$

$$EQ_X^{RoW} = EQ_M^{RoW}$$

These market clearing conditions mean that everything can be expressed in terms of import quantities, substituting $EQ_X^{EU} = EQ_M^{EU}$ and $EQ_X^{RoW} = EQ_M^{RoW}$ in all the above expressions.

Arbitrage conditions

We defined the relationship between importer and exporter prices (arbitrage conditions) before log-differentiating as:

$$P_M^{EU} = P_X^{EU}$$

$$P_M^{RoW} = P_X^{RoW}(1 + \tau^{RoW})$$

where τ^{RoW} is ad valorem tariffs or trade costs.

Arbitrage conditions in log-differentiated terms:

$$EP_M^{EU} = EP_X^{EU} \qquad (12)$$

$$EP_M^{RoW} = EP_X^{RoW} + t^{RoW} \qquad (13)$$

where $t^{RoW} = dln(1 + \tau^{RoW}) = \left((d\tau^{RoW})/P\right)$.

Solving the model

Equations (3), (6), (9), (11), and (13) can be expressed in matrix form:

$$\begin{bmatrix} 1 & 0 & -\delta & 0 & 0 \\ 0 & 1 & 0 & 0 & -\theta \\ 1 & 0 & -\eta_e & 0 & 0 \\ 0 & 1 & 0 & -\eta_e & 0 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} EQ_M^{EU} \\ EQ_M^{RoW} \\ EP^{EU} \\ EP_M^{RoW} \\ EP_X^{RoW} \end{bmatrix} = \begin{bmatrix} \gamma \\ 0 \\ 0 \\ 0 \\ t^{RoW} \end{bmatrix}$$

where

$$\delta = \left((\varepsilon - \eta)/(\alpha_X^{EU})\right) + \eta > 0$$
$$\theta = \left((\varepsilon - \eta)/(\alpha_X^{RoW})\right) + \eta > 0$$
$$\gamma = \left(\varepsilon/(\alpha_X^{EU})\right)EV - \eta\left((1 - \alpha_X^{EU})/(\alpha_X^{EU})\right)EC$$
$$EQ_M^{EU} = -\left((\gamma\eta_e)/(\delta - \eta_e)\right)$$
$$EQ_M^{RoW} = \theta\left((t^{RoW}\eta_e)/(\theta - \eta_e)\right)$$
$$EP^{EU} = -\left(\gamma/(\delta - \eta_e)\right)$$
$$EP_M^{RoW} = \left((\theta t^{RoW})/(\theta - \eta_e)\right)$$
$$EP_X^{RoW} = \left((t^{RoW}\eta_e)/(\theta - \eta_e)\right)$$

Plug in our values for δ and θ:

$$EQ_M^{EU} = \left(\left(\eta_e\left(\eta\left((1 - \alpha_X^{EU})/(\alpha_X^{EU})\right)EC - \left(\varepsilon/(\alpha_X^{EU})\right)EV\right)\right) / \left(\left((\varepsilon - \eta)/(\alpha_X^{EU})\right) + \eta - \eta_e\right)\right) \quad (14)$$

$$EQ_M^{RoW} = \left(\left((\varepsilon - \eta)/(\alpha_X^{RoW})\right) + \eta\right)\left((t^{RoW}\eta_e)/\left(\left((\varepsilon - \eta)/(\alpha_X^{RoW})\right) + \eta - \eta_e\right)\right) \quad (15)$$

$$EP^{EU} = \left(\left(\eta\left((1 - \alpha_X^{EU})/(\alpha_X^{EU})\right)EC - \left(\varepsilon/(\alpha_X^{EU})\right)EV\right) / \left(\left((\varepsilon - \eta)/(\alpha_X^{EU})\right) + \eta - \eta_e\right)\right) \quad (16)$$

$$EP_M^{RoW} = \left(\left(t^{RoW}\left(\left((\varepsilon - \eta)/(\alpha_X^{RoW})\right) + \eta\right)\right) / \left(\left((\varepsilon - \eta)/(\alpha_X^{RoW})\right) + \eta - \eta_e\right)\right) \quad (17)$$

$$EP_X^{RoW} = \left((t^{RoW}\eta_e)/\left(\left((\varepsilon - \eta)/(\alpha_X^{RoW})\right) + \eta - \eta_e\right)\right) \quad (18)$$

Without any constraints on domestic production and consumption in each region, equation (15) provides a unique solution for t^{RoW}, which can be seen by rearranging:

$$t^{RoW} = EQ_M^{RoW}\left(\left(\left((\varepsilon - \eta)/(\alpha_X^{RoW})\right) + \eta - \eta_e\right) / \left(\eta_e\left(\left((\varepsilon - \eta)/(\alpha_X^{RoW})\right) + \eta\right)\right)\right)$$

It is also possible to solve for some combination of EV and EC using equation (14). There are infinite combinations of EV and EC that match the EU export quantities, provided that one is not concerned about matching EU domestic production and consumption quantities. However, we needed to match the BioBaM production and consumption quantities, which we discuss in the next section.

Constraining policies to match production and consumption quantities from biophysical models

The biophysical models also stipulated the levels of production and consumption in each region for each storyline. We therefore had to constrain the solution from the economic model so that it also matched production and consumption quantities.

Use the EU supply equation (1) and (14) to solve for EV and EC. This gives two equations and two unknowns:

$$\left((EQ_S^{EU} - \varepsilon EV)/\varepsilon\right) = EP^{EU}$$

$$EQ_M^{EU} = \eta_e EP^{EU}$$

Combine:

$$EV = \left((EQ_S^{EU})/\varepsilon\right) - \left((EQ_M^{EU})/(\eta_e)\right)$$

This gives the solution for EV.

One can then solve for EC using (2) and (14):

$$\left((EQ_D^{EU} - \eta EC)/\eta\right) = EP^{EU}$$

$$EQ_M^{EU} = \eta_e EP^{EU}$$

Combine:

$$EC = \left((EQ_D^{EU})/\eta\right) - \left((EQ_M^{EU})/(\eta_e)\right).$$

S9. Macroeconomic modelling results

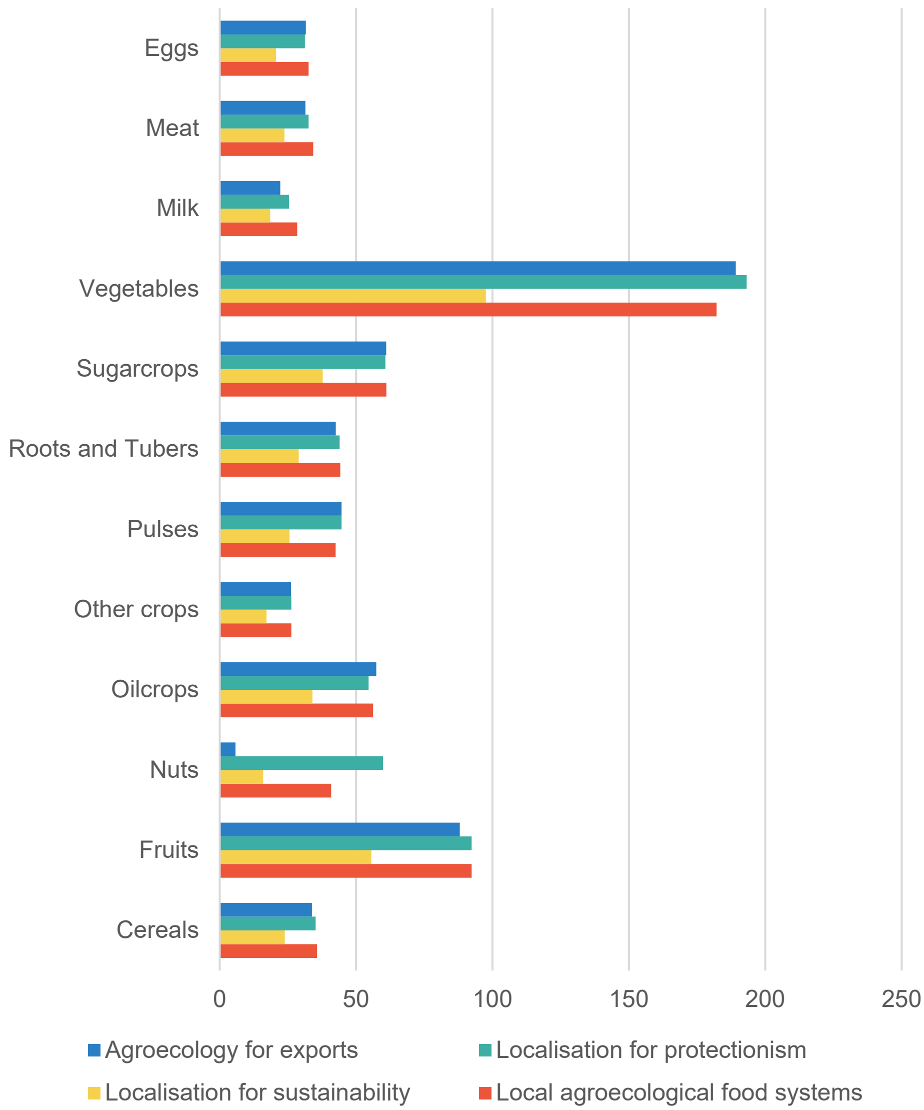

Fig. S9.1. EU import ad valorem tariffs by commodity and storyline compared with the 2050 baseline. Note: Policies expressed as a percentage of the 2050 business-as-usual price.

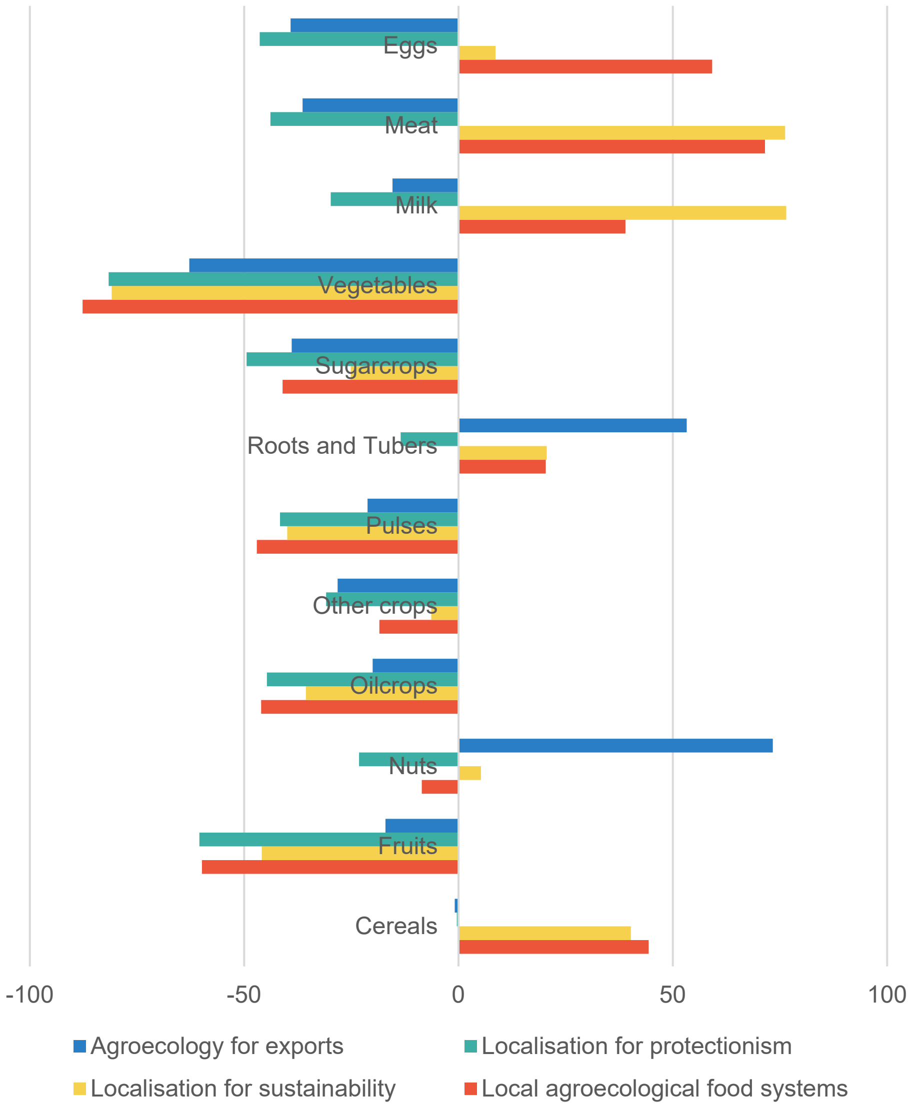

Fig. S9.2. EU consumption taxes by commodity and storyline compared with the 2050 baseline. Note: Policies expressed as a percentage of the 2050 business-as-usual price.

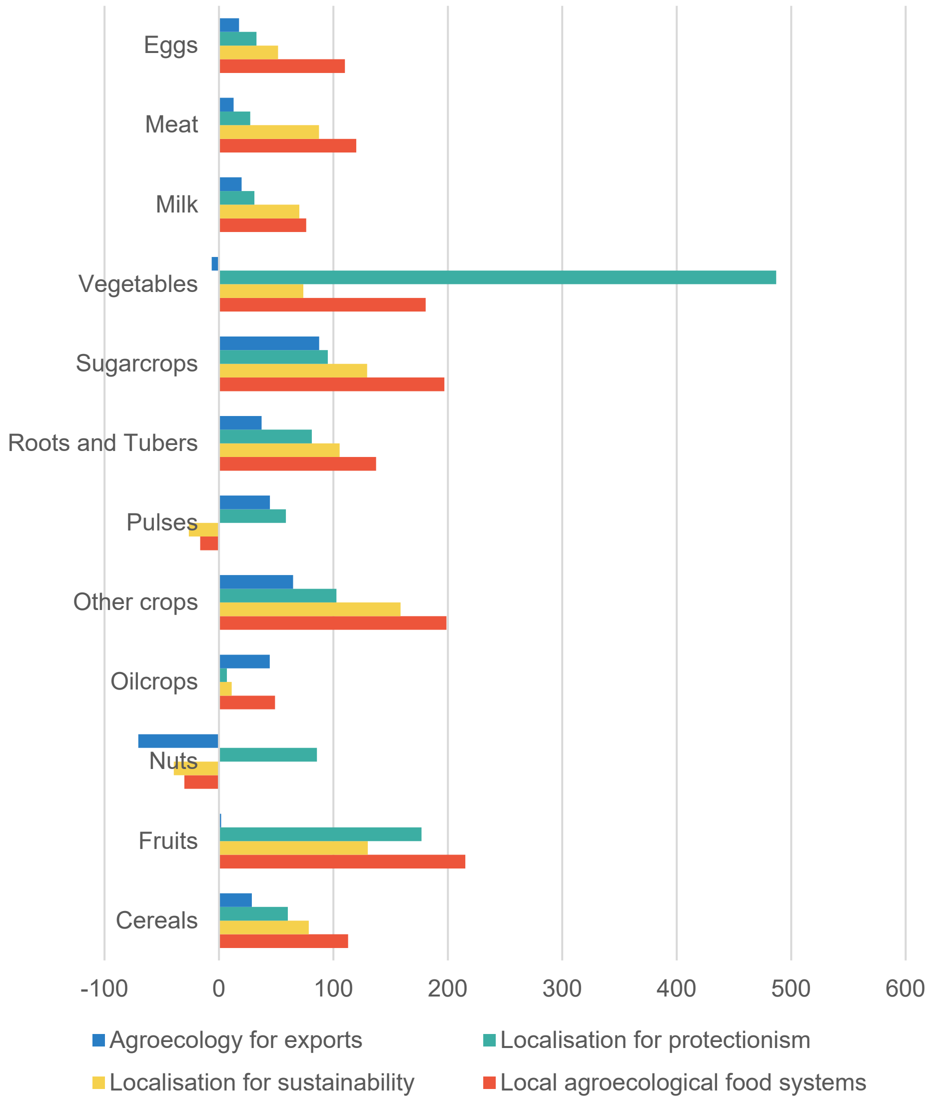

Fig. S9.3. EU production taxes by commodity and storyline compared with the 2050 baseline. Note: Policies expressed as a percentage of the 2050 business-as-usual price.

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