UNISECO

UNDERSTANDING & IMPROVING THE SUSTAINABILITY OF AGRO-ECOLOGICAL FARMING SYSTEMS IN THE EU

Deliverable Report D4.3 Report on Territorial Impacts and Lessons Learnt of the Diffusion of Agro-ecological Farming Systems (AEFS) in the European Union

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EXECUTIVE SUMMARY

The UNISECO project aims to provide recommendations on how the sustainability of agro-ecological farming systems (AEFS) in Europe can be promoted. In this deliverable D4.3, the results from a large-scale implementation of various agro-ecological approaches, from single practices such as undersowing in cereals to more systemic approaches, such as agroforestry, and to a full agro-ecological transformation of the agri-food system are presented. Based on the case-study results from WP3, various bundles of agro-ecological innovations have been identified in a multi-step stakeholder process. Suggested practices and approaches ranged from plot and farm-level to whole food-system level and a selection of those was then chosen for implementation in the two biophysical mass-flow models BioBaM_GHG_EU and SOLm. In BioBaM_GHG_EU, an option space of 432 options was built by combining several variants of a) more or less mixed-farming approaches integrating crop and livestock production; b) livestock diets (fully grass-based ruminant production); c) manure management (conventional, biogas digesters, etc.); d) hedges and undersowing on croplands; e) grassland use in a land sharing or land sparing variant with vegetation regrowth; d) reduced grassland use intensity in high nature value farmland. In SOLm, a detailed implementation of agroforestry systems was implemented, based on parameters from state-of-the-art literature, such as the different crops and trees varieties used and their respective shares per hectare agroforestry, the yield potential of agroforestry, and the performance regarding a number of environmental indicators (e.g. water use, NH3 emissions, C-sequestration). In all these scenarios and options, a number of environmental and socio-economic indicators was assessed, such as land use, GHG emissions, nutrient surplus, etc. or food supply and calorie and protein provision self-sufficiency.

Key results show that many agroecological futures are possible in the EU without compromising food security and with improvements along a number of sustainability indicators if embedded within wider food-systems changes. Sustainable agro-ecological production cannot be addressed without addressing consumption. Key aspects of this are that a) the overall size of the food system is a strong determinant for the potential to increase agro-ecological farming practices and the current amount of livestock production needs to be reduced and redistributed in order to remain within current agricultural land endowment in the future; b) to play out the full potential of improvements, livestock production needs to be linked to cropland (monogastrics) and grassland (ruminants) potentials within the EU, and in combination with innovative livestock diets, is able to re-balance nutrient supply and demand at the sub-national scale; c) in such a contest, an increase in land under agro-ecological practices and a reduction of GHG emissions is possible within the EU in the year 2050 without compromising food security. A particularly large potential for climate change mitigation can be realized with agroforestry and the related carbon sequestration in woody biomass, which can compensate GHG emissions of future agriculture; d) agro-ecological practices such as undersowing cereals with leys and clover allows to reduce the utilization of synthetic nitrogen fertilizers and provide roughage for ruminant livestock and also reduces grazing intensities on grasslands; e) reducing grazing intensities on high natural value farmland is possible without the risk of shortages in grass supply for domestic ruminant livestock or strong ecological impacts. However, in all agroecological scenarios, adequate nutrient supply is a challenge that has to be addressed explicitly.

The information compiled in this report illustrates the large option space that exists for sustainability improvements in the EU agriculture and food systems. It is aimed to help to inform and support the needed actions to implement the farm-to-fork strategy and the EU plans for maintaining biodiversity, as well as the Paris agreement. Policy makers can make use of the information provided in this deliverable to inform

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agricultural policy and decision making to align agricultural production and consumption in the EU with the broad sustainability goals while ensuring long-term food security. Regional policy makers and stakeholders with their detailed, specific knowledge base can gauge which innovations are best suited for a specific region and can then contextualize these agroecological innovations for the specific regions while still firmly linking them to the larger EU agri-food system policies.

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1. INTRODUCTION

The aim of Work package 4 in UNISECO is to discuss and assess the multi-dimensional consequences as well as emerging trade-offs and synergies at the aggregated regional (NUTS2), national and EU-level of agro-ecological innovations in the agricultural sector in the European Union in 2050. These innovations are based on findings from the 15 case studies in UNISECO, which encompass a large heterogeneity of agricultural systems on the transition pathway from purely conventional towards agro-ecological systems. Since WP3 is primarily focusing on production-side measures, WP4 complements this focus by a wider food-systems perspective. Such a perspective is highly complementary to the EU's farm-to-fork strategy, aims to deliver an integrated strategy from food production to food consumption.

Underpinning the assessments are the biophysical models BioBaM_GHG_EU (Erb et al., 2016b; Theurl et al., 2020) and SOLm (Muller et al., 2017; Schader et al., 2015). Both models were significantly expanded within the UNISECO project in order to better capture agroecological innovations on the side of the production systems, and enabling depicting environmental impacts, namely greenhouse gas (GHG) emissions, biodiversity pressures, along with production-consumption indicators such as land-use efficiency or regional self-sufficiency on the side of indicators provided. The assessment of these environmental impacts is based on the detailed agricultural information on land use and biomass flows from production to consumption side and traces biomass flows from ecological processes and agricultural production systems to final consumption with detailed crop production and livestock compartments. BioBaM_GHG_EU and SOLm are diagnostic biomass balance models that can be employed to assess a large number of scenarios in the systematic combination of individual changes in the land and agri-food system.

This deliverable was developed in close cooperation with WP3 which gathered information on agro-ecological innovations in the UNISECO case studies, and with UNISECO Deliverable 4.2, where we assessed the impacts of a set of future agro-ecological storylines in the EU. We here employ spatial analysis to explore to which degree the emerging trade-offs and system effects can be mitigated by exploiting regional characteristics and particularities and thus to implement the agro-ecological innovation bundles to varying degrees in the NUTS 2 regions of Europe.

In UNISECO Deliverable 4.2, we have created five storylines in a participatory process involving all project partners and project stakeholders. The main determinants of the storylines are their level of implementation of agro-ecological farming practices and the localization of food system (i.e. level of trade within the EU and globally). Next to a Business-as-usual scenario, which extends the dynamics and critical aspects of current agri-food systems into the future and highlights current policy barriers to the expansion of agro-ecology, we created two storylines where we integrated elements of agro-ecological farming practices. The first storyline, Agro-ecology-for-export, depicts a future in which medium-large agricultural farms and large companies in the food processing and distribution sectors promote a weak agro-ecological approach as a marketing strategy. The second storyline, Local-agro-ecological-food-systems, reflects the implementation of more advanced stages of agro-ecological transition – redesign.

These two scenarios, which were a first and preliminary look into how elements of agro-ecology in the EU food system would look like, clearly showed that unique combinations of demand and supply side measures incorporating elements of agro-ecology are possible within the current availability of agricultural land. We found that the most decisive factor is the total size of the EU food system, i.e. the total biomass demand in terms of food and feed, much governed by the amount of animal products in diets and the amount of food

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wasted. This allows for room to experiment with agro-ecological production innovations to reduce negative local environmental pressures and increase other socio-economic benefits. Thus, results showed that a decrease in land use, land use intensity and greenhouse gas emissions can be achieved without compromising food security and regional food self-sufficiencies if demand can be moderated. Hence, combining consumption-side measures that mainly aim at realizing less animal source food in diets, and production side measures that aim at shifting from crop-based to roughage-based animal production on the one hand (an agro-ecological systems re-design), and at distributing the different production activities to the regions where they can be done most efficiently, as well as efficiency increases in general, all leads to great environmental improvements. We thus represented agro-ecology by yield changes derived from yield gaps between conventional and organic production (Ponisio et al., 2015), and assumed constant and uniform changes for livestock systems across the European Union in D4.2 In this Deliverable, the focus was on the distribution of cropping areas and livestock numbers defined in certain broad societal storylines and assumptions on diets which were derived from a stakeholder process in WP4.

1.1. Agro-ecological practices in EU farming systems

Current food systems are in many cases unsustainable and have led to the depletion of resources and negative environmental impacts (Rockström et al., 2020; Willett et al., 2019). The heavy use of agro-chemicals, heavy machinery, water, and the increasing reliance on fossil fuels in general has contributed to destabilizing the ecosystem processes which are the basis of agricultural production. Furthermore, the intensification and homogenization of agro-ecosystems has led to an increasing dependence on external inputs, which in healthy agro-ecosystems could mainly be done by the optimization of internal ecological processes. Thus, several experts and high level commissions in international organizations have come to the conclusion that business as usual is not an option and that a radical transformation is necessary (Brunori et al., 2020; Eyhorn et al., 2019; Theurl et al., 2020; Willett et al., 2019).

The concept of agroecology was rather technical at the beginning of the early 20th century, focusing on farming practices and their ecological improvements. This has however changed since. According to Gliessman (2016, 2014), the concept of agro-ecology is based on principles of scientific ecology which is applied to agro-ecosystems management. Looking at agriculture through an ecology lens is a way of looking at agriculture that immediately expands its scope well beyond tilling, sowing and other agricultural practices. Agro-ecology expands the scope of agriculture from the narrow focus of farming practices performed on farm towards the whole universe of interactions among crops, soils and soil organisms, pollinators and environmental conditions, as well as taking the linkages between agricultural production and consumption and the whole food system and the related societal dynamics into account (Gliessman, 2016). Meanwhile, agro-ecology has evolved to an ecology of the entire food system (Mason et al., 2020), with an exponential growth in published research and addressed topics that range far beyond agricultural practices.

A key aspect of agro-ecological systems is reduced external inputs, and much knowledge on agroecological systems' practices is closely related to low-input systems. Many publications have searched for adequate definitions of low-input farming systems, also termed low input or reduced input farming systems, and Rega at al. (2018) provide an excellent overview on definitions. They provide a definition by Nemecek et al (2011) which is based on Parr et al. (1990), according to which low-input farming systems are defined as farming systems that *''seek to optimise the management and use of internal production inputs (i.e. on farm resources) […] and to minimise the use of external production inputs [...] such as purchased fertiliser and pesticides,* *wherever and whenever feasible and practical, to lower production costs, to avoid pollution of surface and ground water, to reduce pesticide residues in food, to reduce a farmer's overall risk, and to increase both short- and long-term farm profitability''* (quote from Rega et al. 2018).

Research on low-input farming systems has meanwhile reached a considerably body of scientific publications (Mason et al., 2020; Rega et al., 2018). Agro-ecology or agro-ecological farming systems, which are one important research stand within such low-input farming research, are being increasingly included at in EU-wide assessments of the future of the EU agricultural system (Poux and Aubert, 2018) Additionally, the German Advisory Council on Global Change (WGBU) has underlined the importance of agro-ecological food systems for the necessary fundamental change that we need to manage land sustainably and to reach the targets of climate-change mitigation set out in the Paris climate agreement (WBGU, 2020). In another study, Wezel et al. (2009) consider agroecology as constituted from the following three angles: as a social movement (in reference to the Latin American (food sovereignty) movements, e.g. from Brazil); as a field of investigation for agronomy (science-driven); and as a set of concrete practices with varying degrees of formalization. This translates into spatially varying approaches, from (1) investigations at plot and field scales such as tillage, cover crops, fertilization, irrigation, etc., (2) investigations at the agroecosystem and farm scales, such as cropping system, crop & cultivar choice, rotation, intercropping; weed, pest & disease management; etc. and (3) investigations covering the whole food system, such as e.g. management of landscape elements (from field to landscape scale) (Wezel et al., 2014). In line with the second and third approach, we aim to investigate the ecological and socio-economic changes induced through the territorial implementation of a set of different agro-ecological innovations throughout Europe.

The Institute for Sustainable Development and International Relations (IDDRI) has developed the TYFA project (Ten Years for Agroecology in Europe), where they have developed a quantitative model simulating the agricultural functioning of the European food system in order to examine the current situation and to develop an agro-ecological scenario for Europe in 2050 (Poux and Aubert, 2018). They start from the notion that the current European food system is highly productive in terms of land use and labour requirements, but not sustainable. It is based on high inputs of agro-chemicals and technology, often detrimental to the environment and human health. Additionally, the massive input of technology is also detrimental for rural job provision (Dorward, 2013). They ask, how a future agricultural system that is based on fewer inputs is possible, and whether such a change is enough for biodiversity conservation and the protection of natural resources, as well as whether such a systems is also able to improve the quality of our food (Poux and Aubert, 2018). Figure 1 shows the main assumptions they have implemented in their assessment.

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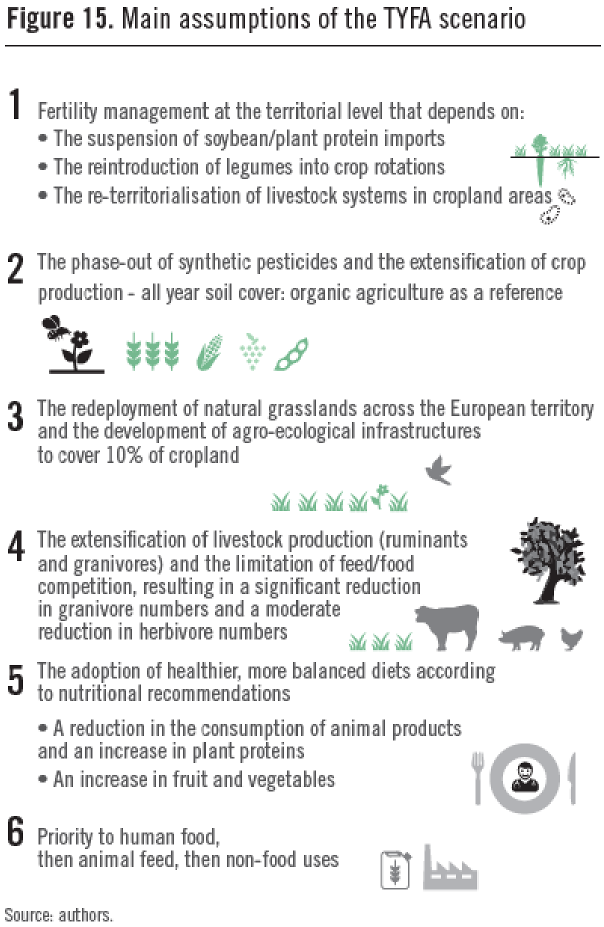

Figure 1: Main assumptions of the TYFA scenarios in (Poux and Aubert, 2018)

These principles are well in line with the production principles of agro-ecology from Anderson et al. (2021a), and they additionally mention a necessary diversification from a landscape perspective, as well as the minimization of the use external resources and inputs. However, the last production principle, i.e. giving priority to human food, then animal feed and lastly to non-food uses, is considerably important and does partly contradict the definition of agroecology from Poux and Aubert (2018). We are coming back to this issue later in this report, i.e. in section 3.2.3.

Poux and Aubert (2018) focus on the EU-28 as their unit of analysis, which they treat as a “black box” and thus omit the internal heterogeneity within the EU-28 agricultural and food system. While the authors acknowledge that this approach is contrary to the principles of agroecology, which embraces heterogeneity and local particularities, they consider their EU-level assessment as an essential prerequisite for participating in discussions on the advancement of agroecology in Europe on a larger scale. They have asked important questions on key elements of cornerstones of agro-ecological systems in Europe, without going as far as addressing the multiple (social, economic and ecological) benefits and impacts a largescale agro-ecological transition would bring to Europe. Nevertheless, they aimed to address all dimensions of the agricultural and food system: fertility management, plant production, land use, animal production, non-food uses, and European diets (Poux and Aubert, 2018). Importantly, they consider agro-ecology not only as production-side measures, but also include European diets, which is in line the modelling philosophies of the two biophysical models used in this study, BioBaM_GHG_EU and SOLm.

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1.2. Aims of this deliverable and a preliminary definition of agro-ecological agri-food system

Agro-ecological practices are not new and are partly applied across farming systems. Currently, agro-ecological systems exist rather isolated, and the main challenge for a transformation to truly sustainable agricultural systems is a territorial, i.e. large-scale adoption of agro-ecological practices. Expanding the scale of agro-ecological experiences and practices (de Molina, 2020; Levidow et al., 2014) to – in this case - an EU-wide scale thus allows to assess whether the aimed advantages of such a transformation can be realized, or if negative trade-offs would occur.

The common agricultural policy (CAP) of the European Union has been an instrument which went from securing and subsidizing food production towards the ambition of integrating climate protection, rural development and animal welfare, albeit there is still much considerable room for improving this integration (Scown et al., 2020). Next to direct payments which subsidize area instead of (formerly) production and which are coupled to basic environmental regulation, Pillar 2 provides (albeit much less) financial compensation for additional and voluntary measures. The CAP reform for 2021-2027, which is currently discussed, presents eco schemes and enhanced conditionality as its key innovations and as successors to cross-compliance and greening measures. They basically aim to enhance incentives to integrate sustainable farming practices as a precondition to receive Pillar 1 direct payments. Eco schemes will be mandatory for EU member states but the concrete arrangements need to be done nationally and regionally (Lampkin et al., 2020). We aim to take up individual measures and practices in this deliverable, and thus provide essential information for benefits and negative impacts for the concrete design of the new CAP.

We here build upon and extend previous empirical work on agro-ecology (Poux and Aubert, 2018), sustainable intensification (Foley et al., 2011; Godfray et al., 2010; Loos et al., 2014; Scherer et al., 2018; Tilman et al., 2011), ecological intensification (Tittonell, 2014), in general food systems modelling encompassing aspects of sustainable food systems. We address this challenge through the following three dimensions. Firstly, we apply a high-resolution biophysical food systems model for 227 regions (mainly Nuts2 level) for the whole European Union (except Cyprus and Malta, which are excluded for data availability reasons, but including the UK) to upscale agro-ecological innovations which we found in 15 case studies conducted in WP3 in the UNISECO project. Secondly, we model a range of environmental and socio-economic consequences at the territorial level to assess whether agro-ecological practices that are generally considered to be beneficial at the plot, field or farm level are also beneficial at the territorial level. And thirdly, the model environment of the two biophysical land use and livestock models BioBaM_GHG_EU and SOLm (Erb et al., 2016b; Muller et al., 2017; Theurl et al., 2020) that allows to calculate a large number of scenarios is employed to assess and compare the impact of individual agro-ecological practices or bundles of practices on a range of indicators and across a broad range of scenario variants of each explicitly modelled parameter (e.g. different diets, or different livestock feeding rations and efficiencies).

For the purpose of UNISECO D4.3 we will adopt and use agro-ecology considering various scales such as field/plot, farm, landscape and food systems. As a consequence, some agro-ecological innovations which we integrate in BioBaM_GHG_EU and SOLm for this deliverable, are more farm and technique related, others are clearly on the food system level – even when the agro-ecological practices are also field or landscape related.

The definition of agro-ecology by (Wezel et al., 2014, 2009) which identifies agro-ecology as an embracing concept including science, agricultural practice and a social movement was used as a starting point within

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Uniseco. There, the agri-food system was contextualized by the SES-framework, i.e. a framework which embeds the latter within a socio-ecological systems perspective, which allows to trace interactions between biophysical and social entities. This adapted SES framework from Ostrom (2009) was designed around following core question: what are the actions initiated at different levels towards agro-ecological transition of farming systems and what are their performances (Guisepell et al., 2018)? These "Focal Action Situations" relate to the actions, the rules and the possible collective organization undertaken towards agro-ecological practices and farming systems. While this dynamic was assessed in Uniseco Work packages 3 and 5 mainly, Work package 4 is complementing this perspective twofold. Firstly, an assessment at the territorial level aims to model the sustainability impacts of a large-scale adoption of these agro-ecological practices at the territorial level. We thus assess the impacts of the "final" stage in the transition pathway from the current toward an agro-ecological landscape and food systems, as defined in Uniseco (Prazan and Aalders, 2019). And secondly, we complement the assessments from WP3 by adding the perspective of dietary changes, thus relocate the farming practices in a total food systems perspective.

Agro-ecological farming and food systems, as assessed in Uniseco in general and in WP4 in specific, include concepts from a broad range of more or less specific or targeted agricultural management practices. These are, among others, practices from **Conservation Agriculture**, which focus primarily on soil quality and properties and alternative soil management and tillage strategies (such as reduced tillage, undersown crops or in general, extension and re-integration of legumes in crop rotations) (Baddeley et al., 2014; Dumanski et al., 2006; Giller et al., 2015; Hobbs et al., 2008; Reckling et al., 2014). **Regenerative Agriculture**, which focus on the maintenance and renewal of natural resources (Lal, 2020; Pretty, 1995) as well as approaches which focus on the sequestration of organic carbon in the soil (Bai et al., 2019; Cardinael et al., 2017; McSherry and Ritchie, 2013). **Low-Input Farming Systems**, which focus primarily on the reduction of the amount of external input such as pesticides or fertilize but may also include reducing working time to gain higher productivity (Nemecek et al., 2011; Rega et al., 2018), **Integrated Farming Systems**, which seem – to different degrees – using both biological and synthetical approaches in nutrient, weed, pest and disease management to reduce negative environmental impacts but also to reduce the yield gap between conventional and organic production (by extension and re-integration of legumes in crop rotations or optimized manure management systems) (Anglade et al., 2015, 2015; Barbieri et al., 2017; Wortmann et al., 2000; Zemann, 2012). **Organic farming systems** as defined by legislation (e.g. EU and USDA), regulations and certification schemes which exclude the use of synthetic chemical pesticides and fertilizers. Different (private) schemes target and emphasise agro-ecological practices to a different degree (for instance biodynamic farming integrates crop, livestock and pasture on a farm level), as well as mixed farming approaches and regional nutrient re-cycling, which aim to close nutrient cycles from livestock and cropping systems (Leip et al., 2015a; Liu et al., 2015; Ryschawy et al., 2012). **Agroforestry**, which aims to integrate perennial woody plants into annual crop or/and livestock farming (Cardinael et al., 2017; Chatterjee et al., 2018; Kay et al., 2019; Nair et al., 2009; Sanchez, 1999). **Sustainable / Ecological Intensification**, which includes aspects of the previous approaches by optimizing strategizes of input – output variables to reduce environmental impacts and enhance productivity (Gaitán-Cremaschi et al., 2020; Scherer et al., 2018; Tittonell, 2014; Wittwer et al., 2017). **Biodiversity / Landscape approaches** which aim to reconceptualize agricultural systems at the landscape level to avoid trade-offs with biodiversity and/or regulating ecosystem services (Maes et al., 2016; Mouchet et al., 2017; Rega et al., 2020). **Agro-ecological food systems** also include (apart from the farm and landscape/agroecosystem level) food production and consumption systems, processing and marketing, economic and political decisions, and consumer habits in society (Gliessman, 2016; Wezel et al., 2009) with

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the aim to gain higher sustainability and to reduce negative environmental and human health-related impacts by e.g. healthier and more balanced diets or priority to human food instead of animal feed (Poux and Aubert, 2018; Schader et al., 2015; Smith et al., 2010). In BioBaM_GHG_EU and SOLm, we do aim to model the environmental and socio-economic impacts of a territorial (i.e. EU-wide) implementation of selected and innovative agricultural practices (or bundles of practices) in the European Union in the year 2050. Additionally, we embed all scenarios for the EU agri-food system in a global agri-food system environment.

In this assessment, we therefore aim to complement the bottom up-case studies from Uniseco WP3 by providing a top-down modelling assessment where we model an upscaling of a range of future agro-ecological systems in the European Union in the year 2050. We thus re-connect livestock and crop/grassland production in the BioBaM_GHG_EU implementation, as well as we are going to explicitly assess shifts between the main agricultural sectors (i.e. livestock systems, cropland production and grasslands), driven by distinct demands for agricultural products and trade assumptions. We furthermore assess the impacts of a large-scale implementation of agroforestry in the EU. Given the importance of the size of the total food system to give room for and enable production-side changes (Davis et al., 2016; Erb et al., 2016b; Muller et al., 2017; Röös et al., 2017; Smith, 2013; Tilman and Clark, 2014; Westhoek et al., 2014; Willett et al., 2019), we combine the production side modelling of agro-ecological practices with different variants of human diets and levels of food wastes and losses in our scenario settings.

1.3. The role of modelling in policy advice

In this section, we shortly take a broader view and provide some thoughts on how modelling such as presented in this deliverable can support policy advice. This is also triggered by the observation that such model results which are based on an option space approach rather than at a prognostic scenario approach are often confronted with the reproach of being unrealistic and hence basically useless and at worst misleading.

First, it is important to emphasize that modelling as done here does not provide forecasts of projections on how the future will develop, but rather option spaces on how it could develop under certain combinations of assumptions (see. Deliverable D4.1). The basis are a number of assumptions, on how the future may look like regarding some key aspects of the agri-food system such as the share of agroecologically managed areas, the feeding rations for livestock, yield expectations or dietary composition. For all these aspects, a number of parameter values covering a rather broad range are chosen (e.g. share of agroecologically managed areas: 25%, 50% or 75%; reduction of animal source food in human diets: 0%, 20%, 40%; etc.) and the option space is then built by calculating model results for all possible combinations. The model results from all these possible combinations (i.e. options) are then assessed according to a number of key indicators such as cropland use, livestock numbers, GHG emissions, nitrogen surplus, labour use, etc. and analyzed with a particular focus on key trade-offs and synergies. In BioBaM all combinations are firstly evaluated in terms of land use feasibility, i.e. whether a certain supply can be met on a specific extent of crop and grassland, which is also defined exogenously. A key example is the relation between increased agroecological production and reduced nitrogen surplus, which shows a synergetic development at lower levels of agroecology, as it brings down nitrogen surplus, but becomes a trade-off at higher shares, as sufficient nitrogen supply becomes challenging. Or the relation between feeding rations with less concentrate feed and the share of animal source food in human diets, which is synergetic, as reduction in concentrate feed use goes along with reduced animal numbers and correspondingly reduced production of animal-sourced food.

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Given the high uncertainty in such modelling the interest is generally in gross changes and differences. Such modelling is not adequate to investigate the difference in a share of 20% or 23% areas under agroforestry in a certain country, but it can assess results from having 15%, 40% or 45% more agroforestry. The focus is then also on larger differences in impacts: if GHG emissions differ by 3 or 5% between two options does not matter, given the large uncertainties, but if they differ by 20% or 40% does. This is then also the aim of building such model-based option-spaces: to identify which combinations of assumptions result in significant differences in impacts, which then allows to provide rather robust statements on where the big levers for change may lie and which particular opportunities or challenges (e.g. captured by synergies and trade-offs) may arise from addressing those. This is the main strength of such approach and also a key feature in comparison to modelling the biophysical impacts from consistent scenario narratives, since this option space approach allows to assess the impacts of changes in one specific parameter by leaving all other parameters constant, resulting in a ceteris paribus scenario approach.

A key aspect of such results is the viability of different options according to certain criteria: e.g regarding land use (e.g. whether the option does not use more land than specified by a certain threshold such as e.g. the current cropland use, i.e. is it viable without deforestation), regarding nutrient supply (e.g. whether the option is viable regarding nitrogen availability for the envisaged crop production or is there a danger of a considerable lack of nutrients, which requires additional actions) or regarding GHG emissions (e.g. whether the options are viable regarding achieving certain GHG emission reduction goals or not). Given the structure of the models used here, we can assess biophysical viability of the options, which means that we can provide results on how the various combinations of assumptions play out regarding biophysical indicators – but we cannot make statements on how economic aspects and market dynamics and consumer and producer decisions will be influenced by these assumptions (besides some gross estimate on how value generation or productivity may change, just related to physical areas, animal numbers and production volumes). In this, the biophysical viability assessments provide a prerequisite for any socio-economic or policy analysis – in case the biophysical viability of an option is not given, it is not worth investigating it further, or, if specific biophysical trade-offs or synergies are identified, it is worth to put a particular focus on how to remedy or build on those when going further towards socio-economic and political discussions. A specific aspect of biophysical viability is consistency, as these models also provide insights into whether certain combinations of assumptions result in agronomically and biophysically consistent systems or not (a prime example being work on vegetarian diets, where the biophysical modelling clearly also traces the meat flows that relate to any egg or milk production).

This type of modelling results can thus provide a rather robust input on how to formulate biophysically viable and consistent policy goals and visions, but not on how to reach those.

Finally, we make a note on some technical aspects of the modelling, as we use two models, one of which is based on a certain type of optimization (BioBaM), while the other is not (SOLm). Grossly speaking, optimization models provide maximal flexibility on what is produced where and how, given certain targets are reached (e.g. minimized land use or GHG emissions) and certain boundary conditions are fulfilled (e.g. providing a minimal level of calories and protein per capita to assure fulfilling the availability aspect of food security). In BioBaM_GHG_EU, all agro-ecological scenarios are based on the condition that 1) livestock production patterns are aligned with domestic production potentials, and that cropland production is driven by the domestic demand. This results in proto-optimal production and food system, at the costs of involving dramatic changes in production pattern suggested (as e.g. the algorithm used in BioBaM_GHG_EUj will suggest to do only monogastric production if no grassland is available in a certain region), which can be remedied by hand only (e.g. requiring a certain share of ruminant production in the same region). Models such as SOLm, on the other hand, are “maximally realistic” being closer to “reality” e.g. captured by baseline or reference scenarios that are used as default values, at the cost of any flexibility regarding this having to be added by hand via assumptions, and at the cost of being inadequate for identifying optimal situations easily. An optimization can thus assess land use and GHG emissions in a future scenario, where livestock production would be relocated all over Europe to best fit the resources availability (which could result in some countries entirely abandoning ruminant or monogastric production, as this could be done more efficiently elsewhere), while non-optimized scenarios could assess how changes in feeding patterns may influence land use and GHG emissions in a future scenario, where much less concentrate feed is used, but relative shares of different animal types in each country remain closer to what is reported today.

Thus, the results from these two modelling approaches complement each other, as the approach pursued in BioBaM_GHG:EU provides insights into what could be possible if done the best way, and SOLm provides insight into what could be possible, if we stay closer to current production patterns which reflect a number of economic, cultural, social etc. national characteristics that may not easily be overridden.

2. METHODS

This section shortly describes the two biophysical models BioBaM_GHG_EU and SOLm used for the assessment of agroecological innovations at territorial level.

2.1. BioBaM_GHG_EU

The territorial assessment is based on a significant expansion of the global biomass balance model BioBaM. The first version of BioBaM (Erb et al., 2016b) was developed as a biophysical accounting model in MS Excel that calculates the balance between biomass supply and biomass demand. The original version had a spatial resolution of 11 world regions and a thematic resolution of 14 biomass demand categories. The previous version did not include GHG accounting or other environmental impact assessments. For UNISECO, the model was set up in a flexible and efficient software environment that enables the calculation of a large number of scenarios with high spatial and thematic resolution. A specific focus was on the subnational level within the EU, where the spatial resolution is at the NUTS2/1 level, while regions beyond the EU are implemented at the country level.

In its basic principle, algorithms in BioBaM_GHG_EU calculate the balance and thus establish consistency between biomass supply and biomass demand for different biomass demand categories and corresponding primary commodities (see D4.1). Scenario settings, i.e. input parameters are exogenously identified, and the balancing procedure indicates infeasibilities if demand cannot be satisfied under given biophysical constraints (e.g. maximum cropland expansion, maximum grazing intensities).

BioBaM_GHG_EU is based on consistent data on biomass flows and land use, and is built upon thermodynamic principles (the law of conservation of mass and energy). It systematically combines biomass flows in ecosystems and socioeconomic systems (including, for example, NPP, used and unused harvests for 40 cultivars for Europe derived from CAPRI, and 58 cultivars for non-Europe, the consumption of final products such as food and fibre). The thematic differentiation in BioBaM_GHG_EU is at the level of 19 final commodity groups (e.g. cereals, oilcrops, ruminant meat, eggs etc.). These flows of final commodities invoke flows of primary biomass, which we relate to land-use databases and which we complemented by assessments of

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greenhouse gas fluxes and further environmental (e.g. grazing intensity, total biomass appropriation - TBA) and socio-economic (e.g. food self-sufficiency, net-trade flows) indicators. A detailed description of BioBaM_GHG_EU can be found in UNISECO D4.1, a forthcoming publication by Kalt et al. (under review), and a detailed description and analysis of the base year data in Mayer et al. (under review).

2.1.1. Indicators

In BioBaM_GHG_EU, a series of indicators for environmental and food autarky related effects are calculated for each of the 432 scenarios included in this study (see section 4). Each indicator is provided for each NUTS2 region, country and world region (Table 1: Parameters and indicators calculated in BioBaM_GHG_EU for each scenario). For details on parameters and items, see Uniseco Deliverable 4.1.

Table 1: Parameters and indicators calculated in BioBaM_GHG_EU for each scenario

Parameter	Items
Land use (Mha)	Cultivated cropland
	Grassland (or grazing land, both terms used interchangeably)
	Fallow cropland
	Cropland converted to grassland
	Cropland left to natural succession
	Grassland converted to cropland
	Grassland left to natural succession
Cropland area by crop group (Mha)	All crop groups names as defined in input file
Grassland by classes (Mha)	All grazing class names as defined in input file and 'original cropland'.
Net imports by crop group (Mt)	All crop group names as defined in input file
Crop production (Mt)	All crop group names as defined in input file
Crop consumption for food (Mt)	All crop group names as defined in input file
Crop consumption for feed (Mt)	All crop group names as defined in input file
Crop residues used as feed (Mt)	Crop residues
Crop consumption for feed by agriproduct (Mt)	All agricultural product names as defined in input file, followed by ' - ' and all crop group names as defined in input file Agricultural products contain animal products and non-food products
Crop residues used as feed by agriproduct (Mt)	All agricultural product names as defined in input file, followed by ' - crop residues'
Crop consumption for other uses (Mt)	All crop group names as defined in input file
Agri. products production (Mt)	All agricultural product names as defined in input file
Agri. products consumption for food (Mt)	All agricultural product names as defined in input file
Agri. products consumption for other uses (Mt)	All agricultural product names as defined in input file
Grass supply (Mt)	All grassland classes (class 1-3)
Grass demand (Mt)	Total grazed biomass
Grazing intensities	All grazing class names as defined in input file and 'original cropland'
Potential self -sufficiency (1)	Land-based self-sufficiency on region level
	Land-based self-sufficiency for regional aggregates level 1 (i.e. country-level)
	Land-based self-sufficiency for regional aggregates level 2 (i.e. world-regional level)
Self-sufficiency (all crops) (1)	Self-sufficiency for all crop groups (e.g. cereals, oilcrops etc.)

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Self -sufficiency by crops (1)	All crop group names as defined in input file
	All crop group names as defined in input file
	All crop group names as defined in input file
Self-sufficiency by agri.products (1)	All agricultural product names as defined in input file
	All agricultural product names as defined in input file
	All agricultural product names as defined in input file
GHG emissions from land use change (annual) (Mt CO2e)	Total annual LUC emissions
GHG emissions from land use change (cumulative) (Mt CO2e)	Total cumulative LUC emissions
GHG emissions from manure management (Mt CO2e)	All agricultural product names as defined in input file
GHG emissions from enteric fermentation (Mt CO2e)	All agricultural product names as defined in input file
GHG emissions: upstream emissions by crop group (Mt CO2e)	All crop group names as defined in input file
TBA: Harvested biomass as share of total NPPpot (1)	A proxy indicator for HANPP, the human appropriation of net primary production. NPP changes from land use change are not considered in this indicator
Regional grazing feasibility (1)	Regional grazing feasibility
N deficit in AE farming	The relative deficit of N fertilizer in AE farming which needs to be covered with synthetic fertilizer
Heterogeneity of land use	Shannon Index of the heterogeneity of agricultural land

The heterogeneity of agricultural land use per region was calculated with the Shannon-Index (Shannon and Weaver, 1949; Spellerberg and Fedor, 2003):

$$H = -\sum_{i=1}^{N} p_i * \ln(p_i)$$

Where in this case *N* is the number of differentiated agricultural land uses (*N*=14, 11 cropland groups and 3 grassland groups) and *p* is the proportion of total land use represented by land use type *i*. Maximum possible heterogeneity was calculated as *Hmax=ln(N)* and the measure of evenness describing the heterogeneity of agricultural land use is produced by dividing *H* by *Hmax*. A high score of evenness therefore represents an even occurrence of all land use types, constituting high heterogeneity of the agricultural land.

2.2. **SOLm**

SOLm is a global mass- and nutrient flow model, calibrated with FAOSTAT data, which means that the default baseline data is the FAOSTAT production areas and animal numbers in the regional, crop and livestock-type resolution as provided by FAOSTAT. Similarly, Commodity Balances and trade flows from FAOSTAT / TRADESTAT are included at the respective level of commodity resolution as available from FAOSTAT. The choice of baseline is flexible and can be done to include the average values for any series of years from 1961 to the newest data available in FAOSTAT. For UNISECO, we calculate with a baseline that refers to the average of 2009-2013. SOLm also includes the reference values for 2050 as provided by FAO in the FOFA 2050 projections described in FAO (2018). This default baseline and 2050 reference scenario data is complemented and refined by a large number of additional data, e.g. on feeding rations, herd structure, manure management, per animal head feed requirements, organic yield gaps, etc., as described in Deliverable D4.1, that contains a detailed presentation of SOLm and BioBaM.

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SOLm basically runs by specifying cropland and grassland areas for all available crop and grass types, and then uses baseline default values for all relevant parameters such as utilization shares of domestically available quantities (e.g. for food, feed, etc.) etc. to derive crop production volumes, related trade flows, feed availability, animal numbers and related production and emissions. All default values can easily be replaced by scenario-specific values, if needed, and by this, SOLm is very flexible in allowing changing parameter values in scenarios to best capture the related storylines. Furthermore, it is easy to refine baseline default values, e.g. by reading more detailed data on country-level agriculture from GHG inventories. This is then also used to cross-check validity, by replicating GHG inventories on country level for the baseline, as well as OECD N- and P-balances.

The general guiding principle in SOLm is to keep everything as close to the reference scenario as possible. Thus, e.g. shares in feed allocated to pigs or chicken, derived from baseline values, are also used in scenarios, unless the scenario assumptions require that this is changed. Similarly, SOLm derives trade flows in scenarios, by using shares of imports from and exports to different countries according to these shares in the baseline, duly adapted by changes in production.

For further details, see UNISECO Deliverable D4.1.

2.2.1. **Indicators**

SOLm calculates a number of indicators on various levels of regional resolution. This covers all relevant parameters for the GHG emissions and nutrient balances (thus, all intermediate parameters as used in the IPCC guidelines are in principle available), as well as suitable sums (e.g. total GHG emissions, etc.). Furthermore, SOLm derives per commodity unit footprints, where a choice between different functional units and allocation methods is possible. For details on parameters and items, see Uniseco Deliverable 4.1.

Table 2 Selected Parameters and indicators calculated in SOLm for each scenario

Parameter	Items
Land use (ha)	Cultivated cropland
	Grassland (or grazing land, both terms used interchangeably)
	Area harvested
Cropland area by crop group (ha)	Crops as in FAOSTAT
Grassland (ha)	Permanent and temporary grasslands separately'
Animal numbers (heads)	Livestock types as in FAOSTAT plus herd structure
Crop production (t)	Crops as in FAOSTAT
Animal production (t)	Crops as in FAOSTAT
Food Balances (t)	As detailed in FAOSTAT FBS, various utilization of domestically available quantities
Trade flows(t)	Imports, exports, production and domestically available quantities
Self sufficiency (shares)	Commodity production (minus exports) in relation to domestically available commodities
GHG emissions (t CO2e)	Various components of GHG emissions as separated in the IPCC guidelines for GHG inventories
N and P balances (tN, t P2O5)	Various components and flows as needed to derive the quantities used in OECD N and P balances

Further environmental indicators	A number of indicators that are captured by per ha or per head or per ton values, partly adjusted for production specific aspects (e.g. yields): examples are water erosion, water use, pesticide use, etc. (see D4.1 for details)
Further sustainability indicators	A number of indicators that are captured by per ha or per head or per ton values, referring to societal or economic aspects, such as labour use, value generation, labour productivity or animal welfare

3. AGRO-ECOLOGICAL INNOVATION BUNDLES

3.1. Transdisciplinary Stakeholder integration

Central in the UNISECO project are 15 case studies on agro-ecological transitions across Europe. They comprise a broad range of agricultural systems and land uses at different stages in an agro-ecological transition. In WP3, case study researchers have utilized decision support tools to gather information from the individual case studies for such innovations. In spring 2020, we have distributed questionnaires to gather additional information from the case studies on these innovations, and checked the feasibility to implement and model them in the two biophysical models utilized in WP4, BioBaM_GHG_EU and SOLm. The questionnaire provided guidelines how to describe case-study innovations for the territorial assessment aimed to gather the relevant information needed in WP4, which aims at upscaling agro-ecological innovations as identified in the case studies to EU level and to analyse the related trade-offs, synergies and sustainability impacts. While agro-ecological practices can already be found in agricultural systems, we here aim to model a large-scale implementation of these practices where they are possible in the whole European Union, and thus assess the territorial impacts of a full switch to agro-ecological systems in the European Union in 2050. The guidelines provided general instructions on how to choose and describe the agro-ecological innovations observed in the case studies in such a way as to represent them in the two biophysical models. Thus, in particular, it described for project partners which information is needed and how to present it to achieve this upscaling.

Examples from the Austrian, Swiss and Swedish case studies were used to illustrate how to choose innovations that can then be used in WP4 for the territorial assessment, and which information should be compiled as a basis for this. We asked each partner to choose a number of key innovations in their case study and to report on them as described below and illustrated in the examples given further down. The innovations can be core innovations in the case study, but they can also be marginal innovations of seemingly low importance, in case the partners judge them to be interesting when scaled up. We aimed at identifying and modelling those agro-ecological innovations that truly make a difference in terms of specific sustainability impacts. Further, innovations were classified according to the scale of implementation, namely:

- plot level, e.g. changing from standard ploughing to reduced tillage,
- farm level, e.g. changing to a new cattle breed that thrives well on a zero-concentrate feed diet, plus corresponding changes in feed production and feed purchase,
- regional/landscape level, e.g. establishing cooperation between different types of farms with the aim to implement an optimised closed-nutrient production system across all participating farms in the region; thus, a vegetable farmer may use manure for fertilization which stems from a dairy farmer

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nearby, and produces forage crops in the crop rotations that are then used as feed by the dairy farmer, etc.

- food-system level, e.g. supporting a shift from dairy production to plant-based production with a corresponding shift in demand to assure consistent implementation of such shifts without the need to export the new produce and to import the shortfall of dairy products, due to unchanged demand.

Sources to identify the innovations are the different case-study related documents, i.e. the SES and farm level DST assessment from WP3 and the actor and policy analysis from WP5. To describe the innovations and their impacts, we asked for the following information. We also asked to indicate how certain/uncertain/robust these various values for the indicators were:

- general description of the innovation
- context, in which the innovation can be applied, e.g. FADN farming system (i.e. farm type, farm size), pedo-climatic conditions, share within high natural value lands, etc.
- indicators for assessing the characteristics, performance and impacts of innovations, e.g. on fertilizer and labour input use, yields, emissions, impacts on soils, etc. – choose the most relevant indicators for the innovation
- values for these indicators for the innovation, noting if certain values are hard to obtain
- values for these indicators in the baseline/reference scenario to which the innovation is compared to.

The quantitative data for the innovations should have been taken from the case study assessments where possible, but it was also possible to use literature values, if needed, in case the available data did not cover all information that is required. We also emphasized that no encompassing literature searches could be conducted; thus, for literature values, ideally partners should have provided us with the relevant references. For some cases, in which relevant data were not accessible these could not be included. After several rounds of feedback from partners, we gathered a list of 51 innovations (see Table 4). We then classified these innovations along the nine different categories (see Table 3).

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Table 3: Classification of innovations from UNISECO case study partners.

Organic practices
Improved manure management systems
Mixed-farming - optimal combination of fodder in crop rotations, grassland use and livestock (e.g. also including combined beef/milk breeds)
Increased diversity in cropping (a: general; b: focus on local crop varieties; c: new crops)
Increased grassland yields (a: mow or graze when most nutritious; b: rotational grazing; c: undersowing of clover in crops, species rich grasslands; d: for sensitivity - extensive use, biodiversity focus: combine with strategies of zero food-competing feed use plus plant-based protein)
Increased soil carbon, driven by a: high-/low sequestration assumptions motivated by different tillage regimes (informed by literature); b: cultivating fallow lands; c: other soil formation
Increased nutrient recycling - i.e. capture these additional nutrient flows from urine, municipal waste, etc.
Implementation of agroforestry
Focusing on the ecosystem services of biodiversity over production

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Table 4: Individual innovations from UNISECO case studies. For more details for colour codes see Table 3. Innovations marked without a colour are not possible to implement in BioBaM_GHG_EU and SOLm. Acronyms for case studies: Austria (AT), Czech Republic (CZ), Finland (FI), France (F), Germany (GE), Greece (GR), Hungary (HU), Italy (IT), Latvia (LV), Lithuania (LT), Romania (RO), Spain (SP), Sweden (SE), Switzerland (CH), United Kingdom (UK). For details on UNISECO case studies visit https://uniseco-project.eu/case-studies.

Short description of the innovation	
Ban on the use of mineral nitrogen fertilizers	CZ
Binding ammonia in manure	LT
Change feed from GMO soy to local maize in dairy (can then be marketed as GMO free)	CZ
Change of dairy breeds (Holsteins for combined breeds)	CZ
Different machinery uses (no need for expensive artificial milk mixers in conventional agriculture; usually are no sprayers; no spreaders artificial fertilizers; but specific machines for undersowing and sowing of mixtures with different grain sizes)	CZ
Diversification of crops	SP
Manure separation into liquid/solid	LT
Mating disruption for plant protection in orchards	GR
Mechanical weeding and green fertilizers	F
Mowing grass for feed when protein content is the highest	LT
No-till/reduced till	AT
Rotational grazing	LT
Special mineral supplement for cattle	LT
Undersowing and species-rich crop and grass mixtures	CZ
Use of biogas digesters for manure in intensive dairy farming	FI
Use of local crop breeds	SP
Cultivating fallow land – with a focus on ecosystem service provision such as soil carbon sequestration	IT
Humus formation program	AT
Magic margins: structures in sloping fields to prevent soil erosion and nutrient runoff	UK
Tailored flower strips for reducing pests and crop plant damage	GE
Innovative crops (sweet potatoes)	CH

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Pumpkins for feed of organic dairy cattle	LV
Recycling nutrients from urine	SE
Agroforestry - Fruit Trees-Crops	AT
Agroforestry - Orchard-Meadows	RO
Agroforestry - Wood-Pastures	AT
Change of crop rotations - in organic farming fodder makes up almost half of arable land, conventional farms about 10%	CZ
Crop rotation on arable land in conventional cattle farms (for own-farm feed provision) / mixed farming	RO
Diversification/mixed farming (livestock, pasture and crops)	RO
Grassland extensification (High Nature Value areas)	RO
Feeding no concentrate feed to ruminants??	RO
Frequent feeding of dairy cows with green fodder from arable land in organic farming	LT
Legumes and oil-seeds for humans instead of animal source products	CZ
Pesticide-free vineyards	SE
Pesticide and herbicide free crop production	IT
Shift of production focus from pigs to cropland production of sprouts	CZ
High Environmental Value (HEV) labelling process	CH
Local value chains for typical products	F
New rental instruments to support agroecological management on rented land (e.g. via tax reductions for land owners if they allow for agro-ecological management, etc.)	IT
On-farm processing of milk into high-value dairy products	LT
Payments for practices that support ecosystem services	LT
Shift from organic cereal for fodder to organic cereal for human consumption	SP
Strengthened network of small sized, local and organic farming entities	SP
The Fontevraud charter and management of landscape to enhance ecological infrastructures	F

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During a range of stakeholder consultations with case study researchers, stakeholders from the individual case studies, the project advisory group (PAG), SRG (steering review group) and MAP (multi-actor platform) members, we have evaluated this information on agro-ecological practices from the plot to the food-systems level. In a workshop during the last stakeholder meeting in November 2020, we aggregated similar innovations to four different bundles that comprise a set of agro-ecological innovations and discussed them with stakeholders (Table 5). Thereby, we did not specifically address the organic production systems, as they are already well codified and addressed in the general scenarios covered in D4.2 (as a representative implementation of agroecological practices). The four innovation bundles are as follows:

Table 5: Bundles of innovations for UNISECO stakeholder workshop in November 2020. Organic scenarios are excluded since that practices are included in the four groups listed below.

Details for group 1: Innovations from the case studies A) improved manure management • Binding ammonia in manure • Separating manure into liquid/solid • Use of biogas digesters for manure in intensive dairy farming B) closing nutrient cycles • Recycling nutrients from urine	**Details for group 2:** Innovations from the case studies A) improved grassland management • Mowing grass for feed when protein content is the highest • Rotational Grazing • Less intensive grassland use (HNV areas) • Feeding no concentrate feed B) provision of ecosystem services besides production • Magic margins: structures in sloping fields to prevent soil erosion and nutrient runoff • Tailored flower strips for reducing pests and crop plant damage
Details for group 3: Innovations from the case studies A) provision of soil carbon sequestration • no-till/reduced till • Cultivating fallow land – with a focus on ES provision such as soil-carbon sequestration • Humus formation program B) Agroforestry • Agroforestry - Fruit Trees-Crops • Agroforestry - Orchard-Meadows • Agroforestry - Wood-Pastures	**Details for group 4:** Innovations from the case studies A) diversified cropping patterns and breeds • Change of dairy breeds (Holsteins for combined breeds) • Diversification of crops • Undersowing and species-rich mixtures are sown more often in OF • Use of local crop breeds • Innovative crops (sweet potatoes) • Pumpkins for feed of organic dairy cattle • Legumes and oil-seeds for humans instead of animal source products • Shift from organic cereal for fodder to organic cereal for human consumption • Green fallows B) optimized mixed-farming systems • Crop rotation on arable land in conventional cattle farms (for own-farm feed provision) / mixed farming • Diversification/mixed farming (livestock, pasture and crops) • Frequent feeding of dairy cows with green fodder from arable land in OF

After lively discussions between WP4 researchers, PAG and SRG members as well as case study researchers from within the UNISECO consortium, we built upon the feedback to decide upon the selection and implementation of the innovations bundles in to be modelled in BioBaM_GHG_EU and SOLm. We then conducted an extensive literature survey to compare the results from UNISECO WP3 to recent publications on agro-ecology, and to map the most relevant agro-ecological practices within the framework of Prazan and Aalders (2019), or to add practices from literature which we could not derive from the UNISECO case studies. We nevertheless checked back these practices with case study experts. Lastly, we allocated different agro-ecological innovation bundles and innovations to either BioBaM_GHG_EU or SOLm. We decided this approach to 1) be able to build upon the strengths of both biophysical models, and to 2) embrace a broad range of

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innovations in the territorial modelling while not 3) feeding to many innovations into one bundle. The last aspect is specifically important so that we are still able to assess the impact of clear, comprehensible and traceable bundles of innovations on the most important sectors of the EU agri-food system.

3.2. Implementation in BioBaM_GHG_EU

Table 6 shows an overview of agro-ecological innovations bundles and the conventional baseline against which the agroecological variants can be compared. We implemented bundles of innovations in diverse agricultural sectors, i.e. livestock production and manure systems, croplands, and grasslands, an approach which is in line with a recent policy-advice document from Lampkin et al. (2020), where they propose new eco-schemes for the new CAP period. We furthermore implement different bundles of agro-ecological innovations for each agricultural sector to be able to assess and compare the consequences of these different practices.

While we here aim to assess a large number of unique combinations of different parameters and variants in the EU agri-food system, we assume in all scenarios that no agricultural land expansion into forests is allowed. It is widely accepted that protecting forests is a central premise for climate change mitigation (Foley et al., 2005; Griggs et al., 2013) because forests store large amounts of carbon (Erb et al., 2018), are biologically highly diverse and provide many important ecosystem services (Chatterjee et al., 2018; IPBES, 2017; Morais et al., 2019). Hence, we assumed that agricultural land remains within the extent of the utilized agricultural land in the base year 2012, thus do not allow for an expansion into forests. However, in some variants we allow for a certain land use change between cropland and grassland, more details can be found in the next section.

We display heatmaps for all 432 scenarios in the following results section as heatmaps, but also reduce the amount of presented scenarios where individual variants do impact the presented indicator. Additionally, we exclude land infeasible scenarios from subsequent analysis. We furthermore present maps at the subnational, i.e. NUTS2, level for spatial patterns for a set of specific scenarios. We provide a specification of the selected parameter variants below each map.

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Table 6: Key parameters and their agro-ecological and conventional variants combined within BioBaM_GHG_EU for the year 2050. Column a) shows the main parameters, columns b)-c) the agro-ecological variants, and column d) the conventional baseline variant for the year 2050. While we have exactly one conventional variant for all parameters, we have two or more agro-ecological variants. For more details for each parameter and variant see text below.

a)	b)	c)	d)
Parameter	**Agro-ecological variants**		**Conventional variants**
Mixed farming systems	**Land-potential based** distribution of ruminants and monogastric livestock across countries/EU.		**Current distribution**
Livestock diets (LD) and FCR	**Co-opt_Cropland** (only by-products for ruminants), -10% efficiency for pigs, poultry, eggs	**Grassland** (only grass for ruminants), -10% efficiency for pigs, poultry, eggs	**BAU**
Animal Waste Manure Managemet System	More biogas digesters, increasing share of pasture-based manure management for pigs, poultry and eggs **(High digester)**		**BAU**
Cropland	**Hedges** on 7% of cropland	Undersowing in cereals (for livestock feed) and only fodder legumes for livestock (**CL feed**)	**BAU**
	100% of cropland under agro-ecological practices in 2050. No cropland expansion into grassland		FAO BAU yields, 20% cropland expansion allowed
Grassland	**Land sparing**	**Land sharing**	**BAU**
	Livestock concentration to GI_{max}, Vegetation regrowth allowed on free grassland area	No vegetation regrowth, same grassland area than in 2012	Vegetation regrowth allowed
GI_{max}	Reduced maximum grazing intensity (Gi_{max}) on High Nature Value land		Current GI_{max},

3.2.1. Farming systems

Agro-ecological variants

Agricultural systems in the EU have undergone a threefold dynamic since 1960. Intensification (i.e. more output per land use unit), specialization and concentration of European agricultural production systems (Poux and Aubert, 2018; Stoate et al., 2009). As a consequence, livestock and crop production systems have spatially segregated, and this territorial specialization has shown negative environmental consequences, e.g. for nutrient cycles (Hou et al., 2016). Additionally, stocking densities have been increased to ratios which are leading to local nutrient surplus enabled by large feed imports. In agro-ecological systems in which animal numbers are aligned with the carrying capacity of the local land stocking densities are brought down to a level where enough agricultural land is available to absorb the quantities of animal manure. Thus, locally-adapted and integrated farming systems are a central pillar of agro-ecological systems.

For the agro-ecological variants, we have implemented distributions of crop and livestock production that divert from the current, highly specialized agricultural systems. Firstly, we stronger connect crop production to the local demand for food, feed and industrial uses. In all scenarios in 2050, cropland production in the European Union is driven by the domestic demand for cropland products, assuming a stronger regionalization of cropland production within the EU. However, in order to avoid strong distortions for EU production systems from dynamics in the RoW regions, we restrict the allowed changes in cropping areas in the year 2050. This means that we assume that in the majority of potential cropland areas in 2050 (i.e. in 75%), the areas from the base year remain equal in all world regions. Given that 75% of the cropland areas remain constant, but yield increases in the FAO BAU (FAO, 2018) scenario will be reached in 2050, production volumes are bound to increase in RoW regions in 2050, eventually leading to higher net-exports to the European Union due to local overproduction as food production volumes grow more quickly as a result of yield and livestock efficiency increases than demand (increased population and changed eating patterns). With this approach we secure that cropping patterns do not completely change and historic and traditional crop systems can be retained, but also leaving room for the satisfaction of local and external demand. Thus, eventual overproduction in the RoW may lead to increasing net-imports in the European Union and reducing domestic production requirements. Re-thinking the free-trade imperative under a World Trade Organization (WTO) trade regulatory framework needs to be a cornerstone of an EU-wide transformation towards an agro-ecological agri-food system.

We implement two different allocation algorithms for monogastric and ruminant livestock in the EU in the agro-ecological production practices in 2050. We aim to increase the share of mixed farming systems, approximated through a more equal balance between cropland and livestock production, which has been found to benefit both, the environmental and the economic performance of farmers (Ryschawy et al., 2012). The production of livestock, is firstly driven by the domestic demand for animal products though human diets. For monogastric livestock, the country-wide demand for animal products is re-distributed across cropland production potentials within the same country. This allows to tighten the link between cropland production and livestock production, leading to synergies between manure availability and croplands, where manure is a central resource for plant nutrients. Ruminant livestock, where we fundamentally change feeding ratios in the agro-ecological practices, are linked closer to grassland availability. A central advantage of ruminant livestock is that it is able to harness resources that are not directly consumable by humans, and we also use this strength as a central mechanism for the re-distribution of livestock systems in the agro-ecological production practices. However, while the production of monogastric animals are remained within each country aligned with demand, we re-distribute ruminant production in 2050 within the whole European Union. We use this approach to assess whether a conversion to mostly roughage feed for ruminant livestock will be possible to meet the demand in the year 2050, which is also important to reduce food-feed competition (Mottet et al., 2017; Van Zanten et al., 2018). Nevertheless, we respect the central role of dairy and beef systems within the EU's agricultural systems. Grassland, if not converted to croplands, can only be made usable for food production through ruminant livestock. Nevertheless, if ruminants are fed with primary crops, food-feed competition arises, but as they can also be fed with legume leys used in crop rotations or as undersown crops, food-feed competition may be reduced, and grazing time for ruminants maintained. Thus, we generally aim to improve the conjunction of ruminant livestock with grasslands, albeit at the cost that countries that

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currently have high shares of landless ruminant systems (Opio et al., 2013; Steinfeld et al., 2013, 2006) have to reduce these systems and re-focus their agricultural production systems.

From a model perspective, the way how production quantities of animal products (meat, milk etc.) in each region are determined, is central. In this context, we use the term "animal product distribution" (or simply "distribution"), referring to the idea that the production of the global livestock biomass demand is distributed among the administrative geographical entities represented in the model (NUTS 2 regions within the EU, countries in the rest of the world). Various distribution approaches have been developed that reflect different ideas on potentials developments of trade and production patterns of livestock products. For example, the "fixed distribution" approach assumes that global production shares of each region remain unchanged; changes in global livestock demand only influence the absolute production amount in each region, but do not influence the relative global production patterns. In contrast, it can be assumed that changes in demand (especially in case of an increase) result in altered production patterns. The "distribution based on cropland or grazing potentials" approach assumes that regions with high production potentials (i.e. the product of available grazing areas in a region, their productivity and the degree to which existing cropland production potentials are currently exploited for monogastric livestock, and the product of available cropland areas in a region and their yields are currently exploited for ruminant livestock) raise their production levels, while in regions with little unused biophysical potentials the absolute production is set to remain relatively constant (ensuing the share of such regions in global production decreases).

We use a "distribution based on cropland or grazing potentials" for the agro-ecological scenarios, where we re-connect livestock and cropland production in the agro-ecological scenarios.

Livestock distribution based on cropland (MONO) and grazing (RUMI) potentials

In this approach, the distribution of ruminant animal products (i.e. bovine, sheep and goat meat, dairy products) is influenced by grazing potentials or, more precisely, the potential production of each animal product within a specific region with regard to the grass supply from grazing areas (grazing). The distribution of monogastric animal products (i.e. pigs, poultry, eggs) is influenced by "cropland potentials", or, more precisely, the potential production of each animal product within a specific region with regard to the supply from cropland.

The potential is calculated for each animal product individually, based on (regionally specific) livestock diets (LD) and feed conversion rates (FCRs). Hence, grazing potentials for ruminant livestock are sensitive to FCR variants. The maximum upper boundary for the potential grass supply is determined by the total actual net primary production on grassland (NPPact) and the maximum grazing intensity of the respective region (NPPact * maximum grazing intensity)[1]. The maximum grazing intensity equals the utilization rate in grassland. The following paragraph provides a mathematical explanation.

First, the base year shares of different animal production systems assigned to each region are translated to individual target production quantities as under "fixed distribution", denoted as $TP_i^{k,t}$, where i is the region, k is the animal product and t is time

[1] In the model, we differentiate between 4 classes of grazing areas, each of which has a specific maximum grazing intensity (see (Erb et al. 2016).

$$TP_{ik,t} = s_{ik,base\_year} \cdot D_{globalk,t} \qquad (2)$$

Second, the target production quantities of each trade cluster C (i.e. for each country) are summed up.

$$TP_{Ck,t} = \sum_{i \in C} TP'_{ik,t} \qquad (3)$$

Third, the "grazing-based" production potentials $GP_i^{k,t}$ are calculated:

$$GP_{ik,t} = \frac{PS_{igrass,t}}{G\_FCR_{ik,t}} \qquad (4)$$

The shares of each region are then calculated based on the total potential of the respective cluster

$$s\_GP_{ik,t} = \frac{GP_{ik,t}}{GP_{Ck,t}} = \frac{GP_{ik,t}}{\sum_{i \in C} GP_{ik,t}} \qquad (5)$$

…and the target production of each cluster distributed according to these shares:

$$TP_{ik,t} = s\_GP_{ik,t} \cdot TP_{Ck,t} \qquad (6)$$

$GP_i^{k,t}$………….Potential production of animal product k in region i at time t; based on potential **grass** supply

$PS_i^{grass,t}$……..Potential supply of grass in region i at time t

$G\_FCR_i^{k,t}$…..Grass-FCR of animal product k in region i at time t

$s\_GP_i^{k,t}$……….Share of global production of animal product k assigned to region i (based on grazing potential)

Conventional baseline

We assume that crop and livestock production shares between countries within the EU remain similar to the base year 2012. We explain this "fixed distribution" approach below.

<u>Fixed distribution</u>

For the base year 2012, livestock production quantities are available from the database described in D4.1 and Mayer et al. (under review). The dataset of the base year is the basis for the "fixed distribution" approach. Using historical data on livestock production quantities in each region, global production shares are determined for each region. In scenarios based on "fixed distribution", these relative shares and thus the pattern of production on global scale as well as within the EU (i.e. the distribution among NUTS 2 regions) is kept static.

Mathematically, exogenously defined regional shares $s_i^{k,base\_year}$ times global demand gives the "target production" of the respective region. While the base year is calibrated to historical data (European Commission, 2015; Faostat, 2021; Kempen and Witzke, 2018), resulting in biomass requirements that are consistent with biophysical production potentials in each region, scenarios with altered parameter settings (for example grass-intensive ruminant diets/FCRs) may be infeasible under the assumption of "fixed distribution". We thus have to differentiate between "actually achievable production" and "target production".

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$$TP_{ik,t} = s_{ik,base\_year} \cdot D_{global k,t} \quad (1)$$

$TP_i^{k,t}$………Target production of animal product k at the time t in region i

$s_i^{k,base\_year}$…………share of region i in global production of animal product k in the base year

$D_{global}^{k,t}$……Global demand for animal product k at time t

Cropland production in this scenario variants assumes the same production patterns within the EU as we assume for the RoW in all scenarios. Thus, in all regions, 75% of the potential cropland utilization in the year 2050 is equal to the base year 2012, and based on projected cropland yield changes, global potential production volumes are matched with global demand. If production > consumption, then an equal reduction of production (based on production shares in the base year) are applied until production = consumption. If global deficits occur, i.e. production < consumption, then production is increased in regions based on domestic production potentials. Deficits are first compensated by production increases within a region (i.e. firstly country-wide, secondly EU-wide, thirdly global trade)

3.2.2. **Human diets and food wastes**

In line with the food systems perspective of agro-ecology (Poux and Aubert, 2018; Wezel et al., 2009), not only production-side changes are necessary, but also the demand for agricultural products through human diets is an important contribution to the vision of agro-ecology. In Europe, the majority of agricultural output is used to feed livestock, and crops that can also be directly consumed by humans, are in direct competition with food security. Additionally, the overconsumption of animal products has been leading to a number of health impacts, facilitating the necessity towards healthier diets. From a modelling perspective, diets drive the demand for agricultural goods, and thus coin the production patterns within the EU and beyond.

We utilize four different human diet variants and food wastes and losses. We firstly apply a future diet which is a high-level expert suggestion for a diet which is beneficial for human health and considerably reduces the environmental impacts of food production in 2050, called the EAT-Lancet diet (Willett et al., 2019). Next to the **EAT-Lancet** diet implementation, we use a slightly refined version of the EAT-Lancet diet (**EAT-Lancet_rumi**) where we want to reflect that ruminants are linked back to land and that we allow for a smaller reduction of ruminant consumption in comparison to monogastrics, i.e. parts of animal products from pigs, poultry and eggs are replaced by milk and meat from ruminant livestock. As ruminant livestock is able to harness resources that are not directly edible to humans, such a diet poses less competition with the production of food for direct human consumption (Schader et al., 2015; Van Zanten et al., 2019, 2018). These changes in diets is also in line with the TYFA report, where the authors also underline that the possibility of decoupling livestock production and crop production is also lower for ruminants than for monogastric animals (Poux and Aubert, 2018), and thus the advantages of ruminant livestock to domestic food security need to be taken into account for dietary changes that are in line with agro-ecology.

For both EAT-Lancet diets, we implement a 50% reduction of food wastes and losses from production to households (Gustavsson et al., 2011; Porter et al., 2001), in line with claims from Willett et al. (2019). We additionally implement the **FAO TSS** projection (FAO, 2018) as a weaker, albeit regionally differentiated (at the country level), sustainable diet with higher shares of animal products than in both EAT-Lancet diets. The FAO TSS diet projection is also combined with a 50% reduction of food wastes and losses. Table 7 summarises the different diets variants.

Lastly, we have implemented a diet which is similar to the current diet in the year 2012, which we have derived from FAO. The **FAO BAU** diets from FAO (2018) are combined with food wastes and losses for the base year and is thus a more conventional trajectory of future human diets and food wastes and losses in BioBaM_GHG_EU.

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Table 7: Average EU diet for the year 2012 and agro-ecological and conventional diet variants for the year 2050 for the EU in kg dry matter per capita and year (kg DM/cap/yr). All values shown in primary equivalents (e.g. pigs indicate per capita pigmeat consumption, milk butter dairy includes cheese and other milk-based products). Values include household wastes. Table shows Median values for EU-28 countries. For data sources see text above.

Per capita diet (kg DM/cap/yr)	**2012**	**2050**			
Median		**BAU**	**Lancet**	**Lancet_rumi**	**FAO TSS**
Cereals	108.4	112.5	83.2	83.2	92.5
Roots and Tubers	14.9	15.1	4.4	4.4	13.7
Sugarcrops	44.5	48.5	10.7	10.7	38.4
Pulses	1.8	2.1	34.6	34.6	2.0
Oilcrops	18.6	20.0	18.1	18.1	18.1
Fruits	14.8	15.3	7.9	7.9	12.4
Vegetables	5.1	5.6	11.8	11.8	4.6
Other crops	9.2	8.9	-	-	7.2
Nuts	3.3	3.3	33.1	33.1	3.0
Bovine Meat	7.7	8.3	2.9	5.5	5.9
Mutton & Goat Meat	0.6	0.5	0.2	0.2	0.4
Milk butter dairy - cow	33.4	34.9	11.9	14.5	30.8
Milk butter dairy - sheep+goat	0.1	-	0.0	0.0	-
Pigs	18.0	20.5	1.7	0.8	13.7
Poultry	9.9	11.6	7.0	3.5	7.8
Eggs	3.3	3.3	1.7	0.9	3.2
Fish	5.3	4.1	5.6	5.6	2.9
Total consumption	299.0	314.6	235.0	235.1	256.6

3.2.3. Industrial and bioenergy use

While we do not explicitly focus on industrial uses and bioenergy production on cropland, we still consider this demand in 2050. This approach differs to the TYFA agro-ecological scenarios where the authors set biofuel demand in the year 2050 to zero and assume that industrial demands are maintained on their 2010 levels. They argue that the development of bioenergy installations has led to the simplification of cropping systems in their supply area, which is not in line with agro-ecology. While we acknowledge their problem definition, we decided that if we neglect the demand for the bio-economy, we neglect a major contribution of the land sector to reaching the Paris climate goals, necessary to avoid drastic impacts from climate change. We thus implement a conservative estimate for the industrial/bioenergy demand in 2050 and utilize 2012 per capita biomass uses from agricultural land for industrial and bioenergy (i.e. biofuel) uses, while the amount of derived energy from biogas digesters depends is explicitly varied between agro-ecological and conventional variants.

3.2.4. Livestock diets (LD) and feeding ratios (FCR)

Agro-ecological variants

We apply adjusted livestock diets (LD) and Feed Conversion Ratios (FCR) to implement agro-ecological innovations within the livestock system. As described in Del. 4.1., we developed FCRs representing feed input per product output both in dry matter for 7 livestock products in 227 NUTS2-regions and 20 world regions for

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the baseline year 2012. Livestock FCRs for sub-national regions within the European Union are based on data from CAPRI2 (Common Agricultural Policy Regionalised Impact) – an economic model funded by the European Commission aiming at support decision making related to Common Agricultural Policy by quantitative analyses. The CAPRI dataset mainly relies on Eurostat statistics, supplemented by national data and a valid consolidation routine for missing values (Britz and Witzke, 2014; Kempen and Witzke, 2018). Nevertheless, certain NUTS2-regions report unrealistic feed compositions with a very low roughage intake for ruminants as well as unrealistically efficient feeding ratios. For these regions, we apply the respective national value in order to eliminate outliers while ensuring to remain consistent with CAPRI input data. The assignment of CAPRI feed and livestock categories to BioBaM_GHG_EU input categories is not straightforward for two CAPRI categories. In order to trace back 'protein-rich feed' and 'energy-rich feed' to their primary crop product, we estimate the average category composition according to feed statistics from FAOSTAT Commodity Balances for the European Union for the years 2011-2013 in average. As a result, we assume 'protein-rich feed' consisting of 3% pulses, 75% oil or oil cake and 22% bran (cereals). We further assign 'energy-rich feed' to be by-products from sugar crops (molasse) and cereals. Equally, animal categories need to get allocated to their product, which is predominantly straightforward (e.g. pigs and pork), but a clear separation of feed for milk resp. for beef production obscures the complex entanglement of both products, especially in regions with a greater share of dual-purpose breeds. Therefore, we not only allocate feed for dairy cows as feed for milk, but also a share of feed for 'raising female cows' and 'breeding heifers' resulting from the ratio in the given region.

Non-European livestock diets and efficiencies are derived from a global dataset for biomass used within the livestock system for the year 2000 (Herrero et al., 2013). In order to align the global data set with the baseline year 2012, we assume annual livestock production efficiency gains of 0.1% for the Global North and 0.24% for the Global South according to implementations of SSP2-livestock storylines within Integrated Assessment Models (IAM), which is described as business-as-usual (Fricko et al., 2017).

The resulting dataset describes crop-specific feed intake per product output in 227 NUTS2-regions and 20 world regions (= feeding ratios or feed efficiency). We differentiate between seven livestock products (milk, beef, sheep and goat milk, sheep and goat meat, pork, poultry and eggs) and seven feed products (cereals, pulses, sugar crops, oil crops, fodder crops, straw and grass) in dry matter primary product equivalents. We calculated primary products and by-products in dry matter equivalents. Therefore, for example, oil crops are used as oil to a smaller extent and oil cake to a bigger extent, both reported as shares of in primary oilcrops. For sheep and goat milk and meat, the livestock diets and feed conversion efficiencies vary tremendously between those for the European regions from CAPRI and the remaining global regions from Herrero et al., (2013). Due to a lack of supporting and reliable external data sources and missing global data from CAPRI, we refer to livestock diets and feeding ratios from the global dataset for all regions including the European Unions in order to avoid unequal estimations between European and global production. Therefore, livestock feed and FCRs for sheep and goat meat and milk in the European Union is differentiated in four regions (Baltic, Central East, MidWest and South).

Agro-ecology within the livestock system is characterised by reducing resp. minimize the competition between human food and animal feed (Poux and Aubert, 2018). Currently, 69% of agricultural land in Europe is used for livestock production (Leip et al., 2015b) and, more specifically, 60% of cereal resp. 70% of oilseed production

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[2] www.capri-model.org

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(Poux and Aubert, 2018). In regard to reduced crop yields resulting from agro-ecological farming practices, a continuation of current feeding practices and human diets further enhance trade-offs in sustainability through intensification of land use. Therefore, agro-ecological feeding systems mainly are characterised by weakening the demand of cropland products, with positive consequences for food-feed competition and the possibility to implement further agro-ecological innovations on cropland such as e.g. ecological infrastructure, agroforestry systems and additional carbon sinks.

We implement two agro-ecological feeding systems (see Table 6), which target changes for ruminants primarily in feed composition (which inevitably also effects feed efficiencies) and for monogastric animals primarily in feed efficiencies (keeping feed composition unchanged). 'Co-opt_Cropland' allows ruminants to only be fed by grass and secondary products from cropland (i.e. crop residues and by-products from oil resp. flour production). This livestock diet variant is using cropland only through the demand of by-products, hence the abbreviation co-opt_Cropland. GL feed entirely relies on grassland for ruminant livestock. Both agro-ecological feeding strategies primarily address products from ruminants due to their ability to digest roughage and convert for humans inedible into edible protein. In our model, agro-ecological farming practices reduce the feed efficiency of monogastric products (pork, eggs and poultry meat) by 10% resulting from increased livestock mobility in regard to animal welfare, but no extended animal life spans as it is usual in organic farming (Gaudaré et al., 2021).

Both agro-ecological FCR variants use the Baseline-FCRs as basis and are further adopted to respective feed strategies. Co-opt_Cropland has two feed sources from cropland: firstly, feed which result as a by-product (e.g. oil cake) from food production is used as high-nutritive feed. Since Baseline-FCRs contain both primary as well as by-products, we estimate the share of by-products based on various sources (see Table 7) for each crop type. The share of each feed crop category identified as by-product in the Baseline-FCRs remains as feed input, while the amounts of cereals, sugar crops, pulses and oil crops identified as directly fed (primary product) is replaced by grass. In order to take the nutritive value into account, we derive substitution factors which compares the required amount of additional feed from grassland with crop feed to produce the same amount of product. The substitution factors are based on standardized values for feed categories and represent the amount of energy they contribute to lactation resp. meat production per kg (=net energy; see Table 8). Among many feed evaluation systems which support in formulating feed rations by matching nutrient supply with animal requirements, we here apply values from the recently updated INRA3 feeding system (Daniel et al., 2020; INRA-CIRAD-AFZ, 2020; Noziere et al., 2018). The substitution factors account for the additional feed requirement of livestock, which results from a switch from concentrate to roughage feed and the regional feed-use efficiency decrease (= higher feeding ratios). While this approach considers additional feed per product due to a lower conversion efficiency of roughage feed, it does not account for additional feed required for a larger number of farm animals to sustain their basic metabolism, leading to higher total feed demand.

Secondly, the 'Co-opt_Cropland' contains a roughage component from cropland. We assume the crop distribution in fodder crops as in the base year (i.e. a mixture of fodder maize, fodder roots, and fodder legumes), but in agro-ecological production practises (such as the cropland feed cropland variant), the amount of fodder legumes, i.e. alfalfa is increased, reflected by a substitution factor accounting for the variance in

[3] French National Research Institute for Agriculture, Food and Environment (INRAE)

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nutritive value between fodder crops. Forage legumes such as alfalfa are considered to become more important in the future and a valuable pillar of agro-ecological and more sustainable ruminant feeding practices (Lüscher et al., 2014). Although the nutritive value is lower compared to fodder maize in regard to energy, it is higher compared to grass and can serve a protein-rich and complement source of roughage for ruminants. Moreover, harvested under undersowing conditions on cropland, alfalfa (and clover in general) is able to substitute artificial nitrogen fertilizer due to symbiotic N2 – fixation (Poux and Aubert, 2018) (also see 3.2.6). In addition, the inclusion of alfalfa or other legume species in temporary grassland or as cover crops contributes to the ecological intensification of lower intensity cropping systems (Wittwer et al., 2017) and possibly reduces negative effects on ecological sustainability.

In contrast, the second agro-ecological feeding system 'GL feed' predominantly considers feed from grassland for ruminants. It therefore fully takes advantage of ruminants' ability to convert roughage into human-edible food, while cropland products are exclusively available for living beings with a monogastric digestion system (humans and monogastric animal like pigs and poultry). The appropriate demand for grass and the maintenance of extensive permanent grasslands as so called 'semi-natural vegetation' (SNV) – has been considered as an important approach in terms of biodiversity conservation as they serve as source of food, stable habitat for reproduction and as a form of connectivity for both mobile and immobile species (Poux and Aubert, 2018). Nevertheless, grazing intensity thresholds need to remain low in comparison to permanent grassland to avoid negative consequences for (vulnerable) natural species.

In line with other agro-ecological innovations, alternative feeding ratios are only implemented for European NUTS2/1 regions, while other world regions follow the BAU scenario. Again, the applied diagnostic approach follows the concept of exploring ranges and possibilities of agro-ecological innovations in the context of a global land-use system and as wells their impacts and does not follow 'realistic' pathways. Regarding the implementation of a grass-based feeding strategy this is specifically relevant due to further challenges which accompanies such adjustments like for example the ability of certain breeds to be solely fed by grass (Hennessy et al., 2020).

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Table 8: Factors applied in the development and implementation of agro-ecological feeding systems building on Baseline-FCRs. *Feed input categories in BioBaM_GHG_EU and their respective share of by-products in Baseline-FCRs. Substitution factors account for the additional feed requirements resulting from a switch from crop feed to alfalfa resp. grass. Factors compare net energy for lactation resp. meat production for different feed types according to INRA feeding system 2018 (UFL and UVF).*

Primary product (= feed input category)	By-product	By-products share in Baseline-FCRs for each feed input category	Source used to estimate by-product share	Substitution factor (= ratio of forage unit for lactation resp. meat production of replaced and replacing feed type) [4]			
				Milk		Meat	
				Alfalfa	Grass	Alfalfa	Grass
Cereals	Bran	10-60%	CAPRI	-	1.3	-	1.4
Sugar crops	Molasse	100%	CAPRI	-	1.1	-	1.2
Pulses	-	0%	CAPRI	-	1.4	-	1.5
Oil crops	Cake	93%	FAO Commodity Balances	-	2.3	-	2.5
Fodder crops	-	0%	-	1.6	1.3	1.8	1.5
Straw	Straw	100%	-	-	0.5	-	0.4
Grass	-	-	-	-	-	-	-

Baseline

As conventional baseline in comparison to agro-ecological feeding efficiencies, we establish a business-as-usual feeding scenario. Similar to above mentioned time-adjustments, we assume an annual feed efficiency gain of 0.1% for the Global North and 0.24% for the Global South to estimate feeding ratios for the year 2050 (Fricko et al., 2017). The efficiency gain results from an increase in crop feed as it had been developed since the 60ies and denoted as 'industrialization processes' (Poux and Aubert, 2018). Further, the efficiency gain can also be related to a higher share of confined livestock and the accompanied reduction in mobility.

[4] INRA-CIRAD-AFZ, (2020)

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3.2.5. Manure management systems

Agro-ecological variants

We derive the distribution of Animal Waste Manure Management Systems (AWMS) from IPCC (2019). The data is provided by world regions, i.e. one aggregated value for Western Europe and Eastern Europe. AWMS are differentiated by animal type into seven categories. We couple the AWMS for ruminant production systems to the livestock feeding system, i.e. the amount of grassland feed and feed from other sources, such as from cropland. We additionally classify whether grassland feed is mowed and thus the livestock is kept indoor, or the grass is directly harvested by livestock from pastures. For the latter share, we use the days where average temperature is > than 5 degrees Celsius plus 4 weeks as a proxy for pasture-based livestock. We calculate this share as follows:

share_on_pasture = (GDD_in_days + days_on_pasture_after_growing_season)/365

GDD denote growing degree days per year, and we add 28 days as a proxy for days after growing season when livestock is allowed to graze directly on grasslands. On these days, we assume manure is directly excreted on grasslands. Thus, the share of grass manure excreted on pasture is an exogenous parameter in BioBaM_GHG_EU, which is co-determined by the feed intake and GDD of the livestock. Consequently, the longer the vegetation period in a country/region, and the higher the amount of grassland feed in livestock diets, the higher the share of manure that is directly excreted onto pastures. For the indoor AWMS systems, we assume that the shares remain constant in all scenarios, but taking into account the non-grassland based feed sources.

For monogastric systems, i.e. pigs, poultry and egg production, we do not directly couple the AWMS to livestock feeding ratios. Here, we assume the following two changes in line with changes in livestock diets and changes in feed conversion ratios between feed and animal products, which we assume to generally decrease in agro-ecological systems due to less intensive livestock systems. For example, more space to roam for livestock is beneficial from an animal welfare perspective, but also comes at the cost of a lower efficiency in the conversion from primary feed into the desired output, i.e. pig meat, poultry meat and eggs.

We assume major changes to monogastric AWMS, which we refer to as the **High-digester scenario**. Firstly, an increase of biogas digester systems, and secondly, and increase in pasture-based (i.e. free-range) livestock systems. Biogas digesters are a useful application to use (excess) manure from monogastric livestock systems for bioenergy production and thus reduce emissions from animal waste handling. Such facilities are a good approach to reduce emissions from livestock manure and enhance nutrient (re-)cycling in regions that suffer from nutrient overload, whereas we aim to reduce nutrient overload in all agro-ecological variants through re-balancing land availability and livestock production. Nevertheless, biogas digesters might be an important lever to avoid trade-offs between agro-ecology and climate-friendly farming, and we will assess whether a strong focus on the instalment of biogas digesters merits a significant contribution to climate change mitigation. Please note that we do not account for the effect of substituting fossil fuels through bioenergy from biogas digesters, making our approach a conservative estimate of the climate benefits of biogas digesters.

We base the changes in AWMS systems on an assessment of the potential of biogas digesters in Europe from Scarlat et al. (2018). There, the authors provide a spatially-explicit analysis of the shares of collectible manure from livestock systems in Europe at the regional, i.e. NUTS2, level. We reduce the share of collectible animal manure per region by 50% and allocate them to digester AWMS from IPCC (2019) for pigs, poultry and eggs.

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We additionally allocate 5% of the total monogastric livestock systems to pasture-based AWMS to account for free-range systems, an assumption which considers the growing attention of consumers on animal welfare (Grunert et al., 2018; Schröder and McEachern, 2004). While agro-ecology aims to raise animals in free-range systems, a full shift of monogastric livestock would imply large losses of collectible manure, and we thus aim that monogastric livestock systems develop in "free-range" and enriched indoor systems which enable the collection of manure. Current AWMS are reduced to the degree on which digester and pasture-based systems are assumed to prevail in 2050

Conventional baseline

We utilize the current shares of AWMS as reported in IPCC (2019)

3.2.6. Croplands

Agro-ecological variants

Croplands (including arable land and permanent crops) cover 56% of the total utilized agricultural area (UAA) in the EU in 2012. We assume two different bundles of agro-ecological innovations on cropland which aim to increase the provision of regulating ecosystem services (Barrios et al., 2020; Benton et al., 2018; IPBES, 2017; Maes et al., 2016; Mouchet et al., 2017), reduce the amount of fertilizer(Dawson and Hilton 2011; Mulvaney et al. 2009), improve soil health and increase the resilience of croplands against erosion (Cardinael et al., 2017; Mäder et al., 2002) and reduce the competition between the production of food for direct human consumption and livestock feed (Karlsson and Röös, 2019; Smith et al., 2010; Van Zanten et al., 2018).

We do not allow for cropland expansion into grasslands or forests, since both land use changes invoke carbon losses and are often detrimental to biodiversity (Erb et al., 2016b; IPBES, 2017, 2019; Kalt et al., 2020; Morais et al., 2019). Thus, the extent of croplands per NUTS1/2 region in the base year 2012 is the maximum extent of cropland in the year 2050 in the agro-ecological variant.

As a general innovation across all bundles, we assume that all cropland production in the European Union in the year 2050 is under agro-ecological practices, an approach which is in line with the TYFA scenarios from Poux and Aubert (2018). It is important to note again that we do not aim to provide "realistic" or "desirable" scenarios, but are only interested in the assessment of biophysically feasible future scenarios on agro-ecology, and thus implement a 100% share of agro-ecological production and consumption patterns to assess the maximum impact of such a change of the EU agri-food system. So far, information on yield changes in agro-ecological systems are extremely scarce, and thus assessments of agro-ecology commonly apply yield gaps between conventional and organic systems to characterize agro-ecological systems. Consequently, in these assessments agro-ecological systems are basically constrained by the same regulations than organic farming, e.g. the complete ban of synthetic fertilizers (Poux and Aubert, 2018).

Agro-ecology, in comparison to organic farming systems, is less defined and more open to a diverse and heterogenous implementation, guided by a set of relatively general and broad guidelines (Altieri, 2009; Anderson et al., 2021b; Poux and Aubert, 2018; Wezel et al., 2009). However, we consider this a decisive strength of agro-ecology, which allows conventional farmers to adapt individual practices while not having the need to engage in the "full package" of practices and regulations that is required for organic farming, i.e. to be able to be certified as organic and thus be able to harvest the benefits in the form of subsidies or higher prices. We here use a different assumption for agro-ecological approaches on cropland. Based on evidence provided by several studies (Barbieri et al., 2017; de Ponti et al., 2012; Knapp and van der Heijden, 2018;

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Ponisio et al., 2015; Schrama et al., 2018; Seufert, 2019), yield gaps between organic and conventional practices are strongly driven by relatively unstable crop yields in organic systems which reduce the long-term stability of organic yields. They argue that improved management, higher diversity in crop rotations and mixed cropping in organic systems allow to considerably reduce organic yield gaps by higher stability of crop yields. Additionally, Betancourt (2020) found that yields in low input systems may even increase. Lastly, while research on agro-ecological systems currently only receives a small proportion of the total R&D budget (Poux and Aubert, 2018), we assume a strong re-direction of the EU research budget towards agro-ecological and sustainable farming. Additionally, knowledge-transfer from science to practitioners to science is central, and transdisciplinary research must be strengthened further to improve this knowledge transfer. Lastly, also knowledge transfer between farmers, where the Uniseco case studies have shown several innovative examples where farmers use social media, must be strengthened and increasingly supported by agricultural chambers and advisors.

We thus divert from the assumption of agro-ecological systems being equal to organic systems by the following changes: Firstly, while we assume a certain share of legumes in crop rotations that are necessary to provide nitrogen inputs from the atmosphere that can be taken up by non-leguminous crops (we assume a nitrogen fixation rate of 50 kg N/yr), we also allow the use of chemical nitrogen fertilizer in agro-ecological systems to compensate for nitrogen fertilization that is not provided by legumes in crop rotations and organic fertilizers and also quantify this amount for each scenario. While chemical fertilizers might be produced from renewables in the future, we utilize current emission rates to demonstrate the additional GHG emissions necessary to compensate N deficits in agro-ecological farming systems.

Secondly, we increase crop diversity in each subnational region, as well as we (thirdly) re-balance the share of livestock production with cropland availability in each sub-national region. As a consequence, we reduce the crop yield gaps between conventional and organic-farming from Ponisio et al. (2015) systems only by 50%, in line with the literature mentioned above. It is further important to note that while the use of synthetic plant protection chemicals is also important for conventional to agro-ecological crop yield gaps, this compartment is not represented in BioBaM_GHG_EU.

In the first agro-ecological bundle (**Hedges**) in addition to the 100% conversion towards agro-ecological farming systems, we implement a minimum of a 7% share of hedges in all croplands in the EU in 2050. If less cropland is utilized in 2050 in comparison to 2012, this share increases to the same degree as cropland decreases. Hedges or hedge rows on cropland provide multiple benefits to provisioning and regulating ecosystem services (IPBES, 2017; M'Gonigle et al., 2015; Ponisio et al., 2019; Poux and Aubert, 2018; Tittonell, 2014) and are thus a crucial aspect of agro-ecological cropping systems. They are also a crucial part of agro-ecological infrastructures which provide corridors and habitats for species, together with extensive grasslands (also part of UAA), but also with e.g. sunken paths, wetlands, grass strips, etc. which are not part of UAA and left constant in our scenarios). We also account for the carbon uptake in above- and belowground vegetation of hedgerows, as well as the soil carbon changes through the conversion of annual cropping systems towards hedge rows.

The second agro-ecological bundle on croplands (**CL-feed**) comprises two practices that enhance the provision of livestock feed from cropland while reducing competition with the production of human food and enhancing nitrogen availability on cropland through the spatial diversification of crop production. Undersowing livestock feed legumes in cereals as cover crops enhances soil stability and soil moisture, as well as it provides shading for soils when no crops are grown. Root systems from undersown crops penetrate soils, loosen soils and thus

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prevent soil erosion and nitrogen leaching. Post-harvest of the main crop, these lays or clover can be grazed by livestock or harvested and then fed to livestock, as well as left on fields to contribute to N provision of subsequent crops (Amossé et al., 2014; Anglade et al., 2015; Baddeley et al., 2014; Dierauer and Gelencser, 2019; Zemann, 2012).

We here apply undersowing of all cereals production in the EU in 2050 with clover. Clovers comprise a large crop diversity which are adapted to the diverse climatic and soil conditions across the EU (Kolbe et al., 2004). However, fodder legumes often cannot be sown in consecutive periods, resulting in longer intervals in crop rotations. We thus only implement undersowing in cereals, to allow for the necessary crop rotations to avoid these incompatibilities. We further assume that one third of the total yield of the undersown crop remains on field for mulching, while the rest is fed to ruminant livestock. Due to inconclusive results on the benefits for soil organic carbon through mulching, we did not implement these effects in BioBaM_GHG_EU. We further assume a slight yield reduction of 10% in comparison to conventional yields, to account for eventual disturbances of and competition with the main crop through the undersown crops for nutrients, water or the necessity for less dense sowing to allow for more light for the undersown crop. We additionally assume that in this scenario all fodder maize in the EU is replaced by fodder legumes, i.e. alfalfa which is grown in crop rotations as temporary grasslands. Forage legumes such as alfalfa can be an important cornerstone of agro-ecological cropping and livestock systems, especially for sustainable ruminant feeding practices (Lüscher et al., 2014) and for handling weeds and build soil fertility on arable land (Bachinger and Zander, 2007). Although the nutritive value is lower compared to high energy-crops such as fodder maize in regard to energy, it is higher comparing to (managed and unmanaged) grass and can serve a protein-rich and complement source of roughage for ruminants.

Conventional baseline

We assume FAO BAU yields for the year 2050 for the conventional baseline (FAO, 2018). We additionally allow for a maximum expansion of 20% of the cropland in the year 2012 in highly suitable grasslands (i.e. grassland class 1, for definitions see (Erb et al., 2007) for more details), if needed. No expansion of croplands into forests is allowed.

3.2.7. **Grasslands**

Agro-ecological variants

Grasslands cover 44% of the total utilized agricultural area (UAA) in 2012. Grasslands are at the core of conservation efforts in agriculture and some provide a multitude of ecosystem services, especially extensively used grasslands (Bernués et al., 2011; Erb et al., 2016a; Petz et al., 2014; Sala and Paruelo, 1997; Velthof et al., 2014). In the EU, there was a considerable loss of permanent grasslands; -14% in area between 1962 and 2010 at the EU-28 level (Poux and Aubert, 2018). Grazing livestock, through which grassland ecosystems are made usable for human societies, contributes to the provision of ecosystem services, e.g. through the use of grasslands in difficult environmental and climatic conditions for agriculture in general, and cropland production in particular (IPBES, 2019; Stolze et al., 2019). However, increasing stocking intensities of livestock in grassland systems needs to be done with caution to be able to realize synergies and avoid trade-offs with e.g. soil organic carbon pools (McSherry and Ritchie, 2013; Morais et al., 2019). Reducing grazing intensities is beneficial for soil carbon stocks is accounted for in BioBaM_GHG_EU based on factors from IPCC (2019).

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As a general agro-ecological innovation across two specific bundles we reduce the maximum grazing intensity in grasslands which are classified as high natural value farmland (Mouchet et al., 2017; Paracchini et al., 2008; Rega et al., 2020). High natural value (HNV) farmland is an indicator developed by the Joint research centre of the European Commission and is a composite indicator that considers relevant land classes and biodiversity considerations. The updated HNV map for 2006 (the closest year to the data which we utilize for this study) at a 100m resolution (European Environment Agency, 2015) was aggregated to match the 1km resolution of the European land use dataset from Plutzar et al. (2016) which gives fractional cover of infrastructure, wilderness, forest, cropland, grassland and subcategories and is consistent with the BioBaM_GHG_EU database. For a detailed description of the refinement of the land use data from Plutzar et al. (2016) see UNISECO Deliverable 4.1 and Mayer et al. (under review). After aggregation, the HNV map also provides fractional cover for 1km² grid cells. To arrive at the grassland area classified as HNV farmland per NUTS1/2 region we calculated the mean between a minimum and a maximum approach. This was necessary since operating with fractional cover leaves room for uncertainty regarding exact spatial coincidence. The minimum grassland area coinciding with HNV farmland was calculated by subtracting all other agricultural land within a grid cell from the HNV area of that cell, which leaves only the remainder of HNV farmland for allocation to grazing land. For the maximum approach we assumed that all HNV farmland within a grid cell coincided with grassland (calculated as [MIN(grazing land, HNV)]). This calculation procedure was performed separately for the three grassland classes in the European Union (permanent meadows and pastures under intensive use, permanent grassland under extensive use, other land under sporadic grazing or maybe grazed. A fourth grazing class is only distinguished in non-European countries, mainly steppes and other low-productive grasslands) in our database, resulting in values for the fraction of each grassland class categorized as HNV farmland per NUTS1/2 region.

The maximum grazing intensity (GI_{max}) is an indicator that relates the biomass appropriated through mowing or directly consumed by grazing livestock with the actual net primary production (NPP_{act}) on these grasslands (Erb et al., 2016a, 2016b; Fetzel et al., 2017; Haberl et al., 2007b; Petz et al., 2014). GI_{max} is the upper limit of grassland intensity within ecological thresholds. We assume that no more than 70% of NPP could be grazed or mowed in highly productive grazing lands and that this ratio decreases with decreasing grassland productivity, down to 20% in low-productive ecosystems which are sometimes used for sporadic grazing only (Erb et al., 2016b, 2007; Haberl et al., 2007a). In absence of general information on concrete levels of reduced grazing intensity that is necessary for enhancing regulating ecosystem service provision, but in line with literature that shows that reducing grazing intensity may reduce the damage to vegetation and can also help to reduce disturbance to birds and accidental loss of nests (Sutherland et al., 2019), and as well as with benefits for soil carbon storage through reduced grazing intensity (IPCC, 2019), we assume a general reduction of the GI_{max} in HNV grasslands of 20%. However, it is important to acknowledge that HNV land faces a double threat, either through intensification, but also through land abandonment. Thus, we assume a moderate reduction of grazing intensity levels allows for continuous usage and reducing risks of overgrazing.

We apply two specific agro-ecological innovation bundles which reflect two opposing strategies of grassland utilization. Firstly, a **land sparing** strategy where we increase the grazing intensity across all grassland classes (classes 1 and 2 which are permanent intensively or extensively managed grasslands, and class 3 which are other grazing lands where only sporadic grazing occurs) to the maximum sustainable level as defined in Erb et al. (2007), also including HNV land. Thus, while the biomass harvest is increased in one part of grasslands, others which are not necessary to provide sufficient grassland biomass for ruminants, are set free for vegetation regrowth. Furthermore, the change in grazing intensity causes changes in soil carbon stocks, which are accounted for in BioBaM_GHG_EU. Land which is not used to cover the demand of the domestic livestock is abandoned and the freed land is available for vegetation regrowth or afforestation and thus to provide a net-carbon sink.

The second strategy is a **land sharing** approach to grassland utilization. In this approach, we divert from the climate-centric land sparing strategy, by considering that grasslands provide a broad range of ecosystem benefits. In this case, grazing intensities are allowed to decline across all grazing classes if grazing demand < total sustainable grazing supply. In this case, soil carbon stocks and litter increase, although no vegetation regrowth that would prevail without grazing or afforestation is allowed.

Conventional baseline

In the conventional baseline, we apply maximum grazing intensities from (Erb et al., 2016b) and allow for vegetation regrowth if grassland is abandoned due to lower feed demand from grazing livestock than the maximum sustainable utilization would provide.

Table 9 provides a summary of the individual agro-ecological and conventional baseline variants for all parameters where we have defined such agro-ecological and conventional variants. For all agro-ecological variants, we have assumed a potentials-based distribution of livestock within the EU, as well as demand driven cropland production. For the conventional baseline we have assumed the distribution of livestock as well as cropland production to continue historic production patterns within the EU until 2050. For a detailed description of all individual variants see text above.

A scenario here is thus a unique combination of one specific variant for all parameters shown in Table 9. As a consequence, only one scenario within the total compilation of 432 scenarios is labelled as a purely BAU scenario, i.e. the combination of all parameter variants that are in listed in column “Variant conventional”. All other scenarios do contain one or more parameter variant that we defined as agro-ecological. For some scenarios, the specific settings may seem very hypothetic. For example, a scenario where the whole EU has adapted a diet that is in line the EAT-Lancet commission dietary recommendations for the year 2050 (Willett et al., 2019), but all production-side parameters remain conventional seems very implausible. However, and this is the key strength of BioBaM_GHG_EU, even such a scenario is useful to understand the contribution of changes in individual parameters for the indicator of interest. This is, because it allows to interpret the impacts such a dietary change has upon the assessed indicator in a ceteris paribus condition, i.e. a condition where all other parameters remain equal.

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Table 9: Summary of parameters and variants in BioBaM_GHG_EU. These parameters and variants are the basis of all 432 individual scenarios presented in the results section.

Parameters	Variant AE	Variant conventional
Human diets	Lancet	FAO BAU
	Lancet_Rumi	
	FAO TSS	
Livestock diets (LD) and Feed conversion ratio (FCR)	Co_opt cropland	BAU
	Grassland	
AWMS	High digester	Default mgmt
Cropland	Hedges	BAU
	CL feed	
GI_{max}	Reduced GI_{max}	Default GI_{max}
GL scenario	Land sparing	Fixed distribution
	Land sharing	

3.3. Implementation in SOLm - Agroforestry

BioBam is used to implement various combinations of different innovations, resulting in the innovation bundles and the related option space of all possible combinations of single innovations as described in the previous section. SOLm was used to complement this analysis of innovation bundles with an assessment of a scenario where agroforestry as a more systemic innovation was rolled out throughout the EU as this could not be covered by similar mechanisms in BioBam as the other innovations but fitted better to the architecture of SOLm, which, on the other hand was less suited for calculating the whole option space of the innovation bundles.

The main challenge for modelling agroforestry systems is their huge heterogeneity. This makes it conceptually difficult to model in such a global food systems model such as SOLm, where some standardization and aggregation is always needed, and it poses considerably challenges on the empirical side, where the heterogeneity hinders easy reviews and meta-analysis on key parameters, aiming at providing average values for various characteristics of agroforestry systems that can claim to have some more general validity.

There are some reviews on agroforestry available, but data on temperate zones and Europe in particular are rather scarce. Nevertheless, some recent reviews provide a good overview of the type of systems that are implemented and there is ample descriptive information on a number of case studies available. For example, the EU-project AGFORWARD is a rich source for knowledge on agroforestry systems (https://www.agforward.eu/index.php/en/; for an overview, see (Burgess and Rosati, 2018)), in particular its

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„Database of agroforestry system descriptions" (Milestone M28), or also (Kay et al., 2019), developed from work in this named project, with a focus on carbon sequestration. Two case studies in UNISECO also contained agroforestry systems (AT and RO), and the relevance of agroforestry for a sustainable agroecological future in the EU has repeatedly been stated, but it is clear that the case study data provides information on the specific systems in the case studies only, and we hence decided to rely on data from literature reviews for modelling agroforestry, complementing the analysis of a basic agroforestry scenario with a number of sensitivity analysis to account for the uncertainty in the parameters used.

3.3.1. **Data sources**

To include agroforestry in SOLm, we conducted a review of the literature with the aim to identify reviews and meta-analyses that could provide some aggregate and generalizable values for key parameters of most important agroforestry systems that are or could be implemented in the EU. This showed that such data is not widely available and only few parameters can be modelled. Most detailed in reviews is information on carbon sequestration in the woody biomass (below and above ground) and on soil carbon(Chatterjee et al., 2018; De Stefano and Jacobson, 2018; Feliciano et al., 2018; Kay et al., 2019), as well as some data on reduction of water and nutrient runoff and soil loss (Zhu et al., 2020), removal of NH_3 from the air (Sutton et al., 2020). There is ample evidence that agroforestry performs well regarding a number of additional aspects, such as biodiversity and pollinator support, heat and draught regulation (both for crops and livestock), etc., but there are no systematic quantitative reviews available to allow to include such aspects in the modelling (Torralba et al., 2016).

Clearly of central importance is data on yields of agroforestry systems. Here again, synthesizing studies are scarce, but some data on yields can be taken from (Lehmann et al., 2020; Pardon et al., 2018; Rivest et al., 2013). Importantly, to derive correct yield values, the yields of the components of the agroforestry system and their respective shares in the area have to be known. Sometimes, a total biomass yields is reported, which is not meaningful, given the very different character of the yields of the tree and crop or grass parts of the agroforestry system. One way to capture yields is the land equivalent ratio LER, that measures how much land the same production as derived from one hectare of an agroforestry system would be required when producing each component in a monoculture. A critical discussion of the LER and how to measure yields in agroforestry can be found in Neumann et al. (2018; Chapter 5 in (Gordon et al., 2017)), who also point out that the LER is not always calculated in the same way and that in many studies, not all information is provided to derive how the LER is calculated and that, furthermore, LER calculations are sometimes wrong. Thus, yields in agroforestry have to be treated with caution.

On the basis of the data from the references mentioned above, we derived average values for various aspects of agroforestry and its impacts to be used in SOLm, as displayed in the tables below. Due to the large heterogeneity of the data, this was a challenging task, but the average values reflect the general levels, with which agroforestry operations may be parametrized with to capture the effects of a larger-scale implementation all over the EU. Given the huge uncertainties, it is then clear that results will lie in a broad range around these mean values, which we deem more informative than the assessment based on lowest to highest values, as e.g. done in Kay et al. 2018, for illustration of the carbon sequestration potential in the woody biomass in agroforestry systems in the EU, resulting in a very large range from 8 to 235 $MtCO_2e$/year (Kay et al., 2019).

First, we address the characteristics of the agroforestry systems, which are the relative shares of the crop and tree parts per area and the yields of the crop and tree parts (Tables 10 and 11). Thereby, yields refer to how much production would be realized on a hectare of the crop or tree part separately, if cropped in the respective agroforestry system. Thus, for example, if wheat yield in a certain agroforestry system with 80% area under wheat is reported to be 5 t/ha, then a hectare of this system would produce 0.8*5 = 4 t/ha wheat. We report yields as shares of monocultural yields (i.e. without agroforestry). The values to be used in SOLm are aggregates of the values reported, accounting for the level of differentiation in SOLm (only wheat, and not spring and winter wheat, for example, which is often indicated to make a difference in agroforestry, due to the difference in shadowing from trees according to the season), and for the fact that yield data comes from a number of case studies, but is used for the whole of Europe. For many crops, no data is available, so we use values from similar crops (e.g. cereal values from oats) or a general value of 0.85 where data is missing. These yields reflect rather conservative assumptions and in the sensitivity analysis, we also implement higher yields (see below).

Table 10: Yield factors for various crops and trees for agroforestry as used in SOLm; synthesized from the literature.

Crop / tree	Value (Yield multiplication factor)	Value used in SOLm	Reference
Pastures	1	0.85	Rivest et al. 2013
	0.75		Lehmann et al. 2020
Forage maize	0.5	0.5	Pardon et al. 2018
Forage (tall fescue/clover)	0.97	0.95	Lehmann et al. 2020
Grain maize	0.66	0.7	Pardon et al. 2018
Winter wheat	0.72	0.7	Pardon et al. 2018
	1.16		Lehmann et al. 2020
Winter barley	0.9	0.7	Pardon et al. 2018
Spring wheat	0.49	0.7	Lehmann et al. 2020
Potatoes	0.49	0.6	Lehmann et al. 2020
	0.7		Pardon et al. 2018
Squash	0.49	0.5	Lehmann et al. 2020
Vegetables	1	1	Lehmann et al. 2020
Apples	1	1	Lehmann et al. 2020
Olives	0.75	0.75	Lehmann et al. 2020
Crops and trees where data is missing		Values from similar crops from above or, if no data is available: 0.85	

Next, we address the area shares of the different components in the agroforestry systems (Table 11). Lehmann et al. (2020) report crop shares from 0.7 to 0.95, but we use aggregated average values from the much broader coverage of case studies as reported in Kay et al. (2019; Supplementary material), which results in the gross

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assumptions as reported in table 11, again derived from a broader interval of reported shares reflecting gross averages.

Table 11: Component shares per unit area for various crops and trees for agroforestry as used in SOLm; synthesized from the literature (Kay et al. 2019).

Climatic zone	Crops	Grass	Trees
Atlantic	0.85		0.15
		0.85	0.15
Continental	0.9		0.1
		0.85	0.15
Mediterranean	0.94		0.06
		0.94	0.06

After these values for the system characteristics of agroforestry, we report the values used to derive a number of environmental impacts. This is done for a number of nutrient losses and pollution related to erosion and to water runoff (both from Zhu et al. 2020; see also (Pavlidis and Tsihrintzis, 2018)) and for reductions in NH3 pollution (taken from Lawson et al. 2020), both collected in table 12. Table 13 collects values for carbon sequestration in soils and woody biomass (above and below ground). Again, all the values reported in tables 12 and 13 reflect very gross average aggregate assumptions for these aspects, serving to give indicative values for what a large-scale implementation of agroforestry throughout Europe may mean.

Table 12: Several environmental indicators for agroforestry systems.

Indicator	Implmenetation in SOLm	Reference
Water runoff	Multiplication of the blue and green water footprints and the water use values from Pfister et al. (2011) by 0.66 for silvoarable and 0.23 for silvopastoral systems	Zhu et al. 2020
Soil erosion	Multiplication of the soil erosion values by 0.29 for silvoarable and 0.25 for silvopastoral systems	Zhu et al. 2020
N runoff	Multiplication of the factor for N leaching/runoff by 0.44 for silvoarable and 0.45 for silvopastoral systems	Zhu et al. 2020
P runoff	Multiplication of the factor for P leaching/runoff by 0.32 for silvoarable and 0.43 for silvopastoral systems	Zhu et al. 2020
Pesticide use	Multiplication of the pesticide use index by 0.76	Zhu et al. 2020
NH3	Assumption that a share of X% agroforestry results in a **reduction** of total NH3 values by X/100*0.3	Lawson et al. 2020

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Table 13: Soil carbon sequestration and carbon in woody biomass in agroforestry systems

Carbon Indicator	System	Value	Reference
Woody biomass (above and below ground)	Atlantic – silvopastoral	1 tC/ha/y	Kay et al. 2019
	Atlantic - silvoarable	0.5 tC/ha/y	Kay et al. 2019
	Continental – silvopastoral	1 tC/ha/y	Kay et al. 2019
	Continental – silvoarable	0.85 tC/ha/y (built from 0.75 tC/ha/y for general silvoarable systems and 1tC/ha/y for silvoarable systems with fruit trees)	Kay et al. 2019
	Mediterranean	1.7 tC/ha/y	Kay et al. 2019
Soil-C sequestration		10 % higher in agroforestry	Chatterjee et al. 2018

We compared these numbers collected for carbon sequestration in woody biomass with the values reported in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019).There, data for Europe reported considerably higher values for most cases (besides for fruit tree orchards) but is much less detailed than the data compiled here. We thus adopted a rather conservative view and refrained from using the IPCC 2019 data. We however accounted for uncertainties in these values by the sensitivity analysis allowing for 20% higher sequestration than reported here (and also for 20% lower values).

3.3.2. Scenarios

Finally, the modelling of agroforestry in SOLm is then driven by assumptions on which shares of croplands and grasslands shall be cultivated under agroforestry, and which crops and tree species may be used for this. The basis for the scenarios for assessing agroforestry is the storyline 5, "Local agroecological food systems", i.e. the storyline that best captures a future sustainable development among the storylines addressed in D4.2 and also is correspondingly located in a global context of such development, as described in Deliverable D4.2. Key general aspects are an implementation of 50% agroecological practices, which here are captured as 25% of all areas under organic production and 25% of all remaining conventional as well as of the organic areas under agroforestry (i.e. to arrive at 50% area shares under agroecological practices, a third of the remaining conventional area is under agroforestry and the total area under agroforestry including combined organic and agroforestry is 31.25% (25% conventional plus ¼ of 25% organic areas)). Thus, in total, 50% of the total areas are cropped agroecologically, either organic, or with agroforestry, or with a combination of both. For comparison, the current area share of agroforestry in the EU is about 9%, mainly located in southern Europe and Bulgaria and Romania (Burgess and Rosati, 2018; den Herder et al., 2017).

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Furthermore, the general assumptions from this storyline on feed and animal productivity prevail (grass-based ruminants, 10% reduction of monogastric efficiency), but the assumptions on yields are captured by the organic and agroforestry yields, not by the general agroecological yield assumptions as described in D4.2. Finally, in the agroforestry scenarios, we do not assume an optimization of cropland and grassland-related livestock production, but keep production patterns close to the reference scenario BAU 2050 (FAO 2018), as described in the general guidelines on how scenarios are built in SOLm as presented in the model documentation of SOLm in Deliverable D4.1.

Within the agroecological areas, the crop/grass and tree area shares per hectare reported above are assumed. To capture the huge uncertainties and heterogeneity in agroforestry systems, some sensitivity analysis regarding the within-systems area shares of crop/grass- and tree components are undertaken. The shares taken from the literature for crops/grass are 0.85, 0.9 or 0.95 respectively (see above), so we also implement corresponding shares of 0.75/0.8/0.85 and 0.9/0.95/0.95 for scenarios with higher and lower tree shares, respectively. Second, we do scenarios with 40% and 66% (i.e. 2/3) instead of 25% under agroecological management. With 25% organic areas, this means 15% and 41% of total areas under conventional agroforestry (i.e. 20% (15/75) and 55% (41/75) of the conventional areas that make up 75% of total areas under agroforestry). Finally, we also do some sensitivity analysis regarding yields, and assume generally higher yields than the ones reported above, that are rather conservative, thus changing from yield factors of 0.5/0.6/0.7/0.75/0.85/0.95/1 to 0.75/0.8/0.85/0.85/0.9/1/1.

For the environmental indicators, we do a sensitivity analysis for the carbon sequestration only, thereby focusing on the carbon in the woody biomass, as also assessed in Kay et al. 2019 for the whole of Europe. First, the sequestration rates are adjusted to the area shares and yields of the tree parts if those change in the scenarios. This does not add alternative scenarios but rather implements the literature values consistently within the different scenarios. Second, we assume basic sequestration rates that are higher/lower by 20% than the ones reported above.

Finally, we also calculate the scenarios with the assumption of organic agriculture having a share of 25% globally and not only for the EU (with global values for 5% outside the EU). This then allows to have system specific trade flows more in line with the production in the EU and showing similar characteristics. This in particular affects the organic monogastric livestock sector, which is considerably smaller with the assumption of 5% global organic areas than could be expected, as the low organic share abroad results in even lower organic feed imports than already present due to the lower trade activities in the scenario. Assuming 25% organic areas globally allows to better see the resulting dynamics without these feed trade effects.

Thus, we have the following combinations of values for various sensitivity analyses around the basis agroforestry scenario, resulting in 3*3*2*3*2=108 expressions of the central scenario (Table 14). Thereby, the 3 values for C-sequestration in woody biomass only affect this indicator and not the rest of the scenarios, thus resulting in an option space with 36 options, in which the C-sequestration in woody biomass comes with 3 values in each, spanning a sensitivity analysis of +/- 20% around a central value:

Table 14: Value combinations for the various sensitivity scenarios derived from the basic agroforestry scenario (values for this basic scenario are in bold print). AF: Agroforestry

Characteristics / Indicator (# versions)	**Values chosen** (central value in **bold** face)
Share of agroforestry / areas under agro-ecological practices (3)	Conventional (covering 75% of total area): **33%**/20% / 55% ; organic (covering 25% of total area) : **25%** /15% / 40% (resulting in total areas under agroecological practices: AF, Organic without AF, AF+Organic) of **50%** / 40% / 66%
Area share of the crop/grass component (3)	**0.85/0.9/0.94**; 0.75/0.8/0.85; 0.9/0.95/0.95
Yield factor in agroforestry (2)	**0.5/0.6/0.7/0.75/0.85/0.95/1**; 0.75/0.8/0.85/0.85/0.9/1/1
Carbon sequestration in woody biomass (3)	**Basic values** (BV); BV plus/minus 20%
Organic share outside the EU (2)	**5%**; 25%

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4. RESULTS

4.1. Land feasibility in Europe in 2050

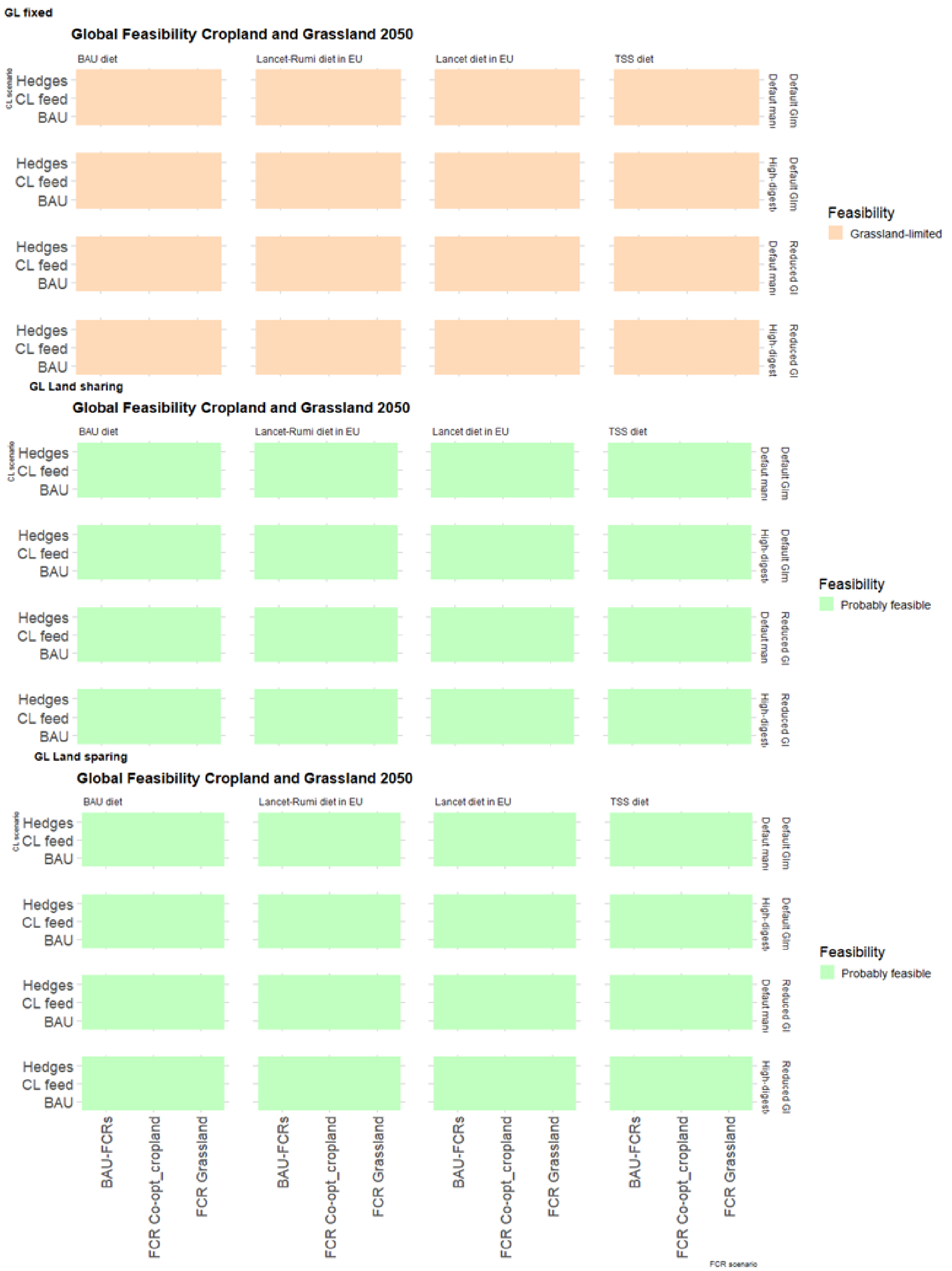

Figure 2: Global land use feasibility in the year 2050 for 432 scenarios. Red colour means that grassland is infeasible, green colour means that scenarios are probably feasible, i.e. the land use feasibility is within +/-5% of the feasibility threshold. Please note that this figure contains 432 scenario combinations.

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Figure 2 shows the land use feasibility for the 432 assessed scenarios in the year 2050. Global feasibility denotes whether on a global level enough cropland and grassland is available to cover the demand for food, feed and fibres. Results show that, under a fixed distribution of each regions' share in total cropland and grassland production, the year 2050 is infeasible. This result seems surprising, since we also assess two scenarios with considerably less demand for animal products in the European Union, i.e. the EAT-Lancet and the EAT-Lancet-Rumi diet. However, we assume that the biomass demand from regions beyond the EU develops according to the FAO BAU assumptions, where regions with current food deficits (e.g. Sub-Saharan Africa) considerably increase their demand for food, feed and fibre biomass. Since we assume in the „fixed distribution" that the EU's regions share in global biomass production remain constant as compared to the base year, the additional demand deriving from non-EU regions is not possible to be covered with exports from the EU under the assumption that the EU's share in global production remains equal to the base year.

In all scenarios where we allow that the EU's regions production shares remain within the domestic land potentials, we see that these scenarios are feasible (i.e. probably feasible denotes a 5% uncertainty range in the final calculation of land use feasibility). Thus, in these scenarios the EU is able to contribute to cover the additional demand from countries beyond the EU which cannot cover their domestic demand in the year 2050. However, these scenarios invoke a re-distribution of cropland and livestock production within the EU, where regions which have unexploited potentials in the base year increase their production to cover these additional demands. Additionally, in these scenarios also livestock production is shifted to regions with higher production potentials, i.e. higher cropland potentials cover the necessary increases in pigs, poultry and eggs production, and higher grassland potentials cover the additional production of dairy and beef production.

While livestock, and here ruminant livestock, sets a (grass-)land boundary to the feasibility of all fixed distribution scenarios in the EU in 2050, the availability of cropland is in none of the assessed scenarios a constraint. Even if cropland production in the EU is bound to re-scale with global demand, the additional demand can be covered within the boundaries that we have defined for all cropland variants (i.e. the fixed distribution scenario variants, where eventual deficits are covered based on regions shares in total cropland production in the base year). Here, also a complete shift towards agro-ecological cropland systems does not pose constraints. This result is based on projected efficiency gains in cropland and livestock systems in non-EU regions, as well as the assumption that regional deficits can be covered by any other region with potentially unused cropland in 2050. However, this is only true from a land availability perspective. There are other constraints, e.g. nitrogen availability from N-fixing plants, that can play a role but are not considered for the land feasibility indicator.

4.1.1. Current patterns of the distribution of animal production in Europe in 2050

Figure 2 clearly shows that the main result regarding land use feasibility is that all scenarios that assume a business as usual development without significant changes in regions shares in agricultural production become **globally** infeasible in the year 2050. This means, that under the assumptions of keeping current production shares in all regions (i.e. NUTS regions in the EU) and that no trade of grass biomass to cover the domestic demand for grass biomass for ruminant livestock is allowed, not enough grazing biomass is available to feed all ruminant livestock. This result holds even true if undersown leys and clover are added to ruminant livestock's diets which, inter alia, reduces genuine grassland demand from ruminants.

Agricultural production volumes are primarily constrained either by land use intensity, i.e. the output of primary biomass from one land unit, or by land use extent, i.e. the land that is under agricultural production.

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Of the 432 scenarios included in this report, one third of all scenarios are cropland feasible but grassland infeasible (i.e. insufficient grazing areas available). All grassland infeasible scenarios show, however, one common feature. In all unique combinations of the individual parameters and variants from Table 9, we assume the distribution of livestock production remaining equal to the base year, i.e. 2012. Thus, changes in the global demand for livestock products directly translate in rescaled regional demand. Grassland infeasibility in the EU is thus driven by demand changes for livestock products within the EU (which, in all agroecological variants decreases), but also by changes in the global demand. Since we assume that the additional demand in 2050 is produced according to a region's share in the global production in 2012, and since the global demand for livestock products is increasing in all scenarios globally due to dietary changes and population growth, regional limitations in grassland production occur. In conclusion, grassland infeasibility means, that while all regions in Europe are able to produce enough biomass for food, feed and other uses on cropland, grassland is limited in individual NUTS2 regions in Europe within a fixed distribution pattern of livestock production. While this assumption of maintaining current production patterns across the whole EU seems quite unlikely, results clearly show that this is also from a biophysical and land perspective not feasible. Thus, if all regions within the EU continue to pursue the current livestock production patterns in the future, they will face strong constraints from grassland availability.

The infeasibility of grassland production in all fixed livestock distribution scenarios does not, however, mean that the whole European Union is exploiting every grassland to the maximum allowed grazing intensity but nevertheless does not manage to cover domestic demand as well as the demand from outside the EU, i.e. export production. For example, NUTS regions in the Netherlands, Northern France or the UK and Ireland have already had in the base year extremely productive and intensively managed grasslands which were exploited near maximum sustainable rates (Estel et al., 2018; Mayer et al., under review; Overmars et al., 2011; Plutzar et al., 2016). Thus, there was not much additional potential to expand ruminant livestock production and consequently biomass harvest from grasslands. However, most regions where the UNISECO case studies are located, are cropland and grassland feasible in a scenario where all parameters are set to the conventional variant (Figure 3).

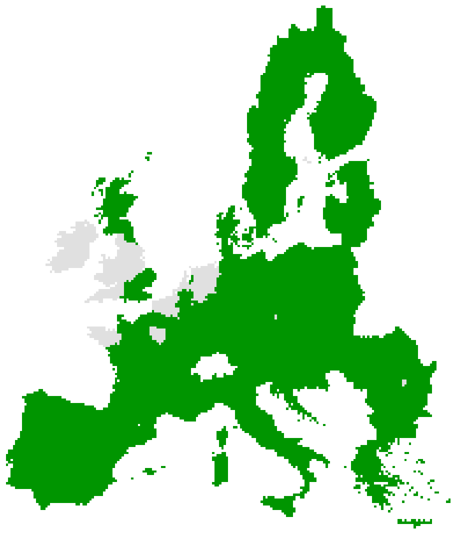

*Figure 3: Regional grazing feasibility at the NUTS2 level in the European Union in the year 2050 in a scenario where all parameters are set to the conventional variants. Regional grassland feasibility is calculated as follows: ((Domestic demand of meat and dairy + eventual interregional demand) * domestic FCR)) / (NPP_{act} * Gi_{max}). Green colored regions are grassland feasible, grey regions are grassland infeasible. No data for Switzerland.*

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Figure 4 shows a map for 227 NUTS1 and NUTS2 regions with the number of grassland infeasible scenarios as shares in total runs with a fixed distribution of livestock production in the EU (n=144). Thus, the higher the number of grazing feasibilities in a region, the more often biomass supply from grassland is not a limit to the feasibility of a specific scenario infeasible. In all 144 scenarios, a global grazing gap prevails, meaning that the global demand for grassland feed cannot meet the demand under these assumptions.

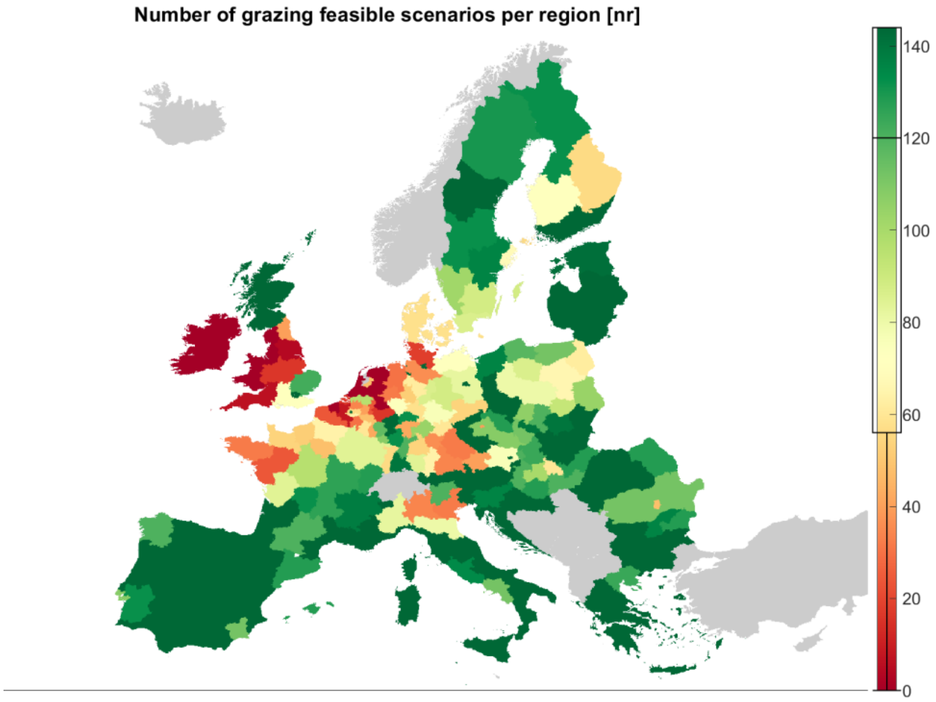

Figure 4: Number of grazing feasible scenarios per region in all scenarios assuming a fixed distribution of animal production in the European Union in the year 2050.

There are a few regions which are always grazing feasible, and these are regions with very low grazing intensities in the base year, thus able to take a considerable increase in ruminant livestock production in the year 2050 under the assumption that each region maintains the share in global production of beef and dairy (which is increasing from 260 Mt DM/yr to 363-390 Mt DM/yr). These are most regions in Spain, Southern France, Italy, most regions in Eastern Europe (except some regions in Poland) and also some more regions in the Baltics. There, potential for increasing ruminant production exist, whereas increasing stocking densities on grassland can trigger a range of subtle, negative ecological aspects. At the other range of feasible scenarios, it becomes clear that in some regions no or nearly no additional ruminant production can be hosted without risking overgrazing. This can be seen for all regions colored in red, mostly found in North-Western and Central Northern Europe, i.e. the British Island (albeit without Scotland), the Benelux regions, and to a lesser extent also in Western France, parts of Germany and Northern Italy. Approximately half of scenarios are grazing infeasible in most parts of Germany, Central and Northern France and also in the South of Finland. Ruminant production systems were, in comparison to domestic feed production capacities in these regions, already quite large in the base year. Further expansion of production would lead to a closer approximation of grazed biomass to NPPact, and thus not, or only under risking negative ecological impacts, possible. Since the 144 scenarios include all three LD variants (BAU, Co-opt_Cropland, Grassland), shifts in livestock feed production can play a role for regional grazing feasibilities, but then (as for the Co-opt_Cropland variant) pressures are only shifted from grasslands to croplands.

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4.1.2. Potential-based distribution of animal production in Europe in 2050

While none of the variants with current production shares of animal products of EU regions in the global demand is grazing feasible (see Figure 2), this pattern is more heterogenous and differentiated for all agro-ecological variants. There, we assume that the production of ruminant milk and meat follows grassland potentials, and consequently allow for a significant re-distribution of production within the EU. Thus, regions with low grazing intensities in the base year host a larger livestock population in 2050 and also increase grazing intensities – while in the agroecological variants thresholds are reduced by 20% in HNV areas to avoid pressure from overgrazing with negative impacts on grassland ecosystem services (Ekroos et al., 2020; Erb et al., 2016a; Godde et al., 2018; Petz et al., 2014).

4.1.3. Cropland in the European Union in 2050

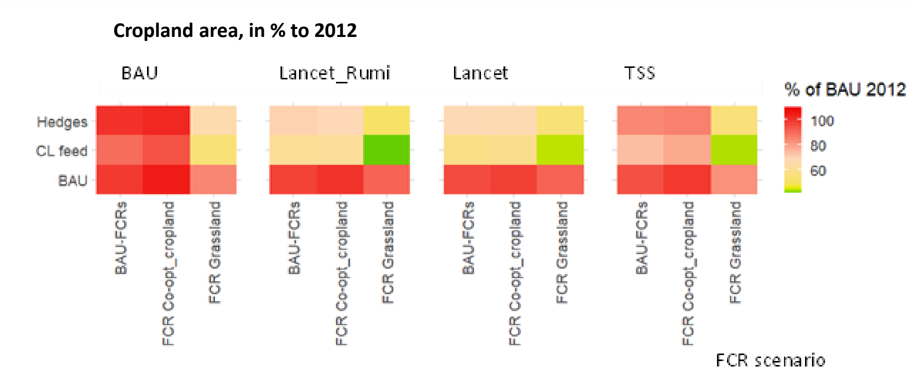

Figure 5: Total cropland in the European Union in the year 2050 , shown as % of the cropland extent in the base year (i.e. BAU 2012). 100% denotes the same value as in BAU 2012, i.e. no change. Please note that this cropland heatmap is only shown for feasible scenarios and for relevant parameters for the chosen indicator. For example, variants of grassland related parameters (e.g. current or reduced GI_{max}) or variants for manure management systems do not have an impact on the indicator that is displayed here and are thus not shown in this figure.

Land use for agricultural production in the European Union in 2050 is feasible under the assumption of a re-distribution of livestock production to domestic land potentials. Figure 5 shows changes in the extent of croplands within the EU in comparison to the total utilized cropland of 121 Mha (million hectares) in 2012. Since we do not allow for cropland expansion (into grasslands) in the agro-ecological variants (i.e. Hedges and CL feed), and for a 20% land use expansion into highly productive grasslands in the conventional scenarios (BAU), a maximum (theoretical) expansion to 120% of the cropland extent in 2012 is allowed. In all scenarios with a global BAU human diet assumption and livestock diets with current patterns – also in the agro-ecological variant of CL-based livestock diets (Co-opt_Cropland) - cropland in 2050 is remaining at comparable extents as in the base year. Here, only a variant with a shift of ruminant feeding ratios to grassland-based feed reduces the required cropland significantly.

Diets play a considerable role for cropland requirements, since they determine the necessary crop production for food, but also through the feed demand from livestock. Reducing the latter, such as assumed in both EAT-Lancet diet variants, does allow for considerable reductions in cropland extent in 2050 while not infringing domestic food availability and still allow for the production of export goods, except in the BAU cropland variant which allows for cropland expansion if needed. Ruminant livestock requires less areas for the production of cropland feed in the CL feed scenario, since parts of the undersown leys are fed to ruminant livestock, reducing the demand for primary cropland for feed production as can be seen in the cropland variant CL feed. The FAO

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TSS human diet scenario shows a mid-range combination of scenarios between the BAU and the two EAT-Lancet human diet variants. Since in both agro-ecological livestock diet variants monogastric livestock is assumed to have a lower feed conversion ratio between primary feed and animal output, the positive effects on cropland requirements through less animal products in human diets are counterbalanced with the higher need of feed per kg of monogastric products in both agro-ecological FCR variants. Thus, results show that an extensification of monogastric livestock within the European Union is possible without increasing cropland demand. The reduction of utilized croplands through a shift of ruminant *livestock's* diets to exclusively grassland feed, leaves room for additional (agro-ecological) measures to reduce cropland intensity in the European Union, as described in Stolze et al. (2019).

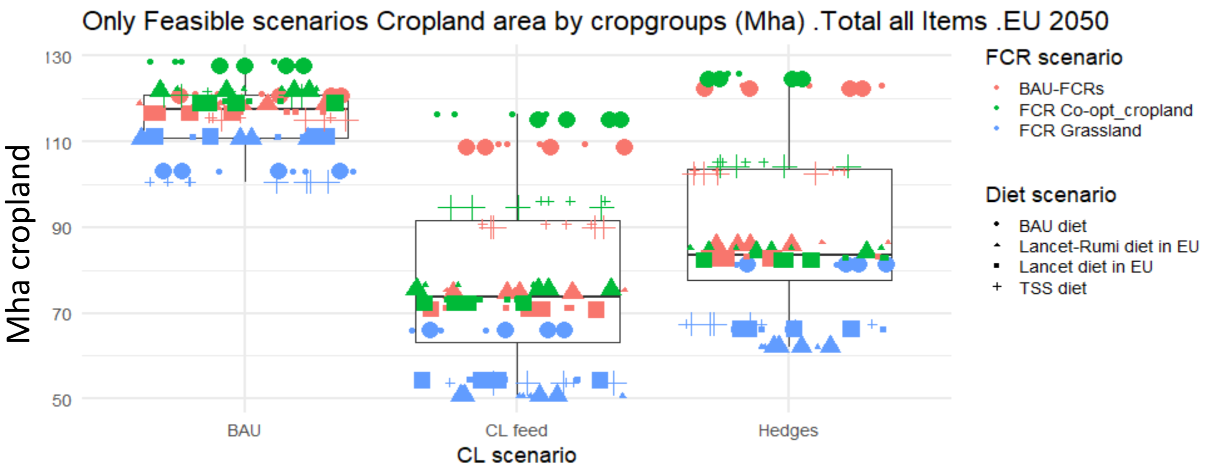

Figure 6: Boxplots that show the impact of individual variants for total cropland extent in 2050. The impact of each parameter is assessed and parameters are classified from those with the largest impact in descending order from x-axis, colour, and shape of marker. Size of markers are not a relevant parameter in this figure. Classification based on regression analysis, only feasible scenarios were included in this analysis, meaning that also variants which do not impact the assessed indicator are included in the boxplot. Boxes indicate the inner two quartiles, i.e. the medium 50%, of all scenarios.

Figure 6 transforms the data shown in the heatmap in Figure 5 into boxplots to identify key drivers of cropland utilization in the 288 land feasible scenarios. We are thus able to systematically assess which parameters and which variants increase or decrease the extent of cropland across all variants. The largest impact clearly have the two alternative cropland scenarios CL feed and Hedges, with half of scenarios with a CL feed variant resulting between 64 Mha and 92 Mha of required cropland in the EU in 2050, which is lower than in the variant Hedges, and considerably lower than in the BAU variants. CL feed variants need less cropland since undersown crops which are used for livestock feed reduce the demand of primary cropland. In both agro-ecology variants, clearly the assumption that the cropland extent in 2012 is the upper limit in the year 2050 has a strong impact on total cropland in 2050, and the maximum allowed cropland use is highest in the BAU CL variant (max = 2012 +20%), the CL feed variant (Max = 2012) and Hedges variant (Max = 2012 – 7% Hedges). The interesting part of this result is, however, that this limit does not lead to cropland infeasibilities in the EU. Furthermore, these results clearly show that implementing agro-ecological approaches in cropland production do not necessarily lead to increasing cropland demand to meet the domestic demand for agricultural biomass. Certainly, production volumes and patterns cannot remain as they were in the base year 2012, but if they change, agro-ecology can even contribute to land savings (e.g. through the utilization of undersown crops for livestock feed) if practices without compromising domestic food security in the European Union.

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Additionally, shifts in ruminant diets have a strong impact on required cropland. Grassland-based feed conversion ratios (FCR Grassland) with less cropland-based feedstuff clearly reduce food-feed competition on cropland, and score well below the median 50% scenarios in all cropland variants. Here, no difference between a standard EAT-Lancet diet recommendation and the EAT-Lancet diet with a higher share of dairy and beef can be observed, indicating that a re-connection of grazing livestock with grasslands is possible, given less total demand within the EU. This effect is reinforced in scenarios where clover from undersowing in cereals is implemented and fodder crops in the EU only contain fodder legumes, instead of a mixture of fodder maize, fodder roots and fodder legumes in the base year. Finally, it is important to consider the total size of the agri-food system in all variants. The effects of agro-ecological cropland and FCR variants are strongest if combined with low-meat, dairy and eggs diets, where these specific combinations considerably decrease the extent of cultivated cropland in 2050.

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4.1.4. Grassland in the European Union in 2050

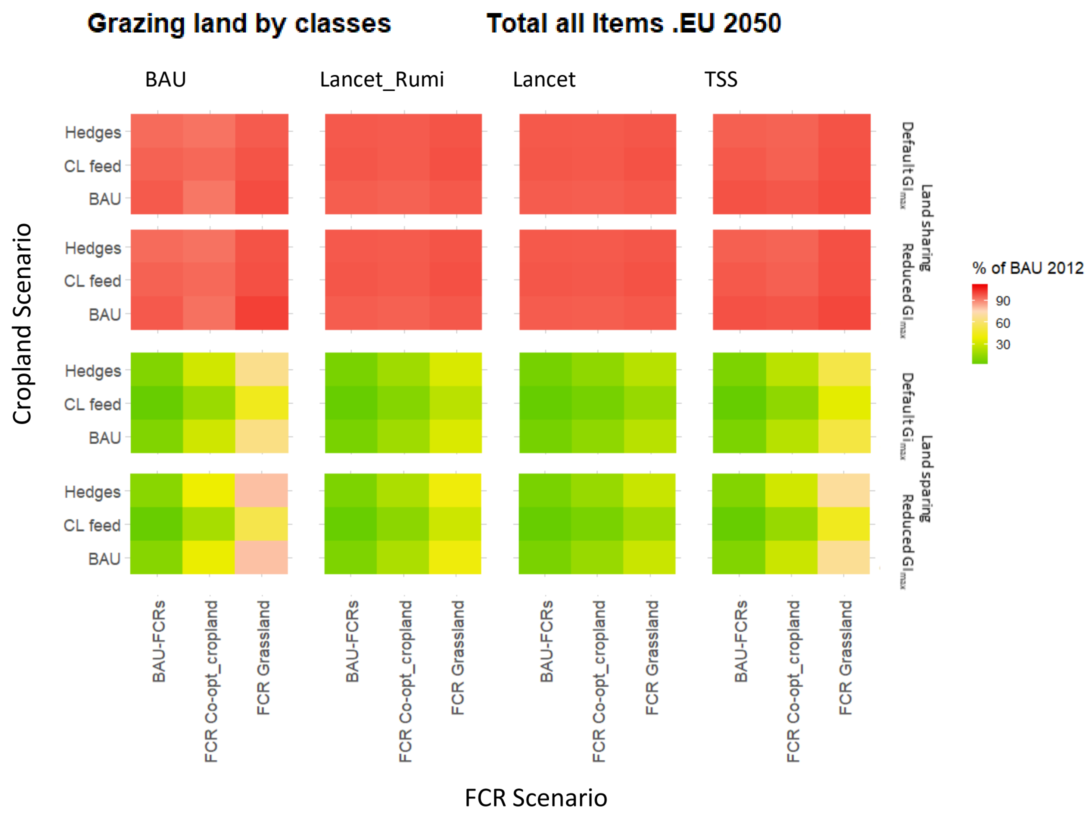

Figure 7: Total grassland in the European Union in the year 2050, shown as % of the grassland extent in the base year (i.e. BAU 2012). 100% denotes the same value as in BAU 2012, i.e. no change. Please note that this heatmap is only shown for feasible scenarios and for relevant parameters for the chosen indicator, i.e. total grassland extent. For example, variants for manure management systems do not have an impact on the indicator that is displayed here and are thus not shown in this figure.

Figure 7 shows the changes of total grassland in the European Union in the year 2050 for 288 grassland feasible scenarios (AWMS variants not shown explicitly). In the land sharing variant (i.e. in which grazing intensities are increased across all grassland if necessary), grassland extent remains at comparably levels to the base year, with the largest reduction in the agro-ecological livestock diet variant where livestock is increasingly fed with cropland by-products and residues. In the agro-ecological variant where ruminant diets are shifted towards grassland feed (FCR grassland), grassland remains at comparable levels to the year 2012 in all variants assessed. In the BAU FCR variants, a slightly higher demand for grasslands remains in all land sharing variants, due to a smaller extent of residues and by-products from cropland production in livestock's diets. All land sparing variants shown here reveal that all variants allow for a reduction of total grassland demand in comparison to BAU 2012. Since grazing areas in 2050 remain at comparable levels to the base year, the effects of reduced demand for milk and dairy products on grazing intensity are likely to be considerable, which is shown in section 4.4.6.

The land sparing variants show drastic changes in grassland extent in 2050. We clearly see the effect of a land sparing assumption in the European Union, where grassland demand is covered by increasing the intensity to GI_{max} in the highest productive grasslands, and the remaining grassland is set free for vegetation regrowth to provide a carbon sink. In both variants, default and reduced GI_{max}, utilized grassland considerably decreases,

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with comparable impacts of livestock diets (i.e. feed conversion ratios FCR) such as in the land sharing variants. Both agro-ecological FCR variants allow for reductions that are > than 40% compared to 2012, and also both agroecological cropland variants results in less required grassland in 2050, with the CL feed variant providing additional land saving potential through the harvested clover from undersowing in cereals on cropland.

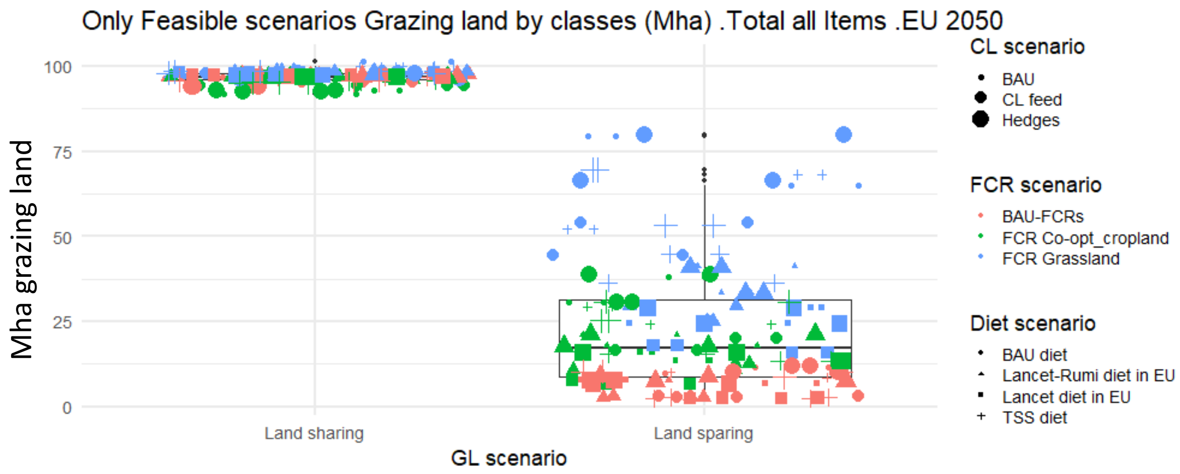

Figure 8: Boxplots that show the impact of individual variants for total grassland extent in 2050. The impact of each parameter is assessed and parameters are classified from those with the largest impact in descending order from x-axis, colour, and shape of marker. Classification based on regression analysis, only feasible scenarios were included in this analysis, meaning that also variants which do not impact the assessed indicator are included in the boxplot.

We again plotted the scenario option space into boxplots, as can be seen in Figure 8. The strongest effect have the two grassland variants, land sharing (left boxplot) and land sparing (right boxplot). In the land sharing variant, no clear effects regarding CL variant and diet can be observed, only FCR variants are making a slight difference (indicated as colours). Thus, the main conclusion here is that a shift towards agro-ecological ruminant livestock diets based exclusively on grassland feed is possible in the European Union without significant impact upon the total grassland extent, independent from whether GI_{max} is reduced in HNV grasslands, as well as independent from the human diet variants included in this assessment. However, it is important to acknowledge that these results are only possible in scenarios where we allow for a EU-wide redistribution of livestock production.

The land sparing variants score at considerably lower grassland extent, with grassland based FCR variants, i.e. only grass from grasslands in ruminant diets, showing the largest range of required grassland in the EU, albeit all variants require less grassland than all land sharing variants. Despite the fact that the highest land saving potentials were reached with BAU FCR variants (i.e. assuming more efficient FCR's than in the agro-ecological variants), both agroecological variants allow for considerable land sparing effects under the assumption of increased grassland intensity. The spared land can thus be used to restore natural vegetation for enhancing ecosystem services, or for a range of nature-based climate solutions (Griscom et al., 2017; Kalt et al., 2019).

Both agro-ecological grassland variants which we have assessed here are not constrained by grassland extent, while all variants with fixed production shares of EU's regions in the total global ruminant production sector are not grassland feasible. Consequently, both agroecological grassland variants are only possible if large-scale changes in ruminant livestock production systems within the EU occur and ruminant livestock production will be closer related to grassland potentials. Thus, regions with low ruminant livestock densities in relation to their grassland / fodder areas need to carefully increase these stocking densities, while regions with high

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stocking densities in 2012 need to reduce the size of their ruminant livestock systems to at least ratios that are within the potentials of their domestic grasslands. Effects on grazing intensities and biodiversity pressures are shown further below in section 4.5.

4.2. Consumption of crops and animal products in the European Union in 2050

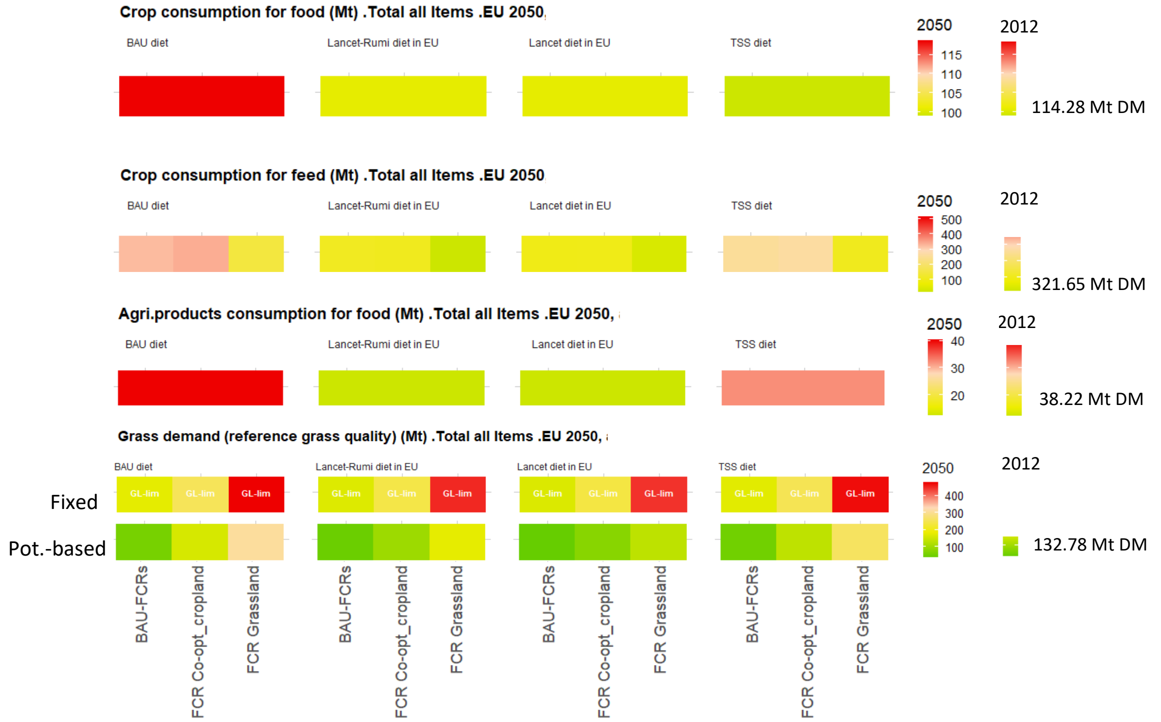

Figure 9: Consumption of crops for food and feed, consumption of animal products and fibres (agri products), and grass demand in the EU in 2012 and 2050 in Mt DM. Consumption of crops and agri products in the EU is only different in human and livestock diets variants, and kept constant in all other variants in 2050 (not shown here). Grassland demand is different based on the assumption of the distribution of ruminant livestock, i.e. fixed or potential-based distribution. Grass demand is reported in grass reference quality, i.e. all grazed biomass is converted to a standard measurement according the nutritional value of the highest quality grassland class (i.e. managed grassland) in terms of metabolizable energy (Van Zanten et al., 2019). Green colors show lower values in 2050 than in 2012, yellow indicate similar range, red indicates higher values in 2050 than in 2012.

Sustainable diets are a complementary and necessary contribution to agro-ecological food systems. We thus assess four different human diet variants, but also three variants of livestock diets, measured as ratios between feed input and animal product output and, denoted as feed conversion rations (FCRs). Direct crop consumption for food remains at the same level in 2050 than in 2012 for the FAO BAU diet variant, while both EAT-Lancet diets (10% less compared to 2012) and the FAO TSS (15% less compared to 2012) diet require slightly less crops for direct human consumption. The latter three diet variants thus assume a reduction of overconsumption of crops in the EU. Animal products account for app. one fourth in in human dietary intake in the BAU scenario, with slightly fewer animal products in FAO TSS diets, and more than a reduction of 50% in both EAT-Lancet diets.

Nevertheless, the production of animal products has led to considerably higher flows of primary biomass from cropland than for direct human consumption. In 2012, more than 320 Mt DM/yr of cropland products were

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needed to feed the livestock in the EU. In a scenario with a BAU diet and cropland based FCR (i.e. explain…), the demand for livestock feed from cropland remains at comparable levels to 2012, with the grassland-based variant for ruminants reducing cropland feed (as ruminants are fed exclusively from grasslands) and allowing for considerably reductions in cropland feed demand. The same pattern, albeit at lower levels of animal feed demand from cropland is visible for the FAO TSS diet, the EAT-Lancet version as defined in Willett et al. (2019), and a stronger reduction in the EAT-Lancet diet version with a higher share of dairy products and ruminant meat. In all diets except FAO BAU with cropland-based livestock diets, cropland demand for livestock feed decreases considerably in 2050 in the assessed variants.

Grassland demand for ruminant livestock was at 133 Mt DM in the year 2012, and shows a very heterogeneous pattern in 2050. In all fixed distribution approaches, the total demand for grassland biomass in the European Union is increasing from moderate to considerably, depending on assumed livestock diets. However, it is important to note that the grass demand cannot be met within the current production patterns within the EU, making these scenarios grassland infeasible. In scenarios where we assume an EU-wide re-distribution of ruminant production based on grassland potentials, grassland demand remains closer to the levels of 2012 (differing by human and livestock diets). Certainly, the share of EU grass-based livestock products in the global production in these scenarios in the year 2050 will shrink, and the additional global demand will be mostly covered from regions beyond the European Union. Lastly, we clearly see a trade-off between livestock feeding variants, where BAU and Co-opt_Cropland variants shift more demand towards croplands, and the grassland-based FCR strongly increases the grazed biomass in 2050.

4.3. Crop production for food, feed and other uses

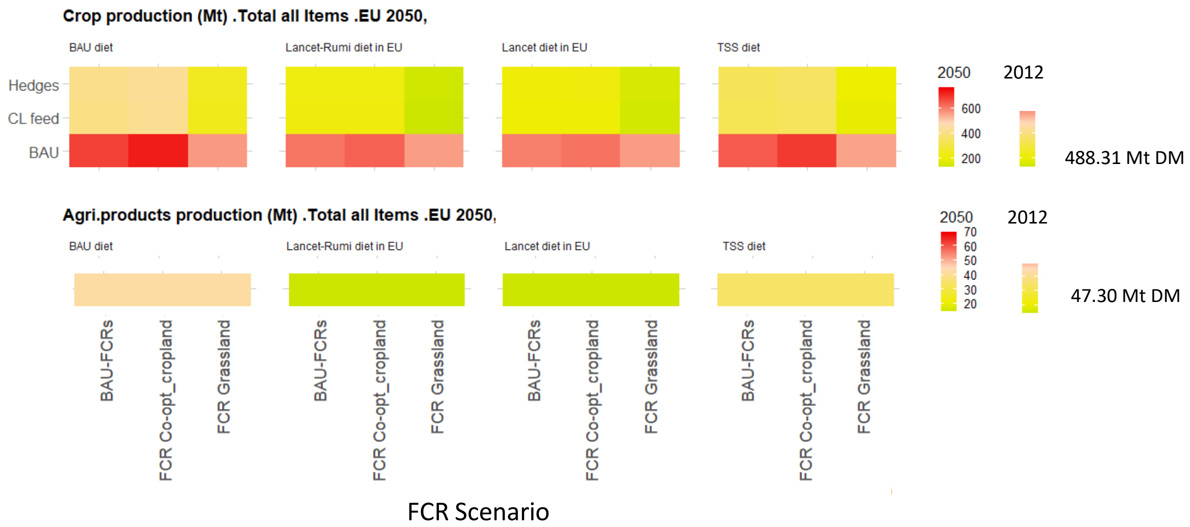

Figure 10: Production of crops and agricultural products in the European Union in 2050 in Mt DM/yr. Crop production is different between cropland variants, the production of agricultural products only differs between diet scenarios. Only feasible variants shown.

Crop production in the European Union in the year 2050 is increasing in all BAU cropland variants, i.e. when xxx, and ranges from 558 Mt DM/yr to 770 Mt DM/yr, as compared to 488 Mt DM/yr in 2012. The highest production volumes are in variants where livestock diets are increasingly based on cropland products, i.e. the Co-opt_Cropland FCR. In all agro-ecological cropland variants, production volumes decrease in comparison to the year 2012, with the lowest production volumes in both EAT-Lancet human diet variants (due to substantially lower meat demand) and alternative FCR variants where ruminant livestock is exclusively fed

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from grasslands, as can be seen in Figure 9. Since cropland production is strongly driven by feed requirements from animals, scenarios with higher volumes of animal products in diets, i.e. the FAO BAU and FAO TSS diet variants (as shown in the lower panel), require more crops to feed the domestic livestock. The higher demand for cropland products, nevertheless, can be covered within the European Union in 2050 albeit at the cost of the expansion of cropland at a maximum rate of 20% of the cropland in the year 2012 if enough high-quality grassland is available in the BAU cropland variant (see Figure 5).

4.4. Impacts

4.4.1. Land-based potential self-sufficiency

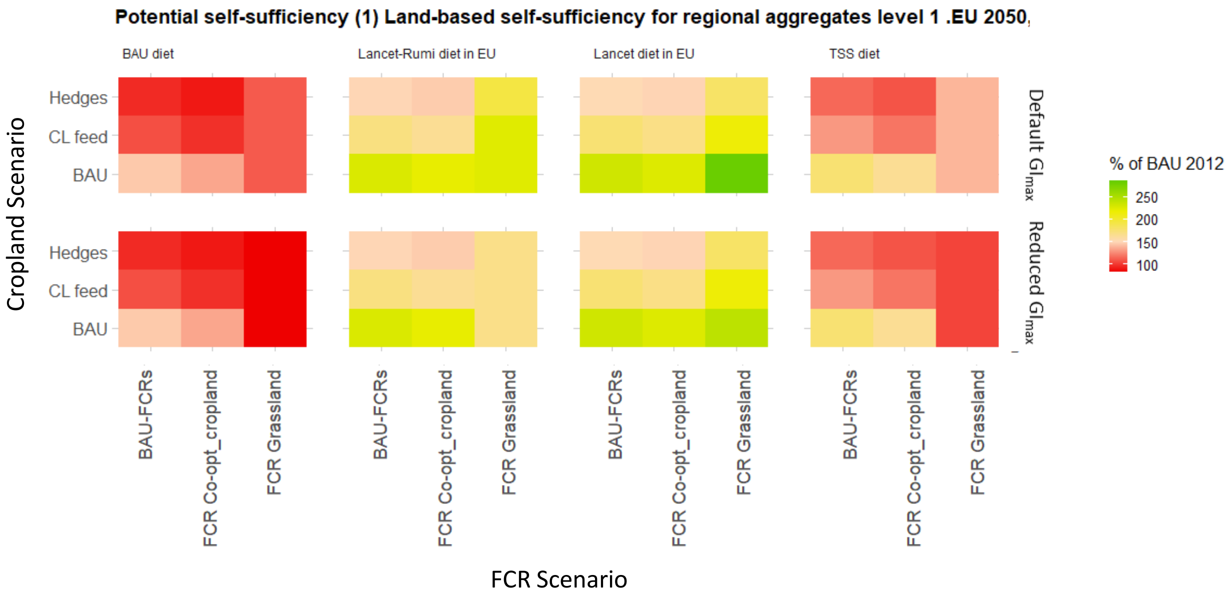

Figure 11: Land-based potential self-sufficiencies for the EU in the year 2050. Values display ratio in comparison to the year 2012, i.e. a ratio of 100% equals the ratio in the year 2012. Only feasible scenarios included in this heatmap.

The potential land-based self-sufficiency in the EU in 2012 was 96%, i.e. the EU was nearly balanced in terms of the potential output from the currently available agricultural land (cropland and grassland) which was needed to cover the primary biomass equivalent for the final demand for agricultural products. This indicator is calculated as domestic production/domestic consumption, and thus converts animal products into the feed equivalent which is needed to produce the necessary quantities of milk and dairy, beef, poultry meat, eggs and pigmeat. In all scenarios in the year 2050, potential self-sufficiencies are increasing, up to 250% in a scenario with reduced dietary demand (variant EAT-Lancet diet) and the grass-based ruminant livestock diet, albeit at the cost of a possible cropland expansion into grassland in the BAU CL variant. The highest potential self-sufficiencies are found for the EAT-Lancet-Rumi and EAT-Lancet diet, meaning that dietary changes have the largest impact upon potential self-sufficiencies. In the two agro-ecological cropland variants potential self-sufficiencies slightly decrease in comparison to the conventional variant (due to lower yields), as well as compared to reduced maximum grazing intensity allowances (GImax) in HNV areas, as lower intensity leads to a higher land demand. Variants with hedgerows on 7% of the total cropland have the largest negative impact on potential self-sufficiences due to the reduction of the extent of cropland, as well as grass-based FCR have in dietary variants with comparable amounts of ruminant livestock products as in 2012.

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Nevertheless, the implementation of agro-ecological cropland, grassland and livestock feeding variants do allow for increasing potential self-sufficiencies in the year 2050, thus making the European Union agricultural systems more resilient against negative impacts for food production from e.g. climate-induced droughts or other extreme weather events without compromising domestic food security. Finally, it is important to note that the potential land-based self-sufficiency is a maximum threshold of agricultural biomass production, and that in most scenarios, these potentials do not needed to be exploited.

4.4.2. Realized self-sufficiencies for crops and grass

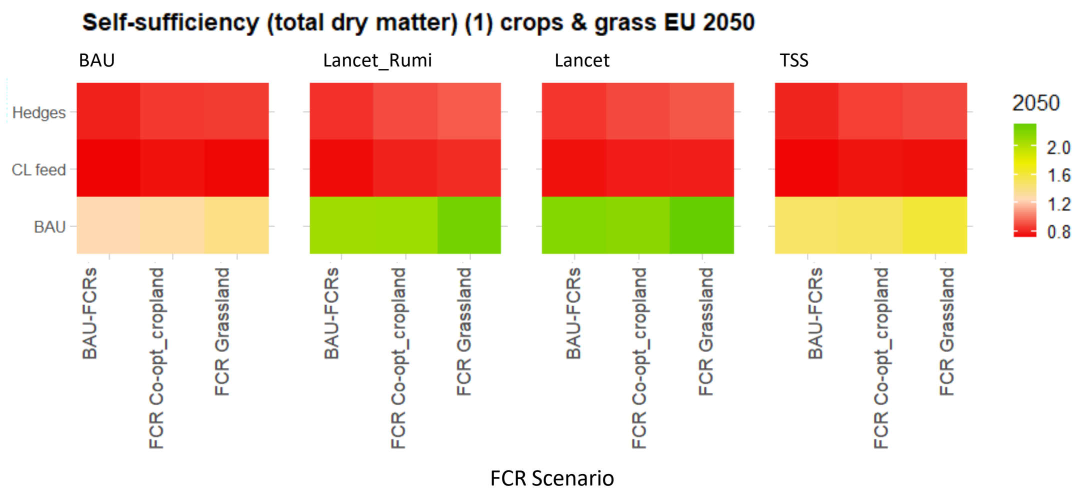

Figure 12: Realized self-sufficiencies for crops and grass in the EU in the year 2050. Values display the realized self-sufficiencies, measured as supply/demand. Only feasible scenarios are included in this heatmap.

While potential land-based self-sufficiencies increase considerably in many scenarios in the year 2050, and diets are an important driver of the potential self-sufficiencies, the actual (or realized) self-sufficiencies show a different pattern. While potential self-sufficiencies are a theoretic potential showing the degree that can be realized if full production potentials are exploited, actual self-sufficiencies show the ratio of actual production measured against domestic demand. In the base year 2012 the realized self-sufficiencies for crops and grass were 108 %. The BAU cropland variant allows for significant increases in self-sufficiencies; in scenarios where the BAU cropland variant is combined with EAT-Lancet human diet variants the EU is producing nearly double the biomass required to meet the domestic demand for food, feed and fibres. A similar pattern, albeit at lower self-sufficiencies, is found for both FAO diets, i.e. FAO BAU and FAO TSS. In all other, agro-ecological cropland variants (Hedges and CL feed), the realized self-sufficiencies in the year 2050 are lower than in the base year, and shrink to values around 80% in mostly the CL feed variant, due to higher net-imports arising from pressures for surplus production from RoW regions. In the Hedges CL variant, mostly in combination with agro-ecological FCR variants, realized self-sufficiencies in the EU increase slightly.

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4.4.3. Total GHG emissions

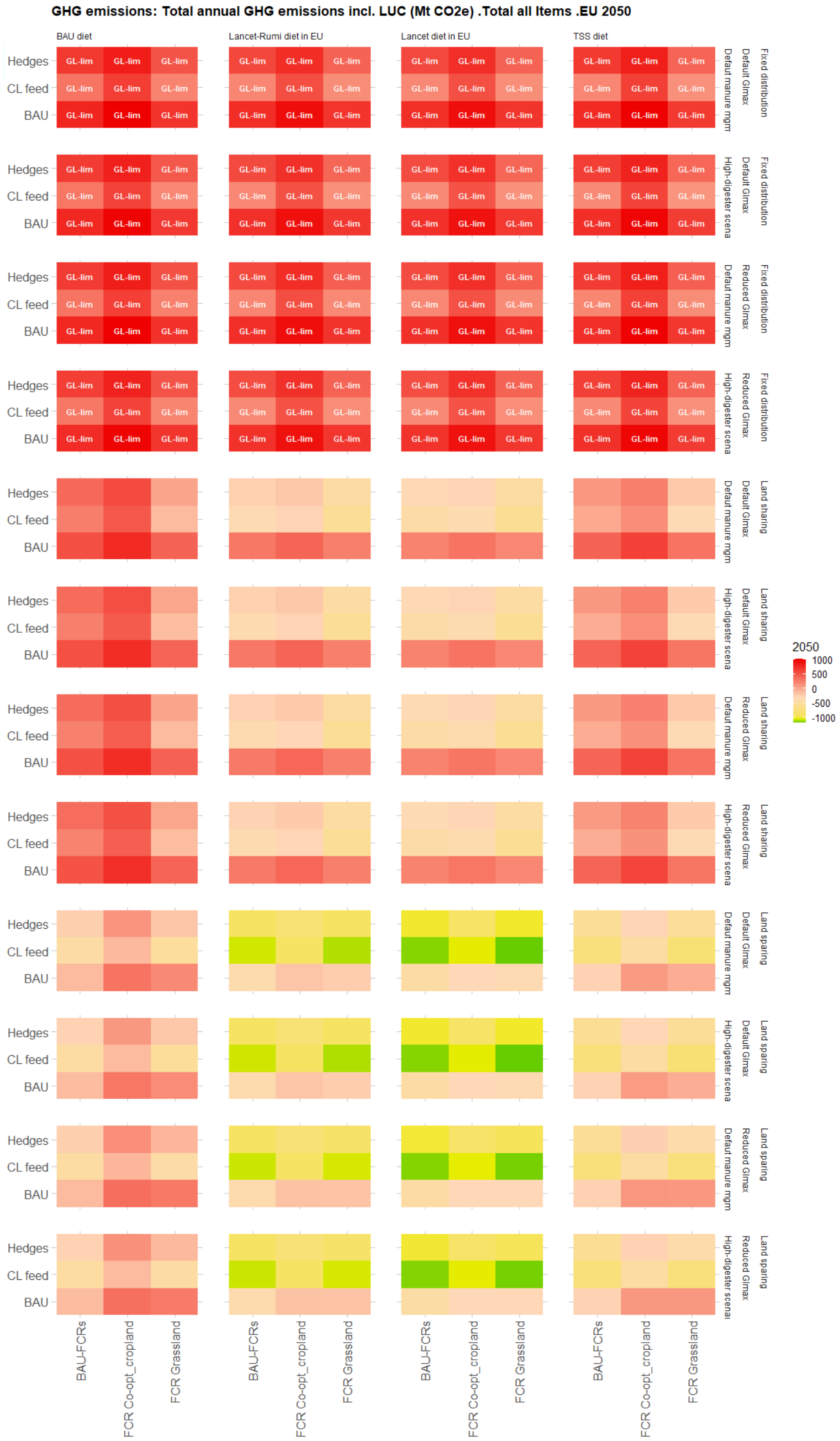

Figure 13: Heatmap for total annual GHG emissions including emissions from land use change in the European Union (including the UK) in the year 2050 in Mt CO_2 equivalents (CO_2e). Scenarios also include grassland infeasible variants. For details on included emissions see methods section.

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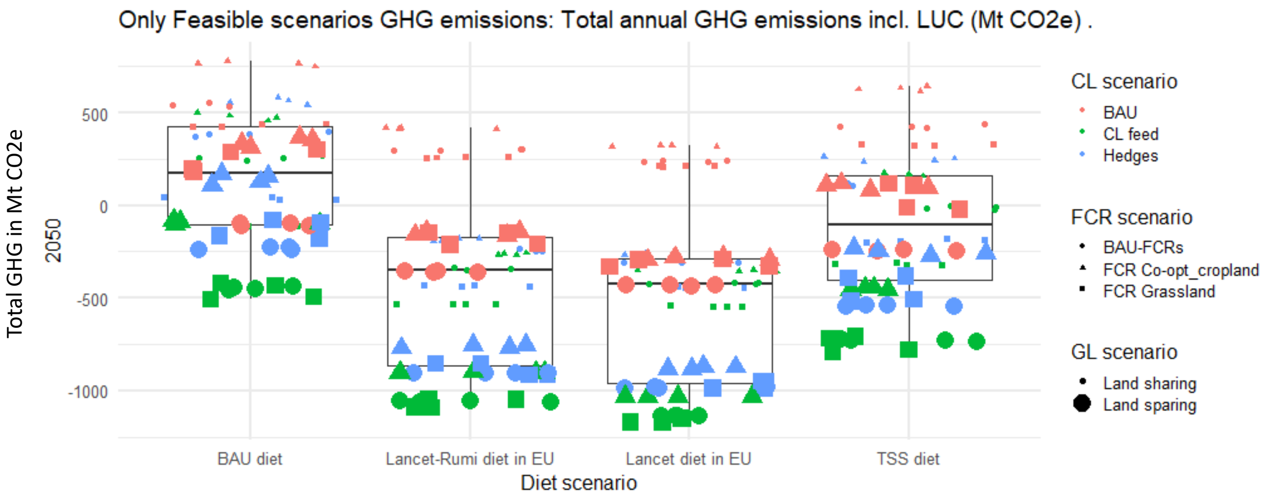

Figure 14: Boxplots for total annual GHG emissions including emissions from land use change in the European Union in the year 2050 in Mt CO_2 equivalents (CO_2e). The impact of each parameter is assessed and parameters are classified from those with the largest impact in descending order from x-axis, color, and shape of marker. Classification based on regression analysis, only feasible scenarios were included in this analysis.

Figure 13 and Figure 14 show a heatmap and a boxplot for total annual GHG emissions in the year 2050 in the European Union. In the base year 2012, the agricultural sector was responsible for 565 Mt CO_2e of GHG emissions, and the heatmap clearly shows that in scenarios with a fixed distribution of animal products, GHG emissions increase drastically in comparison to the base year due to remaining shares of EU regions in global production shares, independent from all other parameters and variants. In some scenarios, mostly those including the conventional cropland variant (BAU cropland), where we allow for 20% cropland expansion and conventional cropland yields, total GHG emission are higher than 1000 Mt CO_2e. Interestingly, the cropland variant Hedges does indeed slightly decrease total GHG emissions in comparison to the BAU cropland variant, but worse than the CL feed variant which includes undersowing in cereals and a full switch of fodder crops to fodder legumes. Clearly, the emissions in all fixed variants are far beyond levels which the EU has agreed on to contribute to reach the Paris climate goals.

In all feasible scenarios, a huge range of total GHG emissions in the year 2050 is visible, from variants with increasing emissions up to 750 Mt CO_2e for scenarios with FAO BAU diets to scenarios with considerable negative GHG emissions. Here, the diet variants EAT-Lancet and EAT-Lancet_Rumi allow for the largest net-carbon sinks in scenarios when they are combined with the CL feed variant and the land sparing variant in grassland utilization. In both EAT-Lancet diet variants, the drastic reduction of animal products clearly benefits total GHG emissions. However, there are also scenarios (mostly those where EAT Lancet diets are combined with the conventional cropland variant) where these lower meat and dairy diet variants have higher total GHG emissions as in scenarios with FAO BAU and FAO TSS diet variants combined with agro-ecological cropland variants. There, synthetic fertilizers which are allowed in BAU cropland variants, drive higher GHG emissions in these scenarios. This clearly shows that both agro-ecological cropland and human dietary variants contribute to reduce total GHG emissions, and that here synergies between agro-ecology on croplands and climate change mitigation can be realized.

We have implemented two agro-ecological variants on grasslands, a land sharing and a land sparing variant, which strongly influence total GHG emissions in all scenarios. The land sparing variant significantly contributes to lower total GHG emissions, and even allows in most scenarios for negative emissions, as major land areas

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can be afforested. Scenarios with the largest net-carbon sink of -1000 Mt CO_2e GHG emissions are possible within a BAU and a grassland-based FCR variant, but only if combined with human dietary variants with reduced demand for animal products. The land sharing variant does not allow to create such large carbon sinks (since no grassland is allowed to be abandoned and utilized for vegetation regrowth), but the considerable reduction of the realized grazing intensity does also reduce total GHG emissions through better maintenance of carbon sinks in grassland soils. Thus, while the benefits in term of GHG emissions of a land sparing variant are very clear, regional particularities and feasibilities, as well as other impacts such as on biodiversity, needs to be considered. Overall, our results show that the reduction of GI_{max} in high natural value farmland (HNV) areas in both agro-ecological variants does not have a significant influence on GHG emissions, since all scenarios are either below GI_{max}, or the reduced grazing intensity does interact with the creation of carbon sinks in the land sparing scenario (albeit not in the land sharing scenario), leading to mixed, but minor effects of this innovation on total GHG emissions.

While the agro-ecological variant of a partial shift of AWMS in pigs, poultry and egg production towards biogas digester systems – albeit counterbalanced with a small increase in pasture-based systems of 5%, was implemented to directly reduce emissions from animal production, the impact on total GHG emissions was not visible in the heatmap in Figure 13. This shows that other factors that do not directly target emissions do have a larger impact than specific (and technical) switches in animal manure management systems. Nevertheless, these switches are one contributing factor to a reduction of total GHG emissions, and thus their impact needs to be assessed.

4.4.4. GHG emissions from enteric fermentation and manure management

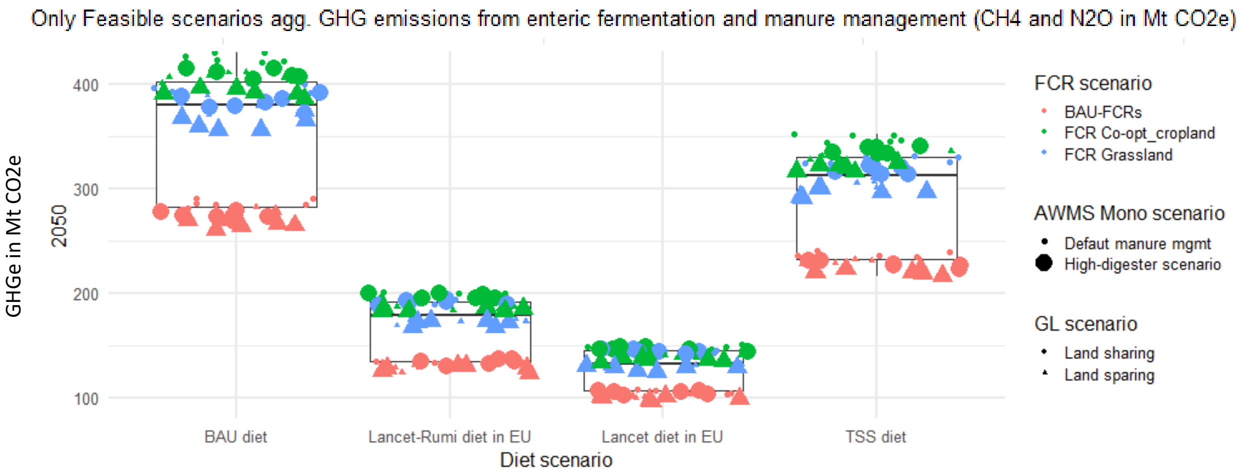

Figure 15: Boxplots for livestock-production related GHG emissions from enteric fermentation and manure management in the European Union in the year 2050 in Mt CO_2 equivalents (CO_2e). The impact of each parameter is assessed and parameters are classified from those with the largest impact in descending order from x-axis, colour, size and shape of marker. Classification based on regression analysis, only feasible scenarios were included in this analysis.

Figure 15 show that diets are the most important factor for the reduction of GHG emissions from enteric fermentation and manure management. The EAT-Lancet diet version with a higher share of beef and dairy products (EAT-Lancet-Rumi) has higher emissions than the EAT-Lancet diet version as defined in Willett et al. (2019), with a higher share of animal products from pigs and poultry. In terms of livestock diets, BAU feeding ratios score lowest for livestock-related GHG emissions, and grass-based diets as well as Co-opt_Cropland livestock diets score higher due to increase methane emission from enteric fermentation/decreased feed

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conversion efficiencies, albeit with distinct patterns across human diet scenarios. The high-digester manure management and the grassland sparing variants also have a positive, albeit comparably small, effect for decreasing GHG emissions from animal production systems in the EU in 2050. The slight reduction of GHG emissions in the land sparing variants is due to the concentration of ruminant livestock on highly productive grasslands, which – in overall terms – provides more high-quality grass than if ruminant livestock is also fed from low-quality grass resources. These results underline the necessity of integrated approaches to release synergies of agro-ecological livestock management practices, i.e. if combined with dietary changes and a total reduction of the EU's livestock system, individual practices are possible without facing trade-offs with necessary emission reductions.

4.4.5. Relative nitrogen deficit in agroecological variants and emissions from N-fertilizer production

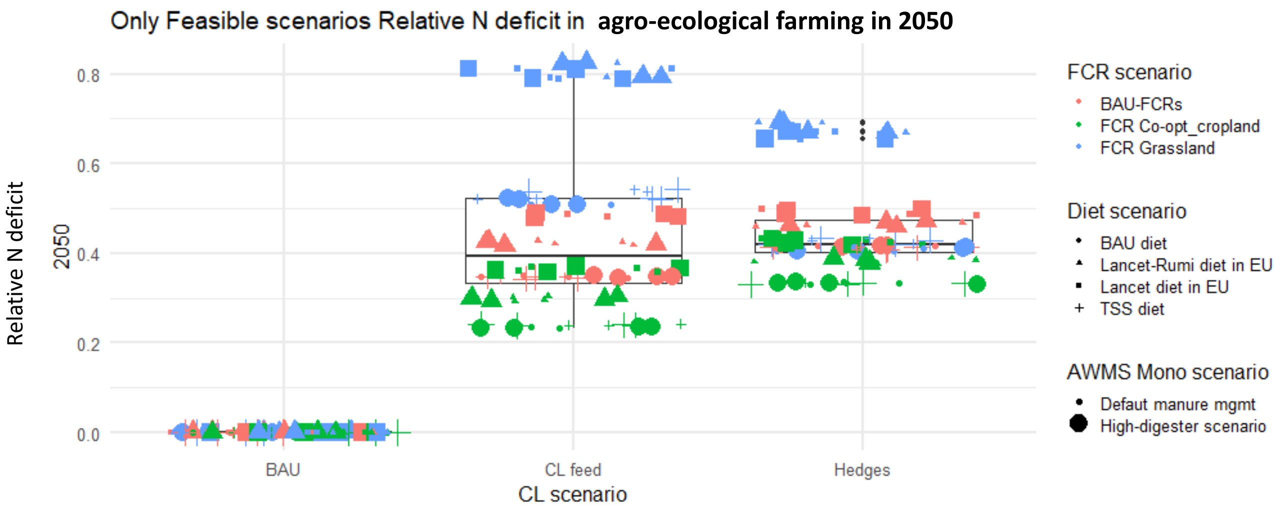

Figure 16: Boxplots for the relative nitrogen deficit in agro-ecological farming in the European Union in the year 2050 calculated as rel_N_deficit = (N_demand - Max_N_supply_organic)/Max_N_supply_organic. The impact of each parameter is assessed and parameters are classified from those with the largest impact in descending order from x-axis, colour, shape and size of marker. Classification based on regression analysis, only feasible scenarios were included in this analysis.

Although agro-ecological farming rests on practices such as increasing legumes in crop rotations or undersowing of legumes (e.g. clover) in annual crops to supply nitrogen and the optimizing of nutrient supply in agro-ecological farming does not necessarily need to prohibit the use of synthetic fertilizers, as is the case in regulated organic farming. Figure 16 displays eventual nitrogen gaps for each scenario before any addition of synthetic nitrogen, shown as deficit relative to the max. supply from organic fertilizers. These gaps are driven by 1) the amount of available livestock manure that can be spread on agricultural land, driven by livestock systems and livestock diets, 2) crop species, and 3) crop yields. Since we do not implement agro-ecological practices in the BAU CL scenario, no relative nitrogen deficits occur as any potential gap after accounting for nitrogen from manure is supplied via synthetic fertilisers. In the two agro-ecological cropland variants, CL feed and Hedges, relative deficits >0.2 occur in the European Union in total. The highest relative deficits are clearly related to the FCR variant Grassland, where ruminant livestock is exclusively fed from grassland, and a higher share of animals are kept on pastures and their manure cannot be used to fertilize crops. The higher nitrogen deficit against the CL variant Hedges is based on the assumption that we do not increase the share of legumes for cereals production (as we do for all other crops which cannot fix nitrogen),

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but only provide nitrogen through undersowing which provides slightly less nitrogen per hectare than if legumes are added to cereals crop rotations in every fourth year. Here we see a clear trade-off between area reducing practices from undersowing and additional nitrogen demand trough insufficient nitrogen provision, albeit this trade-off can be mitigated through improved nitrogen provision from legumes as undersown crops and other targeted measures.

We additionally again see that diets play an important role in agro-ecological agri-food systems, since they drive the demand for animal products and thus co-determine (together with animal waste management systems) the amount of manure that is available for crops. Since livestock is converting nitrogen from feed into both, animal products and manure, only the share that is converted into manure and which can be collected can then be spread on agricultural land. Thus, only livestock diets with higher shares of legumes increase the available nitrogen for total nutrient flows, and consequently leading to lower nitrogen deficits in the CL feed cropland variant. This combination leads in scenarios with grassland-FCR and FAO BAU diets to smaller relative N-deficits than in scenarios with EAT-Lancet and EAT-Lancet-Rumi diets with BAU FCRs in the Hedges CL scenario, distinct to the pattern in the CL feed scenario where nitrogen deficits are slightly lower. Again, this underlines the necessity of an integrated approach to agro-ecology, considering not only individual, but dependent and interrelated parameters.

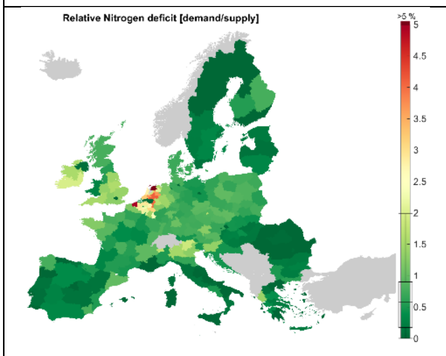
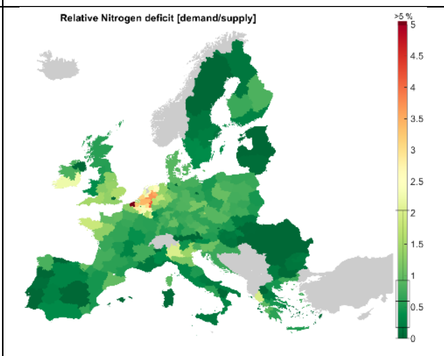
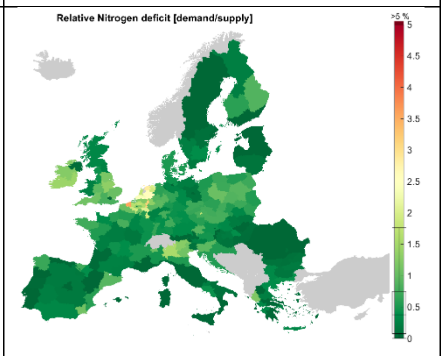
a)	b)	c)
		
CL: CL feed Diet: EAT- Lancet diet FCR: BAU GI_{max}: Reduced AWMS: High digester GL: Land sharing	CL: Hedges Diet: EAT-Lancet-Rumi diet FCR: Grassland GI_{max}: Reduced AWMS: High digester GL: Land sharing	CL: CL feed Diet: EAT-Lancet diet FCR: Co-opt_cropland GI_{max}: Reduced AWMS: High digester GL: Land sharing

Figure 17: Maps showing the regional (NUTS2) patterns of the relative nitrogen deficit in three agro-ecological cropland scenarios in the European Union in the year 2050, calculated as rel_N_deficit = (N_demand - Max_N_supply_organic)/Max_N_supply_organic for three selected agro-ecological scenarios. Parameters and selected variants listed below each map, grey marked parameters are not relevant for the assessed indicator.

Figure 17 displays maps for the relative nitrogen deficit for three selected agro-ecological cropland scenarios in the year 2050. The scenarios are distinct for cropland, human diet and FCR variants. In these three scenarios, relative deficits in scenarios a) and b) range at approximately 0,5 relative deficits in the whole European Union, whereas scenario c) shows a smaller relative deficit of approximately 0,4. Nevertheless, all three scenarios represent a large range of relative nitrogen deficits across EU NUTS2 regions, from zero deficit found across

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all regions except for Central Europe, where also the highest relative deficits occur. In the Netherlands and Belgium, deficits > 3 occur in scenarios a) and b), whereas in a scenario with increasing legumes production on cropland (undersowing in cereals and a full switch to fodder legumes, i.e. temporary grasslands) also the highest peaking regions reduce the relative nitrogen deficit. In these regions, the comparably high deficits are also driven by the highest cropland yields in the European Union, thus, a stronger reduction of yields would also benefit synthetic nitrogen requirements.

Overall, these three maps clearly show that the implementation of agro-ecological practices on cropland needs regionally-adapted approaches which consider the specific characteristics of each region into account, but it also shows that across most regions in Europe such practices can be widely adopted without running into large nitrogen deficits that need to be compensated with synthetic nitrogen fertilizers. Thus, the question arises what these gaps mean for fertilizer-related emissions?

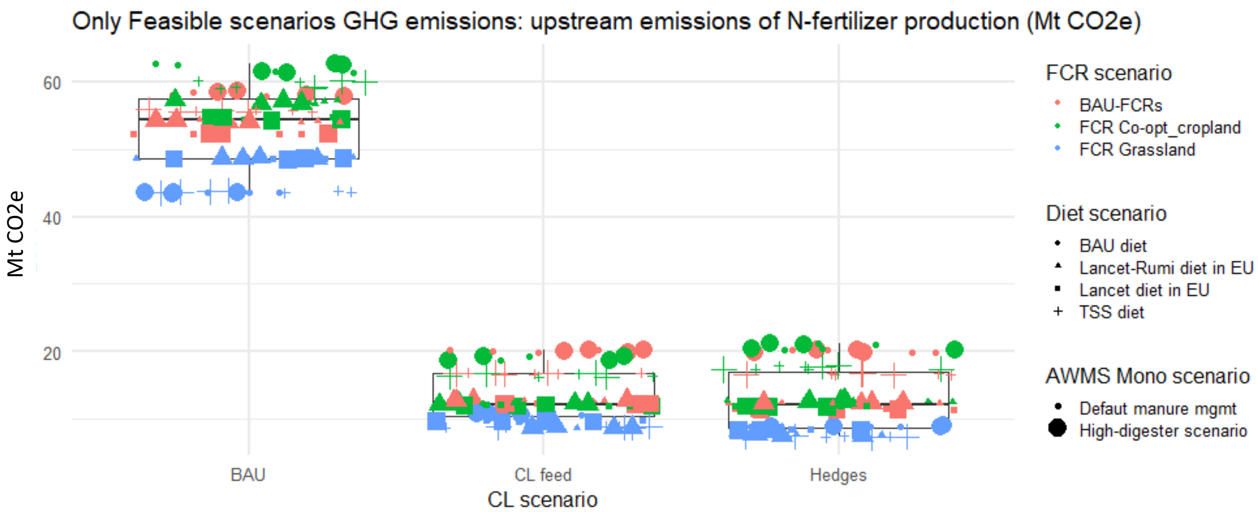

Figure 18: Boxplots for upstream emissions of Nitrogen-fertilizer which is applied to croplands in the European Union in the year 2050 in in Mt CO2e. Parameters are classified as in Figure 16 to facilitate comparability between these two figures.

While Figure 16 might lead to the conclusion that the comparably large relative nitrogen deficits in variants with grassland-based FCRs is also leading to a higher demand for synthetic fertilizer and thus leading to high emissions from fertilizer production, Figure 18 clearly shows that this is not the case. Both agro-ecological cropland variants (CL feed and Hedges) have considerably lower demand for synthetic nitrogen than the BAU cropland variant. Additionally, the FCR variants also reveal that the grassland-based FCR variant has indeed the lowest demand for synthetic fertilizer, and that variants with a BAU diet have the highest demand for chemical nitrogen fertilizer, causing emissions from fertilizer production of approximately 20 Mt CO_2e in 2050.

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4.4.6. **Grass supply from grassland and grazing intensity**

Biomass supply from grasslands plays a central role in ruminant livestock diets. In the year 2012, 133 Mt DM/yr of grass were either grazed or mowed and fed to livestock in the European Union. We applied two alternative FCR variants, one where ruminant livestock is exclusively fed from grasslands (FCR Grassland), and an intermediate version where ruminant livestock is only fed from secondary cropland products and fodder crops (Co-op_Cropland). Heatmaps for total grass supply and demand from ruminant livestock in the EU in 2050 for all land feasible scenarios are shown in Figure 19.

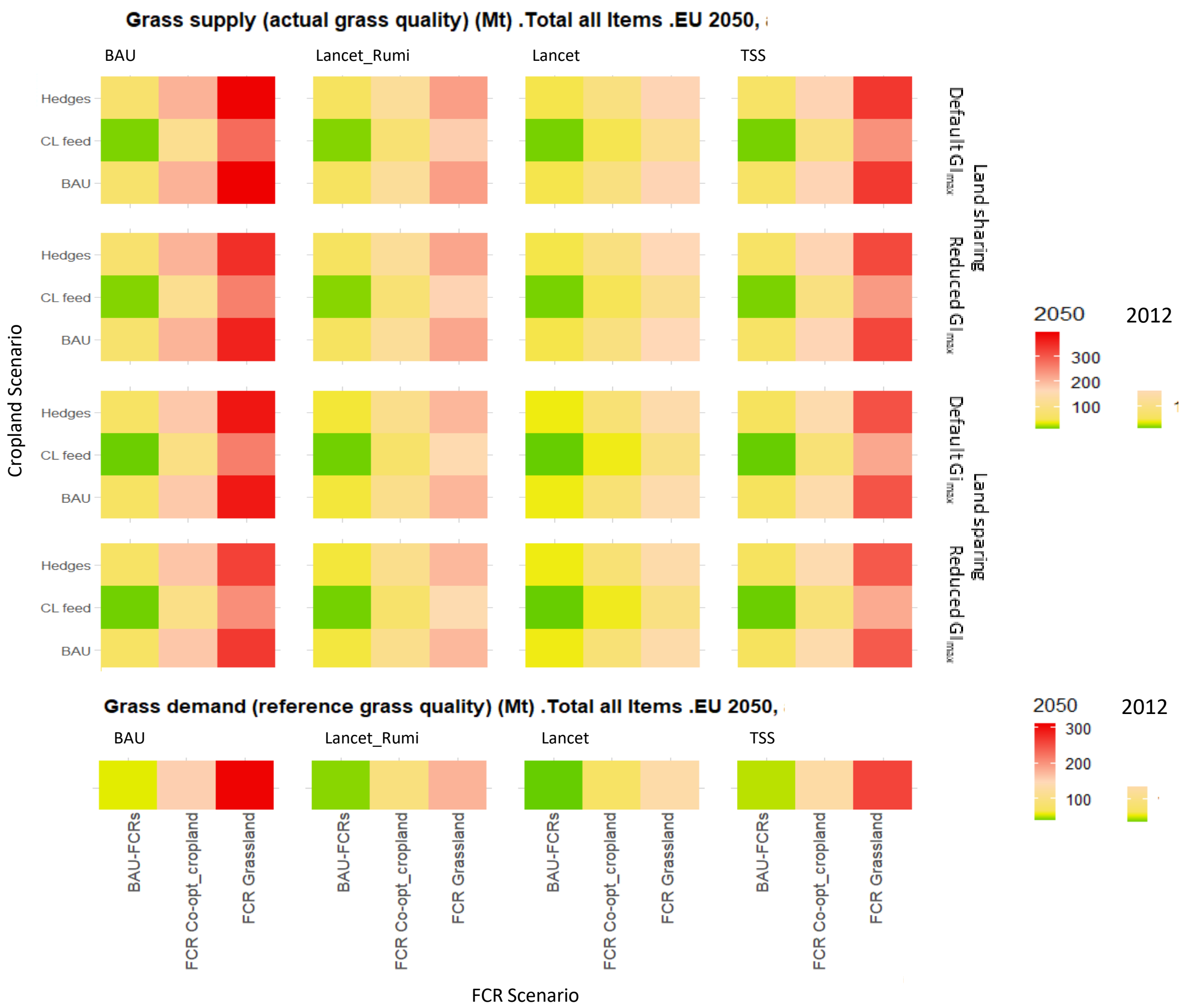

Figure 19: Heatmap for total grass supply and total grass demand in the European Union in 2050 in Mt DM/yr. Grass supply is shown in actual grass quality, i.e. depicting the variations in the nutritional value of three grassland quality classes, whereas total grass demand is shown in reference quality. It is standardized on the highest quality grassland class (i.e. managed grassland) according to the metabolizable energy converted into feed units of three different grassland classes (Van Zanten et al., 2019). Grassland demand is only shown for scenario variants of human and livestock dies, i.e. other variants do not influence grass demand. Only grassland-feasible scenarios are shown, AWMS variants are not shown for total grass supply as it does not affect grass supply or demand.

Total grass supply from grasslands in the European Union in the year 2050 is driven by domestic demand from ruminant livestock at the NUTS-level, since we do not allow for trade of grass biomass. Thus, grassland supply equals grass demand per NUTS region, and only in regions where demand > total potential output (i.e.

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grassland in ha * NPPact * GImax), grass supply is at maximum output, which is - among others - depending on the default or reduced GImax variant. The highest supply, far beyond the necessary supply in 2012 of 165 Mt DM/yr is clearly found in FCR grassland variants when combined with high demand for ruminant products (FAO BAU and FAO TSS, and to a lesser extent EAT-Lancet-Rumi). Additionally, in Co-opt_Cropland variants the grass demand is higher than in the base year 2012, except for the cropland variant CL feed, where Alfalfa in crop rotations and clover from undersowing in cereals considerably reduces grassland biomass demand for ruminants. This pattern can be seen across all human dietary scenarios, and additionally, the CL feed shows the smallest demand for grassland biomass, since Alfalfa and undersown leys replace grassland biomass. Even if alfalfa requires primary cropland to grow, this is clearly a positive impact of this agro-ecological cropland variant.

Total grass demand in the EU was 165 Mt DM/yr in the base year, when ruminant diets consisted of a mixture of crops originating from cropland (feed concentrates including imported soy, fodder crops and by-products from food processing) and grassland feed from pastures and meadows. In the year 2050, grassland demand is driven by two parameters. Human diets that determine the level of ruminant production, and the feed conversion ratios which define the ratio between livestock feed and the desired output at the level of feed (input of grass, fodder crops etc.) and the animal product (output of dairy and meat). Grass biomass demand is ranging from 40 – 50 Mt DM/yr in variants with low demand for animal products (EAT-Lancet and EAT-Lancet-Rumi human diet with BAU FCR) to medium levels that are driven either by low human demand for animal products or FCR variants that contain BAU or similar to BAU ratios of cropland feed to levels which are far beyond current grass demand. The latter scenarios are either driven by grassland-based FCRs, i.e. feeding only grass from grasslands to ruminants, or high demand for ruminant products in human diets (FAO BAU and TSS variants) and are leading to a maximum of a threefold increase (480 Mt DM/yr) in grassland feed demand compared to the demand in 2012. These scenarios considerably reduce feed demand from cropland, but certainly at the cost of a massive rise in grazing intensities on grasslands.

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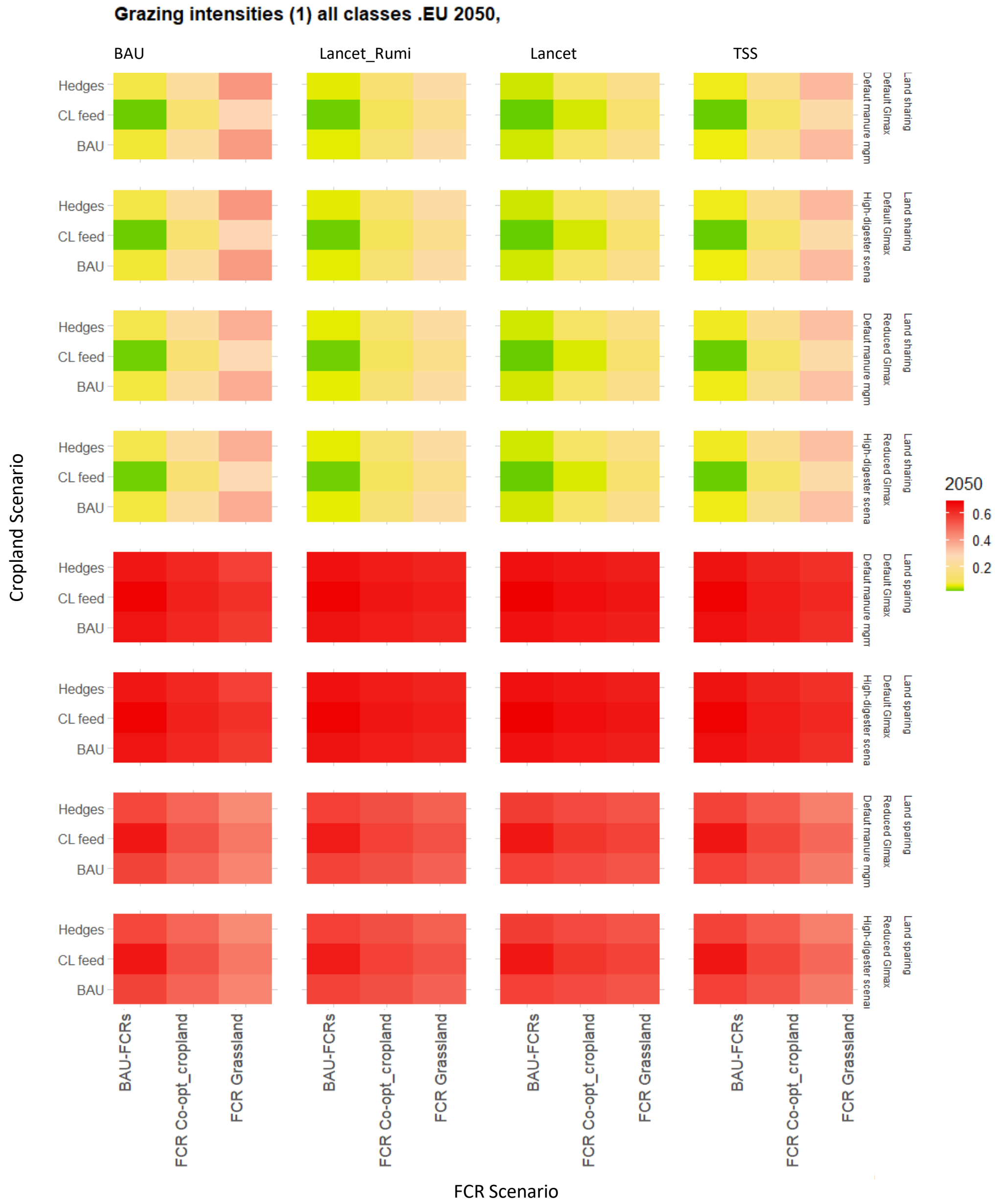

Figure 20: Heatmap for grazing intensities in the European Union in 2050, shown as % of grazed biomass in $NPP_{act.}$. Only feasible scenarios shown.

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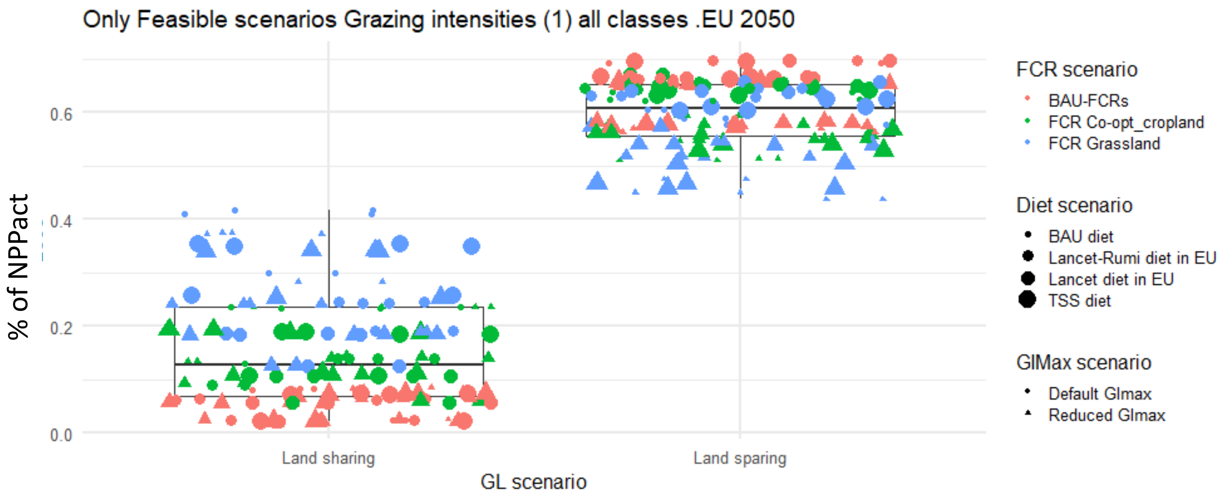


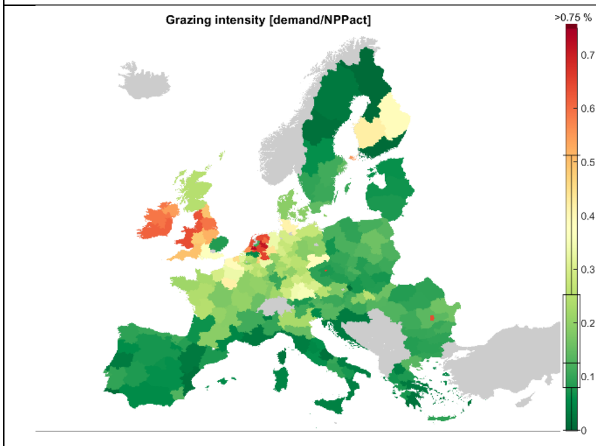
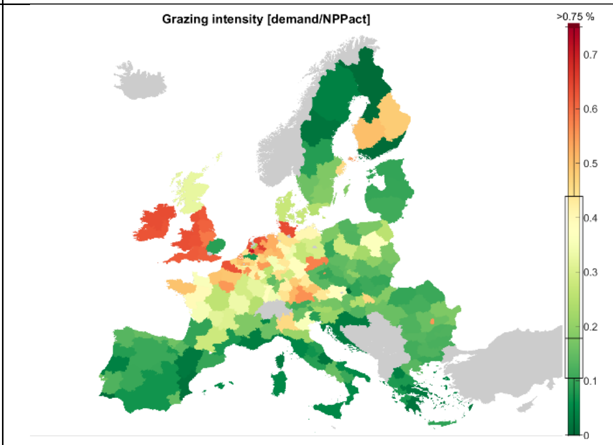
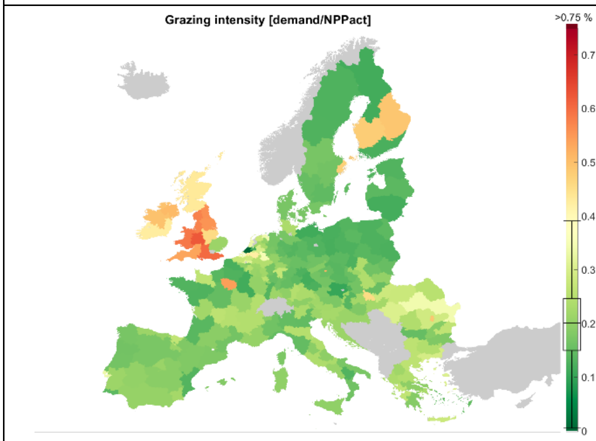
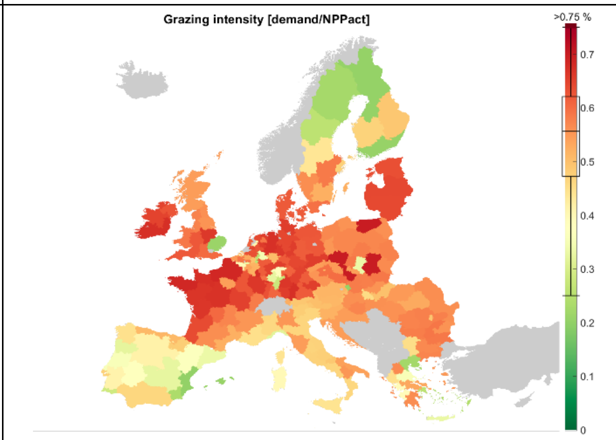
Figure 21: Boxplots for grazing intensities in the European Union in the year 2050 in % (demand/NPP_{act}). The impact of each parameter is assessed and parameters are classified from those with the largest impact in descending order from x-axis, colour, shape and size of marker. Classification based on regression analysis, only feasible scenarios were included in this analysis.

Grazing intensities are measured as the actually grazed biomass in relation to the net primary production (NPP_{act}) in the same year i.e. grazing intensity is an indicator of biomass harvest on grasslands. Only a certain share of the total biomass that grows on grassland can be grazed, and stalk biomass, losses due to trampling from livestock, or undigestible plants cannot be harvested and remain on grasslands. The actual average grazing intensity across the European Union in the base year was 18% of NPP_{act}, which means that 18% of the biomass that is available on grassland was either grazed or mowed, with a considerable range between low and high intensity regions. In the year 2050, we clearly see that the most decisive differences in grazing intensities are driven by the grassland utilization variant. In the land sharing variant, grazing intensities are only increased to supply the necessary demand across all grassland classes, and no grassland that prevailed in the base year is allowed to be set free for vegetation regrowth. This extreme assumption, i.e. that all grassland is grazed and mowed at intensities needed to meet demand, shows that many scenarios in 2050 do not necessarily increase 2012 grazing intensities. These are mostly scenarios with the BAU FCR variant, in which substantial amounts of ruminant feed is also supplied from croplands, albeit also many scenarios with the Co-opt_Cropland FCR variant stay below the intensity in the base year as ruminant feed is also supplied from by-products. Grass-based FCR variants increase the average grazing intensity in the EU compared to 2012 through higher demand for grass biomass. In scenarios where these ruminant diets are combined with agro-ecological human diets, the highest grazing intensities in the EU will range well below 40% of NPP_{act}. However, it is important to note that in none of these scenarios the defined GI_{max} boundaries, even in scenarios with a reduced GI_{max} in HNV areas, are exceeded. Thus, a full switch to grassland-based ruminant diets is feasible in the EU in 2050 without reaching ecological thresholds in grasslands. Again, this is only possible with reduced ruminant products in diets and a renunciation of current ruminant production systems and a strong re-coupling of ruminant systems to grassland potentials within the EU, and a shift of ruminant production from Western and Central Europe to South, Eastern and Northern Europe.

The land sparing variant is clearly driven by the aim to reduce the climate-impact of agricultural systems. Increasing grassland utilization, measured in terms of biomass harvest from the same grassland area, in highly productive grasslands and allowing vegetation regrowth in less productive grassland systems is gaining increasing attention from scientists and policy makers. We here ask the question whether land sparing can be

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773901.

combined with agro-ecological farming practices in the EU in 2050 and find that all scenario variants assuming a potential-based and land sparing grassland utilization are feasible, and that in none of these scenarios the maximum grazing intensity is exceeded. In all scenarios, nevertheless, grazing intensities are increasing beyond 40% of NPPact, which is higher than in all land sharing variants. Interestingly, grassland-based FCR variants in combination with reduced GImax in HNV areas show the lowest grazing intensities, lower than in the other FCR variants. This is due to the reasoning in BioBaM_GHG_EU that also grasslands of lower quality with lower ecological thresholds are utilized, reducing the overall grazing intensities in comparison to the Co-opt_Cropland FCR variant, where these grasslands are utilized to a lesser extent and thus more vegetation regrowth can take place. The highest total grazing intensities are found in the BAU FCR variants where primarily high-quality grasslands with higher GImax are used, but on less actually grazed land (see Figure 7).

a)	b)
	
2012	CL: BAU Diet: BAU diet FCR: BAU GI_{max}: Default **GL: Fixed distribution** AWMS: Default
c)	d)
	
CL: Hedges Diet: Lancet-rumi diet FCR: Grassland GI_{max}: Reduced **GL: Land sharing** AWMS: High digester	CL: Hedges Diet: Lancet-rumi diet FCR: Grassland GI_{max}: Reduced **GL: Land sparing** AWMS: High digester
e)	f)

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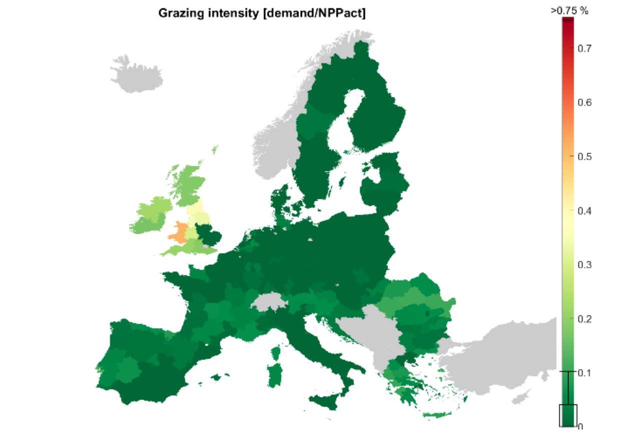

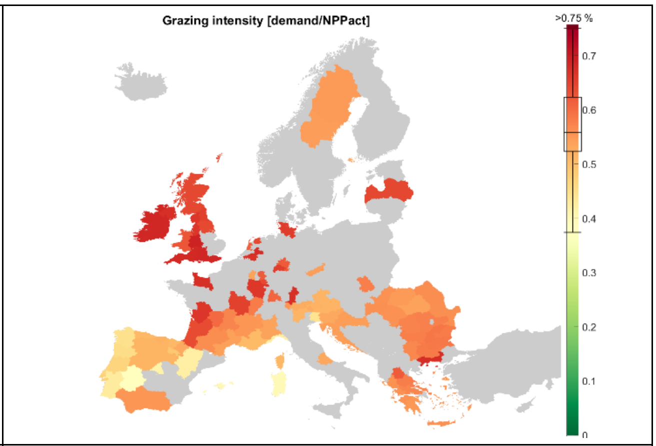

CL: CL feed Diet: Lancet diet FCR: Co-opt_Cropland GI_{max}: Reduced **GL: Land sharing** AWMS: High digester	CL: CL feed Diet: Lancet diet FCR: Co-opt_Cropland GI_{max}: Reduced **GL: Land sparing** AWMS: High digester

Figure 22: Six maps showing the regional (NUTS2) patterns of grazing intensities in 2012 and for one conventional and four agro-ecological farming systems in the European Union in the year 2050 in % (grazing demand/NPP_{act} on grassland). The maps contain the average grazing intensity across 3 different grazing classes, which also have different grazing intensity thresholds, and where the spatial distribution of grazing classes also influence average GI. Parameters and selected variants listed below each map, grey marked parameters are not relevant for the assessed indicator. Please note that the scenario in b is grazing infeasible. Grey regions in maps either indicate no data (Switzerland and Norway), or if grazing intensity is zero (i.e. no ruminant livestock production in this region). This can happen due to full conversion of grazing class 1 into cropland, or because the other classes are not required for grass production and thus left over for vegetation regrowth.

Figure 22a shows the heterogeneous spatial patterns of grazing intensity in 2012 and for a number of options in 2050 across regions. We here compare six selected different scenarios out of total n=432 scenarios, whereas we differentiate between a land sharing and a land sparing variant, which have the largest impact on grazing intensities. In 2012, in the Benelux regions and most regions on the British Islands, grazing intensities were considerably higher than the EU average, at rates closely approximating ecological thresholds, leaving very little room for further intensification without severely compromising ecological processes. In Central Europe, grazing intensities were in most regions between 30% and 40%, while regions in Southern, Eastern and Northern Europe had relatively low grazing intensities, showing that extensive grassland systems prevail in these regions. Figure 22c and Figure 22d show spatial patterns of grazing intensities in two selected scenarios with agro-ecological innovations targeting linking ruminant systems back to grasslands. Under a land sharing grassland variant, average grazing intensities slightly increase, but grazing intensities in highly intensive regions in 2012 decrease, with the highest GI ranging at 40% of NPPact. This pattern is clearly distinct in the land sparing variant, which aims at utilizing highest productive grasslands as intensively as possible without risking overgrazing. There, the average GI increases to 55% of NPPact, and in regions in Central Europe and the British Islands, where all grassland consists of class 1, i.e. high-quality grasslands, to the maximum of 70% of NPPact. Nevertheless, less overall grassland is needed in these scenarios, and consequently freed up grassland areas are utilized to provide a carbon sink through vegetation regrowth. In a conventional scenario, i.e. integrating all conventional parameter variants (Figure 22b), grazing intensities increase across the whole EU in comparison to 2012 due to high domestic demand from conventional human diets and export production of ruminant products, with regions scoring at GI > 70% of NPPact, making these regions grazing infeasible, albeit in many regions grazing intensities remain below critical ecological thresholds.

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Scenarios which integrate the CL feed cropland variant as well as livestock systems that are exclusively fed with by-products from croplands are shown in Figure 22e and Figure 22f. In a land sharing cropland variant, grazing intensities considerably decrease across the EU, with an average GI below 10% of NPPact. Only in the British Islands, GI is at approximately 30% of NPPact, whereas in all other regions a massive extensification is possible while providing enough feed for the required domestic and export-destined production volumes of ruminant products. In this scenario, legumes that are produced on cropland provide enough feed to allow for such a decrease. In the land sparing variant, grazing intensities increase, albeit at a lesser extent as in Figure 22c and Figure 22d. Additionally, in many regions cropland grass output is enough to feed ruminants and no grass biomass from grasslands is needed. Overall, this scenario shows that innovative ruminant feeding approaches are able to provide enormous areas for carbon mitigation policies.

The patterns of grazing intensities in the three different FCR variants show opposite patterns in the land sparing and in the land sharing variants. Grazing intensity, hence, is strongly influenced by, firstly, decisions whether intensification on highly productive grasslands should be pursued further, albeit at remaining within ecological thresholds, or whether all grasslands should be utilized equally which allows for considerable grazing intensity reductions in intensive grasslands. And secondly, feeding ratios for ruminant livestock do have different impacts based on how grassland is utilized in the future in the EU. In conclusion, the results show that grazing intensities are driven by several factors, including factors that lie beyond grasslands (share of cropland feed in ruminant livestock's diets) and which are strongly driving the balance between grassland extent, biomass output and spatial allocation of the utilization of grasslands. The land sparing variant is clearly beneficial for climate change mitigation, while the reduced grazing intensities in the land sharing variant tend to be beneficial for a range of other regulating and cultural ecosystem services.

4.4.7. Clover from undersowing in the CL feed scenario

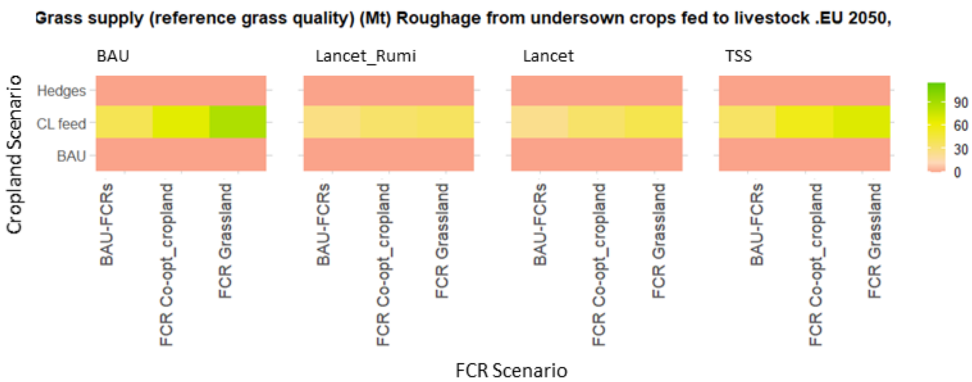

Figure 23: Heatmap for grass supply from undersowing in cereals in the European Union in 2050 in Mt DM/yr. Undersowing in cereals is one innovation on croplands in the CL feed scenario.

We have implemented undersowing of all cereals production in the EU in 2050 with clover in the CL feed scenario, where part of the undersown crop remains on field for soil enhancement, and one part is used to feed ruminant livestock. This is an assumption based on information from scientific literature, for example (Anglade et al., 2015; Baddeley et al., 2014; Reckling et al., 2014; Wortmann et al., 2000; Zemann, 2012), since undersown crops do not work easily in all regions of the EU due to pedoclimatic conditions. Nevertheless, we used a conservative assumption of yields and nitrogen provisioning. Still, the potential biomass volumes that are produced in 2050 with this assumption are considerable. The highest production volumes of more than 70

Mt DM/yr were found for Grassland FCR scenarios in combination with FAO BAU and FAO TSS diet, and slightly lower production volumes in the same diet variants if combined with the Co-opt_Cropland FCR variant, where less cereals are required to feed farm animals due to the assumption that only by-products from food manufacturing are fed to livestock. Nevertheless, also in both EAT-Lancet diet variants, more than 25 Mt DM/yr of clover from cropland can be fed to ruminant livestock. These considerable production volumes of clover then consequently decrease the grassland demand for ruminant livestock. The main strength of ruminants is to convert grass biomass to edible products, but allowing grazing intensities to decrease while enhancing soil structure and nitrogen provision in croplands using undersown crops is clearly a synergistic effect of an agro-ecological innovation that brings systemic benefits to agricultural land in 2050.

4.4.8. **Biodiversity pressures**

Figure 24: Heatmap for total biomass appropriation (TBA) in the European Union in 2050 in % of BAU 2012. TBA is calculated as harvested biomass from cropland and grassland (HANPP$_{harv}$) / potential Net Primary Production (NPP$_{pot}$) on the same, i.e. the utilized agricultural area. Only grassland-feasible scenarios are shown, AWMS variants are not relevant for TBA and thus not shown in this heatmap.

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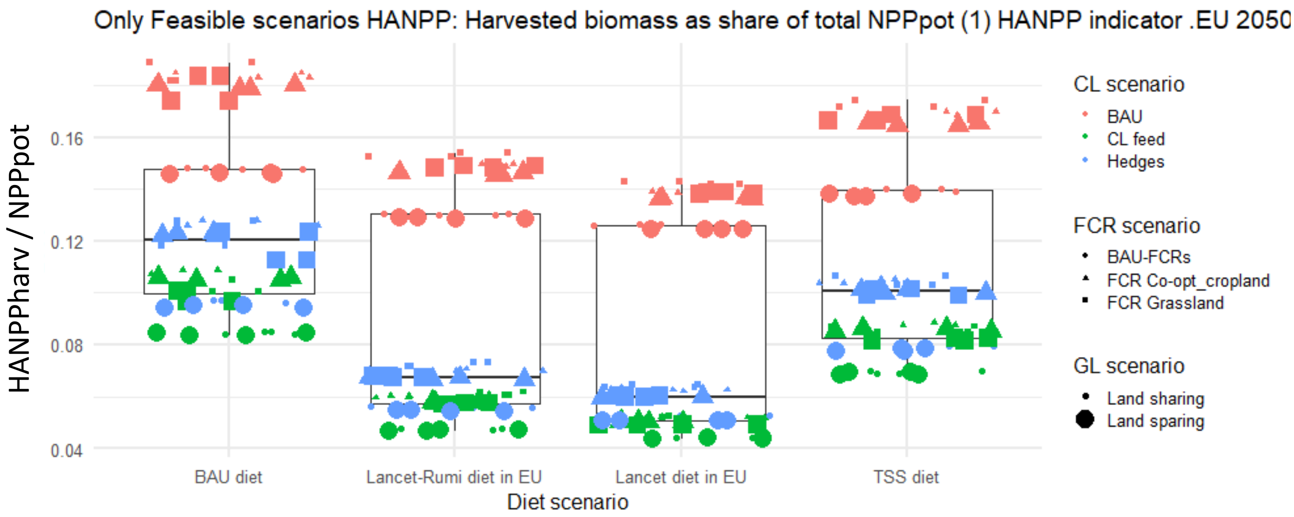
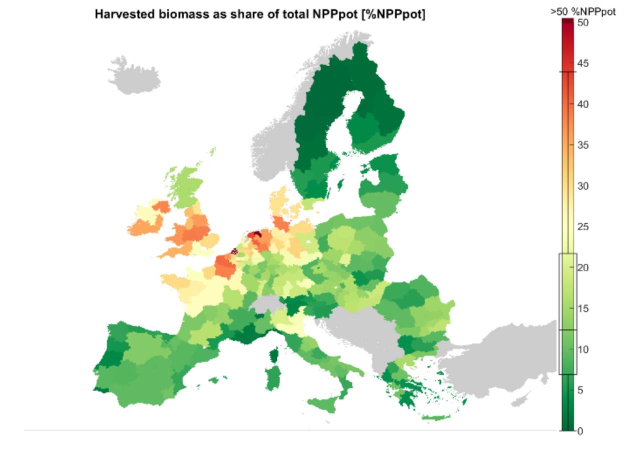
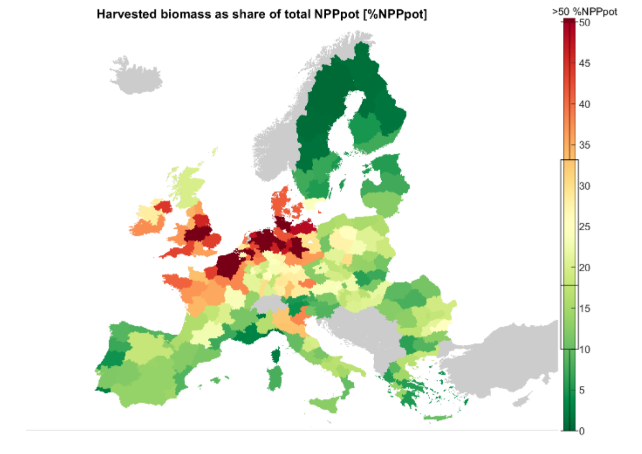
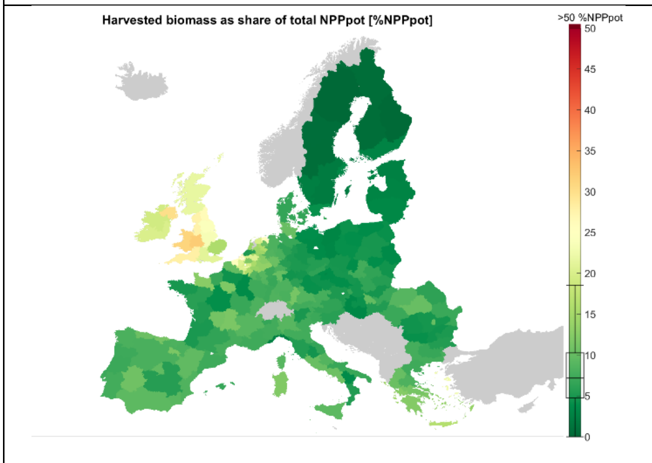
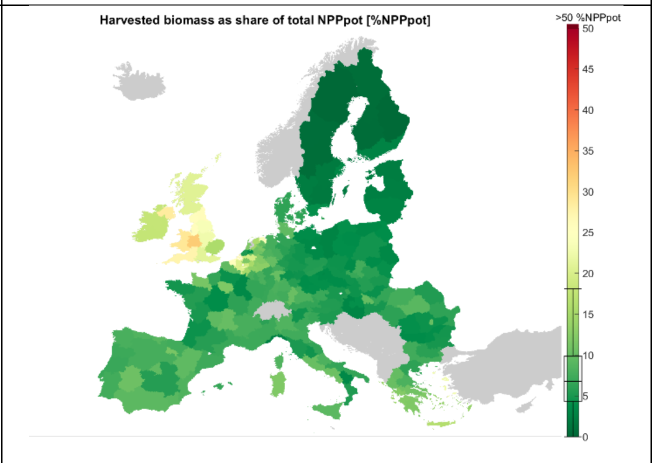


Figure 25: Boxplots for total biomass appropriation (TBA) in the European Union in the year 2050 in % ($HANPP_{harv}/NPP_{pot}$). The impact of each parameter is assessed and parameters are classified from those with the largest impact in descending order from x-axis, colour, shape and size of marker. Classification based on regression analysis, only feasible scenarios were included in this analysis.

The highly aggregated indicator Total Biomass Appropriation (TBA), i.e. the ratio of production potentials and harvested biomass, is a proxy indicator for the alteration of biodiversity pressures on agricultural land. This indicator is based on the species-energy hypothesis (Haberl et al., 2007b, 2005, 2004; Pelletier and Tyedmers, 2010) which holds that species richness is larger the more energy is available in the system. However, we do not differentiate the types of biomass that are harvested and thus different effects are not considered in this indicator. For example, grass biomass removal has different impacts on biodiversity than if the same amount of biomass is removed from cropland. Nevertheless, and at an aggregated level, changes in energy flows are a solid proxy for alterations in biodiversity pressures in agro-ecosystems.

In the base year 2012, total biomass appropriation at the EU level was 13% of NPPpot, and scenarios for 2050 show a large range of changes in 2050. All agro-ecological cropland variants, independent from human diets, livestock diets and grassland utilization show a reduction of TBA in 2050 in the EU, due to lower yields. Additionally, diets also drive TBA, with the lowest pressures in both EAT-Lancet diet variants, due to lower demand of animal product and hence feed. However, the EAT-Lancet-Rumi diet shows slightly higher TBA ratios than the EAT-Lancet diet, since ruminant livestock systems shift livestock feed harvest away from cropland to grazing land which means that more low-quality feed (grass) is needed to produce the same amount of meat. Additionally, shifts from primary crops in livestock diets towards by-products and grazed biomass also lead to higher demand in primary feed biomass, due to lower nutritional value in these feeds.

In all BAU cropland variants, TBA at the EU level remains at the same level or increases beyond the current level of 13% TBA. BAU cropland variants in combination with agro-ecological FCR variants increase TBA, with the highest ratios of a 50% increase of TBA in scenarios with conventional (i.e. BAU) human diets and cropland variants, in combination with agro-ecological FCR variants. This is a result of high yield in cropping in BAU cropland variants and use of more grass in ruminants diets in agro-ecological feeding regimes, requiring more biomass. Grasslands variants (land sharing vs. land sparing, and reduced GImax) do only have marginal effects on total TBA, as the same amount of biomass is appropriated in these variants but more intensively in the case of land sparing, hence using less land, and more extensively in land sharing, using more land. Overall, this result again confirms that a systemic perspective that goes beyond production-side measures alone is central for a smooth transition towards agro-ecological agri-food systems in the EU, and to realize environmental benefits through the reduction of the total biomass appropriation. Nevertheless, careful and integrated implementation of agro-ecological approaches are fundamental to avoid trade-offs (e.g. potential income threats to small farmers, if current price and subsidy policies are not adapted) and a transition towards agro-ecological farming systems needs to be integrated into a larger transition towards agro-ecological food systems.

a)	b)
	
BAU 2012	CL: BAU Diet: BAU diet FCR: BAU GI_{max}: Default **GL: Fixed distribution** AWMS: Default
c)	d)
	
CL: Hedges Diet: Lancet-rumi diet FCR: Grassland GI_{max}: Reduced **GL: Land sharing** AWMS: High digester	CL: Hedges Diet: Lancet-rumi diet FCR: Grassland GI_{max}: Reduced **GL: Land sparing** AWMS: High digester
e)	f)

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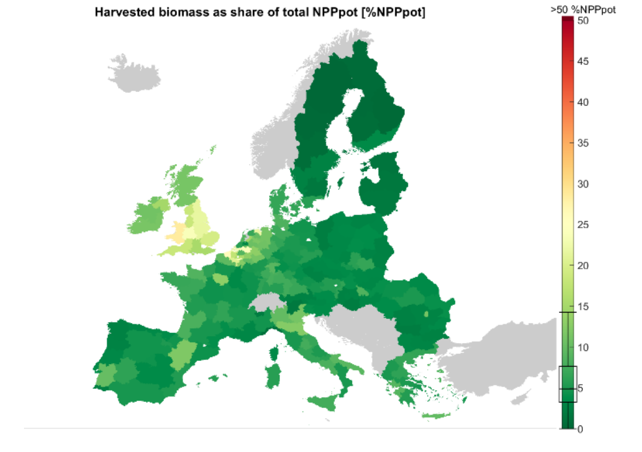 	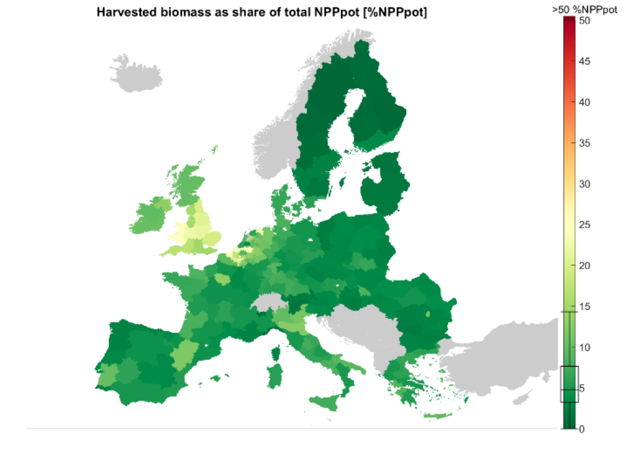
CL: CL feed Diet: Lancet diet FCR: Co-opt_Cropland GI_{max}: Reduced **GL: Land sharing** AWMS: High digester	CL: CL feed Diet: Lancet diet FCR: Co-opt_Cropland GI_{max}: Reduced **GL: Land sparing** AWMS: High digester

Figure 26: Six maps showing the regional (NUTS2) patterns of TBA in 2012 for one conventional and four agro-ecological farming scenarios in the European Union in % ($HANPP_{harv}/NPP_{pot}$). Parameters and selected variants listed below each map, grey marked parameters are not relevant for the assessed indicator.

The analysis of the spatial effects of the innovations on the total agricultural biomass appropriation (TBA; the ratio of total biomass harvest to total potential NPPpot on agricultural areas, including freed cropland) reveals a key feature. This indicator, that is closely related to the Human Appropriation of Net Primary Production (HANPP), changes the patterns of NUTS regions in the EU drastically. The level of TBA in the base year is relatively low and ranges between 10% and 22% at the level of European regions, albeit in the Benelux countries, Northern France and the British Islands reaches levels of nearly 50%. In an agro-ecological production-side scenario combined with FAO BAU human diets, TBA is increasing in most regions, albeit in some regions, in particular of intensive ruminant production in Central Europe, TBA decreases only slightly due to the extensification of livestock diets with forage replacing concentrate feeds. In consequence, and in general terms, TBA is more evenly distributed among Europe, but some extreme values in regions of the Central-North (i.e. the Benelux countries) prevail. The reduction of HANPP peaks can point to a positive biodiversity effect of the agro-ecological scenarios with a potential distribution of livestock, as considerable biodiversity pressures can be expected to be associated with HANPP extremes (Haberl et al., 2007b).

The six maps in Figure 26 show TBA patterns across the European Union in the base year 2012 for one conventional and four agro-ecological parameter variants in the year 2050. TBA, i.e. harvested biomass as share of NPPpot, in the base year were highest in Central Europe and the British Islands, reaching values in the range of 30% to 45% of TBA In a conventional scenario, these values increase across many regions in the EU, and reach even values of 50% TBA. On the contrary, all agro-ecological scenarios (Figure 26c - Figure 26f) clearly show that less biomass is harvested and that thus TBA decreases below 10%, with an even stronger reduction in variants where ruminant livestock is increasingly fed from cropland, thus allowing for stronger reduction in grasslands than in the variants in Figure 26c and Figure 26d. Figure 26e and Figure 26f compare TBA in a land sharing and a land sparing variant. In the land sharing variant, the biomass is harvested from larger areas, while in the land sparing varnt, biomass is harvested from less areas. Thus, on the areas harvested, TBA is relatively high, but since large areas are not utilized in the land sparing variant, the average

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TBA ratio across the whole NUTS2 regions becomes lower. Here, clearly distinct sub-regional patterns will arise, which calls for subsequent assessments at a higher spatial resolution.

4.4.9. Net-trade between the European Union and the Rest of the World

BioBaM_GHG_EU is integrated in the global BioBaM_GHG biophysical model where we have implemented a range of agro-ecological innovation bundles in the EU that are distinct across all 432 scenarios, whereas we assume that the Rest of the World develops according FAO BAU assumptions across all scenarios. Thus, we are able to show the impacts of distinct developments between the European Union and the global context in terms of changes of net-trade flows.

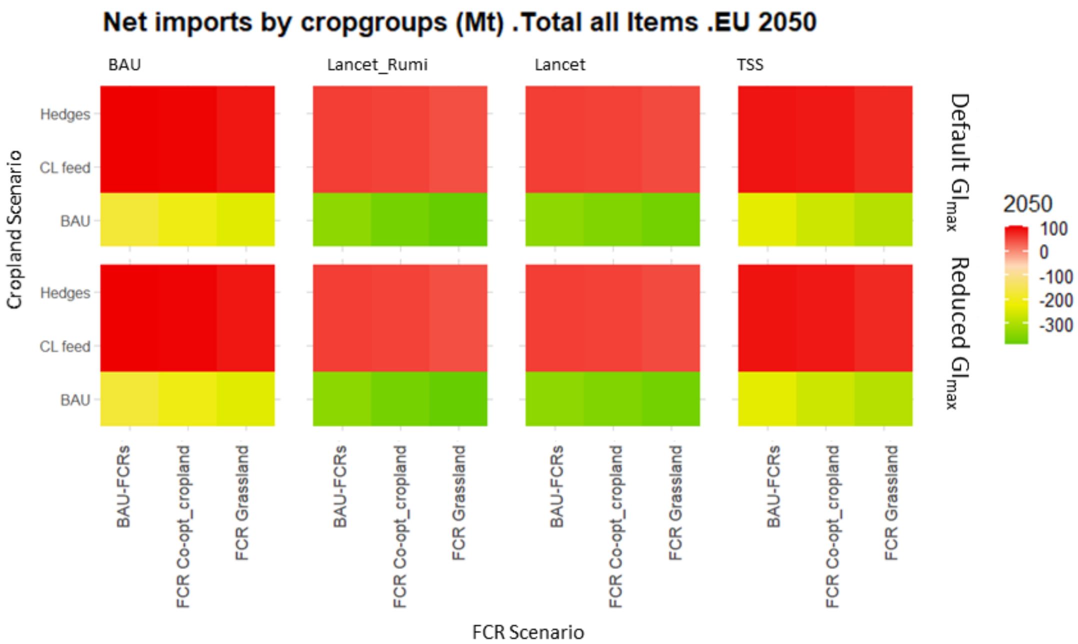

Figure 27: Heatmap for total net-imports of cropland products in the European Union in the year 2050 for 288 feasible scenarios. Net-imports are shown as positive, net-exports as negative values. Net-trade flows calculated as total demand of cropland products in the EU – total supply of cropland products in the EU. Only relevant parameters included in heatmap.

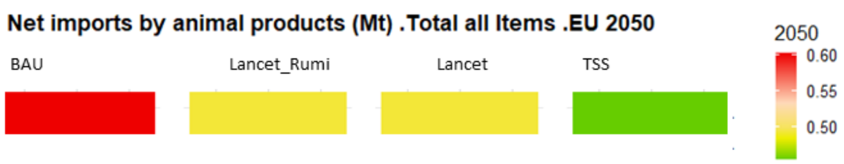

Figure 28. Heatmap for total net-imports of animal products in the European Union in the year 2050 for 288 feasible scenarios. Net-imports are shown as positive, net-exports as negative values, higher net-imports shown in red colours. Net-trade flows calculated as total consumption of animal products in the EU – total production of animal products in the EU. Only relevant parameters included in heatmap.

Figure 27 and Figure 28 show net-trade patterns of crops and animal products in the European Union in 2050. The European Union was nearly balanced in terms of the external trade-balance in crops in the year 2012, with app. 12 Mt DM/yr of net-imports. The highest net-imports were for oilcrops (>60 Mt DM/yr), mostly to feed domestic livestock, and the highest net-exports were for cereals (app. 50 Mt DM/yr). This pattern changes

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dramatically in the year 2050 in all scenarios. The most striking pattern is that the EU is a strong net-exporter of cropland products in the BAU CL variant, whereas in both agro-ecological variants, the EU is turning to a net-importer of cropland products, with the FCR Grassland variant reducing total net-imports of cropland products due to the fact that more biomass demand is covered from domestic grasslands. High net-exports of cereals, as it was the domestic pattern in the EU in the base year, cannot be maintained under a full shift towards agro-ecology in 2050. This pattern emerges because lacking demand for imports from non-EU regions due to increasing yields in these regions for these bulk commodities, which are mostly used to feed livestock, will lead to shrinking production volumes and consequently reduce net-exports.

Net-trade for animal products shows a similar pattern, albeit here diets are the only driver that determines this pattern, and no differences between e.g. cropland variants result from BioBaM_GHG_EU. This is due to the reasoning that the production of animal products is exclusively driven by local demand, and that the increasing global demand as assumed in the FAO BAU diet variant, is mostly covered from regions beyond the European Union.

So, why is the Europe Union becoming a net-importer of cropland products, and why is the nearly net-trade balance of animal products decreasing under agro-ecological variants? RoW regions increase their production according to the FAO BAU assumptions (FAO, 2018), and when the EU is assumed to undertake a complete shift towards agro-ecological production on all croplands as well as shifting to livestock systems away from highly-intensive high input – high output systems, production will become less “efficient” in terms of the magnitude that can be produced on agricultural land, and might run into strong competition from regions abroad. While the basic algorithm in BioBaM_GHG_EU is purely driven by biophysical factors, it assumes that non-EU regions follow a business-as-usual trajectory in their agricultural systems, leading to the production of surplus goods which need to be exported. Since the EU will reduce excessive surplus production destined for exports for e.g. wheat, the EU is likely to face strong and adverse pressure from comparably cheaper products from beyond the European Union which push into the EU agrarian markets. Only in a BAU CL variant, the EU will become an even stronger net-exporter of agricultural products, but there the current patterns will be continued in the future, and agro-ecological practices only play the (marginal) role they currently do.

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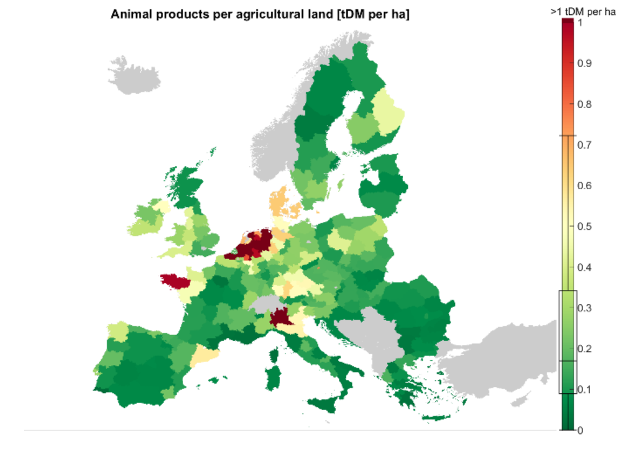
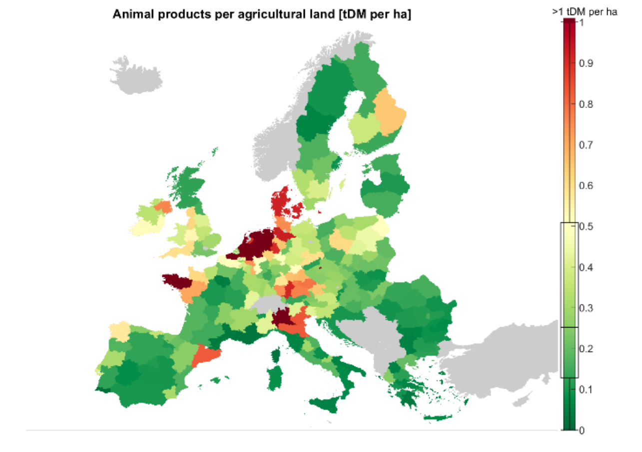
4.4.10. **Animal production in relation to total utilized agricultural land**

A major share of agricultural land is destined to produce feed for livestock production systems. In the European Union, a considerably larger amount of agricultural biomass is fed to livestock when compared to the biomass that is produced for direct human consumption (see Figure 9 on page 63). We thus developed an indicator that relates the amount of animal products (in ton of dry matter) to total utilized agricultural land (in hectares), so compare regions by their metabolic value of their livestock production systems.

a)	b)
	
BAU 2012	CL: BAU Diet: BAU diet FCR: BAU GI_{max}: Default **GL: Fixed distribution** AWMS: Default
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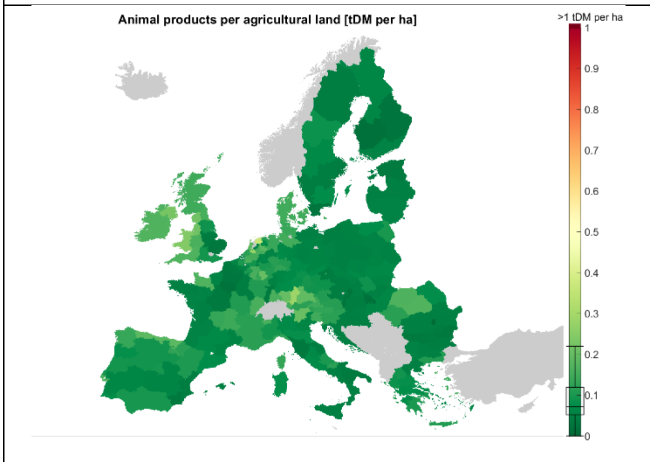	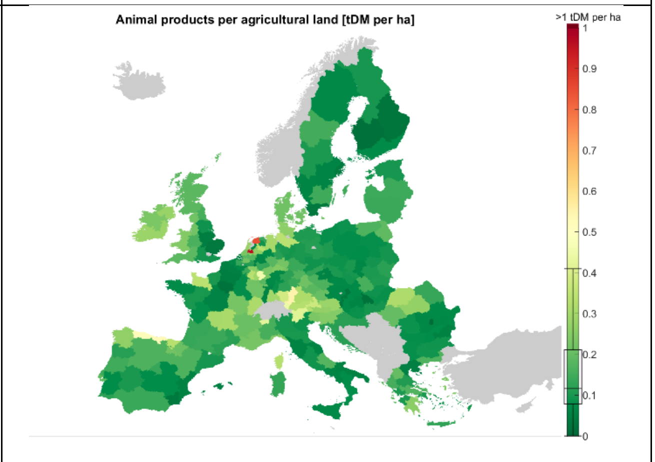
CL: Hedges Diet: Lancet-rumi diet FCR: Grassland GI_{max}: Reduced **GL: Land sharing** AWMS: High digester	CL: Hedges Diet: Lancet-rumi diet FCR: Grassland GI_{max}: Reduced **GL: Land sparing** AWMS: High digester

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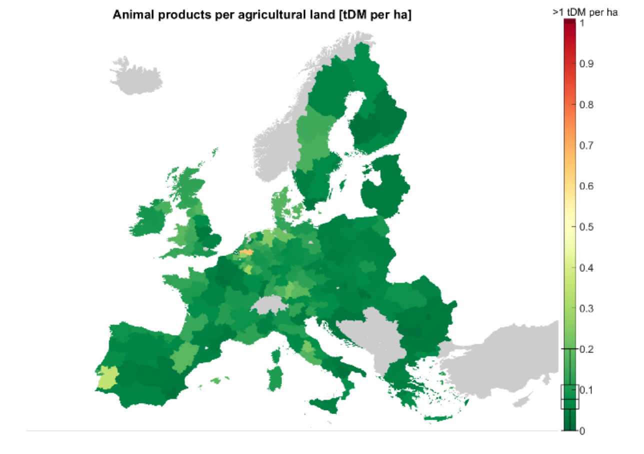
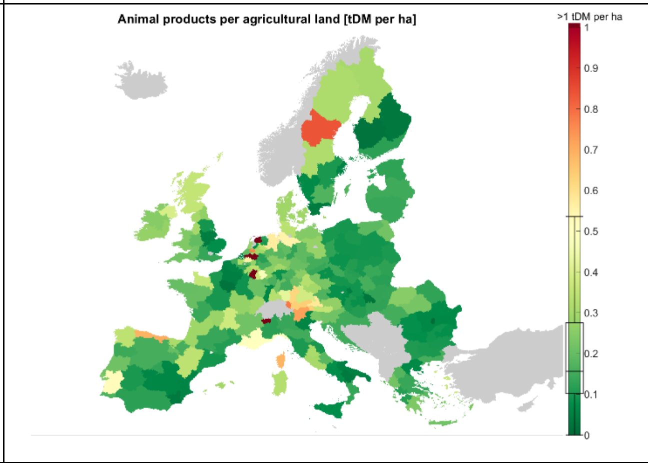
e)	f)
	
CL: CL feed Diet: Lancet diet FCR: Co-opt_Cropland GI_{max}: Reduced **GL: Land sharing** AWMS: High digester	CL: CL feed Diet: Lancet diet FCR: Co-opt_Cropland GI_{max}: Reduced **GL: Land sparing** AWMS: High digester

Figure 29: Six maps showing the regional (NUTS2) patterns of animal production per agricultural land in 2012 and for one conventional and four agro-ecological farming scenarios in the European Union in t DM per ha. Parameters and selected variants listed below each map, grey marked parameters are not relevant for the assessed indicator.

In the European Union, in the base year 2012 nearly 0.2t DM/ha of animal products were produced on each hectare of agricultural land, i.e. cropland and grassland (Figure 29a). This map clearly shows the hotspots of livestock production in the EU, with values ranging at nearly 1 t DM/ha. Given the metabolic losses between the conversion of cropland and grassland biomass, and the final animal products, such values can be considered as extremely high, which is also evidenced in the scientific literature where these regions do face negative animal-production related environmental impacts (Leip et al., 2015b). In a conventional variant for the year 2050, even more regions reach higher values and increase the amount of animal products per ha to values around 0.4 t DM/ha, clearly increasing environmental pressures in these regions.

Figure 29c - Figure 29f show the same indicator for four scenarios with agro-ecological parameter variants. There, an interesting pattern is revealed. While for the TBA indicator the agro-ecological cropland-based variants score better in terms of biomass harvest in relation to the potential NPP, a different pattern for animal products per ha can be observed. In both land sparing variants, animal production per agricultural land is higher, driven by the overall reduction of agricultural land for the provision of carbon sinks. Additionally, individual regions still have very high production volumes of animal products per ha, whereas the general pattern shows a more even distribution of animal production per ha, and thus a more even integration of animal production and agricultural land use across the EU. In all land sharing variants, the highest ratio is approximately 0.2t DM/ha, which is as high as the EU average in the base year 2012.

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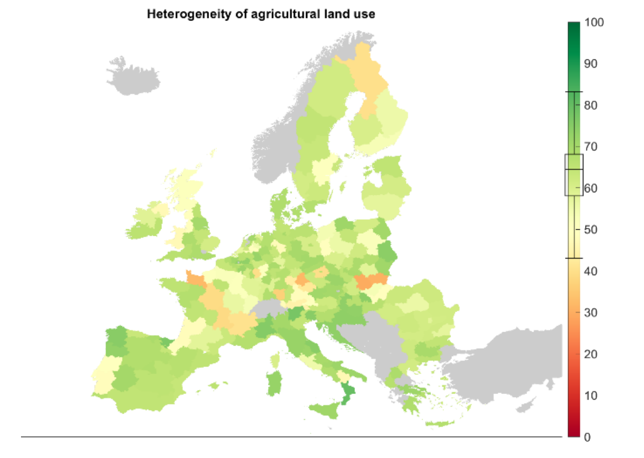
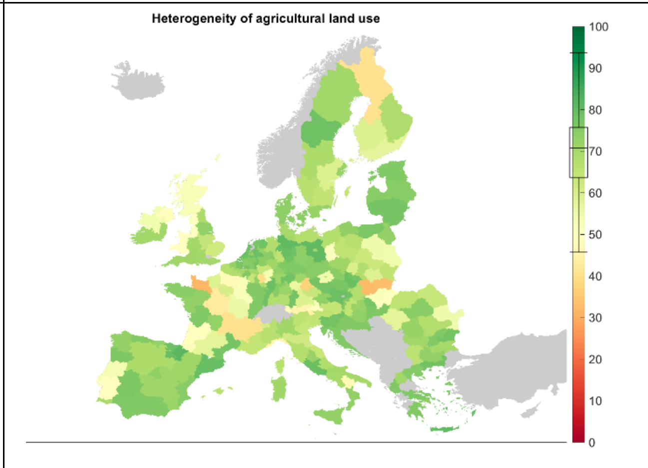
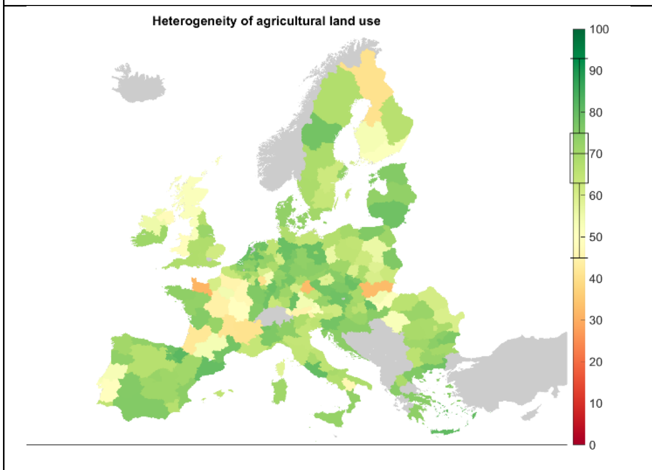
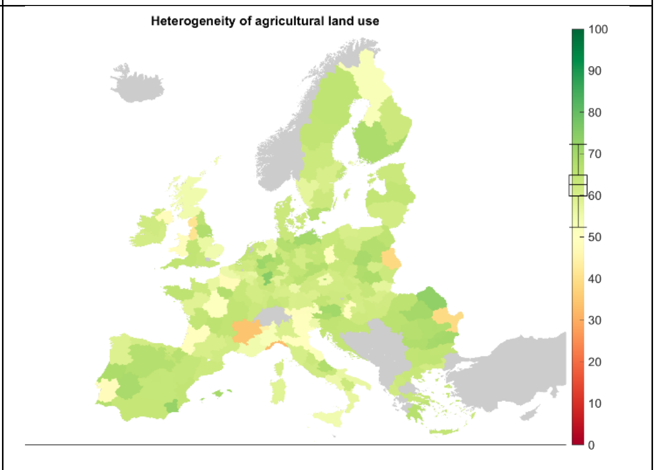
4.4.11. Heterogeneity of land use (Shannon Index)

<table>
<tr><td>a)</td><td>b)</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>BAU 2012</td><td>CL: BAU
Diet: BAU diet
FCR: BAU
GI_{max}: Default
GL: Fixed distribution
AWMS: Default</td></tr>
<tr><td>c)</td><td>d)</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>CL: Hedges
Diet: Lancet-rumi diet
FCR: Grassland
GI_{max}: Reduced
GL: Land sharing
AWMS: High digester</td><td>CL: Hedges
Diet: Lancet-rumi diet
FCR: Grassland
GI_{max}: Reduced
GL: Land sparing
AWMS: High digester</td></tr>
</table>

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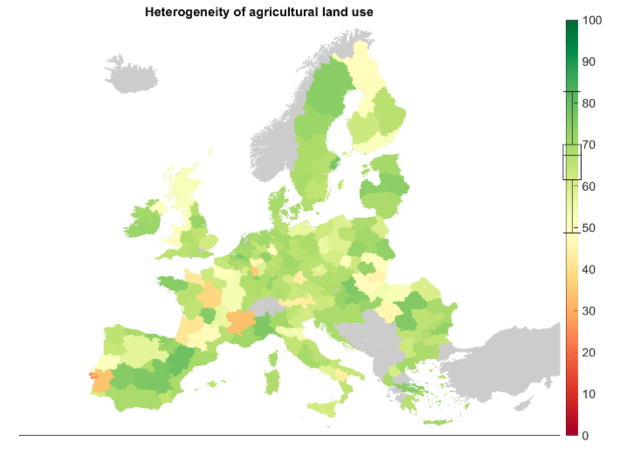
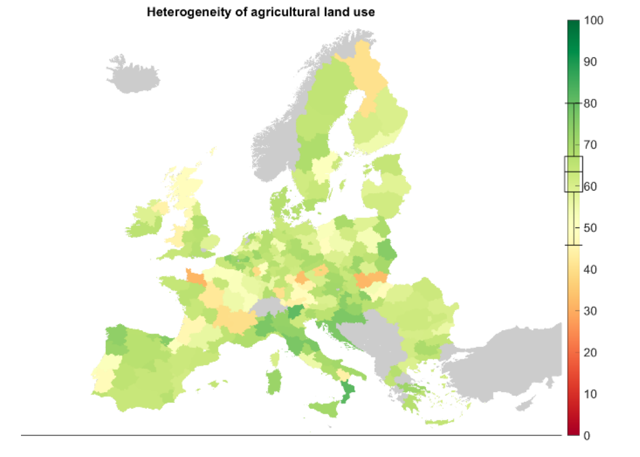
e)	f)
	
CL: CL feed Diet: Lancet diet FCR: Co-opt_Cropland GI_{max}: Reduced **GL: Land sharing** AWMS: High digester	CL: CL feed Diet: Lancet diet FCR: Co-opt_Cropland GI_{max}: Reduced **GL: Land sparing** AWMS: High digester

Figure 30: Six maps showing the regional (NUTS2) patterns of the heterogeneity of agricultural land use in 2012 and for one conventional and four agro-ecological farming scenarios in the European Union from zero (no heterogeneity) to 100 (maximum heterogeneity). Parameters and selected variants listed below each map, grey marked parameters are not relevant for the assessed indicator. This indicator is based on the following land use classes (n=14): cereals, roots and tubers, oilcrops, sugarcrops, pulses, fruits, vegetables, nuts, other crops, other fibres, fodder crops, and grazing land class 1, class 2, class 3.

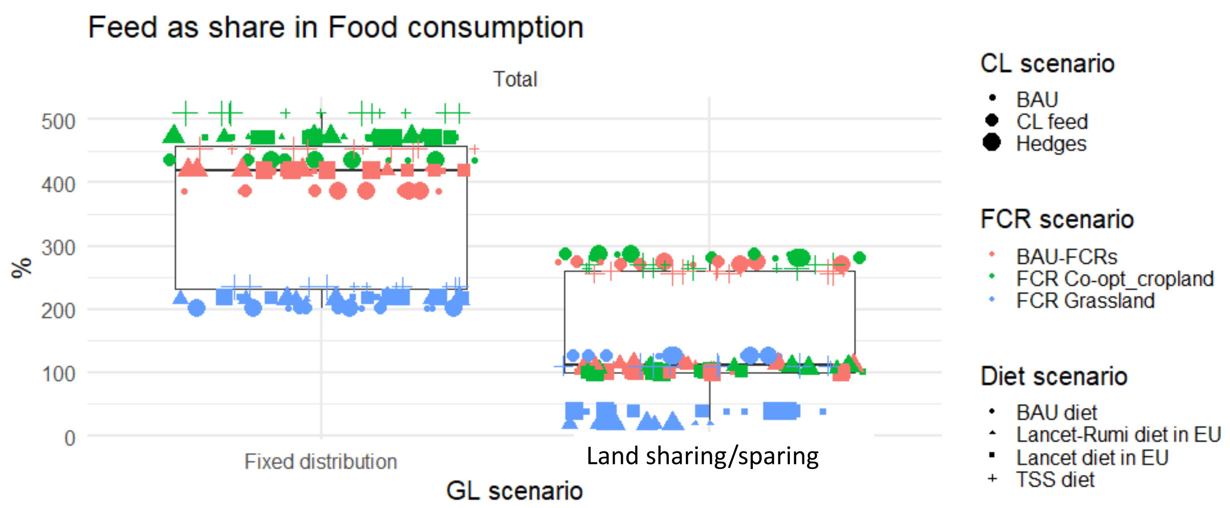
We here assess changes in the heterogeneity of agricultural land use in the base year and in five selected scenarios for the year 2050. Heterogeneity is represented by the agricultural land Shannon-Index, a widely used indicator to show species diversity in ecosystems. In the year 2012, average heterogeneity was at approximately 65%, with regions in Northern Italy and regions in Belgium and North-Western Germany, as well as individual regions across the whole EU showing relatively heterogeneous agricultural land use patterns. The most homogeneous, i.e. specialized land use patterns can be found in regions in France and individual other regions across the EU, with some highly specialized regions where either only comparably few crops were grown, or regions where grasslands dominated. For the latter regions is must be noted that due to harsh climatic or ecological conditions only grassland systems are feasible.

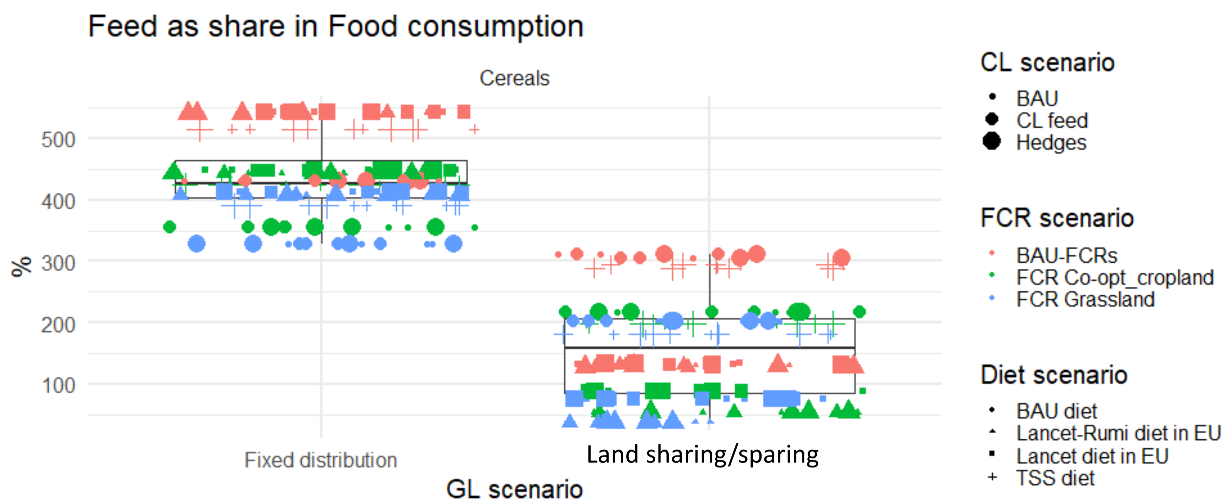
For all scenarios in the year 2050 we assume that in 75% of croplands the cropping patterns of 2012 are continued, due to the reason that otherwise the full production of specific crop groups might be shifted to regions beyond the European Union due to higher yields. Thus, the changes within the EU are limited to 25% of cropland, while we allow for unrestricted land use change dynamics in grasslands (for a detailed description of allowed changes in grasslands see Methods section). A conventional scenario in 2050, as can be seen in Figure b), also shows a slight overall increase in the Shannon-Index due to a bit more heterogenous diets, and while some still very specialized regions persist, the general pattern shows an improvement in the diversity of agricultural land use.

Figures c) – f) show the Shannon index for four agro-ecological scenarios. There, the land sharing variant clearly scores higher than the land sparing variant in terms of the realized heterogeneity in agricultural land use, as for the latter extensive grasslands are converted to forests, thus reducing the heterogeneity of grasslands. Nevertheless, it also becomes clear that the scenario c) shows the highest Shannon Index, 70% average for the whole EU, and the most diverse agricultural systems reaching more than 90%, i.e. the extent of crop groups and grazing classes reaching nearly full equality. This very heterogeneous land use is found in many NUTS regions which had rather homogeneous agricultural land in the base year, and where the farming systems are getting more diverse and thus can also react more flexibly to demand changes for agricultural products. Furthermore, farmland heterogeneity is beneficial for farmland biodiversity through the provision of a more diverse habitat structure and is specifically important in the European Union where intensification has led to more homogeneous cropland patterns (Benton et al., 2003; Maes et al., 2016; Poux and Aubert, 2018; Weissteiner et al., 2016)

4.4.12. Competition between food and feed

The reduction of competition between food and feed production is a central ambition in agro-ecological food systems. We here present boxplots for the share of feed utilization and food consumption for the main crop types (not including grass from grasslands) in livestock feed, and include all 432 scenarios, i.e. also the grazing infeasible scenarios with a fixed crops and animal production distribution, to see the differences between conventional and agro-ecological variants.





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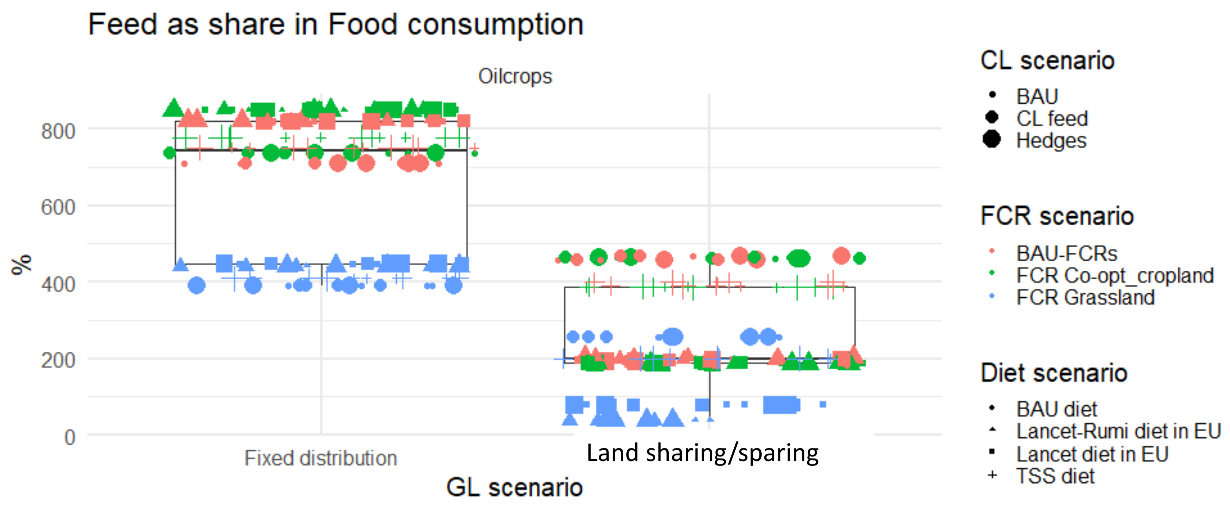

Figure 31: Boxplots for the ratio of livestock feed vs. food consumption in the European Union in the year 2050 in % (feed/food). The impact of each parameter is assessed and parameters are classified from those with the largest impact in descending order from x-axis, colour, shape and size of marker. Land sharing/land sparing has no impact upon this indicator and are thus shown together. Classification based on regression analysis, all 432 scenarios were included in this analysis. Please note the different scale on the y-axis in Boxplot 3 for oilcrops.

For all feed crops that can also be directly consumed by humans (cereals, oilcrops, pulses, sugarcrops), 320 Mt DM/yr were consumed by livestock and 114 Mt DM/yr directly for human consumption in the EU. In the fixed distribution of animal products variant in 2050, which we assume for conventional parameter variants, the share of feed vs. food is even increasing for nearly all BAU variants. Please note that for all Co-opt_Cropland FCR variants, the amount of food vs. feed competition can be misleading, since there only by-products from food processing are fed to livestock. There, it is thus important to mention that we eliminate all primary staple crops from being fed to livestock, and all cropland products are secondary products from food production and fodder crops, and this competition arises only for usage for e.g. the production of bioenergy. However, since oil cake could potentially be also transformed to human edible products (Drozłowska et al., 2020), also the Co-opt_Cropland variant poses food vs. feed completion, albeit at a lower level. Temporary grasslands on cropland that contain legumes enhance nitrogen provisioning in crop rotations, whereas e.g. fodder maize does not. In both agro-ecological farming systems variants, i.e. the land sparing and land sharing grassland variants, food vs. feed competition is decreasing, mostly in variants where ruminant livestock is exclusively fed from grasslands. Nevertheless, there are also a range of FCR variants where food vs. feed competition is considerably reduced. In scenarios where these FCR variants are combined with low-meat diets (EAT-Lancet and EAT-Lancet-Rumi human diets), nearly equal amounts of cropland products are utilized for food and feed production, which is much less than the 3fold surplus of feed production in the European Union in the base year 2012. Clearly, this is still a high amount of cropland feed for livestock, which needs to be reduced further to secure long-term domestic food security in the EU.

Cereals and oilcrops are the most important feed crops in the European Union, and the consumption for livestock feed was 3 (cereals) to 5 (oilcrops) times higher than for direct human consumption. For both crops, the agro-ecological scenario variants decrease food vs. feed competition, and again, scenario variants with grassland FCR show that highest benefits in terms of avoided cropland competition. Interestingly, in the Co-opt_Cropland FCR variant, comparably low ratios is in the grassland FCR can be observed, indicating that innovative livestock feeding systems indeed reduce the feed demand from cereals without shifting pressures

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to grasslands. Such a shift is not that clearly visible for oilcrops, one reason might be that oilcrops have been playing a larger role in livestock feed, but since oilcrops in this FCR variant mostly contains oil cakes, i.e. secondary products from oil production, a further reduction of oilcrops production would also lead to insufficient provision with vegetal oils for direct human consumption. Thus, the high food vs. feed competition ratios for oilcrops in the agro-ecological cropland-based FCR also needs to be interpreted by considering this fact. For cereals, however, we clearly see that scenarios which combine BAU FCRs with FAO BAU or FAO TSS diets lead to considerably higher amounts of cereals required in livestock systems. There, the spatial re-allocation of livestock production (and thus also the invoked changes in livestock diets which are regionally distinct) does not change the extent of food versus feed cropland competition in the EU as if compared to the base year 2012.

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4.5. Trade-offs for selected scenarios

In the following and concluding section of the results we aim to show trade-offs for a range of impacts which we presented in the sections before. We therefore select again five scenarios which we have already presented in the section above. One scenario shows the conventional baseline in the year 2050, with only conventional parameter variants. It is important to remind again that this scenario is grazing infeasible in the European Union, which means that not enough grassland is available to cover the demand for domestic ruminant livestock. Nevertheless, including a conventional baseline helps to better understand the impacts of four selected agro-ecological scenarios. There we present the base year data (2012) and a BAU 2050 scenario which only includes conventional (i.e. BAU) parameter variants. We then present two scenarios which primarily aim to relieve pressure from cropland through a shift of grassland-feed for ruminants, but also to increase ecological infrastructure in croplands though setting 7% of the cropland in the year 2012 free for hedgerows. We additionally select two scenarios which primarily target croplands with the aim to decrease food/feed competition and implementing a range of agro-ecological practices from the Uniseco case studies which are upscaled to the EU level. Grassland use is considered either through a land sharing or a land sparing variant (variants CL feed). Again, we also show results for a land sharing and a land sparing variant.

Table 15: Parameters and variants for the base year 2012 and five selected conventional and agro-ecological scenarios in the year 2050.

2012	**BAU 2050** CL: BAU Diet: BAU diet FCR: BAU GI_{max}: Default GL: Fixed distribution AWMS: Default
Hedges land sharing 2050 CL: Hedges Diet: EAT-Lancet-rumi diet FCR: Grassland GI_{max}: Reduced GL: Land sharing AWMS: High digester	**Hedges land sparing 2050** CL: Hedges Diet: EAT-Lancet-rumi diet FCR: Grassland GI_{max}: Reduced GL: Land sparing AWMS: High digester
CL feed land sharing 2050 CL: CL feed Diet: EAT-Lancet diet FCR: Co-opt_Cropland GI_{max}: Reduced GL: Land sharing AWMS: High digester	**CL feed land sparing 2050** CL: CL feed Diet: EAT-Lancet diet FCR: Co-opt_Cropland GI_{max}: Reduced GL: Land sparing AWMS: High digester

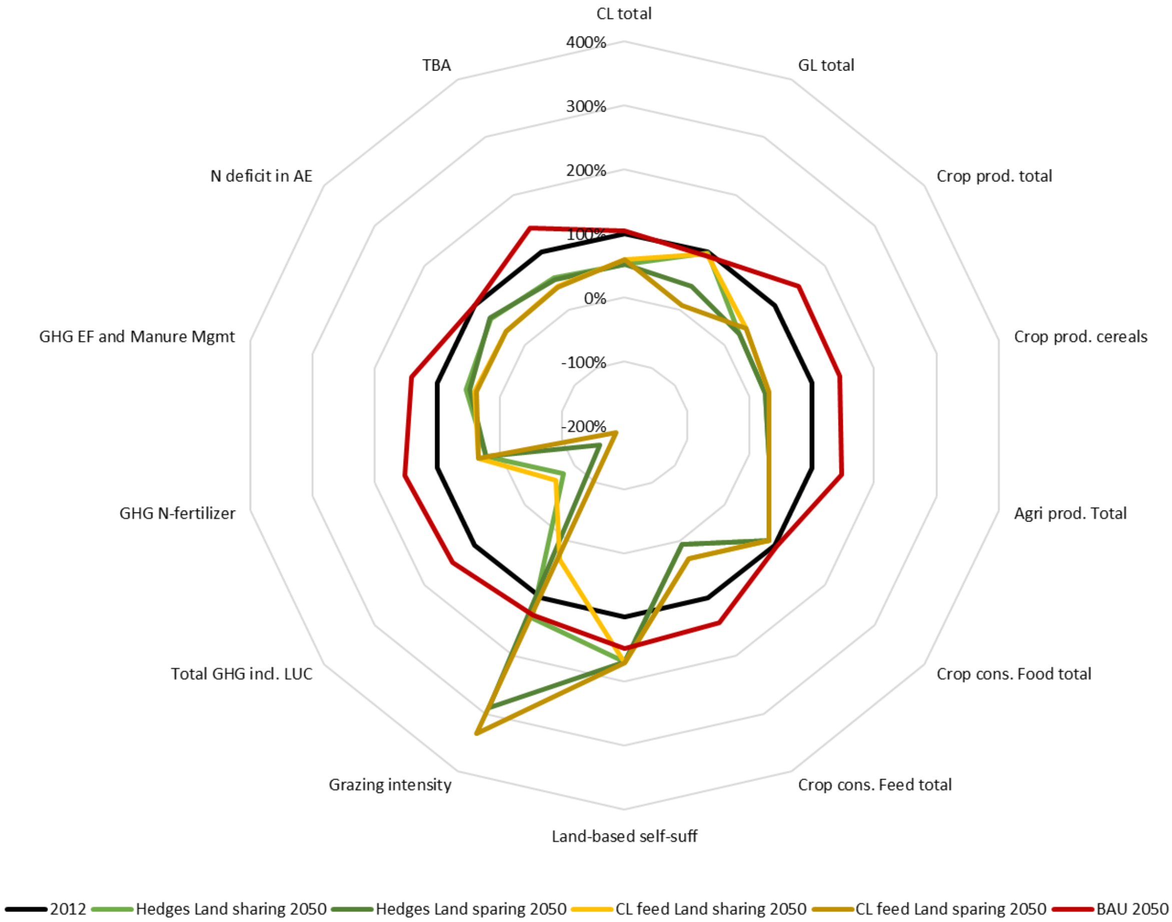

Figure 32: Socio-economic and environmental impacts of five scenarios in 2050, i.e. four agro-ecological and one conventional scenario in the European Union. The year 2012 is shown in black lines, values are displayed as % in comparison to the year 2012. Please note that the indicator nitrogen deficit in agro-ecological farming for 2012 and BAU 2050 indicates no deficit, and values for all other scenarios show the absolute ratio for each scenario in the year 2050.

We here present a spider-web diagram for five selected scenarios in the EU in the year 2050. Total cropland remains constant in the BAU variant, but in all agro-ecological scenarios decrease. The pattern is distinct for grassland, where in both land sharing variants the extent of grassland is kept constant, whereas in both land sparing variants grassland considerably decreases. In the CL feed land sparing variant, undersowing in all cereals production provides such considerably amounts of feed biomass that less than 10% of the grassland in the base year is needed to feed the ruminant livestock. However, also crop production decreases in all agro-ecological scenarios, and this can be clearly seen for the most important bulk crops in the EU in the base year, cereals. This is also related to the reduced production of agricultural products due to decreased demand of animal products in the EAT-Lancet diet variants, where the majority are animal products. Thus, crop consumption for feed is also decreasing in the EU, to less than 10% compared to 2012 in the Hedges variant, where no primary cropland products which are used as staple crops are fed to livestock. Clearly, the land-based potential self-sufficiency would increase in all agro-ecological scenarios, due to reduced domestic demand, even if hedgerows are grown on 7% of all EU cropland to improve the ecological infrastructure. This pattern of increasing potential self-sufficiency can also be observed in a conventional scenario, albeit at the cost of a potential cropland expansion into grasslands, which comes at the cost of CO2 emissions from land use change.

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Grazing intensity is changing in opposite directions in the scenarios assessed here, driven by distinct assumptions on spatial patterns of grassland utilization. Both land sparing variants considerably increase GI, albeit in the Hedges scenario overall GI is lower due to slightly less reductions in total grassland, a dynamic that is driven by distinct grass production potentials between these scenarios (due to different FCRs). In the Hedges scenarios, we also implement EAT-Lancet_rumi diet with a higher share of ruminant products compared to the standard EAT-Lancet diet, and interestingly, this allows for slightly lower grazing intensities in the year 2050. The main intention of the land sparing and land sharing grassland variants was to show synergies between agro-ecology and climate-smart farming practices, which can be seen for GHG emissions. While GHG emissions considerably increase in the BAU 2050 scenario, clearly a way which is not in line with the Paris climate goals, all agro-ecological scenarios show potentially large reductions in agricultural GHG emissions, where both land sparing provide considerably carbon sinks, and also the land sharing variants score at negative emissions in the year 2050. This result is, on the one hand driven by large reductions in GHG emissions from N-fertilizer production, and at the other hand from a considerable reduction in livestock-related GHG emissions. The reductions in N-fertilizer requirements are based on a higher share of legumes in crop rotations, which increases land demand, but brings considerable savings for GHG emissions. Nitrogen deficits in 2050 in the AE systems are at app. 70% in the Hedges scenarios, and 40% in the CL feed scenarios, where less manure is dropped at pastures and is thus available to be utilized on croplands. This deficit needs to be compensated with synthetic fertilizers. Nevertheless, we assume that all ruminant livestock which is fed from croplands is raised in indoor systems, where trade-offs with animal-welfare need to be considered. It thus becomes clear that agro-ecological cannot fully ban synthetic N-fertilizers, but need to find a balance between the utilization of organic fertilizers, improving the nitrogen provision from better crop rotations and still allowing for synthetic fertilizer if deficits occur. If current N-utilization ratios would remain, this would result in a 50% increase of emissions from N-fertilizer production necessary to compensate for insufficient nitrogen provision from legumes and livestock manure, as well as if current livestock systems and manure management systems remain, livestock-related GHG emission would also increase by 40%.

Total biomass appropriation (TBA) in 2050 is bound to increase under a BAU scenario, but upscaling agro-ecological practices to the EU level in the four agro-ecological scenarios allows to considerably decrease TBA. There, reductions to levels of approximately 50% of the pressures in 2012 can be reached. This benefit is clearly driven by less biomass harvest from both cropland and grassland due to changed demand, and allows for a diminution of biodiversity pressures on agricultural land.

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4.6. Agroforestry

Here we present the results from the calculations for scenarios with increased shares of agroforestry all over the European Union and Switzerland. We display results for the following indicators, arranged in 6 groups (Table 16), for the various scenarios with large-scale implementation of agroforestry (AF) throughout the EU plus Switzerland as described in section 3.3

Table 16: Indicators for the agroforestry scenarios.

Land use	Cropland: crops without agricultural trees (ha)
	Cropland: agricultural trees (ha)
	Grassland (ha)
	Total cropland + grassland (ha)
Livestock and animal welfare	
	Cattle (heads)
	Pigs (heads)
	Chickens (heads)
	Animal welfare: antibiotics use index
	Animal welfare: heat stress index 2050
Food availability and self-sufficiency	
	Calories per capita (kcal/cap/day): total
	Protein per capita (g/cap/day): total
	Calories per capita (kcal/cap/day): crop based
	Protein per capita (g/cap/day): crop based
	Calories per capita (kcal/cap/day): animal based
	Protein per capita (g/cap/day): animal based
	Self sufficiency calories (share)
	Self sufficiency proteins (share)
Labour use and productivity	
	Labour use - total, crops (h)
	Labour use - total, animals (h)
	Labour use - total (h)
	Producer value - crops ($)
	Producer value - animals ($)
	Producer value - total ($)
	Labour productivity - crops ($/hour)
	Labour productivity - animals ($/hour)
	Labour productivity - total ($/hour)
GHG emissions and C-sequestration in woody biomass	
	GHG emissions - animals, enteric ferment. (t CO2e)
	GHG emissions - animals, manure management (t CO2e)
	Total GHG emissions - animals (t CO2e)
	Tot GHG em - crops/grass, no Defor/OrgSoils (t CO2e)
	Tot GHG em - crops/grass, with Defor/OrgSoils (t CO2e)
	Tot GHG em - all act, no Defor/OrgSoils (t CO2e)
	Tot GHG em - a (relative to total agric. GHG emissions)
	C sequestered in woody biomass (tC)
	ONLY Availabl (relative to total agric. GHG emissions)
	C sequestered in woody biomass (tC)
Further einvironmental indicators	
	Irrigation water (m3)
	Irrigation water (m3) - water stress adjusted
	Total CED (MJ)
	Soil water erosion (t soil lost)
	Aggreg. Pest. use level (index)
	NH3 emissions - areas (tNH3)
	NH3 emissions - animals (tNH3)
	NH3 emissions - total (tNH3)
	OECD N balance: inputs (tN)
	OECD N balance: outputs (tN)
	OECD N balance: Inputs - outputs (tN)
	OECD N balance per ha (tN/ha)

Below, the results are presented in tables representing the option spaces spanned by the various combinations of parameter choices, aggregated on the whole EU+CH level. The parameters that change are the share of agroforestry areas (low, medium, high), the crop component share within agroforestry areas (low, medium, high), the yield level in agroforestry (low, high) and C-sequestration in woody biomass (low, medium and high), see section 3.3.2 for details.

Results are displayed in relative values of scenarios with respect to the baseline 2012 and also with respect to the reference scenario 2050 (besides N surplus per hectare, where absolute values are displayed). We also used a colour coding to make the results more readable, applying different scales as displayed in Figure 33.

A general observation is that the differences between the different agroforestry options are not that large for most indicators. This is partly due to the fact that we report total values for all production, wherein agroforestry is a share only, which results in different parameter choices for the agroforestry systems playing out less prominently in the total values.

It is important to note that the model used here (SOLm) works differently than the BioBaM_GHG_EU model used for the results in the previous sections of chapter 4. A key difference is that BioBaM_GHG_EU optimizes

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the cropping patterns subject to certain goal functions and boundary conditions, while SOLm start from the reference situation and derives the scenario implementation in close connection to this. Thus, BioBaM_GHG_EU results in general display the potential that could be achieved in a world where agriculture and the food system is organized optimally regarding the goals addressed and the aspects covered in the model, while SOLm pays more credits to observed nationally differing production and consumption patterns and trade-flows, thus capturing a more "realistic" world (in the sense of being closer to observed production, trade and consumption patterns) at the cost of not being able to optimize. In this, the results from both models complement each other, by indicating the potential of an optimal organization of the system on the one hand contrasted to a less optimal organization that in exchange captures better current national peculiarities of agriculture and the food systems.

Scale A: the higher the worse	Scale B: the higher the better	Scale C: the higher the better, range 0 - 1	Scale C: the higher the better, range 1 - 4	Scale D: the lower the better, range 0.5 - 1
0.5 - 1.75	0.5 - 1.75	C_0-1	C_1-4	D_0.5-1
0%	0%	0%	0%	0%
10%	10%	10%	20%	10%
20%	20%	20%	40%	20%
30%	30%	30%	60%	30%
40%	40%	40%	80%	40%
50%	50%	50%	100%	50%
60%	60%	60%	120%	60%
70%	70%	70%	140%	70%
80%	80%	80%	160%	80%
90%	90%	90%	180%	90%
100%	100%	100%	200%	100%
110%	110%	110%	220%	110%
120%	120%	120%	240%	120%
130%	130%	130%	260%	130%
140%	140%	140%	280%	140%
150%	150%	150%	300%	150%
160%	160%	160%	320%	160%
170%	170%	170%	340%	170%
180%	180%	180%	360%	180%
190%	190%	190%	380%	190%
200%	200%	200%	400%	200%
210%	210%	210%	420%	210%
220%	220%	220%	440%	220%
230%	230%	230%	460%	230%

Scale E: the lower, the better - but beyond some level it worsens again (deficit)
0.05 - (-0.05)
0.050
0.040
0.030
0.020
0.010
0.000
-0.010
-0.020
-0.030
-0.040
-0.050

Figure 33: Scales used in the results from the agroforestry scenarios

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4.6.1. **Land use**

Land use is dominated by the basic assumption to keep total land use constant. This results in some shifts towards less grasslands, where such are cultivated under new agroforestry tree areas. The biggest change refers to the agroforestry tree areas that increase significantly by factors up to almost 400% in case of high shares of AF area and low shares of the crop component on agroforestry plots (Figure 34).

percentage value relative to the baseline 2012

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
Cropland: crops without agricultural trees (ha)	low (default)	110%	104%	106%	102%	101%	104%	97%	106%	106%	104%	A
	high	110%	104%	106%	102%	101%	104%	97%	106%	106%	104%	A
Cropland: agricultural trees (ha)	low (default)	99%	211%	178%	262%	280%	220%	377%	182%	161%	215%	C_1-4
	high	99%	211%	178%	262%	280%	220%	377%	182%	161%	215%	C_1-4
Grassland (ha)	low (default)	100%	96%	98%	94%	93%	96%	89%	97%	98%	96%	A
	high	100%	96%	98%	94%	93%	96%	89%	97%	98%	96%	A
Total cropland + grassland (ha)	low (default)	105%	105%	105%	105%	105%	105%	105%	105%	105%	105%	A
	high	105%	105%	105%	105%	105%	105%	105%	105%	105%	105%	A

percentage value relative to the reference 2050

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
Cropland: crops without agricultural trees (ha)	low (default)	100%	94%	96%	92%	91%	94%	88%	96%	96%	95%	A
	high	100%	94%	96%	92%	91%	94%	88%	96%	96%	95%	A
Cropland: agricultural trees (ha)	low (default)	100%	212%	180%	265%	283%	222%	380%	184%	163%	217%	C_1-4
	high	100%	212%	180%	265%	283%	222%	380%	184%	163%	217%	C_1-4
Grassland (ha)	low (default)	100%	96%	98%	94%	93%	96%	89%	97%	98%	96%	A
	high	100%	96%	98%	94%	93%	96%	89%	97%	98%	96%	A
Total cropland + grassland (ha)	low (default)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	A
	high	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	A

Figure 34: Land use change in the different options, relative to the baseline (top) and to the reference 2050 (bottom)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773901.

4.6.2. **Livestock and animal welfare**

In all scenarios, livestock numbers are reduced by about 40-50% (Figure 35). For ruminants, this is due to the shift to fully grassland-based diets, i.e. without any concentrate feed, as well as a reduced utilization rates of grasslands to 80%, reflecting less intensive systems, combined with the 25% organic shares, and with reduced grassland areas (and on those, reduced yields) due to agroforestry; in combination, this results in this substantial reduction of cattle numbers. Monogastric numbers drop as the scenarios are based on considerably reduced trade flows, i.e. in particular feed imports, which correspondingly results in lower monogastric numbers in the EU. The shift to partly organic production further reduces the feed base due to lower yields. The reduction in livestock numbers directly translates in corresponding reductions in adverse animal welfare impacts.

percentage value relative to the baseline 2012

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
Cattle (heads)	low (default)	91%	47%	48%	44%	45%	48%	42%	47%	49%	45%	A
	high	91%	47%	49%	45%	46%	48%	43%	48%	49%	46%	A
Pigs (heads)	low (default)	111%	58%	60%	54%	57%	60%	52%	58%	61%	55%	A
	high	111%	60%	62%	58%	59%	61%	55%	61%	62%	58%	A
Chickens (heads)	low (default)	113%	62%	64%	57%	61%	64%	55%	62%	65%	58%	A
	high	113%	64%	66%	61%	63%	65%	59%	65%	66%	62%	A
Animal welfare: antibiotics use index	low (default)	102%	57%	59%	53%	55%	58%	51%	57%	59%	54%	A
	high	102%	59%	60%	56%	57%	59%	54%	59%	61%	57%	A
Animal welfare: heat stress index 2050	low (default)	101%	58%	60%	54%	56%	59%	52%	58%	60%	55%	A
	high	101%	60%	61%	57%	58%	60%	55%	60%	62%	58%	A

percentage value relative to the reference 2050

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
Cattle (heads)	low (default)	100%	51%	53%	48%	50%	52%	46%	52%	54%	49%	A
	high	100%	52%	54%	50%	51%	53%	47%	53%	54%	51%	A
Pigs (heads)	low (default)	100%	52%	54%	49%	51%	54%	47%	53%	55%	49%	A
	high	100%	54%	56%	52%	53%	55%	50%	55%	56%	53%	A
Chickens (heads)	low (default)	100%	55%	57%	51%	54%	57%	49%	55%	58%	52%	A
	high	100%	57%	59%	55%	56%	58%	52%	58%	59%	55%	A
Animal welfare: antibiotics use index	low (default)	100%	56%	58%	52%	55%	57%	50%	56%	58%	53%	A
	high	100%	58%	59%	55%	56%	58%	53%	58%	60%	56%	A
Animal welfare: heat stress index 2050	low (default)	100%	57%	59%	53%	56%	59%	51%	58%	60%	54%	A
	high	100%	59%	61%	57%	58%	60%	54%	60%	61%	58%	A

Figure 35: Livestock numbers (cattle, pigs, chickens) and animal welfare indicators related to antibiotics use and heat stress in 2050, relative to the baseline (top) and to the reference 2050 (bottom).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773901.

4.6.3. **Food availability and self-sufficiency**

In all scenarios, food supply drops somewhat, in particular for animal sourced food which is reduced significantly by 40-50%, corresponding to the change in animal numbers and trade patterns. In this, self-sufficiency increases, though, as it changes from about 60% in the baseline and 55% in the reference 2050 to almost 80% in the scenarios (Figure 36). This self-sufficiency, has however to be seen in relation to the total production levels which are about 20% less than in the baseline and 10% less than in the reference 2050. Thereby, it is important to note that the reference levels 2050 for the EU and Switzerland reflect projections for high income countries with generally somewhat reduced total food supply levels and shares of animal source food in diets (in contrast to the global patterns, where both these indicators increase). The underlying dynamics in these patterns is the reduction of animal source food, which disproportionally increases the potential to produce plant-based food, thus allowing for less intensive production systems without drops in total calorie and protein production. The reduction in calorie and protein supply in these scenarios is also significantly driven by the reduction of imports. In total, these reductions are not a problem, as the overall calorie and protein levels supplied are still sufficient to assure food security, going from about 3200 kcal/cap/day and 90g protein/cap/day in the reference 2050 to 2750-3000 kcal/cap/day and 80-90g protein/cap/day in the various scenarios.

percentage value relative to the baseline 2012

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
Calories per capita	low (default)	90%	79%	81%	76%	79%	81%	76%	79%	81%	76%	B
(kcal/cap/day): total	high	90%	81%	82%	79%	81%	82%	78%	81%	82%	80%	B
Protein per capita	low (default)	84%	79%	81%	76%	79%	81%	75%	80%	82%	77%	B
(g/cap/day): total	high	84%	81%	82%	79%	80%	82%	78%	82%	83%	80%	B
Calories per capita	low (default)	98%	94%	97%	91%	94%	96%	90%	94%	97%	91%	B
(kcal/cap/day): crop based	high	98%	97%	98%	94%	96%	98%	94%	97%	98%	95%	B
Protein per capita	low (default)	96%	99%	102%	95%	98%	102%	93%	100%	103%	95%	B
(g/cap/day): crop based	high	96%	102%	104%	99%	101%	103%	97%	103%	104%	100%	B
Calories per capita	low (default)	74%	50%	51%	48%	49%	51%	46%	50%	51%	48%	D_0.5-1
(kcal/cap/day): animal	high	74%	51%	52%	49%	50%	51%	48%	51%	52%	50%	D_0.5-1
Protein per capita	low (default)	74%	65%	66%	63%	64%	66%	62%	65%	66%	64%	D_0.5-1
(g/cap/day): animal based	high	74%	66%	67%	65%	65%	66%	63%	66%	67%	65%	D_0.5-1
Self sufficiency calories	low (default)	92%	136%	136%	134%	135%	136%	134%	136%	136%	134%	B
(share)	high	92%	136%	137%	136%	136%	137%	135%	136%	137%	136%	B
Self sufficiency proteins	low (default)	92%	118%	119%	117%	118%	119%	116%	119%	119%	117%	B
(share)	high	92%	119%	120%	118%	119%	120%	117%	119%	120%	119%	B

percentage value relative to the reference 2050

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
Calories per capita	low (default)	100%	89%	91%	85%	88%	90%	84%	89%	91%	85%	B
(kcal/cap/day): total	high	100%	91%	92%	88%	90%	92%	88%	91%	92%	89%	B
Protein per capita	low (default)	100%	95%	97%	91%	94%	97%	90%	95%	98%	92%	B
(g/cap/day): total	high	100%	97%	99%	95%	96%	98%	93%	98%	99%	95%	B
Calories per capita	low (default)	100%	97%	99%	93%	96%	99%	93%	97%	99%	93%	B
(kcal/cap/day): crop based	high	100%	99%	100%	97%	98%	100%	96%	99%	100%	97%	B
Protein per capita	low (default)	100%	103%	106%	98%	102%	105%	97%	103%	106%	99%	B
(g/cap/day): crop based	high	100%	106%	108%	103%	105%	107%	101%	106%	108%	104%	B
Calories per capita	low (default)	100%	67%	69%	64%	66%	69%	63%	68%	69%	65%	D_0.5-1
(kcal/cap/day): animal	high	100%	69%	70%	67%	67%	69%	65%	69%	70%	67%	D_0.5-1
Protein per capita	low (default)	100%	88%	89%	85%	87%	89%	83%	88%	89%	86%	D_0.5-1
(g/cap/day): animal based	high	100%	89%	90%	87%	88%	89%	85%	89%	90%	88%	D_0.5-1
Self sufficiency calories	low (default)	100%	147%	148%	146%	147%	148%	146%	147%	148%	146%	B
(share)	high	100%	148%	148%	147%	148%	148%	147%	148%	149%	147%	B
Self sufficiency proteins	low (default)	100%	129%	130%	127%	128%	129%	126%	129%	130%	127%	B
(share)	high	100%	129%	130%	128%	129%	130%	127%	130%	130%	129%	B

Figure 36: Per capita calorie and protein supply and self-sufficiency, relative to the baseline (top) and to the reference 2050 (bottom).

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4.6.4. **Labour use and productivity**

Labour use and value generation increase in total production and in crop production and decrease in animal production (Figure 37). While these changes result in low increases in labour productivity in the crop and livestock sector separately, in combination, overall labour productivity drops in these scenarios, mainly due to the drop in size of the livestock sector. Thus, strategies, to support high value commodity production from the crop sector are needed to replace the high-value livestock production and to avoid reductions in labour productivity in agriculture in these agroforestry scenarios. The empirical basis for the results on labour productivity is rather weak, as larger data sets on labour use and value generation in fruit and vegetable production are scarce and in agroforestry they are basically non-existent. Generally, one can assume that food products form the agroforestry sector tend to be rather high value (nuts, fruits, etc.), but labour requirements are also higher.

percentage value relative to the baseline 2012

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
Labour use - total, crops (h)	low (default)	111%	197%	186%	215%	220%	200%	252%	187%	180%	198%	B
	high	111%	197%	186%	215%	220%	200%	252%	187%	180%	198%	B
Labour use - total, animals (h)	low (default)	93%	52%	54%	49%	51%	53%	47%	53%	55%	50%	B
	high	93%	53%	55%	51%	52%	54%	48%	54%	55%	52%	B
Labour use - total (h)	low (default)	107%	171%	162%	184%	189%	173%	214%	162%	157%	170%	B
	high	107%	171%	162%	185%	189%	173%	215%	162%	157%	171%	B
Producer value - crops ($)	low (default)	142%	195%	187%	207%	216%	200%	241%	185%	181%	191%	B
	high	142%	199%	190%	213%	220%	202%	249%	189%	184%	198%	B
Producer value - animals ($)	low (default)	108%	56%	58%	52%	54%	57%	50%	56%	58%	53%	B
	high	108%	57%	59%	54%	56%	58%	52%	58%	59%	56%	B
Producer value - total ($)	low (default)	126%	129%	126%	134%	140%	133%	151%	125%	124%	126%	B
	high	126%	132%	128%	139%	143%	135%	156%	127%	125%	131%	B
Labour productivity - crops ($/hour)	low (default)	129%	99%	100%	96%	98%	100%	95%	99%	101%	97%	B
	high	129%	101%	102%	99%	100%	101%	98%	101%	102%	100%	B
Labour productivity - animals ($/hour)	low (default)	116%	107%	107%	107%	107%	107%	107%	107%	107%	106%	B
	high	116%	107%	107%	107%	107%	107%	107%	107%	107%	107%	B
Labour productivity - total ($/hour)	low (default)	118%	76%	78%	73%	74%	77%	71%	77%	79%	74%	B
	high	118%	77%	79%	75%	76%	78%	73%	79%	80%	77%	B

percentage value relative to the reference 2050

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
Labour use - total, crops (h)	low (default)	100%	179%	169%	195%	199%	181%	228%	169%	163%	179%	B
	high	100%	179%	169%	195%	199%	181%	228%	169%	163%	179%	B
Labour use - total, animals (h)	low (default)	100%	56%	58%	53%	55%	57%	50%	57%	59%	54%	B
	high	100%	57%	59%	55%	56%	58%	52%	58%	60%	56%	B
Labour use - total (h)	low (default)	100%	159%	151%	172%	176%	161%	200%	151%	146%	159%	B
	high	100%	159%	151%	172%	176%	161%	200%	151%	146%	159%	B
Producer value - crops ($)	low (default)	100%	137%	131%	145%	152%	140%	169%	130%	128%	134%	B
	high	100%	140%	133%	150%	155%	142%	175%	133%	129%	139%	B
Producer value - animals ($)	low (default)	100%	52%	54%	48%	50%	53%	46%	52%	54%	49%	B
	high	100%	53%	54%	50%	51%	54%	48%	54%	55%	51%	B
Producer value - total ($)	low (default)	100%	103%	100%	106%	111%	105%	120%	99%	98%	100%	B
	high	100%	105%	102%	110%	113%	107%	124%	101%	99%	104%	B
Labour productivity - crops ($/hour)	low (default)	100%	77%	78%	75%	76%	78%	74%	77%	78%	75%	B
	high	100%	78%	79%	77%	78%	79%	77%	79%	79%	78%	B
Labour productivity - animals ($/hour)	low (default)	100%	92%	92%	92%	92%	92%	92%	92%	92%	92%	B
	high	100%	92%	92%	92%	92%	92%	93%	92%	92%	92%	B
Labour productivity - total ($/hour)	low (default)	100%	65%	66%	62%	63%	65%	60%	65%	67%	63%	B
	high	100%	66%	67%	64%	64%	66%	62%	67%	68%	65%	B

Figure 37: Labour use, value generation and labour productivity, relative to the baseline (top) and to the reference 2050 (bottom).

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4.6.5. GHG emissions and C-sequestration in woody biomass

Corresponding to the changed production patterns, GHG emissions drop significantly in the scenarios due to the reduction of size in the livestock sector. GHG emissions in the crop production also drop somewhat. In total, this results in GHG emission reductions by about 20-40%, also depending on whether emissions from organic soils and deforestation are included or not (the latter does not play a big role in the EU ,while the former does; Figure 38). An important aspect of agroforestry is carbon sequestration in woody biomass. Accounting for this results in a climate change mitigation potential of about 30-70% of reference 2050 emissions, or of 60-100% of the remaining emissions in each scenario. This shows that agroforestry has a huge – albeit quite uncertain - potential to contribute to climate change mitigation in agriculture. A sensitivity analysis of +/-20% of the C-sequestration potential correspondingly results in correspondingly higher and lower values, i.e. spanning about 25-85% or 50-120%. To lower the ranges of these estimates, better data would be needed, but the results here are in live with the estimates of Kay et al. 2019, which are based on the same values, but implemented in simpler types of scenarios not covering the whole food system.

It is however important to emphasize that carbon sequestration in woody biomass is both non-permanent and comes with a saturation dynamic – it thus cannot replace true emission reduction strategies, as otherwise, the net mitigation effect would vanish after reaching a new equilibrium of carbon stored in the biomass or in case the tree biomass is lost, e.g. due to heavy draught, pest- and disease-outbreaks or fires. The mitigation potential strongly reacts to the share of agroforestry implemented and the size of the tree component on agroforestry areas, and high shares in each clearly result in highest sequestration values.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773901.

percentage value relative to the baseline 2012

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
GHG emissions - animals, enteric ferment. (t CO2e)	low (default)	93%	53%	55%	50%	51%	54%	47%	54%	55%	51%	A
	high	93%	54%	55%	51%	52%	54%	49%	54%	56%	52%	A
GHG emissions - animals, manure management (t CO2e)	low (default)	101%	53%	55%	50%	52%	54%	48%	54%	55%	51%	A
	high	101%	55%	56%	52%	53%	55%	50%	55%	56%	53%	A
Total GHG emissions - animals (t CO2e)	low (default)	95%	53%	55%	50%	52%	54%	47%	54%	55%	51%	A
	high	95%	54%	56%	51%	52%	55%	49%	55%	56%	53%	A
Tot GHG em - crops/grass, no Defor/OrgSoils (t CO2e)	low (default)	124%	92%	96%	85%	90%	95%	83%	93%	97%	86%	A
	high	124%	94%	98%	89%	93%	97%	86%	95%	98%	90%	A
Tot GHG em - crops/grass, with Defor/OrgSoils (t CO2e)	low (default)	113%	98%	100%	94%	97%	100%	93%	98%	100%	95%	A
	high	113%	99%	101%	96%	98%	100%	95%	99%	101%	97%	A
Tot GHG em - all act, no Defor/OrgSoils (t CO2e)	low (default)	104%	65%	68%	61%	64%	67%	59%	66%	69%	62%	A
	high	104%	67%	69%	64%	65%	68%	61%	68%	70%	65%	A
Tot GHG em - all act, with Defor/OrgSoils (t CO2e)	low (default)	104%	76%	78%	72%	74%	77%	70%	76%	78%	73%	A
	high	104%	77%	78%	74%	75%	78%	72%	77%	79%	75%	A
C sequestered in woody biomass (tC)	low (default)	-	44%	27%	71%	43%	26%	67%	45%	27%	72%	C_0-1
	high	-	44%	27%	71%	43%	26%	67%	45%	27%	72%	C_0-1
The following : Scenario value relative to scenario total GHG emissions value (incl. Defor/org soils)												
C sequestered in woody biomass (tC)	low (default)	-	58%	35%	98%	57%	34%	95%	59%	35%	99%	C_0-1
	high	-	57%	34%	95%	57%	34%	93%	58%	34%	96%	C_0-1

percentage value relative to the reference 2050

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
GHG emissions - animals, enteric ferment. (t CO2e)	low (default)	100%	57%	59%	54%	56%	58%	51%	58%	60%	55%	A
	high	100%	58%	60%	55%	56%	59%	53%	59%	60%	57%	A
GHG emissions - animals, manure management (t	low (default)	100%	52%	54%	49%	51%	54%	47%	53%	55%	50%	A
	high	100%	54%	55%	51%	52%	55%	49%	54%	56%	52%	A
Total GHG emissions - animals (t CO2e)	low (default)	100%	56%	58%	52%	54%	57%	50%	56%	58%	53%	A
	high	100%	57%	58%	54%	55%	57%	52%	57%	59%	55%	A
Tot GHG em - crops/grass, no Defor/OrgSoils (t CO2e)	low (default)	100%	74%	78%	69%	73%	77%	67%	75%	78%	70%	A
	high	100%	76%	79%	72%	75%	78%	70%	77%	80%	73%	A
Tot GHG em - crops/grass, with Defor/OrgSoils (t	low (default)	100%	87%	89%	84%	86%	88%	83%	87%	89%	84%	A
	high	100%	88%	89%	85%	87%	89%	84%	88%	89%	86%	A
Tot GHG em - all act, no Defor/OrgSoils (t CO2e)	low (default)	100%	63%	65%	59%	61%	65%	56%	63%	66%	60%	A
	high	100%	64%	66%	61%	63%	65%	59%	65%	67%	62%	A
Tot GHG em - all act, with Defor/OrgSoils (t CO2e)	low (default)	100%	73%	75%	69%	72%	74%	68%	73%	75%	70%	A
	high	100%	74%	75%	71%	73%	75%	69%	74%	76%	72%	A
C sequestered in woody biomass (tC)	low (default)	-	42%	26%	68%	41%	25%	64%	43%	26%	69%	C_0-1
	high	-	42%	26%	68%	41%	25%	64%	43%	26%	69%	C_0-1
The following : Scenario value relative to scenario total GHG emissions value (incl. Defor/org soils)												
C sequestered in woody biomass (tC)	low (default)	-	58%	35%	98%	57%	34%	95%	59%	35%	99%	C_0-1
	high	-	57%	34%	95%	57%	34%	93%	58%	34%	96%	C_0-1

Figure 38: GHG emissions of the crop and livestock sector and total, as well as C sequestration in woody biomass, relative to the baseline (top) and to the reference 2050 (bottom). C sequestered in woody biomass reports the additional C sequestered in the trees in agroforestry, hence no values for 2050 are reported Furthermore, the values reported there are in relation to total GHG emissions (incl. deforestation and organic soils) in the baseline or reference scenario 2050 (fourth and third last rows) and in relation to the total GHG emissions (incl. deforestation and organic soils) in each scenario (second to last and last row).

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4.6.6. **Further environmental indicators**

Finally, we report on a number of other environmental indicators. For irrigation water use, CED, erosion and pesticide use index, a main driver is a shift in the scenarios from cereal and forage crops (feed for ruminants) towards more vegetable and fruit crop areas, which result in higher water demand and pesticide use. Agroforestry reduces irrigation water needs and organic agriculture reduces pesticide use, but to the extent implemented, this cannot compensate for the increases in water requirements and only somewhat regarding pesticide use due to changed cropping patterns (Figure 39). However, AF helps to mitigate these impacts but in any case, irrigation water and pesticide use is something to focus on when shifting towards future food system options with increased vegetable and fruit shares.

percentage value relative to the baseline 2012

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
Irrigation water (m3)	low (default)	132%	125%	130%	117%	130%	133%	126%	123%	129%	113%	A
	high	132%	128%	132%	121%	133%	135%	131%	126%	131%	118%	A
Irrigation water (m3) - water stress adjusted	low (default)	136%	135%	140%	129%	140%	143%	136%	135%	140%	127%	A
	high	136%	138%	141%	132%	142%	144%	140%	137%	141%	131%	A
Total CED (MJ)	low (default)	98%	106%	108%	104%	105%	107%	102%	107%	108%	105%	A
	high	98%	107%	108%	105%	105%	107%	103%	107%	108%	106%	A
Soil water erosion (t soil lost)	low (default)	111%	80%	88%	67%	80%	88%	68%	80%	88%	66%	A
	high	111%	80%	88%	67%	80%	88%	68%	80%	88%	66%	A
Aggreg. Pest. use level (index)	low (default)	113%	90%	91%	89%	93%	93%	94%	89%	91%	87%	A
	high	113%	90%	91%	89%	93%	93%	94%	89%	91%	87%	A

percentage value relative to the reference 2050

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
Irrigation water (m3)	low (default)	100%	94%	99%	89%	99%	101%	96%	93%	98%	86%	A
	high	100%	97%	100%	92%	101%	103%	99%	95%	99%	89%	A
Irrigation water (m3) - water stress adjusted	low (default)	100%	100%	103%	95%	103%	105%	100%	99%	103%	93%	A
	high	100%	101%	104%	97%	104%	106%	102%	100%	104%	96%	A
Total CED (MJ)	low (default)	100%	109%	110%	107%	107%	109%	104%	109%	110%	108%	A
	high	100%	109%	110%	108%	108%	109%	105%	110%	111%	109%	A
Soil water erosion (t soil lost)	low (default)	100%	72%	79%	60%	72%	79%	61%	72%	79%	60%	A
	high	100%	72%	79%	60%	72%	79%	61%	72%	79%	60%	A
Aggreg. Pest. use level (index)	low (default)	100%	80%	81%	79%	83%	83%	83%	79%	80%	77%	A
	high	100%	80%	81%	79%	83%	83%	83%	79%	80%	77%	A

Figure 39: Irrigation water use, Cumulative Energy Demand, Soil wter erosion and pesticide use index; relative to the baseline (top) and to the reference 2050 (bottom).

NH3 emissions are substantially reduced in the agroforestry scenarios, mainly due to the reductions in livestock numbers, but also due to the beneficial effect of agroforestry on NH3 emissions, as can be seen from the values on area based NH3 emissions (Figure 40). In this, agroforestry can contribute importantly to reaching NH3 reduction goals.

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percentage value relative to the baseline 2012

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
NH3 emissions - areas (tNH3)	low (default)	119%	79%	85%	71%	78%	84%	69%	80%	85%	72%	A
	high	119%	81%	86%	74%	80%	85%	72%	82%	86%	75%	A
NH3 emissions - animals (tNH3)	low (default)	94%	48%	50%	43%	46%	50%	41%	48%	51%	44%	A
	high	94%	49%	51%	45%	47%	50%	43%	49%	51%	46%	A
NH3 emissions - total (tNH3)	low (default)	101%	56%	59%	50%	55%	59%	48%	56%	60%	51%	A
	high	101%	57%	60%	53%	56%	59%	50%	58%	61%	53%	A

percentage value relative to the reference 2050

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
NH3 emissions - areas (tNH3)	low (default)	100%	66%	71%	59%	65%	70%	58%	67%	71%	60%	A
	high	100%	68%	72%	62%	67%	71%	60%	69%	72%	63%	A
NH3 emissions - animals (tNH3)	low (default)	100%	51%	54%	46%	49%	53%	44%	51%	54%	47%	A
	high	100%	52%	54%	48%	50%	54%	46%	52%	55%	49%	A
NH3 emissions - total (tNH3)	low (default)	100%	56%	59%	50%	54%	58%	48%	56%	59%	51%	A
	high	100%	57%	60%	52%	56%	59%	50%	57%	60%	53%	A

Figure 40: NH3 emissions; relative to the baseline (top) and to the reference 2050 (bottom).

As a last indicator we analyze nitrogen surplus as defined by the OECD, i.e. total N inputs to areas (mineral fertilizer, crop residues and manure, as well as N fixation and N deposition and N in seeds) minus total N output in biomass production. The general pattern is one of drastic reduction in N inputs due to reduced feed imports and thus manure quantities and reduced mineral fertilizer use. This results in a nitrogen deficiency in all scenarios (Figure 41). This is a key aspect of low external input and more localized food systems that can also be observed in assessment of large-scale implementation of organic agriculture (Barbieri et al., 2021; Muller et al., 2017) (Muller et al. 2017, Barbieri et al. 2021). The nitrogen deficit in absolute numbers amounts to about 9.5 million tN in the AF scenarios considered, which is about 3 times the biological nitrogen fixation in these scenarios. The total nitrogen fixation in the scenarios (both on croplands and grasslands) is about 30% higher than in the reference scenario for 2050 and the areas with N fixing plants are at a share of about 9% overall in the scenarios (25% on the organic areas). Thus, there is some room for improvement regarding this, but adequate N supply remains a key challenge of more sustainable food systems that build on reduced feed crop production and low external input systems. Besides increased N fixation, there is considerably potential for additional N supply from better closed N cycles (e.g. recycling N in human excreta, etc.). Finally, there is also potential to use more mineral fertilizers to close this gap, which quantities, due to the 25% share of organic agriculture are already considerably below the levels reported in the baseline or reference scenario for 2050.

Thus, the problem of adequate N supply of these systems seems not unresolvable, but it remains in any case a key challenge to put particular focus on, also e.g. in the context of the 25% organic area share goal of the farm to for strategy of the European Commission.

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percentage value relative to the baseline 2012

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
OECD N balance: inputs (tN)	low (default)	115%	47%	48%	44%	46%	48%	42%	47%	48%	45%	A
	high	115%	47%	49%	46%	46%	48%	44%	48%	49%	46%	A
OECD N balance: outputs (tN)	low (default)	115%	105%	109%	99%	103%	107%	95%	106%	109%	101%	A
	high	115%	107%	110%	103%	105%	109%	99%	108%	111%	105%	A
OECD N balance: Inputs - outputs (tN)	low (default)	113%	-198%	-205%	-186%	-194%	-203%	-180%	-200%	-206%	-189%	A
	high	113%	-203%	-209%	-195%	-199%	-206%	-188%	-205%	-210%	-198%	A
OECD N balance per ha (tN/ha)	low (default)	107%	-188%	-195%	-177%	-185%	-193%	-171%	-190%	-196%	-180%	A
	high	107%	-193%	-198%	-185%	-189%	-196%	-179%	-195%	-199%	-188%	A
below: absolute values												
OECD N balance per ha (tN/ha)	low (default)	0.027	-0.047	-0.049	-0.044	-0.046	-0.048	-0.043	-0.047	-0.049	-0.045	E
	high	0.027	-0.048	-0.049	-0.046	-0.047	-0.049	-0.045	-0.049	-0.050	-0.047	E

percentage value relative to the reference 2050

	Yield level in AF	Ref. 2050	AF scenarios									
Tree/crop ratio			medium			low			high			
Share AF areas			medium	low	high	medium	low	high	medium	low	high	Scale
OECD N balance: inputs (tN)	low (default)	100%	41%	42%	39%	40%	41%	37%	41%	42%	39%	A
	high	100%	41%	42%	40%	40%	42%	38%	42%	43%	40%	A
OECD N balance: outputs (tN)	low (default)	100%	91%	94%	86%	89%	93%	83%	92%	95%	88%	A
	high	100%	93%	96%	89%	91%	94%	86%	94%	96%	91%	A
OECD N balance: Inputs - outputs (tN)	low (default)	100%	-175%	-182%	-165%	-172%	-180%	-159%	-177%	-183%	-167%	A
	high	100%	-180%	-185%	-173%	-176%	-183%	-166%	-182%	-186%	-175%	A
OECD N balance per ha (tN/ha)	low (default)	100%	-175%	-182%	-165%	-172%	-180%	-159%	-177%	-183%	-167%	A
	high	100%	-180%	-185%	-173%	-176%	-183%	-166%	-182%	-186%	-175%	A
below: absolute values												
OECD N balance per ha (tN/ha)	low (default)	0.027	-0.047	-0.049	-0.044	-0.046	-0.048	-0.043	-0.047	-0.049	-0.045	E
	high	0.027	-0.048	-0.049	-0.046	-0.047	-0.049	-0.045	-0.049	-0.050	-0.047	E

Figure 41: Nitrogen balance; relative to the baseline (top) and to the reference 2050 (bottom).

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5. DISCUSSION AND CONCLUSIONS

We here present the first assessment of 432 scenarios for the EU in the year 2050 in which different combinations of conventional and agro-ecological farming and eating practices are modelled as well as a complementary analysis of 36 scenarios (with additional sensitivity analysis on one parameter) of agroforestry futures in the EU in 2050. In doing that, we went one step further from Deliverable 4.2 where we did not model agro-ecological farming practices in detail. Furthermore, we extend and refine the agro-ecological scenario from Poux and Aubert (2018) through a higher spatial resolution and the provision of a large range of detailed combinations of different agro-ecological and conventional parameter variants for e.g. cropland and grassland production or livestock feeding ratios. However, in this deliverable we do not specify how to reach these scenarios, but instead focus on the land feasibility of these scenarios and their socio-economic and environmental impacts.

The main results gained from this deliverable show that a range of future agro-ecological scenarios are land feasible and that many environmental benefits can be released if agricultural systems adopt wide-ranging changes that include several innovations from the plot to the food-systems level. Diets also play a crucial role since they determine the total size of the food system, but in all agro-ecological scenarios are feasible and even provide enough food and feed biomass if EU-wide diets follow a business-as-usual trajectory. This is an important insight since a paradigm shift within the European Union could be observed through e.g. the farm to fork strategy, which aims to transform the focus from solely food production towards securing ecosystem services and maintaining cultural landscapes. Though, still many challenges towards truly sustainable farming and food consumption systems persist. The central policy instrument to guide food production in the European Union towards a pathway which integrates food production with environmental protection and a reduction of negative impacts is the Common Agricultural Policy (CAP). Lately, the CAP reform for 2021-2027, where the legislative proposal had been discussed within the first trilogue in November 2020, presents eco schemes as its key innovation. They aim to incentivise sustainable farming practices and could include agro-ecological farming practices within Pillar 1 direct payments. Eco schemes are supposed to be mandatory for EU member states but with the possibility to plan their own innovations which allow a national and regional adaption (Lampkin et al., 2020). Thus, regional differentiation is important to identify which practices are best suited for all regions and where specific actions within the assessed strategies may be needed to curb local stronger adverse effects.

Agro-ecology is not a straightforward and precisely defined concept, and there is still an intense and controversial debate about individual topics that range from plot-based agricultural management to the wider socio-economic and cultural context (Migliorini et al., 2020). Agro-ecological farming systems, as implemented in BioBaM_GHG_EU and Solm (via agroforestry) in this deliverable, take up several sustainable and innovative production and consumption patterns, which are derived from the UNISECO case studies and scientific literature. We then upscaled individual or combined practices to the territorial (i.e. EU-wide) level to show the impacts of a wide-spread adoption across the EU. We clearly see that the consumption-side (i.e. food consumption, and especially the consumption of animal products) is a major driver of changes in production changes as well as more sustainable human diets which contain less animal products. Both changes open up room for the implementation of innovative production measures through an overall reduction of the size of the food systems measured in total land use and in particular in total biomass production. If diets in the European Union change towards a diet which is proposed in a large-scale expert panel (Willett et al., 2019), agro-ecological production measures are feasible without overstretching domestic agricultural land and avoiding deforestation. Clearly, a reduction in the total size of the agri-food system would under the current subsidy and price regime lead to less income for farmers, clearly not a feasible option. Thus, a much better integration and remuneration of the protection of ecosystem services and environmental and landscape protection must be a central part of the new common agricultural policy, as well as stricter regulations for harmful but avoidable agricultural practices that deviate from goals outlined in e.g. the Farm to Fork or the new EU biodiversity strategy. These findings strongly underline the necessity of systemic, food-systems approaches towards agro-ecology to avoid negative trade-offs from the territorial adoption of agro-ecological agri-food systems (Fuchs et al., 2020) and release socio-economic and environmental synergies.

We have allowed for additional synthetic nitrogen fertilizers in agro-ecological farming systems, which is a major difference to current organic systems in the European Union, and have quantified the additional demand for synthetic nitrogen fertilizers in this deliverable. We consider such an approach as a central aspect for currently conventional farmers to adopt agro-ecological farming practices without having the responsibility to adopt all other regulations that are necessary to be certified as organic. Clearly, the price premium for organic products compensates for the transaction costs invoked by a shift towards organic farming, but literature has shown that agro-ecological products also have the potential to be economically viable through higher gross margins for such products (van der Ploeg et al., 2019).

Freeing up agricultural areas through an overall reduction in the size of the food system would allow for a range of positive effects on the environment. These are (extended and modified): 1) generally for the production of food, for example more food legumes in crop rotations to enhance N provision for subsequent crops; 2) general extensification of arable farming by e.g. establishing integrated production, organic or agroforestry systems. 3) qualitative protection of habitats and establishment of habitat corridors or in general more biodiversity-friendly cultivation systems and measures (e.g. hedges). 4) reinforcement of water protection goals, especially in areas with nitrate problems in groundwater bodies or eutrophication, or challenges in surface waters, e.g. through the implementation of adequate riparian strips or reduction of fertilizer quantities in land use (extensification). 5) expansion of nature reserves especially in areas that are valuable in terms of nature conservation, rewetting of bog soils by contract nature conservation by the farmers. 6) at marginal yield sites, enable natural succession for extensification or even renaturation and naturalization of ecosystems to preserve room for species and habitats of particular importance (open process protection), for example for large mammals such as bears, lynxes or wolves.

Notwithstanding, if the EU is to undergo a full conversion towards agro-ecological production on all croplands and grasslands, including animal production, agricultural production will become less “efficient” in terms of the production output from agricultural land. As a result, the European Union is becoming a net-importer of cropland products in all agro-ecological scenarios due to surplus production in non-EU regions, despite having potential unused agricultural land within the European Union, which nevertheless converts to forests (carbon mitigation) or is left fallow and thus can provide positive environmental benefits. Consequently, the EU might then face strong and adverse pressure from comparably cheaper products from beyond the European Union which push into the EU agrarian markets under a free-trade paradigm. Thus the EU needs to find the delicate balance between strengthening domestic agro-ecological production, trade regulations which avoid competition with products that are produced with much less regulations and drive deforestation (Fuchs et al., 2020). Policy makers thus are urgently asked to provide legal and regulatory conditions to secure EU agricultural production and the livelihoods of domestic farmers, as well as to maintain the viability of key agricultural markets. Here, an adequate and well implemented farm-to-fork strategy will become central.

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Furthermore, CAP payments should both support farmers income and the transition towards more sustainable farming systems strengthening labour force (e.g. through payments per agricultural working unit) and the provision of ecosystem services in agricultural systems (Lampkin et al., 2020). To conclude, without any protective measures, and subject to the free-trade order of the world trade organization, dynamics beyond the European Union are likely to strongly impact domestic market dynamics. Further economic assessments thus need to consider this impact to be able to provide meaningful results for EU-wide policy making.

This deliverable provides a large number of possible agro-ecological agri-food system futures in the European Union. The key interest was to upscale agro-ecological farming practices to the territorial level, and while we have a sub-national spatial resolution, we did not yet fully incorporate regional pedo-climatic, socio-economic and farming systems (e.g. farm size and structure) specific characteristics. Still, the main focus of this deliverable was to assess the impacts of a large-scale implementation of agro-ecological agri-food system characteristics in the EU. Therefore, the results from this deliverable provides essential information for policy makers from the EU to the regional level to see which practices are promising to deliver benefits on the farm level and beyond.

- The overall size of the food system is a strong determinant for the potential to increase agro-ecological farming practices
- The current amount of livestock production needs to be reduced in order to remain within current agricultural land endowment in the future
- Linking livestock production to cropland (monogastrics) and grassland (ruminants) potentials within the EU, and in combination with innovative livestock diets, is able to re-balance nutrient supply and demand at the sub-national scale.
- An increase in land under agro-ecological practices and a reduction of GHG emissions is possible within the EU in the year 2050. A particular potential for climate change mitigation can be realized with agroforestry and the related carbon sequestration in woody biomass, which can amount to compensation of significant shares of GHG emissions of future agriculture.
- Agro-ecological practices such as undersowing cereals with leys and clover allows to reduce synthetic nitrogen fertilizers and provide roughage for ruminant livestock and also reduces grazing intensities on grasslands
- Reducing grazing intensities on high natural value farmland is possible without the risk of shortages in grass supply for domestic ruminant livestock.
- In all agroecological scenarios, adequate nutrient supply is a challenge that has to be addressed explicitly. One approach is to resolve it with additional use of mineral fertilizers, or also with increased legume shares or also better closed nutrient cycles, e.g. utilizing the nutrients in human excreta. In any case do the nitrogen use levels stay well below the use levels of the baseline and reference scenarios, thus in any case leading to considerably improvements regarding nutrient surplus.

The European Union is one of the leading global player in terms of the production of food which is produced under strong environmental and social regulations. Nevertheless, current practices and the total size of agri-food system still need much improvement if the farm-to-fork strategy and the EU plans for maintaining biodiversity, as well as the Paris agreement should be reached. Thus policy makers at the EU-level can make use of such information provided in this deliverable to re-formulate agricultural policy to align agricultural production in the EU with the aforementioned goals and to secure long-terms food security in the European Union. Regional policy makers have the regional knowledge to gauge which innovations are best suited for a specific region and can now better contextualize these changes within the larger EU agri-food system. Ultimately and in a best-case scenario, this report helps to strengthen the agro-ecological transition, from farmers to consumers, through the provision of quantitative information about the territorial impacts if their innovative and sustainable practices are upscaled and widely adopted within the European Union.

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