Science of the Total Environment 847 (2022) 157612

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

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

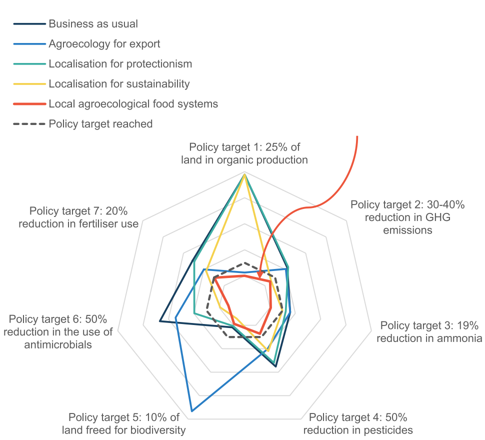
Elin Röös [a,*], Andreas Mayer [b], Adrian Muller [c], Gerald Kalt [b], Shon Ferguson [d,e], Karl-Heinz Erb [b], Rob Hart [d], Sarah Matej [b], Lisa Kaufmann [b], Catherine Pfeifer [c], Anita Frehner [c], Pete Smith [f], Gerald Schwarz [g]

[a] Department of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala, Sweden
[b] University of Natural Resources and Life Sciences, Department of Economics and Social Sciences, Institute of Social Ecology (SEC), Schottenfeldgasse 29, Vienna, Austria
[c] Department of Socioeconomics, Research Institute of Organic Agriculture FiBL, Ackerstrasse 113, 5070 Frick, Switzerland
[d] Department of Economics, Swedish University of Agricultural Sciences, Uppsala, Sweden
[e] Research Institute of Industrial Economics (IFN), Stockholm, Sweden
[f] Institute of Biological and Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen AB24 3UU, UK
[g] Thünen Institute of Farm Economics, Bundesallee 63, 38116 Braunschweig, Germany

HIGHLIGHTS

- Five explorative storylines for future EU food systems were developed and modelled.
- Implementation of agroecology and localisation of food systems were explored.
- Large-scale organic farming for export risks increasing environmental impacts in EU.
- EU policy targets can be met when agroecology is combined with dietary change.
- Unchanged preferences and technology will require unrealistic taxes and tariffs.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:
Food systems
Livestock
Climate change
Biodiversity
Farm-to-fork
New Green Deal

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

* Corresponding author.
E-mail address: elin.roos@slu.se (E. Röös).

http://dx.doi.org/10.1016/j.scitotenv.2022.157612
Received 14 March 2022; Received in revised form 20 July 2022; Accepted 20 July 2022
Available online 25 July 2022

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 change 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) highlight the importance of agroecological approaches. Agroecological farming practices include crop-livestock integration, low-input management, reliance on local resources and diversification (Altieri and 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). In addition, it can be interpreted as a science, a social movement and a set of practices (Wezel and 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 and 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 and Röös, 2019). On the European level, Poux and 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), 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

The storylines form the qualitative context (*i.e.* narrative) in which the 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 and Maas, 2015; Rounsevell and 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 and 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 the 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 and Aalders, 2019). Summaries of the storylines are given in Section 2.2 and the full storylines can be found in the Supplementary Material S1.

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

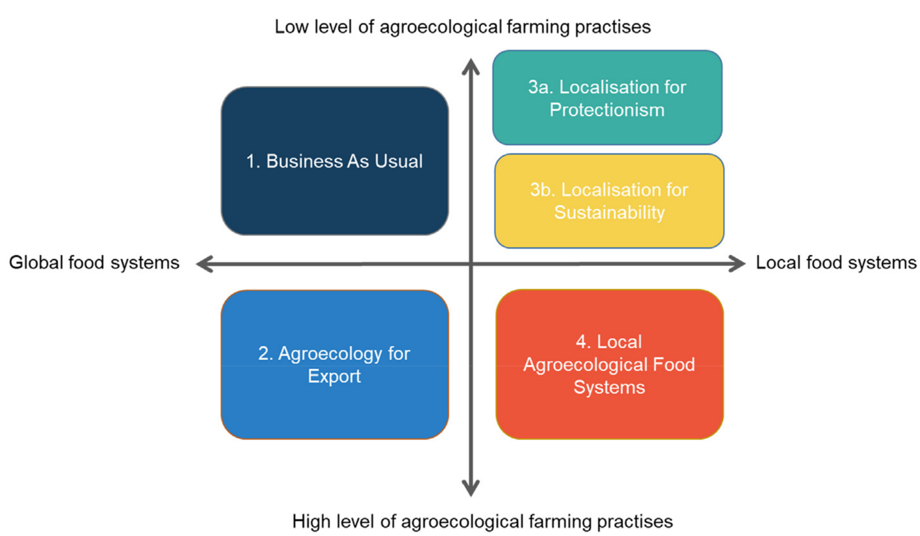


Fig. 1. Scenario cross and the five storylines developed in this study.

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 through 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 (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. 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 and Witzke, 2015; Kempen and 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 synthetic 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

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 [a]	50% of monogastric meat in the EAT-*Lancet* diet [a] 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.

commodities for export. In *Localisation-for-sustainability* and *Local-agroecological-food-systems*, no expansion of cropland was allowed.

3.2.2. Livestock production

Livestock diets from CAPRI were assumed for the EU (Britz and 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 redistributed 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 quantity of foods from 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 storylines, 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).

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 these 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-*

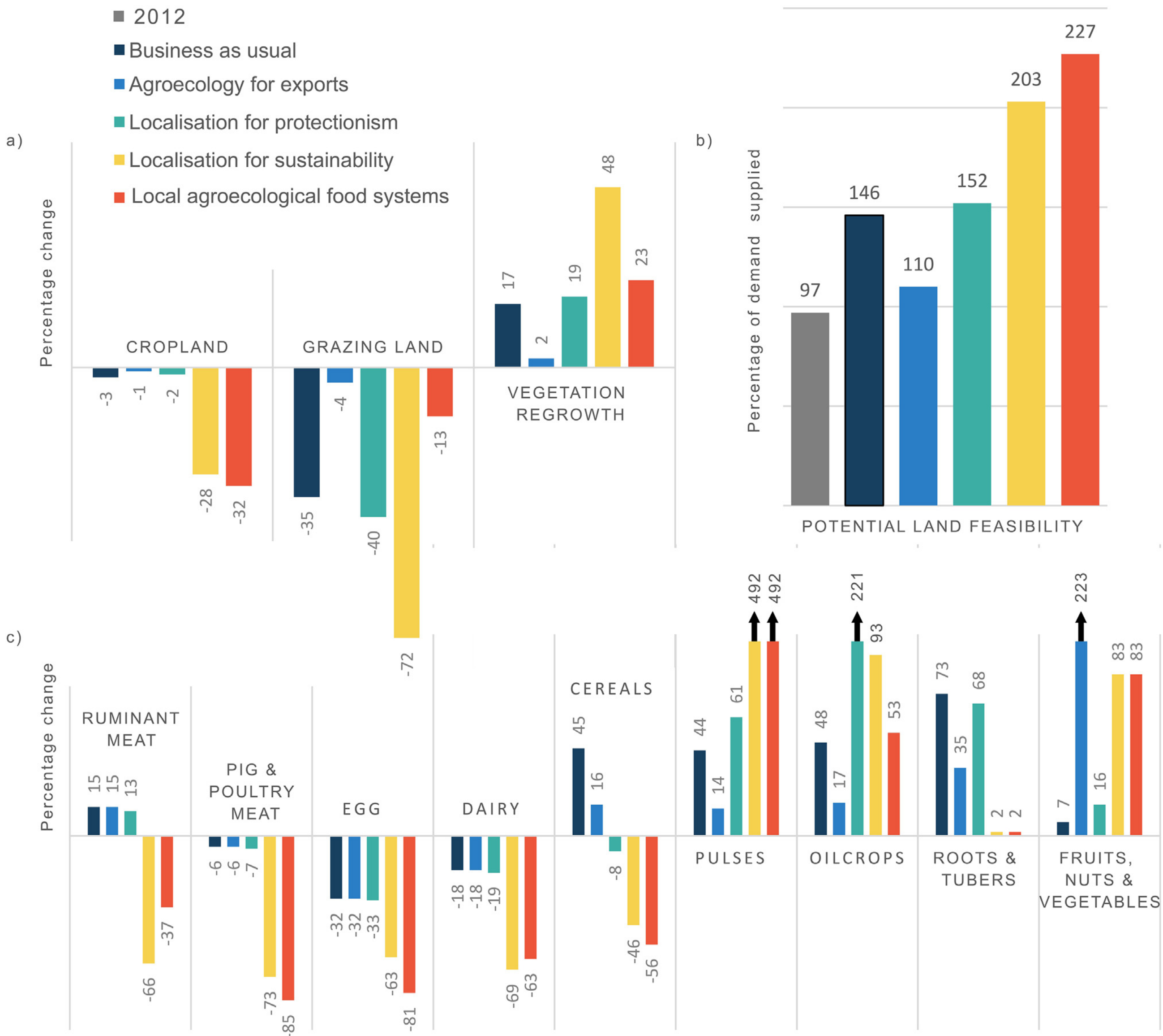


Fig. 2. (a) Percentage change in cropland and grazing land and percentage of total agricultural land available for vegetation regrowth across storylines, (b) potential land feasibility in the European Union (EU), *i.e.* the extent to which available agricultural land in 2012 can theoretically support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

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.

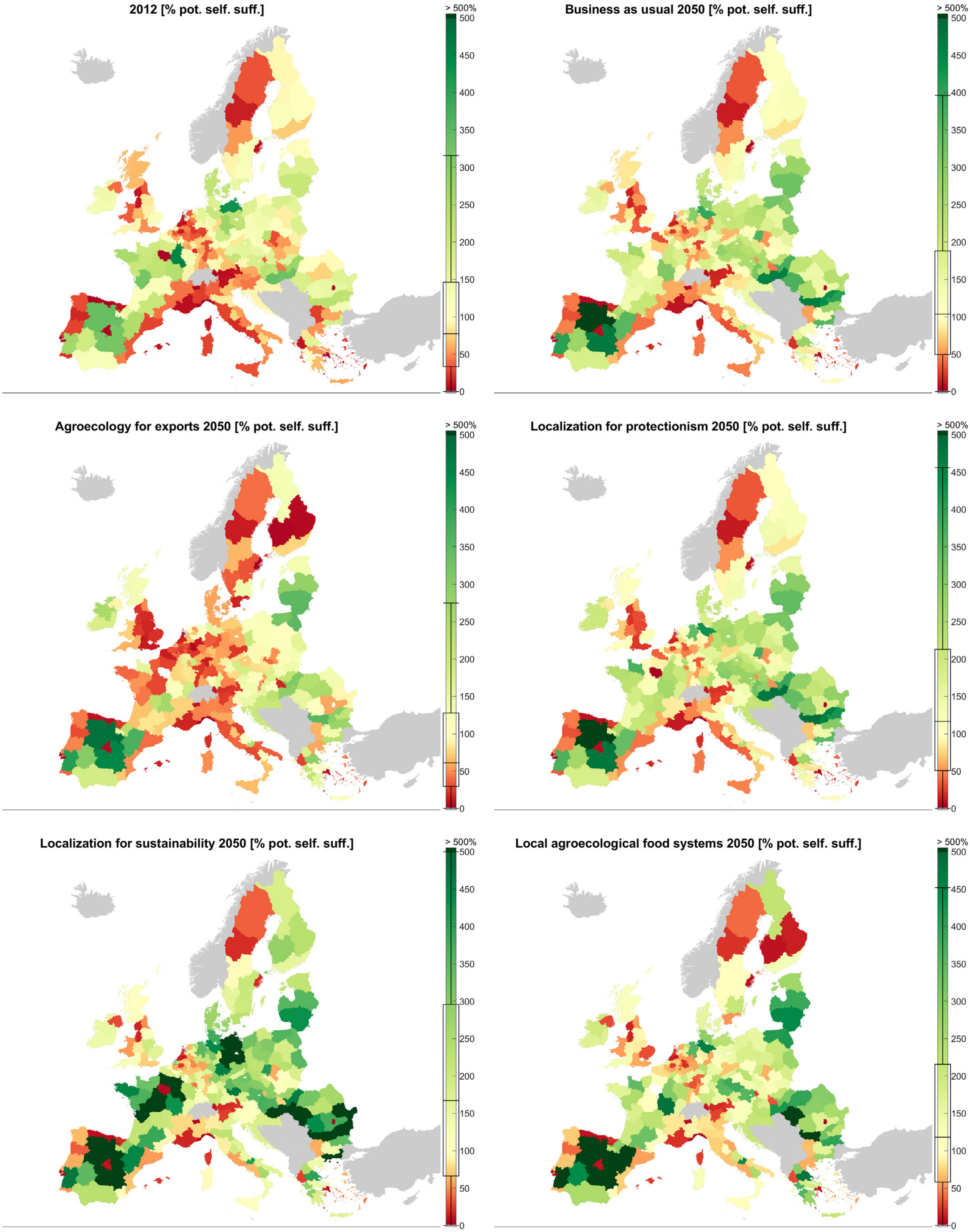


Fig. 3. Potential land feasibility (the ratio between the area of land needed to supply demand in a region and the available land in that region considering allowed expansion of cropland) in sub-regions (NUTS2) across the different storylines.

3.3.4. Environmental impact

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 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 synthetic 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 storylines (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 substantially, 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).

3.3.5. Socio-economic consequences

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 also 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 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 strategy (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

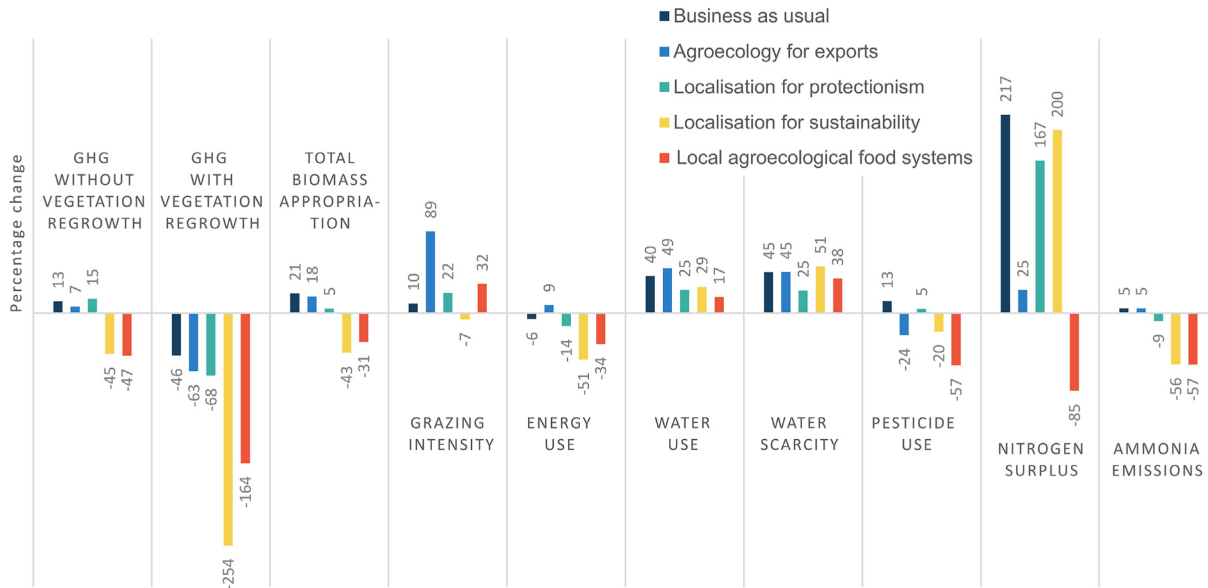


Fig. 4. Environmental impacts of the storylines in relation to the baseline year 2012.

strategy includes a goal of reducing the use of antimicrobials in livestock production by 50% (EC, 2020a).

5. Policy measures for realising the storylines

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 and 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 and 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; Figs. 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.

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 and Chaloupka, 2009; Smed et al., 2016).

5.2.1. Agroecology-for-exports

To recap, 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,

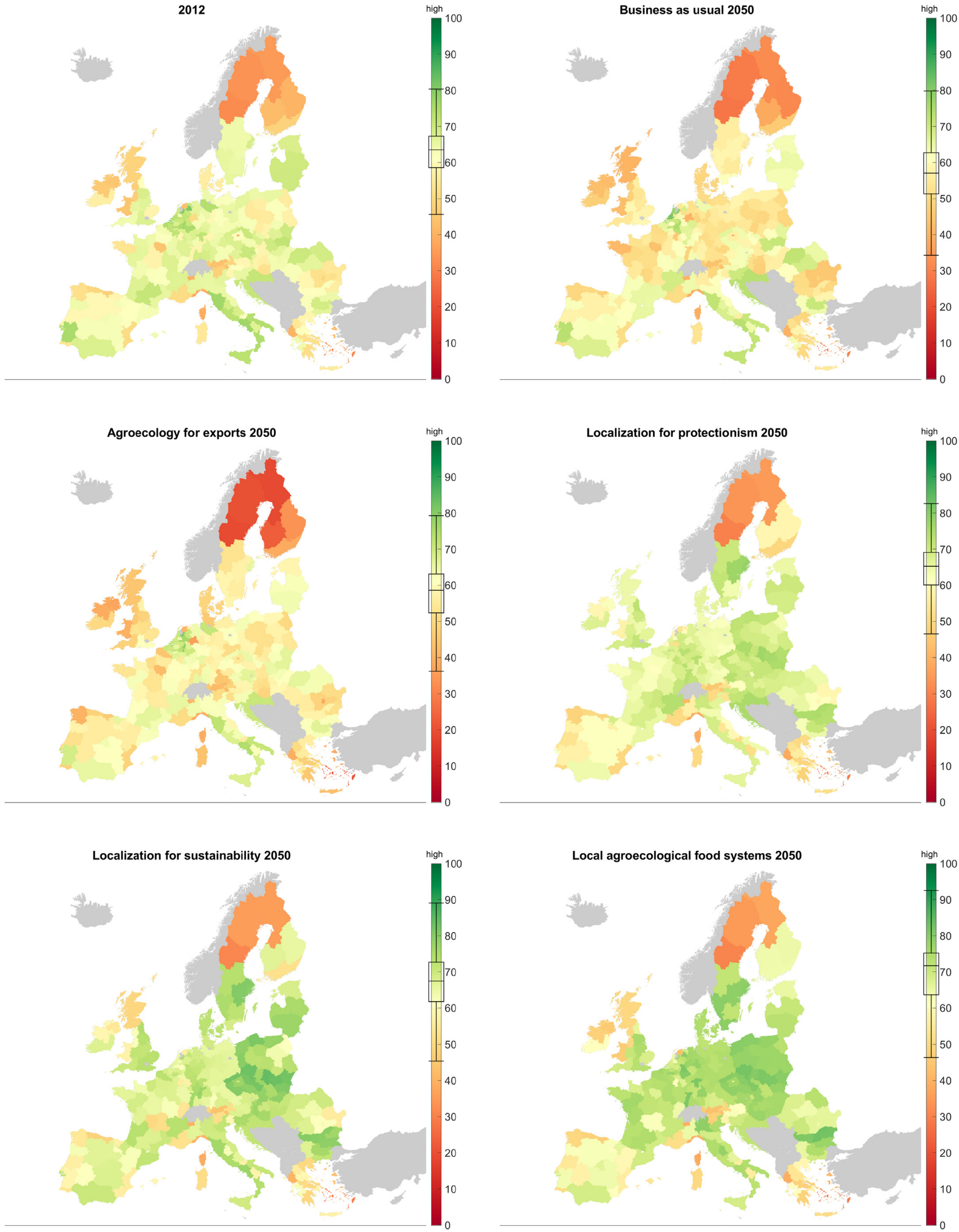


Fig. 5. Heterogeneity of agricultural land use per region in the different storylines, calculated as Shannon Index based on 14 agricultural land uses (11 cropland uses, 3 grassland uses). A high score represents high heterogeneity.

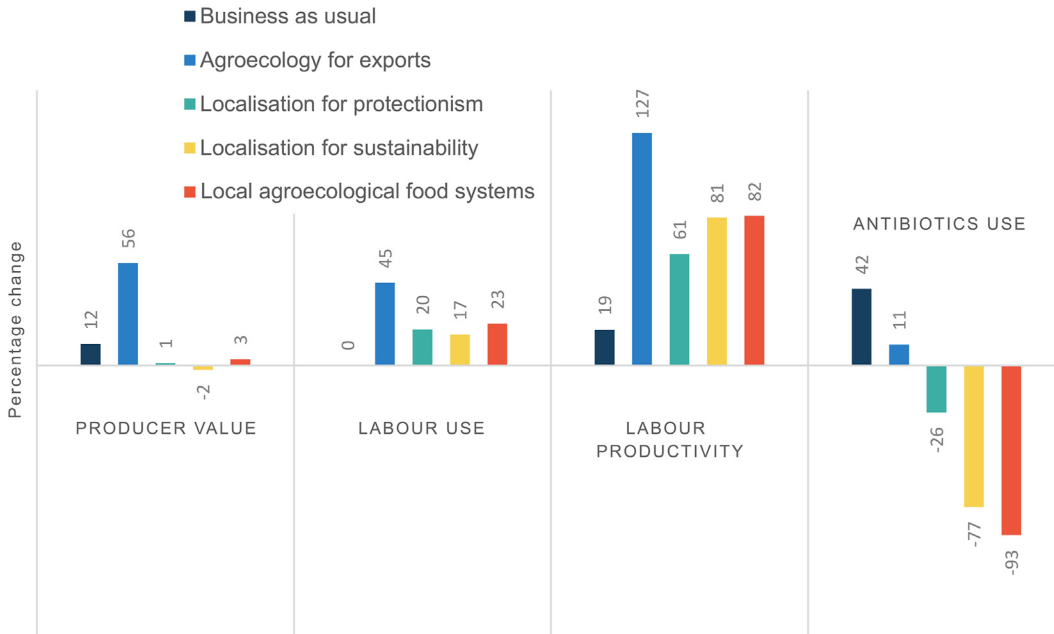


Fig. 6. Percentage change in socio-economic variables in the different storylines in relation to the baseline year 2012.

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

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

Policy area	Target	1. Business as usual	2. Agroecology for exports	3a. Localisation for protectionism	3b. Localisation for sustainability	4. Local agroecological 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 pesticide 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 fertiliser 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%

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

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 storyline, 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 from increases in yield and livestock productivity being used for additional production, environmental pressures could be aggravated.

However, as illustrated by our second storyline with 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 and 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 and 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/l, 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 and 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 the 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.

CRediT authorship contribution statement

Röös Elin: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft, Funding acquisition. **Mayer Andreas:** Conceptualization, Methodology, Investigation, Writing – review & editing, Project administration, Funding acquisition. **Muller Adrian:** Conceptualization, Formal analysis, Software, Methodology, Writing – review & editing, Project administration, Funding acquisition. **Kalt Gerald:** Formal analysis, Software, Methodology, Writing – review & editing. **Ferguson Shon:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **Erb Karl-Heinz:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Hart Rob:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **Matej Sarah:** Formal analysis, Methodology, Software, Visualization, Writing – review & editing. **Kaufmann Lisa:** Formal analysis, Methodology, Software, Writing – review & editing. **Pfeifer Catherine:** Formal analysis, Methodology, Software, Writing – review & editing. **Frehner Anita:** Formal analysis, Methodology, Software, Writing – review & editing. **Smith Pete:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Schwarz Gerald:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

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

Acknowledgements

This scenario work was developed as part of the Uniseco project (https://uniseco-project.eu/), an EU funded research project (Grant Agreement No. 773901), involving 17 partners across 15 EU member states, aiming to develop innovative approaches to enhance understanding of socio-economic and policy drivers and barriers to further development and implementation of agroecological practices in EU farming systems. Our thanks to all stakeholder and project partners who contributed to development of the storylines. Shon Ferguson acknowledges financial support from Jan Wallanders och Tom Hedelius stiftelse and the Marianne and Marcus Wallenberg Foundation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.157612.

References

Alston, J.M., Norton, G.W., Pardey, P.G., 1995. Science Under Scarcity: Principles and Practices for Agricultural Research Evaluation and Priority Setting. Cornell University Press, Ithica, NY.

Altieri, M.A., Rosset, P., 1996. Agroecology and the conversion of large-scale conventional systems to sustainable management. Int. J. Environ. Stud. 50, 165–185. https://doi.org/10.1080/00207239608711055.

Bajželj, B., Laguzzi, F., Röös, E., 2021. The role of fats in the transition to sustainable diets. Lancet Planet. Health 5 (9), E644–E653. https://doi.org/10.1016/S2542-5196(21)00194-7.

Barbieri, P., Pellerin, S., Seufert, V., et al., 2021. Global option space for organic agriculture is delimited by nitrogen availability. Nat. Food 2, 363–372. https://doi.org/10.1038/s43016-021-00276-y.

Bezner Kerr, R., Madsen, S., Stuber, M., et al., 2021. Can agroecology improve food security and nutrition? A review. Global Food Security, 100540 https://doi.org/10.1016/j.gfs.2021.100540.

Billen, G., Aguilera, W., Einarsson, R., et al., 2021. Reshaping the european agro-food system and closing its nitrogen cycle: the potential of combining dietary change, agroecology, and circularity. One Earth 4 (6), 839–850. https://doi.org/10.1016/j.oneear.2021.05.008.

Bowles, N., Alexander, S., Hadjikakou, M., 2019. The livestock sector and planetary boundaries: a 'limits to growth' perspective with dietary implications. Ecol. Econ. 160, 128–136. https://doi.org/10.1016/j.ecolecon.2019.01.033.

Britz, W., Witzke, P., 2015. CAPRI model documentation. https://www.capri-model.org/dokuwiki/doku.php.

Clapp, J., 2017. Food self-sufficiency: making sense of it, and when it makes sense. Food Policy 66, 88–96. https://doi.org/10.1016/j.foodpol.2016.12.001.

Connor, D.J., 2018. Organic agriculture and food security: a decade of unreason finally implodes. Field Crop Res. 225, 128–129. https://doi.org/10.1016/j.fcr.2018.06.008.

Connor, D.J., Mínguez, M.I., 2012. Evolution not revolution of farming systems will best feed and green the world. Glob. Food Secur. 1 (2), 106–113. https://doi.org/10.1016/j.gfs.2012.10.004.

CoR, 2021. Opinion. Agroecology. https://cor.europa.eu/EN/our-work/Pages/OpinionTimeline.aspx?opId=CDR-3137-2020 [Accessed 03-08-2021].

Den Boer, A.C.L., Broerse, J.E.W., Regeer, B.J., 2021. The need for capacity building to accelerate food system transformation. Curr. Opin. Food Sci. 42, 119–126. https://doi.org/10.1016/j.cofs.2021.05.009.

Dumont, B., Farruggia, A., Garel, J.-P., Bachelard, P., Boitier, E., Frain, M., 2009. How does grazing intensity influence the diversity of plants and insects in a species-rich upland grassland on basalt soils? Grass Forage Sci. 64, 92–105.

EC, 2020. Farm to Fork Strategy – for a fair, healthy and environmentally friendly food system. European Commission. https://ec.europa.eu/food/farm2fork_en.

EC, 2020. EU Biodiversity Strategy for 2030. European Commission. https://ec.europa.eu/environment/strategy/biodiversity-strategy-2030_en.

EC, 2021. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021PC0555&from=EN.

EC, 2021. The 3 Billion Tree Planting Pledge For 2030. European Commission. https://ec.europa.eu/environment/pdf/forests/swd_3bn_trees.pdf.

Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M.C., Haberl, H., 2016. Exploring the biophysical option space for feeding the world without deforestation. Nat. Commun. 7, 11382. https://doi.org/10.1038/ncomms11382.

EU, 2016. Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2016.344.01.0001.01.ENG.

EU, 2018. REGULATION (EU) 2018/848 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 on organic production and labelling of organic products and repealing Council Regulation (EC) No 834/2007. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32018R0848.

EU, 2021. Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119.

Eurostat, 2021. Website of Eurostat. European Commission. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Organic_farming_statistics [Accessed 03-08-2021].

FAO, 2018. The future of food and agriculture – alternative pathways to 2050. Food and Agriculture Organisation of the United Nations, Rome. http://www.fao.org/3/I8429EN/i8429en.pdf.

FAO, 2018. The 10 Elements of Agroecology: Guiding the transition to sustainable food and agricultural systems. Food and Agriculture Organisation of the United Nations, Rome. http://www.fao.org/3/i9037en/i9037en.pdf.

FAO, 2020. Website of FAOSTAT. Food and Agriculture Organisation of the United Nations. Statistics Division. http://www.fao.org/faostat/en/.

Food, Farming &, Countryside Commission, 2021. Farming for Change Mapping a route to 2030. https://ffcc.co.uk/assets/downloads/FFCC-Farming-for-Change-Mapping-a-route-to-2030-with-addendum.pdf.

Fricko, O., Havlik, P., Rogelj, J., et al., 2017. The marker quantification of the shared socioeconomic pathway 2: a middle-of-the-road scenario for the 21st century. Glob. Environ. Chang. 42, 251–267. https://doi.org/10.1016/j.gloenvcha.2016.06.004.

Fuchs, R., Brown, C., Rounsevell, M., 2020. Europe's green Deal offshores environmental damage to other nations. Nature 586. https://www.nature.com/articles/d41586-020-02991-1.

Gallardo-López, F., Hernández-Chontal, M.A., Cisneros-Saguilán, P., Linares-Gabriel, A., 2018. Development of the concept of agroecology in Europe: a review. Sustainability 10, 1210. https://doi.org/10.3390/su10041210.

Gardner, B.L., 1987. The Economics of Agricultural Policies. Macmillan, New York.

Godfray, C., 2015. The debate over sustainable intensification. Food Security 7, 199–208. https://doi.org/10.1007/s12571-015-0424-2.

GOS, 2017. A National Food Strategy for Sweden – more jobs and sustainable growth throughout the country. Short version of Government bill 2016/17:104. Government Offices of Sweden. https://www.government.se/498282/contentassets/16ef73aaa6f74faab86ade5ef239b659/livsmedelsstrategin_kortversion_eng.pdf [Accessed 03-08-2021].

Griscom, B.W., Adams, J., Ellis, P.W., et al., 2017. Natural climate solutions. PNAS 114, 11645–11650. https://doi.org/10.1073/pnas.1710465114.

Guisepelli, E., Fleury, P., Vincent, A., Aalders, I., Prazan, J., Vanni, F., 2018. Adapted SES framework for agroecological farming systems and guidelines for assessing sustainability of agricultural systems in Europe. Deliverable 2.1. Understanding and Improving the Sustainability of Agro-ecological Farming Systems in the EU (UNISECO), Report to the European Union, p. 90 https://doi.org/10.5281/zenodo.4568477.

Haberl, H., Erb, K.H., Krausmann, F., et al., 2007a. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. PNAS 104, 12942–12947. https://doi.org/10.1073/pnas.0704243104.

Haberl, H., Erb, K.-H., Plutzar, C., et al., 2007. Human appropriation of net primary production (HANPP) as indicator for pressures on biodiversity. Sustainability indicators A scientific assessment 271–288. https://www.researchgate.net/publication/258261619_Sustainability_Indicators_A_Scientific_Assessment_SCOPE_67.

Herrero, M., Havlík, P., Valin, H., et al., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc. Natl. Acad. Sci. 110 (52), 20888–20893. https://doi.org/10.1073/pnas.1308149110.

HLPE, 2019. Agroecological approaches and other innovations for sustainable agriculture and food systems that enhance food security and nutrition. Committee on World Food Security, High Level Panel of Experts on Food Security and Nutrition. FAO, Rome.

IPCC, 2019. In: Shukla, P.R., Skea, J., Buendia, E. Calvo, Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Pereira, J. Portugal, Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J. (Eds.), Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems.

Kalt, G., Mayer, A., Haberl, H., et al., 2021. Exploring the option space for land system futures at regional to global scales: the diagnostic agro-food, land use and greenhouse gas emission model BioBaM-GHG 2.0. Ecol. Model. 459, 109729. https://doi.org/10.1016/j.ecolmodel.2021.109729.

Karlsson, J.O., Röös, E., 2019. Resource-efficient use of land and animals—Environmental impacts of food systems based on organic cropping and avoided food-feed competition. Land Use Policy 85, 63–72. https://doi.org/10.1016/j.landusepol.2019.03.035.

Karlsson, J.O., Carlsson, G., Lindberg, M., Sjunnestrand, T., Röös, E., 2018. Designing a future food vision for the nordics through a participatory modelling approach. Agron. Sustain. Dev. 38 (6), 59. https://doi.org/10.1007/s13593-018-0528-0.

Kempen, M., Witzke, P., 2018. Improvement of the stable release of the CAPRI model: fertilizer and feed allocation routines. Deliverable 3: Revised Feed Module for CAPRI. Specific Contract No. Joint Research Centre 154208.X39.

Kok, K., Biggs, R., Zurek, M., 2007. Methods for developing multiscale participatory scenarios: insights from southern Africa and Europe. Ecol. Soc. 12 (1). http://www.ecologyandsociety.org/vol12/iss1/art8/.

Kreidenweis, U., Humpenöder, F., Stevanović, M., et al., 2016. Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. Environ. Res. Lett. 11, 085001. https://doi.org/10.1088/1748-9326/11/8/085001.

Lampkin, N., Schwarz, G., Bellon, S., 2020. Policies for agroecology in Europe, building on experiences in France, Germany and the United Kingdom. Landbauforschung J. Sustain. Org. Agric. Syst. 70 (2), 103–112. https://doi.org/10.3220/LBF1611684471000.

Lee, H., Brown, C., Seo, B., Holman, I., Audsley, E., Cojocaru, G., Rounsevell, M., 2019. Implementing land-based mitigation to achieve the Paris agreement in Europe requires food system transformation. Environ. Res. Lett. 14, 104009. https://doi.org/10.1088/1748-9326/ab3744.

Mayer, A., Muller, A., Kalt, G., et al., 2021. Deliverable Report D4.3 Report on Territorial Impacts and Lessons Learnt of the Diffusion of Agro-ecological Farming Systems (AEFS) in the European Union. Understanding and Improving the Sustainability of Agro-ecological Farming Systems in the EU (UNISECO), Report to the European Union. https://doi.org/10.5281/zenodo.5576260.

Mitter, H., Techen, A.K., Sinabell, F., et al., 2020. Shared socio-economic pathways for european agriculture and food systems: the eur-Agri-SSPs. Glob. Environ. Chang. 65 (2020), 102159. https://doi.org/10.1016/j.gloenvcha.2020.102159.

Mora, O., Le Mouël, C., de Lattre-Gasquet, M., et al., 2020. Exploring the future of land use and food security: a new set of global scenarios. PLoS ONE 15 (7), e0235597. https://doi.org/10.1371/journal.pone.0235597.

Morais, T.G., Teixeira, R.F.M., Lauk, C., Theurl, M.C., Winiwarter, W., Mayer, A., Kaufmann, L., Haberl, H., Domingos, T., Erb, K.-H., 2021. Agroecological measures and circular economy strategies to ensure sufficient nitrogen for sustainable farming. Glob. Environ. Chang. 69, 102313. https://doi.org/10.1016/j.gloenvcha.2021.102313.

Moschitz, H., Muller, A., Kretzschmar, U., Haller, L., de Porras, M., Pfeifer, C., Oehen, B., Willer, H., Stolz, H., 2021. How can the EU farm to fork strategy deliver on its organic promises? Some critical reflections. EuroChoices 20, 30–36. https://doi.org/10.1111/1746-692X.12294.

Muller, A., Schader, C., El-Hage Scialabba, N., et al., 2017. Can organic agriculture feed the world in 2050: a critical assessment of the challenges and opportunities. Nat. Commun. 8, 1290. https://doi.org/10.1038/s41467-017-01410-w.

Muller, A., Mayer, A., Erb, K.H., Kalt, G., Lauk, C., Theurl, M., Kaufmann, L., Frehner, A., Pfeiffer, C., Moakes, S., Schader, C., 2020. Report on the methodological specification

of the spatially-explicit modelling framework. Deliverable D4.1. Understanding and Improving the Sustainability of Agro-ecological Farming Systems in the EU (UNISECO) https://doi.org/10.5281/zenodo.4555461 [Accessed 03-08-2021].
Muth, R.F., 1964. The derived demand for a productive factor and the industry supply curve. Oxf. Econ. Pap. 16, 221–264. https://www.jstor.org/stable/2662270.
Nyborg, K., Anderies, J.M., Dannenberg, A., et al., 2016. Social norms as solutions. Policies may influence large-scale behavioral tipping. Science 354, 6308. https://doi.org/10.1126/science.aaf8317.
OECD, 2019. Nutrient Balance. OECD Agriculture statistics. Organisation for Economic Cooperation and Development, Paris. https://data.oecd.org/agrland/nutrient-balance.htm.
OECD, 2021. Producer and Consumer Support Estimates. OECD Agriculture statistics. Organisation for Economic Cooperation and Development, Paris. https://stats.oecd.org [accessed 19-10-21].
Pérez-Soba, M., Maas, R., 2015. Chapter 3: scenarios: tools for coping with complexity and future uncertainty? In: Jordan, A.J., Turnpenny, J.R. (Eds.), The Tools of Policy Formulation. Actors, Capacities, Venues and Effects. Edward Elgar Publishing
Petz, K., Alkemade, R., Bakkenes, M., Schulp, C.J.E., van der Velde, M., Leemans, R., 2014. Mapping and modelling trade-offs and synergies between grazing intensity and ecosystem services in rangelands using global-scale datasets and models. Glob. Environ. Chang. 29, 223–234. https://doi.org/10.1016/j.gloenvcha.2014.08.007.
Ponisio, L.C., M'Gonigle, L.K., Mace, K.C., Palomino, J., de Valpine, P., Kremen, C., 2015. Diversification practices reduce organic to conventional yield gap. Proc. R. Soc. B Biol. Sci. 282, 20141396. https://doi.org/10.1098/rspb.2014.1396.
Poux, X., Aubert, P.M., 2018. An Agroecological Europe in 2050: Multifunctional Agriculture for Healthy Eating Findings From the Ten Years for Agroecology (TYFA) Modelling Exercise. Institut du développement durable et des relations internationales, Paris.
Powell, L.M., Chaloupka, F.J., 2009. Food prices and obesity: evidence and policy implications for taxes and subsidies. Milbank Q. 87 (1), 229–257. https://doi.org/10.1111/j.1468-0009.2009.00554.x.
Prazan, J., Aalders, I., 2019. Typology of AEFS and practices in the EU and the Selection of Case Studies. Deliverable Report D2.2. Understanding and Improving the Sustainability of Agro-ecological Farming Systems in the EU (UNISECO), Report to the European Union, p. 57 https://doi.org/10.5281/zenodo.4116344.
Riahi, K., van Vuuren, D.P., Kriegler, E., et al., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Chang. 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.
Röös, E., Bajželj, B., Smith, P., et al., 2017. Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. Glob. Environ. Chang. 47, 1–12. https://doi.org/10.1016/j.gloenvcha.2017.09.001.
Röös, E., Mayer, A., Erb, K.H., et al., 2021. Deliverable Report D4.2 Report on Participatory Scenario Development of Agroecological Farming Systems. Version 1.1. Understanding and Improving the Sustainability of Agro-ecological Farming Systems in the EU (UNISECO), Report to the European Union. https://doi.org/10.5281/zenodo.5576228.
Rounsevell, M.D.A., Metzger, M.J., 2010. Developing qualitative scenario storylines for environmental change assessment. WIREs Clim. Chang. 1, 606–619. https://doi.org/10.1002/wcc.63.
Säll, S., Gren, I.M., 2015. Effects of an environmental tax on meat and dairy consumption in Sweden. Food Policy 55, 41–53. https://doi.org/10.1016/j.foodpol.2015.05.008.
Schwarz, G., Vanni, F., Miller, D., 2021. The role of transdisciplinary research in the transformation of food systems. Agric. Food Econ. 9, 35. https://doi.org/10.1186/s40100-021-00207-2.
van Selm, B., Frehner, A., de Boer, I.J.M., et al., 2022. Circularity in animal production requires a change in the EAT-lancet diet in Europe. Nature Food 3, 66–73. https://doi.org/10.1038/s43016-021-00425-3.
Smed, S., Scarborough, P., Rayner, M., Jensen, J.D., 2016. The effects of the danish saturated fat tax on food and nutrient intake and modelled health outcomes: an econometric and comparative risk assessment evaluation. Eur. J. Clin. Nutr. 70 (6), 681–686. https://doi.org/10.1038/ejcn.2016.6.
Smith, L.G., Kirk, G.J.D., Jones, P.J., et al., 2019. The greenhouse gas impacts of converting food production in England and Wales to organic methods. Nat. Commun. 10, 4641. https://doi.org/10.1038/s41467-019-12622-7.
Springmann, M., Mason-D'Croz, D., Robinson, S., et al., 2018. Health-motivated taxes on red and processed meat: a modelling study on optimal tax levels and associated health impacts. PLOS ONE 13 (11), e0204139. https://doi.org/10.1371/journal.pone.0204139.
Sumner, D., Wohlgenant, M., 1985. Effects of an increase in the Federal Excise tax on cigarettes. Am. J. Agric. Econ. 67 (2), 235–242. https://doi.org/10.2307/1240674.
Sun, Z., Scherer, L., Tukker, A., et al., 2022. Dietary change in high-income nations alone can lead to substantial double climate dividend. Nature Food 3, 29–37. https://doi.org/10.1038/s43016-021-00431-5.
Theurl, M., Lauk, C., Kalt, G., et al., 2020. Food systems in a zero-deforestation world: dietary change is more important than intensification for climate targets in 2050. Sci. Total Environ. 735, 139353. https://doi.org/10.1016/j.scitotenv.2020.139353.
Tuck, S.L., Winqvist, C., Mota, F., Ahnström, J., Turnbull, L.A., Bengtsson, J., 2014. Land-use intensity and the effects of organic farming on biodiversity: a hierarchical meta-analysis. J. Appl. Ecol. 51, 746–755. https://doi.org/10.1111/1365-2664.12219.
Wezel, A., Soldat, V., 2009. A quantitative and qualitative historical analysis of the scientific discipline agroecology. Int. J. Agric. Sustain. 7 (1), 3–18. https://doi.org/10.3763/ijas.2009.0400.
Wezel, A., Goris, M., Bruil, J., Félix, G.F., Peeters, A., Bàrberi, P., Bellon, S., Migliorini, P., 2018. Challenges and action points to amplify agroecology in Europe. Sustainability 10, 1598. https://doi.org/10.3390/su10051598.
Wezel, A., Gemmill Herren, B., Bezner Kerr, R., Barrios, E., Gonçalves, A.L.R., Sinclair, F., 2020. Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. Agron. Sustain. Dev. 40, 40. https://doi.org/10.1007/s13593-020-00646-z.
Wiebe, K., Zurek, M., Lord, S., et al., 2018. Scenario development and foresight analysis: exploring options to inform choices. Annu. Rev. Environ. Resour. 43 (1), 545–570. https://doi.org/10.1146/annurev-environ-102017-030109.
Willett, W., Rockström, J., Loken, B., Springmann, M., et al., 2019. Food in the anthropocene: the EAT–Lancet commission on healthy diets from sustainable food systems. Lancet 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.
WTO, 2020. Trade Policy Review: European Union 2020. World Trade Organisation. https://www.wto.org/english/tratop_e/tpr_e/tp495_e.htm.
Zurek, M., Hebinck, A., Selomane, O., 2021. Looking across diverse food system futures: implications for climate change and the environment. QOpen 1, 1–39. https://doi.org/10.1093/qopen/qoaa001.