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# Exploring the option space for land system futures at regional to global scales: The diagnostic agro-food, land use and greenhouse gas emission model BioBaM-GHG 2.0

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ABSTRACT

Close to 40% of Earth's land area is used for agriculture to provide humankind with plant- and animal-based food, fibers or bioenergy. Future trends in agricultural land use, livestock husbandry and associated environmental pressures are determined by developments in the food sector, agricultural productivity, technology, and many other influencing factors. Scenario analysis helps to understand their complex interaction and obtain quantitative insight. We here present an in-depth description of the agricultural land use model BioBaM-GHG 2.0 ("BioBaM"), designed for evaluating large numbers of agricultural and livestock production scenarios assembled on the basis of exogenous assumptions on food systems, crop yields and other factors. BioBaM determines the feasibility of specific parameter combinations and the corresponding greenhouse gas (GHG) emissions from agricultural activities, livestock husbandry, land-use change and other activities. We provide a description of the software environment, the model's data structures, input and output variables and model algorithms. To illustrate the model's capabilities and the scope of model applications, we describe two exemplary studies performed with BioBaM: We assess implications of agro-ecological innovations and the feasibility of their widespread application in order to illustrate their implications in terms of agricultural self-sufficiency and GHG emissions. This first case study aligns a small number of individual scenarios with qualitative storylines. We also showcase a "biophysical option space approach", which represents a comprehensive sensitivity analysis regarding the multidimensional uncertainties inherent to main influencing parameters, i.e. projections for diets and yields; assumptions on cropland use for bioenergy, and regarding grassland intensification. The global potential of forest regeneration for climate change mitigation serves as an example for this second approach. The option space comprises 90 scenarios and encompasses the full range of literature estimates on GHG mitigation from afforestation in 2050 (0.5 – 7 Gt $CO_2$/yr). It further shows that the potential is zero under certain diet-yield-combinations. Assuming zero energy crop cultivation and global convergence to a healthy reference diet, the sequestration potential of afforestation rises to 10 Gt $CO_2$/yr in 2050. These exemplary applications illustrate how option spaces developed with BioBaM can complement scenario-based assessments that usually focus on small numbers of individual scenarios: Option spaces shift attention to a wider scope of conceivable futures and thus support a comprehensive view on systemic relations and dependencies, whereas analyses with few scenarios allow apprehension of much more detailed scenario narratives and qualifications.

## 1. Introduction

### *1.1. Purpose and scope of agricultural land-use modelling*

Over the last 300 years, global agricultural land has expanded fivefold (Ramankutty et al., 2018) and today accounts for close to 40% of Earth's land area (FAO, 2021). Agriculture has been the main cause for deforestation (Garcia et al., 2020; Kissinger et al., 2012; Williams, 2006), and has also become a major contributor to environmental degradation (Springmann et al., 2018; Steinfeld et al., 2006; Tilman,

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1999; Willett et al., 2019) and climate change, causing about one fifth of today's annual anthropogenic greenhouse gas (GHG) emissions (Arneth et al., 2019; Vermeulen et al., 2012; WRI, 2021).

In scientific research on the prospective development and impacts of agriculture, scenario analysis has emerged as the major method to understand complex interactions between food systems, agricultural production and environmental pressures at various scales (see, e.g., Audsley et al., 2006; FAO, 2018; Poux and Aubert, 2018; Stürck et al., 2018; Wolf et al., 2015). Different modelling techniques are used for deriving scenarios, including empirical-statistical, process- or agent-based approaches (Lambin et al., 2000). Economic optimization and equilibrium models are most widely applied in the scientific literature. Prominent examples for economic models include the GAPS model (Global Agriculture Perspectives System; Kavallari et al., 2016) used for deriving the scenarios of the Food and Agricultural Organization of the United Nations (FAO, 2018) and the CAPRI model (Common Agricultural Policy Regionalised Impact Analysis Model; Britz and Witzke, 2014) developed for assessing domestic and global effects of the European Union's Common Agricultural Policy (e.g. Britz and Hertel, 2011; Pelikan et al., 2015; Wolf et al., 2015). Other important models include IMAGE (Rose et al., 2011; Stehfest et al., 2009), GLOBIOM (Havlik et al., 2018, 2013; Valin et al., 2013) and MAgPIE (Dietrich et al., 2020; Lotze-Campen et al., 2010), which are parts of larger modelling frameworks called "Integrated Assessment Models" (IAMs), and the IMPACT model of the International Food Policy Research Institute (Robinson et al., 2015).

Fig. 1 illustrates the scope and purpose of the agricultural land-use models as understood in the present context. Based on exogenous drivers like dietary changes, population or economic development, the demand for agricultural commodities, comprising crops and agricultural products like meat or vegetable oil is determined (demand side). Future developments of the relevant drivers are often adopted from authoritative studies, or diverse pathways reflecting different expectations or world views are contrasted against each other, as in the case of the Shared Socio-Economic Pathways (SSPs, see O'Neill et al., 2017; Roe et al., 2019). The production side, on the other hand, is modelled on the basis of parameters like land cover, crop yields, agricultural practices (e.g. conventional/organic farming) etc. Established models like GLOBIOM and MAgPIE feature spatially explicit representations of land and are capable of modelling land-use change based on economic considerations. A core characteristic of such agricultural land-use models is how a balance between demand and supply is established. In economic partial equilibrium models like the abovementioned, this is achieved through endogenous adjustments in market prices that ultimately lead to equality between supply and demand for each product (Havlik et al., 2018). Economic parameters like regionally diverse production costs and demand elasticity's influence the quantities and location of agricultural production and consumption. Usually, assessing the impacts of agricultural production, e.g. greenhouse gas (GHG) emissions, land-use change or derived parameters such as water consumption for irrigation represent the core aims of scenario development. Further scenario-specific implications, such as trade patterns, changes in regional self-sufficiencies are a direct outcome of the demand-supply balancing algorithms.

BioBaM, abbreviated for Biomass Balance Model, was designed as a biophysical accounting model that calculates the balance between biomass supply and biomass demand (Erb et al., 2009a). It follows a "diagnostic approach" (Erb et al., 2016) based on exogenous trajectories for demand (i.e. fixed demand, as opposed to price elastic demand usually implemented in economic models) and scenario-specific restrictions on, or limitations to land-use change. Such restrictions include regulatory aspects (e.g., protected areas) and biophysical framework conditions (e.g., suitability of grazing areas for crop production), and can further reflect specific research questions (e.g., which projections for diets are feasible in a world without further expansion of cropland areas?). The original focus of BioBaM was on determining the feasibility of various dietary projections with future land use and production patterns according to scenarios from authoritative institutions, especially the Food and Agriculture Organization of the United Nations (see FAO, 2018); the feasibility was determined by a mass-balance approach.

### 1.2. Development history and design principles of BioBam

The original version of BioBaM ("BioBaM 1.0"; Erb et al., 2009) was based on three consistent and spatially explicit databases for the year 2000 on land use (Erb et al., 2007), biomass flows from harvest to use (Krausmann et al., 2008) and human appropriation of net primary production (Haberl et al., 2007a). It was used, amongst others, to assess global biomass potentials for bioenergy (Erb et al., 2012; Haberl et al., 2011, 2010) and future option spaces for food and agriculture (Erb et al.,

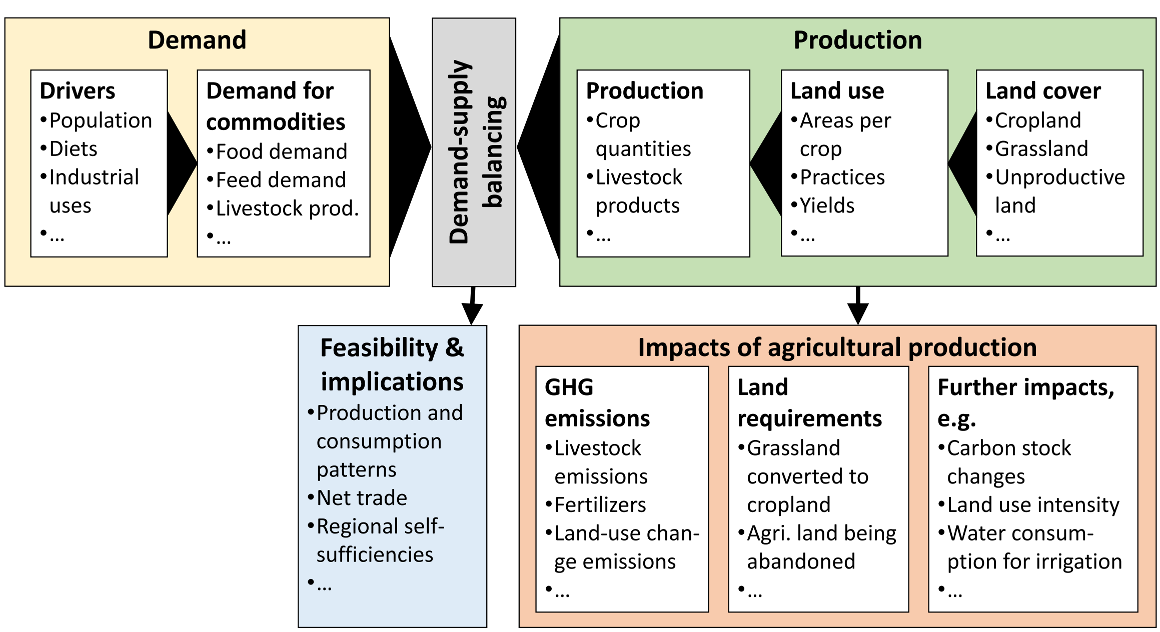


**Fig. 1.** Schematic illustration of the scope of agricultural land-use modelling (authors' own illustration).

2016). By combining various projections for crop variants (yields), livestock efficiencies, human diets etc. under different limitations for cropland expansion and grazing intensity, it was used to calculate global biomass supply-demand balances for 500 scenarios of the global agro-food system in 2050 (Erb et al., 2016). The results were combined to a biophysical “option space” of feasible futures, in which demand for cropland products matches supply by at least 95% (considering a 5% uncertainty range) and grazing intensities on grassland (the ratio of grazed or mowed biomass to actually prevailing net primary productivity) stay below ecological thresholds.

BioBaM 1.0 was entirely implemented in Microsoft Excel, had rigid data structures comprising, for example, 11 world regions and 14 biomass demand categories (see, e.g., Erb et al., 2016), and accounted for a limited number of environmental pressures, such as land-use intensity and total biomass appropriation, but not for key pressures and impacts such as GHG emissions. BioBaM 1.0 produced “snapshot” (i.e. single-year) scenarios” and was designed to explore a broad range of conceivable futures, regardless of what is considered likely or desirable from the present perspective. Agricultural land was not allowed to encroach into forests (“zero deforestation assumption”) and trade quantities between world regions was computed solely on the basis of biophysical parameters and resulting supply and demand relations. In BioBaM 1.0, trade was not influenced by historical trade patterns–a core difference to economic models with similar scope as well as the Sustainability and Organic Livestock model SolM (Müller et al., 2020) that has been maintained to the current version of BioBaM.

BioBaM was subsequently expanded to include greenhouse gas (GHG) emissions from agricultural production, livestock husbandry and land-use change (LUC). Building on the option space developed in (Erb et al., 2016), the extended model (“BioBaM-GHG”) is suitable for feasibility assessments of global food system scenarios complemented with GHG balances. A study performed with BioBaM-GHG (Theurl et al., 2020b) shows that human and livestock diets are the main determinant of GHG emissions–with highest GHG emissions found for scenarios including high meat demand, especially if focused on ruminant meat and milk–, whereas gains in crop yields are of minor significance. Another application of BioBaM-GHG is presented in (Kalt et al., 2020), an assessment of global agricultural bioenergy potentials based on latest crop yield and diet scenarios issued by (FAO, 2018). By applying BioBaM-GHG, systemic GHG effects of providing agricultural biomass for energy, which are often overlooked in bioenergy potential assessments (Haberl, 2013), are quantified.

We here report on further developments towards BioBaM-GHG 2.0. These were motivated by three core aims: first, to provide flexibility in terms of geographical resolution (i.e. being able to develop scenarios on various scales, ranging from world regional to sub-national level), timeframes and milestone years (i.e. calculating scenario results for intermediate years, not just one specific target year, as in BioBaM 1.0), and data structures, such as the number and aggregates of considered crops and agricultural products, and their conversion processes (e.g. feed conversion rates of agricultural/animal products; FCRs); second, to support variations in model algorithms, reflecting different rationales of scenario development or addressing specific research questions (e.g. unimpeded global trade vs. self-sufficiency ambitions in specific regions; maintaining current regional production patterns of animal products vs. re-distribution based on, for example, biophysical potentials for ruminant grazing); and third, to implement the model in an adequate and efficient software environment that enables the calculation of large numbers of scenarios with high regional resolution, while maintaining easy-to-use input data handling and scenario management via standardized MS Excel worksheets.

BioBaM-GHG 2.0 represents the successful implementation of these aims. This paper provides a description of the software environment, its data structures, input and output variables and model algorithms (Methods section). To illustrate the scope of possible research questions, we further describe two exemplary model applications, discuss technical aspects of the respective approaches and present selected scenario results (Results section). A Discussion and Conclusions section concludes the main article. Comprehensive descriptions of input and output parameters as well as mathematical model descriptions are provided in the Supplementary Information (SI) to this article.

## 2. Methods

### 2.1. Concepts of scenario development

For illustrating the basic concepts of scenario development supported by BioBaM, we assume various exogenous data for 3 input parameters A, B and C (Fig. 2): The input data are generally differentiated by region and are time-dependant (i.e. represented by individual time series for each region). For example, parameter A may represent population development, B diets and C projections for crop yields; three variants are assumed for each input parameter in Fig. 2. The most common scenario approach in scientific literature is to develop a small number of individual scenarios (case a) where only certain combinations of parameter settings are considered. In contrast, the “option space approach” BioBaM is designed for (case b) is characterized by combining all available parameter settings, leading to large numbers of scenarios, because every particular combination of assumptions on all input parameters defines one “scenario”. The analysis of an option space can focus on the feasibility of the various scenarios (as in Erb et al., 2016), or certain quantitative results (such as total or disaggregated greenhouse gas emissions as dependent on variations of specific input parameters, as in Theurl et al., 2020), whereas the interpretation of single scenarios is usually not in focus of such studies.

For some parameters, only certain combinations of parameter settings are possible. For example, changes in livestock systems may imply different feed compositions as well as changes in manure management. In such situations, changes in feed composition and manure management parameters (e.g. emission factors) need to be coupled, resulting in a reduced option space where only certain parameter combinations of B and C are considered (see case c in Fig. 2). In this sense, case a, which is characterized by few individual scenarios with certain parameter combinations, can be understood as a special case of an option space where only coupled parameter settings occur. Although BioBaM is designed for large numbers of scenarios (up to several hundred scenarios) being calculated in parallel, it supports parameter coupling for all dynamic input data and can also be applied for calculating individual scenarios (see Section 3).

### 2.2. Software environment and data handling

The version of BioBaM presented here (BioBaM-GHG 2.0) was implemented in Mathworks MATLAB (Version R2018a) format, with data export from and import to MS Excel realized with VBA macros. Input data (see Fig. 3) include model run settings, structural settings (regional units, commodity definitions and their characteristics etc.), biophysical data like areas and crop yields, and various parameters for calculating impacts, primarily GHG emissions. The MATLAB code is structured into three phases: (1) initialization (including data import, data validity and completeness checks, interpolation etc.), (2) main model algorithm (calculating scenario results), and (3) post-processing (preparation of export tables, export to csv files). Exported data tables are arranged in a way suitable for pivot tables, in order to allow efficient and flexible data handling in MS Excel. Fig. 3 provides further information on the respective sub-routines; complete lists of input and results variables are provided in the SI.

### 2.3. Data structures

#### 2.3.1. Space

BioBaM supports three layers of geographical units (“Layer 1 – 3″). In

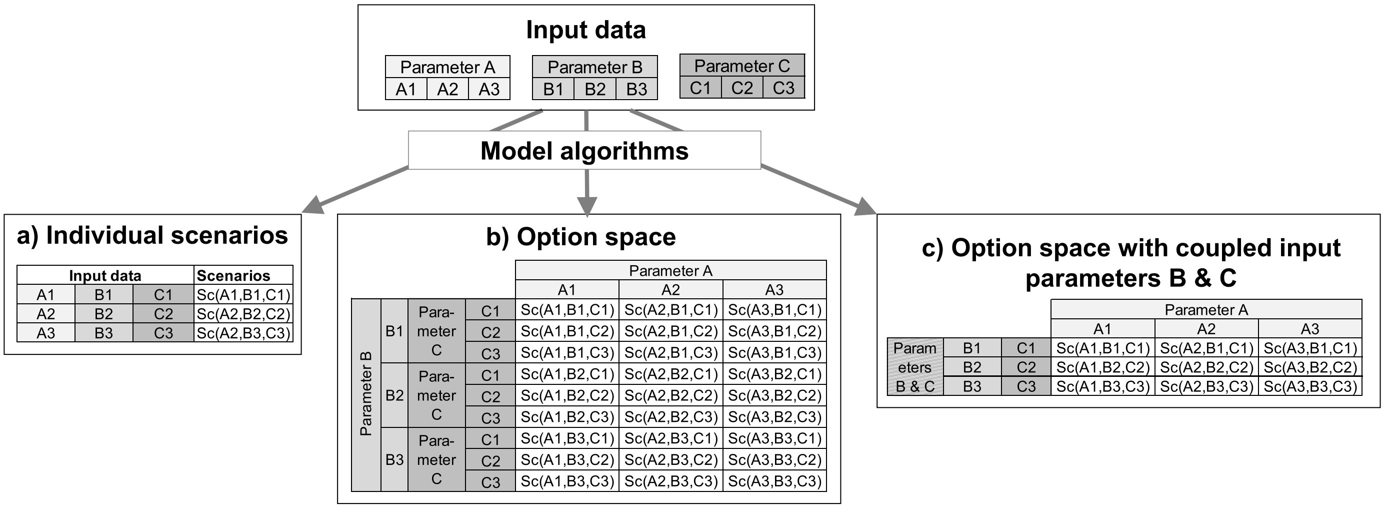


**Fig. 2.** Schematic illustration of different concepts of scenario development supported in BioBaM. *Sc*(axe,By,Cz) represents the entirety of the scenario resulting from the combination of parameter settings axe, By and Cz.

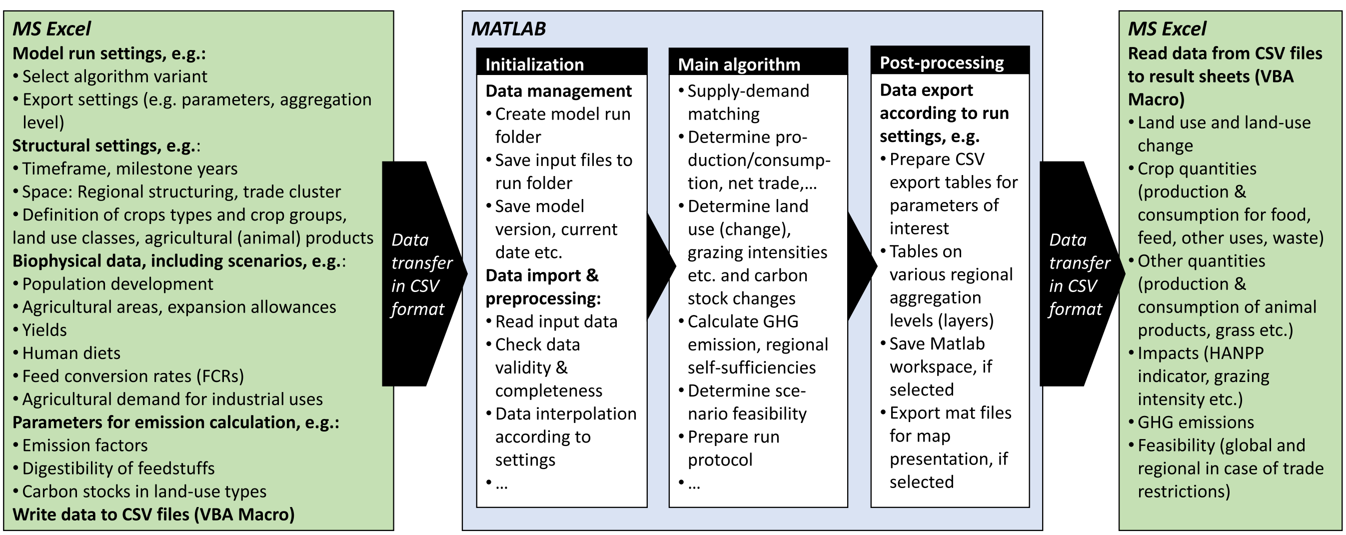


**Fig. 3.** Software interfaces and data management in BioBaM-GHG 2.0.

the present default dataset, these layers are sub-national administrative divisions (NUTS1/2 regions in the EU; Layer 3), countries and world regions. For Non-EU countries, currently no sub-national level data are available, thus the sub-national and the country-layer (Layer 2) are identical. The main model algorithms are performed on the highest geographic detail level; units on this level are referred to as “regions”, regardless of whether they correspond to sub-national divisions (as is the case for the EU) or countries (all Non-EU countries), and the structure of geographic layers as “region structure”. The main advantage of geographic layers is simplified input and output data handling: Most input data can be specified on either layer, in order to be inherited to the respective sub-units in the course of data pre-processing. For example, human diets are usually provided on country level, or data on manure management systems on world regional level (Layer 1), due to the absence of more detailed information. If needed, however, the model is capable of implementing specific data on Layer 2 or 3. Certain input data, such as agricultural areas or population must be provided on regional level since they are defining characteristics of each region (see SI for a full list of input parameters and their characteristics). Similarly, model results can be displayed for each element at all layers.

Further regional groupings that are entirely independent from the layered region structure are “trade clusters” and groups of regions for results evaluation. Trade clusters are groups of regions that maintain intensive trade relations (e.g. all NUTS2-regions within the EU); the definition of trade clusters (which is flexible and can be amended in concordance with particular research questions) influences production patterns and, in effect, regional trade balances for crops and agricultural products (see Section 2.4). Depending on the research question and scenario design, trade clusters may be identical to layers but can basically be defined as any aggregate of Layer 3 units. Trade within clusters is prioritized over imports from or exports to regions outside of the respective cluster. To emulate trade relationships at different levels, two layers of trade clusters may be defined (e.g., all sub-national regions of country as first layer, and international free trade areas as second layer).

Model results sometimes need to be interpreted for regional groupings that do not correspond to the regional layers (e.g. country groups representing Northern, Southern, Eastern and Western Europe, as in Röös et al., 2020). To make results readily available for any such groupings in the results sheets (especially ratio values or indicators that cannot be simply aggregated, like self-sufficiency or land-use intensity), it is possible to designate regional groupings for results evaluation.

### 2.3.2. Time

All calculations in BioBaM are performed on annual level. The timeframe is defined in the model settings by specifying a base year, a final year and optional intermediate years. For example, in the first application presented in Section 3.1, we considered one intermediate year (2030) between the base year (2012) and the final year (2050). Final and intermediate years are referred to as "scenario years"; all considered years as "milestone years". All model outputs are calculated for each milestone year. All exogenous input data must be provided for the base year. For the sake of convenience in input data handling, data input for intermediate years and the final year is optional, and missing values are filled during the initialization routine, based on inter-/extrapolation rules: If no scenario data are provided for a certain input parameter, base year data are assumed to remain constant. If input data are provided for at least two milestone years, the missing data are obtained through interpolation.

### 2.3.3. Commodities

With regard to crops, BioBaM differentiates between crop types and crop groups. For example, crop types are cultivar species like wheat and maize, which are grouped to the crop group "cereals". Parameters like yields, nitrogen contents or residue-to-crop ratios are defined on the level of crop types; for diets, feed conversion rates (FCRs) etc., crop groups are used. This allows for flexibility in diets/FCRs: depending on which crop types are available within the region or as imports, the composition of crop groups used as food or feed may vary. This approach aligns well with the level of detail used in typical reference diets in literature. Reference diets are usually composed of categories like cereals or roots, and do not specify crop species (despite differences in nutrient contents between crops types in such broad groups). The full list of crop types and crop groups implemented in the most recent version of the model is provided in the SI.

Besides crops, agricultural commodities represented in BioBaM include grass, crop residues (straw, stover etc.) and "agricultural products". Grass is produced on permanent and temporary grassland/grazing areas and on temporary cropland (i.e. fodder leys) and is – just like crop residues – an optional component of livestock diets (primarily of ruminants). Crop residues are characterized by crop-specific parameters (residue-to-crop-ratios, nitrogen contents and suitability as animal feed). Agricultural products are secondary commodities like meat and milk. They primarily include animal products but other commodities like liquid biofuels may also be modelled as agricultural products. A common feature of all agricultural products is that they are produced from primary commodities (crops, residues and/or grass) and thus characterized by exogenously defined primary commodity-to-product conversion factors. Livestock production is thus modelled as processes converting feed to specific products (cf. Bouwman et al., 2005; Herrero et al., 2013; Wirsenius, 2003). The conversion factors are in this context referred to as feed conversion ratios (FCRs) and correspond to exogenous defined livestock diets.

## 2.4. Model algorithms

The following sections explain the algorithms for matching crop supply with demand (Section 2.4.1), for modelling land-use change (2.4.2), and for determining regional production patterns of agricultural products like meat or milk (2.4.3). The calculation of GHG emissions is largely based on IPCC default methods and thus not explained in detail here (see SI for mathematical descriptions and specific data sources); $N_2O$ emissions are addressed briefly in connection with the methods regarding nitrogen cycles (Section 2.4.4).

The demand for agricultural commodities is determined by parameters such as population, diets and FCRs, which are dynamic and region-specific exogenous input data. Due to regional variations in production-side parameters (e.g. yields, FCRs), the regional distribution of production has an influence on total land requirements and resulting parameters like land conversion. The model algorithms for determining the regional distribution of agricultural production are thus central to all model outcomes. They are explained in the subsequent sub-sections.

### 2.4.1. Matching crop supply with demand

In BioBaM, the algorithms for determining production quantities and their regional distribution are exclusively based on biophysical parameters, such as agricultural areas, yields, FCRs, area expansion allowances etc. These are external input data obtained from statistical databases, spatial-explicit information, projections from authoritative studies, or self-derived scenario-specific assumptions (see Table S1 in the SI).[1] With crop demand being determined by exogenous data and run settings (distribution approaches), crop production is adjusted to demand situations by straightforward calculation steps based on regional production potentials (i.e. available cropland and regionally diverse yields). To be able to replicate future production patterns according to scenarios from authoritative institutions (e.g. FAO, 2018), BioBaM supports the definition of initial (ex-ante) production patterns. Implemented as exogenous cropland areas per region and crop, ex-ante cropland allocation serves as initial situation for adjusting production to demand in scenario years.

Fig. 4 shows a schematic illustration of the interrelations between exogenous input data and parameters calculated within the model. The calculations are performed for each region individually. Supply-side calculations (left part of Fig. 4) are performed on the level of crop types and aggregated to crop groups; demand-side calculations (right part) are entirely on crop group level, as diets and FCRs are defined on the basis of crop groups. The ex-ante crop group balance (the difference between ex-ante supply and demand; relevant on regional and global level) is a main parameter for the subsequent supply-demand matching algorithm. Ex-ante cropland allocation may be omitted altogether; it depends on the scenario design and the underlying narratives whether ex-ante allocation is indicated. For example, for a business-as-usual scenario where significant changes in production and trade patterns are considered unlikely, choosing constant ex-ante crop shares in each region makes sense. In contrast, a research question that depends on considering reduced international trade flows and more regional self-sufficiency can better be addressed without ex-ante allocation, as this results in stronger influence of regional demand on production patterns (see scenarios in Section 3.1).

Having determined the ex-ante crop group balance for each Layer 3 region, the supply-demand matching algorithm is executed. It attempts to bring supply and demand into equilibrium by simply adjusting crop production quantities within the limits of biophysical feasibility and cropland expansion allowances (exogenous data). The individual steps of the algorithm that is performed for each milestone year and each scenario in parallel, using multi-dimensional matrices, are explained in Table 1. Model run settings determine whether individual steps of the balancing algorithms are executed or not, thereby influencing crop production patterns. For example, preference for supply from within the region or within trade clusters can be deactivated, resulting in the steps 2, or 3 and 4, respectively, to be skipped; the program then proceeds directly to the next higher spatial level. At each spatial level, crop deficits are reduced as far as possible, by allocating area to the production of crops that are in deficit. This allocation is performed in a way that

[1] This is a major difference to (partial) equilibrium models, where crop supply and demand are brought into equilibrium by mimicking market mechanisms. The regional distribution of crop production in such models is determined by economic parameters, i.e. production costs linked to site-specific conditions such as crop yields and labor costs. Optimization algorithms ensure that supply meets demand at the lowest possible overall costs while respecting model- and/or scenario-specific constraints (e.g. maximum or minimum allowed area shares for each crop type, boundaries to self-sufficiencies, maximum change rates; see Dietrich et al., 2020; Havlik et al., 2018).

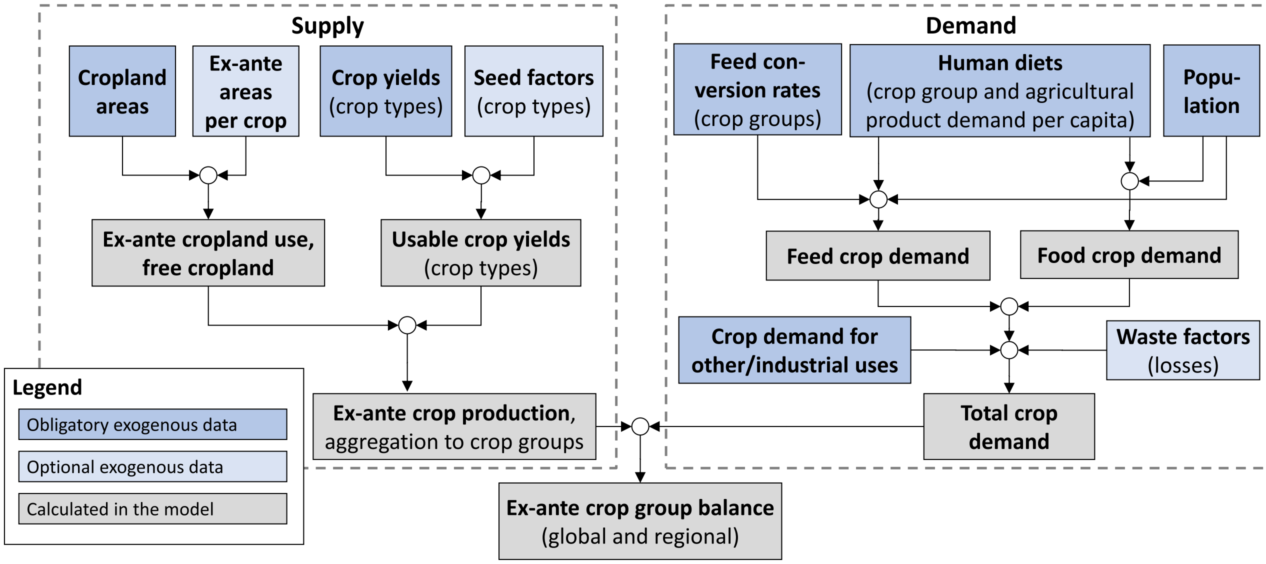


**Fig. 4.** Schematic illustration of basic calculation routines related to crop supply and demand. The result from this calculation, the ex-ante crop group balance, is the basis for the endogenous supply-demand matching algorithm.

**Table 1**
Main calculation steps of the supply-demand-matching algorithm in BioBaM-GHG 2.0.

| | Purpose and condition(s) | Applied algorithm |
|---|---|---|
| 1. | If global crop production resulting from ex-ante cropland allocation exceeds global demand, the oversupply is eliminated | Crop production is decreased by reducing the cropland area assigned to the crop group(s) that is/are in surplus; the reduction is distributed proportionally to the ex-ante production in each region |
| 2. | Check crop balance for each region (Layer 3) individually; increase intra-regional production if… (1.) ex-ante cropland allocation results in regional deficit and (2.) priority to regional supply is activated (exogenous scenario setting). | Intra-regional deficits are covered through additional intra-regional production up to the maximum possible extent, by utilizing all available cropland as well as grazing land denoted as suitable for crop cultivation; conversion to cropland may further be subject to scenario-specific limitations |
| 3. | Check crop balance for each trade cluster individually (at cluster level 1); increase production within clusters if… (1.) trade on cluster level 1 is activated (exogenous scenario setting), (2.) there are remaining crop deficits after step 2, and (3.) there are regions with unused cropland or land available for cropland expansion in the respective trade cluster. | To the extent that this is possible, deficits in regions belonging to a trade cluster are covered through additional production within the respective cluster (i.e. intra-cluster trade); as in step 2, cropland may be expanded within scenario-specific limitations |
| 4 | Same as step 3, but on cluster level 2. | |
| 5. | Check global crop balance; production is increased if… (1.) global trade is activated (exogenous scenario setting), (2.) there are remaining crop deficits after step 4 and (3.) there are regions with unused cropland or land available for cropland expansion. | Remaining crop deficits are to the extent possible covered through additional production in any region worldwide (i.e. global trade); as in step 2 and 3, cropland may be expanded within scenario-specific limitations |
| 6. | Check cropland feasibility | Scenario is denoted as "cropland feasible" if no crop deficit remains due to area limitations (either at the global scale, or at smaller-than-global scale, in combination with trade restrictions) |

does not prioritize certain crop groups over others; if insufficient cropland is available to cover the deficits of all crop groups at a certain spatial level, the allocation algorithm ensures that all deficits are reduced in equal shares. Finally (step 6), the allocation of crop groups to cropland in each region is definite. If crop deficits remain, the scenario is found to be infeasible.

### *2.4.2. Land use, land-use change and carbon stocks*

The following land-use categories are represented in the model: cultivated cropland, fallow cropland, grazing land (broken down by grassland classes of different productivity and grazing suitability; see Erb et al., 2016), and regenerated vegetation (forest, shrub land etc.) and unproductive areas (settlements/infrastructure) on areas formerly used as agricultural land. The representation of land in the base year is limited to cropland and grazing land, as deforestation for agricultural land expansion has so far been disregarded in model applications ("zero deforestation assumption"; see Erb et al., 2016).

Land use in the base year is exogenous and based on statistical databases and maps (e.g., (Erb et al., 2007; Eurostat, 2021; FAO, 2021, 2018). Land-use change in scenario years is determined by agricultural demand, land characteristics (e.g. suitability of grazing land as cropland) and scenario-specific assumptions, such as maximum allowed cropland expansion. Table 2 summarizes the relevant types of land-use change and their effects on carbon (C) stocks.

The calculation of C stock is based on the components biomass, litter and soil and largely consistent with IPCC methods and default parameters (e.g., soil and litter C stocks are assumed to require 20 years until they are in a new equilibrium state; annual amount of $CO_2$ emissions or removals resulting from this C stock change extending over a twenty-year period is, in accordance with IPCC Tier 1 principles, assumed constant). The currently implemented regional parameters are based on IPCC climate zones, ecosystem zones and soil maps (see IPCC, 2006; Batjes, 2010; FAO, 2012), and thus reflect regional variation in temperature, precipitation and soil types (see SI for a detailed explanation). Unproductive areas are only considered to reflect loss of agricultural land to built-up area, infrastructure etc. Vegetation regrowth is basically

**Table 2**
Land use and land-use change in BioBaM-GHG 2.0. Drivers for land use (change) and considered effects on carbon stocks (in italic letters). Methodological details regarding carbon stock changes are explained in the supplementary information.

| New LU → Former LU ↓ | Cultivated cropland | Fallow cropland | Grazing land | Unproductive areas | Regenerated vegetation |
|---|---|---|---|---|---|
| **Cultivated or fallow cropland** | Existing cropland required to cover crop demand; *If perennial crops are involved, change in crop types is associated with change in biomass carbon stocks* | Cropland temporarily not required to cover crop demand; *eventual C stock benefits of fallows are temporary and thus disregarded* | 2 conditions: 1. Cropland is not required to cover crop demand, 2. grazing demand is exceeding maximum supply from existing grazing land; *Change in biomass and soil C stock* | Exogenous scenario assumption (built-up area/ infrastructure expansion, land degradation,…); *C stock change disregarded due to vast uncertainties* | Cropland permanently not required to cover crop demand; *Regionally specific C accumulation functions for biomass; increased C stocks in litter and soil* |
| **Grazing land** | 3 conditions: 1. Additional cropland is required to cover crop demand; 2. Suitable grazing land is available for conversion to cropland; 3. Conversion is compatible with scenario-specific cropland expansion allowance; *Change in biomass and soil C stocks* | Not relevant | Existing grazing land required to cover grass demand; *Change in grazing intensity causes change in soil C stock* | Exogenous scenario assumption (infrastructure expansion, land degredation, …); *C stock change disregarded due to vast uncertainties* | 3 conditions: 1. Grassland abandonment is allowed, i.e. activated in the model run settings; 2.Grazing land permanently not required to cover grass demand; 3. Grassland abandonment assumed in case of declining grazing intensities (see text) *Regionally specific C accumulation functions for biomass; increased C stocks in litter and soil* |

assumed to occur naturally if agricultural land is permanently left idle. On cropland, vegetation regrowth usually corresponds to forest regrowth due to the climatic conditions on most of the world's cropland areas, but may also represent conversion to shrub land or other vegetation types with relatively low C stock. The regionally specific C accumulation curves are supplied to the model as exogenous time series on annual level (see SI).

In comparison to the comprehensive statistics on global cropland use and productivity, data on grassland productivity and utilization are sparse, even for regions with good agricultural statistics such as the EU. In BioBaM, roughage supply potentials from grassland are calculated from regional specific net primary productivity (NPP) data and maximum sustainable grazing intensities. Defined as the ratio of grazing harvest to actual productivity (see Erb et al., 2016; Fetzel et al., 2017; Kalt et al., 2020; Petz et al., 2014), grazing intensities (GI) characterize the intensity of grassland use and vary from zero to the maximum sustainable value ($GI_{max}$). To account for different grassland "qualities", i.e. variability in NPP and maximum grazing intensities within regions, grassland is split into quality classes. Each class is characterized by its area and regional specific NPP and $GI_{max}$ values. Differences in nutritional values of grass ("grass qualities"; cf. van Hal et al., 2019) are accounted for by converting dry matter quantities to equivalents of "high-quality" grass.

Grassland use in the base year is defined by data from livestock statistics and empirical data on FCRs, i.e. by calculating the grass intake of livestock (under consideration of feed intake from cropland sources). Grazing intensities are thus derived from consumption quantities and the available grazing land. We assume that grass supply from the different classes is proportional to their respective production potentials, taking palatability and accessibility constraints into account (Fetzel et al., 2017; Haberl et al., 2007a).

For scenario years, the default assumption is that the grazing intensity continues to be determined by the demand; changes in grazing intensities over time cause C stock changes. Two optional algorithms have been implemented to develop different scenarios regarding grassland use: a) To simulate grassland abandonment in case of decreasing demand, it can be assumed that GI may not decrease below the base year value; if this were to happen, parts of the grassland area are abandoned (see Table 2). b) The optional setting "universal grazing intensification" results in grass supply being concentrated to the most productive areas, thereby freeing up less productive grassland for vegetation regrowth (usually forest regeneration; see Section 3.2). Technically, this is achieved by setting the GI of all grassland classes to $GI_{max}$ and reducing the area to the minimum extent required to supply the grass demand. Areas of low-productivity grassland classes are reduced first, highly productive grazing areas last.

Depending on exogenous scenario assumptions on diets, FCRs, loss of agricultural land, etc., as well as the regional distribution approach applied for animal products (see next section), the GI required to supply the demand in a certain region may exceed the maximum sustainable threshold $GI_{max}$. By default, it is assumed that grass is not traded between regions; in this case, the result is a "regional grazing infeasibility". The occurrence of regional grazing infeasibilities indicates that the mass balances in this scenario are not closed. However, this does not necessarily mean that the scenario or model run is useless; as long as this partial inconsistency between supply and demand is taken into account in the interpretation, regional infeasibilities sometimes provide valuable insight (e.g., for determining regions where it is impossible to maintain current livestock production quantities if the use of concentrate feed is phased out; see Theurl et al., 2020a).

### 2.4.3. *Agricultural product distribution*

Regional production patterns of animal production and other secondary commodities are not necessarily linked to regional resource availability (Naylor et al., 2005). Livestock husbandry, particularly in intensive systems, is often largely based on concentrate feeds from other regions, countries and continents. Social, economic and other influencing parameters on regional production patterns (see, e.g., Robinson et al., 2014; Steinfeld et al., 2006) are beyond the scope of the model. Thus, we developed different approaches for deriving regional production patterns for agricultural products that are suitable for different contexts or research questions. Table 3 provides an overview and brief explanations for these approaches. The respective algorithms distribute the global demand, corresponding to the global "target production", amongst all geographic regions. They are thus referred to as "distribution approaches".

### 2.4.4. *Nitrogen cycle and $N_2O$ emissions*

Nitrogen cycles are a relatively complex aspect of the model that have a considerable impact on GHG emissions via various mechanisms. A simplified illustration of the related calculation routines, which are performed for each region individually, is provided in Fig. 5. Calculations related to nitrogen cycles on cropland are located in the left part of the figure, those related to the livestock sector in the right part. Nitrogen removals from cropland comprise harvested crops and crop residues permanently removed from the field (mainly residues used as feed; straw

**Table 3**
Distribution approaches for agricultural products (i.e. livestock products and biofuels) in BioBaM-GHG 2.0.

| | Available options | Explanation | Rationale & applications |
|---|---|---|---|
| **A) Distribution approaches on global scale** | **A1. Fixed distribution** | Target production is distributed according to exogenous shares; shares can be constant (e.g. correspond to base year-shares) dynamic and scenario-specific | Used for base year calibration; Suitable for business-as-usual and ceteris-paribus scenarios |
| | **A2. Demand-based distribution** | Target production corresponds to demand in each region | Suitable for assessing the feasibility of regional self-sufficiency scenarios |
| | **A3. Potential-based distribution**<br>A3a. Based on cropland potential<br>A3b. Based on grazing potential<br>A3b. Based on cropland & grazing potential | Target production is distributed according to production potentials (i.e. equal exploitation of production potentials in all regions); | Suitable for explorative scenarios that allow significant changes in global production patterns, and global feasibility assessments that should not be constrained by projecting historical production patterns into the future |
| **B) Distribution approaches with regional clusters** | **B1. Fixed distribution amongst clusters, potential-based within clusters**<br>B1a. Based on cropland potential<br>B1b. Based on grazing potential | Target production shares are fixed (exogenous) values for region clusters (e.g. countries); based on production potentials, the production within each cluster is further distributed to the smallest regional units. Production potentials can be determined based on cropland or grazing land constraints | Enables maintaining global production patterns, while allowing some degree of redistribution (e.g. within countries or continents), in order to use potentials more evenly than under "fixed distribution assumptions" |
| | **B2. Demand-based distribution amongst clusters, potential-based within clusters**<br>B2a. Based on cropland potential<br>B2b. Based on grazing potential | Production patterns correspond to demand patterns on a chosen aggregation level (e.g. world regions); further distribution to the smallest regional units is performed as in B1 | Used for assessing feasibility of self-sufficiency at different geographical scales (e.g. on country-level), while maintaining a more detailed regional level of disaggregation (e.g. sub-national level) |

used for livestock bedding is assumed to be returned to the field). Nitrogen inflows include livestock manure available for field application, atmospheric deposition, biological nitrogen fixation and synthetic fertilizer application. For the base year, synthetic fertilizer use is available from FAO statistics. Together with the other inflows and removals calculated within the model, this exogenous data is used to derive regionally specific nitrogen use efficiencies (NUEs; cf. EU Nitrogen Expert Panel, 2016; Lassaletta et al., 2014). NUEs are by default assumed to remain constant in each region. Hence for scenario years, NUEs are known parameters and can be used for deriving future synthetic fertilizer requirements. Assumptions on future NUE developments can also be implemented via regionally specific exogenous change factors.

It is thus assumed that synthetic fertilizer is applied for balancing the gap between the required amount of nitrogen and organic nitrogen sources. This practice, however, is only feasible in conventional agriculture, whereas in organic farming, the use of synthetic fertilizer is prohibited (Dabbert et al., 2004; Ma and Joachim, 2006; Sanders, 2013).

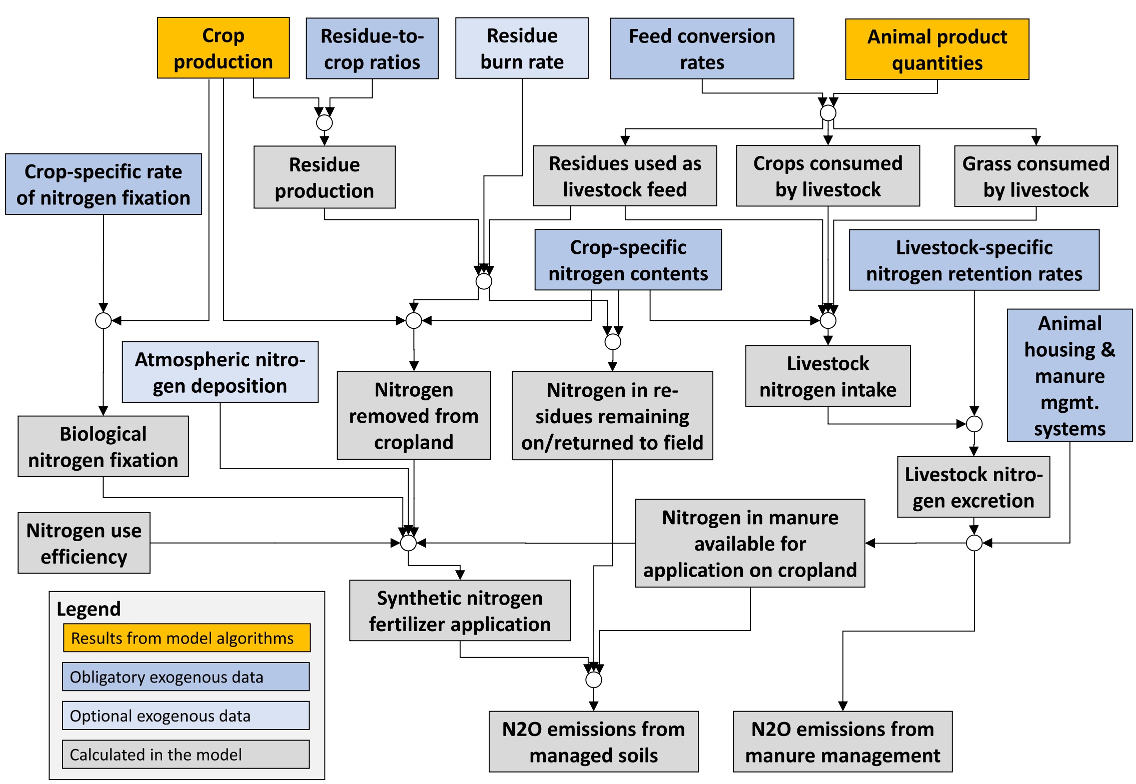


**Fig. 5.** Schematic illustration of nitrogen and $N_2O$ emission calculations.

**Table 4**
Narratives, technical implementation and differences in input data of the five scenarios presented in Röös et al. (2020).

| Storyline | Business-as-usual | Agro-ecology for exports | Localisation for protectionism | Localisation for sustainability | Local agro-ecological food system |
|---|---|---|---|---|---|
| Acronym | BAU | Aeexp | LfP | LfS | LAEsyst |
| **Global socio-economic context (narratives)[a]** | SSP2 – Middle of the road | SSP5 – Fossil-fuelled Development – Taking the Highway | SSP3 – Regional Rivalry – A Rocky Road | SSP1 – Sustainability – Taking the Green Road | |
| **Technical implementation in BioBaM** | | | | | |
| **Allowed crop-land expansion into grazing land** | Moderate (+ 20%) | High (+ 70%) | | No expansion allowed | |
| **Ex-ante allocation of area to crops** | Crop shares as of 2012 | | No ex-ante allocation (demand-orientated production within each EU country) | | |
| **Agricultural product distribution** | Fixed distribution as of 2012 | Fixed distribution amongst word regions, potential-based within EU. | Demand-based distribution amongst countries, potential-based within countries | | |
| **Trade cluster settings** | Global trade; no preference to intra-EU trade | Only level 1 trade clusters: EU and other world regions | Level 1: Individual EU countries; Level 2: EU and other world regions | | |
| **Storyline-specific input data** | | | | | |
| **Human diets in EU (Rest of the World: FAO BAU[b])** | FAO BAU[b] | | | Healthy reference diet[d] | Based on healthy reference diet[d], but more ruminant products |
| **Livestock diets** | BAU trend (slight improvements as compared to base year) | Shift to grass- and crop residue-based ruminant diets; + 10% on specific feed demand of monogastrics | BAU trend (slight improvements as compared to base year) | | Shift to grass-based ruminant diets; + 10% on specific feed demand of monogastrics |
| **Share of cropland under AE practices[e]** | Same as in 2012 | Fruits, vegetables and nuts: 75% organic[f]; all other crops: 20% organic | Same as in 2012 | | 50% conventional, 50% organic |
| **Crop wastes[c]** | Same as in base year | | 15% reduction | 50% reduction | |

Comments:.
a) see O'Neill et al. (2017).
b) BAU: Business as usual scenario (see FAO, 2018).
c) Supply chain losses.
d) See Willett et al. (2019).
e) Conventional yields are derived from FAO (2018), organic yields from data on yield gaps according to Ponisio et al. (2015).
f) In the Aeexp scenario, unused cropland is used for export production of fruits, vegetables and nuts (see scenario description). This export production is 100% organic.
Source: authors, based on Röös et al. (2020).

To be able to consider this limitation and investigate its relevance in scenarios with high shares of organic farming (see Section 3.2) a separate nitrogen balance is calculated for areas under organic farming. Biological fixation of catch crops and under sown crops is considered as additional nitrogen source on organic farming areas. The model determines whether a closed nitrogen balance is possible and calculates the size of an eventual nitrogen deficit for each region.

Nitrogen inputs to cropland in the form of synthetic fertilizers, residues and manure determine soil $N_2O$ emissions. The corresponding algorithms and default emission factors are derived from IPCC Guidelines (IPCC, 2019). Mathematical descriptions for nitrogen-related algorithms and emissions are provided in the SI.

#### *2.4.5. Further model features and validation of base year results*

Apart from the abovementioned $CO_2$ emissions from carbon stock changes and $N_2O$ emissions from manure management and managed soils, the following GHG sources are considered in BioBaM: methane emissions from enteric fermentation in livestock, manure management and rice cultivation, nitrous oxide emissions from residue burning, and GHG emissions from field operations and synthetic fertilizer production ("upstream emissions").

Further model outputs that are useful for characterizing scenario developments include self-sufficiency indicators, calculated for all geographic entities of interest (Layers 1–3 and further regional groupings defined for this specific purpose). Apart from self-sufficiencies with individual crops and agricultural products, total crops and total harvested biomass, "potential self-sufficiencies" are provided for each milestone year. Calculated as the ratio of available agricultural area to the area required for supplying the intra-regional demand, it gives insight into the attainable degree of self-sufficiency irrespective of the specific production patterns emerging in the considered scenario.

As a simplified indicator for human appropriation of net primary productivity (HANPP; see Erb et al., 2009; Haberl et al., 2013, 2007b), BioBaM further calculates the ratio of total biomass harvest in each spatial entity relative to the total potential net primary productivity on the used agricultural area (exogenous data). This indicator is suitable as a proxy for assessing trends in biodiversity pressures (see Haberl et al., 2005; Mayer et al., 2021a; Vačkář et al., 2016).

A comparison of GHG emission results from BioBaM for the base year 2012 with datasets in literature (e.g., Crippa et al., 2019; FAO, 2020; Herrero et al., 2013), performed as a means of model validation, yields the following insight: Differences amongst literature data are often considerable, mainly due to different methods and sometimes inconsistent data bases (mainly in the Global South). On world regional level, BioBaM results for the most relevant GHG emission categories, enteric fermentation and manure management, are mostly within the ranges of literature data. For regions with high data quality, such as Europe or North America, the different calculations methods applied in BioBaM (based on livestock feed intake; see SI) and FAOSTAT (based on livestock heads; see Tubiello et al., 2015) produce very similar results. Larger differences are found for regions like Sub-Saharan Africa or South-Eastern Asia, where data uncertainties are generally higher and different methods exacerbate data inconsistencies. A comprehensive comparison of BioBaM results with literature data on world region level is provided in the SI (Section 3.1).

## 3. Exemplary model applications

We present two exemplary model applications to demonstrate how BioBaM is used to investigate concrete research questions. The first application is an individual scenario approach with one business-as-usual scenario and four scenarios characterized by an expansion of agro-ecological practices in the EU, the second one an option space approach investigating global potentials for forest regeneration as climate mitigation measure under different food-system pathways. The following sections provide brief descriptions of these exemplary model applications. The complete scenario results are available from Zenodo data repositories (Kalt et al., 2021; Mayer et al., 2021b).

### *3.1. Scenarios for agro-ecological practices in the EU*

In the research project UNISECO (Schwarz, 2020), BioBaM is applied for developing quantitative scenarios to storylines about expansion of agro-ecological farming practices. The storylines, developed as part of a co-creation process with stakeholders, primarily differ with regard to two dimensions: (1) the level of implementation of agro-ecological practices, and (2) the localisation of the food system, i.e. the evolution of international trade within the EU and globally. The full storylines, their rationale and the process of developing them are described in Röös et al. (2020), and the purpose to bring them into this paper is purely to illustrate how BioBaM can be used to model biophysical results of such narratives. Thus, this section gives only a brief overview of the storylines and how they have been implemented in the model. This includes variations in model algorithms (e.g. agricultural product distribution approaches, trade cluster settings) as well as in input data (Table 4). Although the scope of the performed model runs is global, the focus of this scenario analysis is on the EU and thus, selected results are presented for the EU, broken down by countries.

The **Business-as-usual (BAU)** storyline describes a future in which globalization of the EU food system, and the specialization of farming systems and regions continues. This is implemented by projecting base year characteristics into the future: ex-ante crop shares as well as the production distribution of agricultural product in 2050 correspond to those in 2012. The EU is defined as one trade cluster within a global food system. Diets are not substantially changed but follow current trends (BAU scenario according to FAO, 2018), and there are no changes in FCRs.

The second storyline, titled **"Agro-ecology for exports" (Aeexp)**, assumes a future where humanity counts on technological progress to achieve sustainable development. Agro-ecological practices are a means to produce high-value foods for trade between EU member states but also for exports to newly affluent foreign economies. The technical implementation is similar to the previous one and includes a fixed distribution of animal products production amongst world regions. In contrast to the implementation of BAU, production patterns within the EU are allowed to shift regionally; this is necessary to facilitate a second characteristic of the storyline implementation: Agro-ecological ruminant husbandry is achieved through substituting concentrate feed with grass. Thus, production is required to shift towards regions with high grassland potentials. Further characteristics include improved FCRs of monogastrics and, corresponding to the narrative of the Aeexp storyline, higher cropland expansion allowance (up to +70% in NUTS2 regions with sufficient suitable land available for conversion to cropland).

High cropland expansion allowance is also a feature of the third storyline, called **"Localization for protectionism" (LfP)**. Set in a future with increasing rivalry between nations, nationalism and regional conflicts, it is characterized by individual countries aiming for reduced dependence on imports. Current regional patterns are thus broken up and agricultural production is primarily determined by national demand. Core aspects of the technical implementation are an omitted ex-ante allocation of cropland (i.e. crop production is first of all determined by national demand) and demand-based production of animal production within each individual country.

These settings, reflecting societies that favour local/national production over imports, are also applied for the last two storylines, called **"Localization for sustainability" (LfS)** and **"Local agro-ecological food system" (LAEsyst)**. However, in these scenarios, the driving force behind local food systems is the ambitious pursuit of sustainability goals. This is further reflected in more sustainable diets and reduced food wastes. LAEsyst features a high 50%-share of organic or AE farming. Another characteristic of LAEsyst is that pressure on cropland is reduced by substituting ruminant for monogastric animal products and a

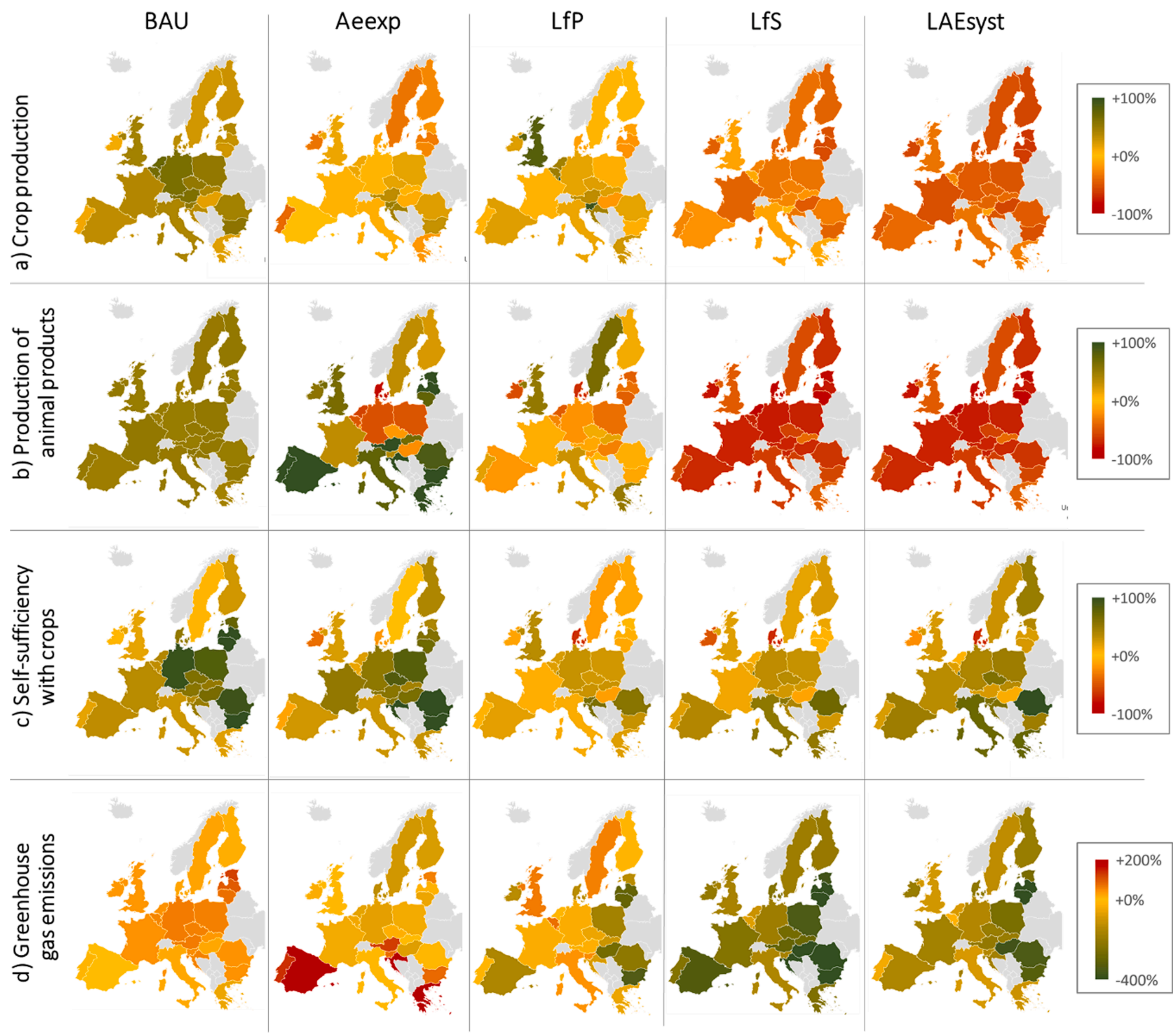


**Fig. 6.** Production of crops and animal products (a and b), self-sufficiency with crops (c) and greenhouse gas emissions (d) in the five scenarios in 2050 as compared to the base year 2012. Panels a, b and d present relative changes to the base year, panel c the difference of the self-sufficiency in 2050 to the one in 2012. Note that panel d has a different scale than panels a, b and c. The complete set of scenario data is available from the Zenodo repository (Mayer et al., 2021b).

shift to largely grass-based ruminant diets.

Selected scenario results are presented on country-level in Fig. 6. In the BAU scenario, the production of crops and animal products in the EU increase significantly in practically all countries. Facilitated by crop yield improvements and cropland expansion, this is a consequence from rising global demand, caused by population dynamics as well as changes in diets. The self-sufficiency with crops as well as agricultural greenhouse gas emissions rise in most countries, in eleven countries by more than 50%.[2]

The Aeexp scenario shows comparatively moderate changes in crop production quantities, mainly due to a shift from concentrate feed to grass. Hence, the demand for feed crops within Europe declines significantly but is compensated partly by additional production for direct human nutrition. To facilitate largely grass-based ruminant livestock systems, livestock breeding is transferred to regions with large underused grazing potentials, such as Spain, Portugal or the Baltics (Fig. 6b). Changes in crop self-sufficiencies are similar to those in BAU. The total GHG emissions in the EU, dominated by $CH_4$ emissions from enteric fermentation, show only minor changes as compared to 2012. Due to major changes in the distribution of livestock production, GHG emissions in Spain, Portugal, Greece, Austria and Croatia rise significantly (by a factor of two to three), whereas other countries (like Belgium, Netherlands, France, Germany, Denmark and Sweden) experience considerable reductions (by 48 to 95%).

In the three "local production" scenarios (LfP, LfS, LAEsyst), imports and exports are cut significantly, especially those of animal products. If human diets follow a Business-as-usual trajectory (LfP), re-orientation on local food systems implies a slight reduction in the total production of animal products; crop production and GHG emissions from livestock production and agricultural activities remain relatively constant in most countries. However, a reduction in ruminant livestock and efficiency gains in FCRs result in large grassland areas being abandoned. The resulting vegetation regrowth creates a considerable carbon sink that offsets much of the agricultural emissions. Total GHG emissions, including carbon stock effects, thus decline to 23% of the level in 2012.

The agriculture and land sector can even become a strong net carbon sink if Europeans cut food wastes by 50% and switch to healthy diets with significantly less consumption of animal products, as assumed in LfS and LAEsyst. In these local production scenarios, the livestock sector

[2] Note that the shares of manure management systems are assumed to remain constant, and technical measures for reducing GHG emissions in livestock systems are disregarded.

**a) Cumulative $CO_2$ sequestration due to afforestation (Gt $CO_2$)**

| Energy crop demand | Crop yields | Grassland intensification: No intensification; Human diets: FAO BAU | FAO SSS | FAO TSS | Healthy ref. diet | Vegan (USDA) | Universal intensification; Human diets: FAO BAU | FAO SSS | FAO TSS | Healthy ref. diet | Vegan (USDA) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Zero | FAO BAU | -65 | -55 | -96 | -142 | -589 | -262 | -248 | -322 | -399 | -642 |
| Zero | FAO SSS | -46 | -39 | -81 | -125 | -560 | -230 | -216 | -283 | -368 | -622 |
| Zero | FAO TSS | -72 | -62 | -101 | -148 | -595 | -270 | -255 | -334 | -407 | -649 |
| Medium | FAO BAU | -27 | -24 | -52 | -105 | -531 | -199 | -183 | -250 | -333 | -583 |
| Medium | FAO SSS | -19 | -16 | -39 | -90 | -508 | -162 | -141 | -215 | -296 | -565 |
| Medium | FAO TSS | -31 | -26 | -57 | -109 | -537 | -204 | -184 | -261 | -345 | -589 |
| High | FAO BAU | -10 | -8 | -16 | -37 | -467 | -61 | -39 | -126 | -226 | -506 |
| High | FAO SSS | -4 | 0 | -15 | -30 | -443 | -15 | 0 | -78 | -177 | -487 |
| High | FAO TSS | -10 | -9 | -16 | -40 | -470 | -71 | -50 | -130 | -232 | -510 |

**b) Total cumulative land-use change emissions/ sequestration (Gt $CO_2$)**

| Energy crop demand | Crop yields | Grassland intensification: No intensification; Human diets: FAO BAU | FAO SSS | FAO TSS | Healthy ref. diet | Vegan (USDA) | Universal intensification; Human diets: FAO BAU | FAO SSS | FAO TSS | Healthy ref. diet | Vegan (USDA) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Zero | FAO BAU | -21 | -11 | -55 | -121 | -538 | -197 | -182 | -256 | -352 | -591 |
| Zero | FAO SSS | 2 | 11 | -33 | -100 | -510 | -161 | -147 | -214 | -318 | -568 |
| Zero | FAO TSS | -31 | -20 | -63 | -129 | -546 | -208 | -191 | -270 | -361 | -599 |
| Medium | FAO BAU | 13 | 18 | -14 | -85 | -483 | -140 | -123 | -190 | -290 | -534 |
| Medium | FAO SSS | 26 | 32 | 5 | -66 | -459 | -99 | -77 | -152 | -250 | -513 |
| Medium | FAO TSS | 7 | 14 | -22 | -91 | -489 | -146 | -127 | -203 | -302 | -540 |
| High | FAO BAU | 30 | 34 | 20 | -24 | -421 | -15 | 6 | -76 | -190 | -459 |
| High | FAO SSS | 42 | 48 | 28 | -11 | -398 | 31 | 46 | -28 | -141 | -440 |
| High | FAO TSS | 26 | 30 | 17 | -28 | -425 | -26 | -6 | -82 | -198 | -464 |

**Fig. 7.** Cumulative global $CO_2$ emissions (positive numbers) or sequestration (negative numbers) from land-use in 90 scenarios to 2050. Panel a) shows $CO_2$ sequestration from afforestation, panel b) total cumulative land-use change emissions/sequestration in Gt $CO_2$. Projections for yield and diets are adopted from FAO (2018), where three scenarios are presented: Business as usual (FAO BAU), Stratified societies (FAO SSS) and towards sustainability (FAO TSS). The complete set of scenario data is available from the Zenodo repository (Kalt et al., 2021).

shrinks by 70%, leading to a considerable decrease in feed crop demand. Downsizing crop production is thus possible without reducing the crop self-sufficiency within the EU. In LAEsyst, crop demand is further reduced by favouring ruminant products from grassland-based livestock systems over cropland-based animal products. This reduces pressure on cropland and opens additional space for agro-ecological practices, but also results in higher GHG emissions than in LfS.

### 3.2. Forest regeneration for climate change mitigation

Forest regeneration on agricultural areas (or afforestation) has recently raised considerable attention as a "natural climate solution" in scientific literature (Bastin et al., 2019; Doelman et al., 2019; Fuss et al., 2018; Griscom et al., 2017; Humpenöder et al., 2014; Kreidenweis et al., 2016; Lenton, 2014). Although results on its global GHG mitigation potential differ widely (from 0.5 to 7 Gt $CO_2$/yr in 2050; Fuss et al., 2018; Lenton, 2014), forest regeneration is widely regarded as a promising long-term option for sequestering $CO_2$ from the atmosphere.

However, previous assessments did not investigate the relevance of main influencing parameters on the size of areas available for afforestation (e.g., human diets, crop yields) in a systematic way. Moreover, the latest yield and diet projections according to (FAO, 2018) have so far not been considered in such assessments. We here present an option space application of BioBaM which is based on these FAO projections, allowing to assess the influence of these influencing factors on future afforestation potentials. Further option space dimensions include the demand for energy crops (which is expected to grow considerably and thus create a significant additional demand for cropland in many climate stabilization scenarios; see Roe et al., 2019) and grassland intensification. Three variants of energy crop demand development are assumed: zero demand; medium demand (283 million hectare (Mha) cropland in 2050) is based on the SSP2 scenario, and high demand (724 Mha in 2050) on the SSP5 scenario according to Rogelj et al., (2018). Besides diet projections from FAO (2018), we consider scenarios with global convergence to the healthy and sustainable "EAT-Lancet" reference diet (Willett et al. (2019) and to a healthy vegan diet according to USDA and HHS (2010). The grassland variants are "No intensification" (default assumption; see Section 2.4.2) and "Universal intensification", where grazing intensities are increased to the maximum sustainable value to make land available for afforestation. All scenarios are based on a medium projection for population development (according to SSP2; see Fricko et al., 2017).[3]

While Fuss et al. (2018) quantify mitigation potentials in literature with annual values referring to 2050, we here focus on cumulative amounts from 2012 to 2050; the corresponding annual values are provided in the SI. Fig. 7a shows cumulative $CO_2$ sequestration due to afforestation for all 90 scenarios, and panel b the total cumulative LUC emissions/sequestration. The $CO_2$ sequestration due to afforestation ranges from 0 in scenarios based on the "Stratified societies scenario"

[3] Various projections for population development (according to SSP1, 2 and 5) were considered for the option space but finally omitted due to their minor influence in comparison to other parameters.

(SSS) (FAO, 2018) and high energy crop demand to about 650 Gt $CO_2$-equivalent (Gt $CO_2$e) in a scenario with vegan diets, crop yields according to the "Towards sustainability scenario" (TSS), universal grassland intensification and zero energy crop demand. In scenarios with FAO-based diets, up to 334 Gt $CO_2$e are sequestered until 2050 if grassland use is intensified globally. Without intensification on grassland, the upper limit is reduced to 101 Gt $CO_2$e. Hence, grassland intensification represents a key lever for unlocking the carbon mitigation potential of afforestation. In scenarios with high energy crop demand, the afforestation potential is reduced significantly: to a maximum of 16 Gt $CO_2$e without and 130 Gt $CO_2$e with grassland intensification, assuming FAO-based diets. This result highlights the trade-off between afforestation and large-scale bioenergy deployment.

Fig. 7b shows the total cumulative $CO_2$ emissions/sequestration from LUC. Besides C stock changes from afforestation, they also include the effects of grassland conversion to cropland, changes in grazing intensities and shifts in cultivated crops (e.g. towards perennial/tree crops like fruits and nuts) (see Table 2). In most FAO-diet scenarios without grassland intensification, the $CO_2$ benefits from afforestation are more than compensated by these other land-use changes. However, under the condition of universal grassland intensification, the land sector becomes a net C sink in most scenarios. Although grassland intensification also results in C stock losses on grassland, its net effect is clearly favourable. In FAO-diet scenarios with medium energy crop demand, the cumulative $CO_2$ emissions until 2050 amounts to 77 – 203 Gt $CO_2$e.

The option space further illustrates that global convergence to healthy or vegan diets would increase the afforestation potential significantly. Under these assumptions, the land sector could supply a high energy crop demand and still become a net carbon sink during 2012 – 2050.

## 4. Discussion and conclusions

Many of the most difficult and pressing global sustainability challenges (cf. O'Neill et al., 2018; Rockström et al., 2009) are strongly related to agriculture (Öborn et al., 2013). Ensuring food security and healthy nutrition for a rising world population and tackling environmental degradation, deforestation, loss of biodiversity and other environmental problems while adapting to and mitigating climate change are highly complex endeavors. Humankind relies on the insight obtained through scientific approaches for devising adequate countermeasures and ensuring high quality of life for future generations.

Scenario development is one of the main scientific approaches applied to gain understanding of the manifold interrelations characterizing global agro-food and land-use systems and their contribution to climate change. Scenario studies usually comprise small numbers of individual scenarios that are based on specific storylines or socioeconomic framework conditions. For example, the Shared Socio-economic Pathways (SSPs; O'Neill et al., 2017) provide narratives for five qualitative descriptions of future changes in demographics, economy, policies, lifestyle, etc. that serve the climate research community as a common reference for deriving individual scenarios. Although specific interpretations and model implementations vary (see, e.g., Popp et al., 2017), storyline-based scenario development is characterized by modelers designing specific sets of parameter settings and exogenous framework conditions that are considered as consistent, plausible and suitable for deriving a quantitative representation of a specific storyline or narrative. Although the purpose of scenario development is inherently different from forecasting or predicting, storyline-based scenarios could be argued to imply some degree of prognosis, or at least tend to reflect expectations and world views of scenario developers (cf. Gambhir et al., 2019; Schneider, 1997; Trutnevyte et al., 2016); they are based on the assumption that certain developments are more or less likely under specific settings or framework conditions. It is on the basis of this presumption that model developers derive storyline-specific sets of input data (e.g. linking globally converging diets to moderate population increases in SSP2, titled "Middle of the Road", and unhealthy, meat-rich diets to high population increases in SSP3 "Regional Rivalry"; see O'Neill et al., 2017; Popp et al., 2017). This approach is assumed to result in scenarios that are not only internally consistent but also plausible and representative for the underlying storylines, while acknowledging that it is impossible to know beforehand how future trajectories of many important parameters will unfold. Apart from SSP-based scenarios developed with Integrated Assessment Models (Riahi et al., 2017; Rogelj et al., 2018), the FAO's Alternative Pathways to 2050 (FAO, 2018) are a typical example for such storyline-based scenario studies. Such storyline-based scenarios are well suited for certain research questions and purposes, and the influence of expert judgement on plausibility and likelihood of certain developments should certainly never be disregarded in scenario development and interpretation. Still, it appears justified that scholars have argued for scenario developers to embrace a wide range of uncertainties (Morgan and Keith, 2008; Trutnevyte et al., 2016) and to "expect the unexpected" (cf. Bennett et al., 2003; Pérez-Soba and Maas, 2015).

Although BioBaM is also suitable for storyline-based scenario development (see Section 3.1), it is designed for a different, yet complementary, approach to exploring complex interrelations and the implications of specific development paths: Instead of deriving small numbers of scenarios that each represent a particular worldview, and maybe complementing them with sensitivity analyses regarding selected parameters, the option space approach does not single out specific pathways; it acknowledges the inherent unknowability of future long-term developments of crucial influencing factors, shifts attention to a wider scope of conceivable futures and thus supports a comprehensive view on systemic relations and dependencies, irrespective of what is considered as plausible or realistic. It furthermore allows to put specific parameter combinations (i.e. one individual scenario) in context, to assess the weight of individual parameters (i.e. whether diets or yields have a larger impact on, e.g., GHG emissions) and to generally embrace the large uncertainty of the future development of the global agri-food system.

While BioBaM is not designed for assessing economic effects or determining optimal pathways, it emphasizes the basic idea of scenario analysis: To approach research questions involving complex systems from a "what if-perspective", aiming for a deeper understanding of systemic interaction. An exceptional feature of the BioBaM algorithms is that they are entirely based on biophysical parameters, while many socio-economic, regulatory and legislative issues are deliberately disregarded. This implies that BioBaM is suitable for other research questions than agro-economic models, and should thus not be seen as competing but rather complementary to other established modelling approaches.

The diagnostic approach and specific algorithms of BioBaM imply limitations that must be considered in study designs as well as scenario interpretation. In accordance with its aims, BioBaM calculates neither economic equilibria nor cost-optimal development paths; scenarios obtained with BioBaM are internally consistent in terms of biomass production and consumption (or otherwise labelled as "infeasible"), but may appear as improbable or even outlandish under current economic framework conditions. The ex-post evaluation of BioBaM scenarios is a viable option to gain insight into possible economic implications, respectively the likelihood of scenarios under economic criteria (see Röös et al., 2020). It should also be noted that core model parameters such as crop yields are defined exogenously, while they could be significantly influenced by feedback mechanisms not reflected in the model. For example, shortage of cropland may lead to rising land prices and thus create stronger incentives for breeding high-yielding crops than in a situation with lower demand for cropland. While it is technically feasible to implement such feedback mechanisms, their implementation in BioBaM would imply considerable changes in the model architecture. This may represent a significant limitation for certain research questions. The diagnostic nature of BioBaM scenarios and option spaces implies challenges for communicating results, as most researchers and stakeholders are used to different modelling philosophies and objectives, such as identifying likely or cost-optimal pathways. Another challenge for communicating the results is associated with the model's capacity to derive global scenarios with multiple layers of geographic units. This feature should not seduce users to interpret results for individual regions without considering the wider spatial context and underlying assumptions.

The model applications presented in this paper serve as examples for the types of studies BioBaM is designed for: They concern biophysical possibilities and limitations at various spatial scales, investigate relationships between agricultural demand and environmental pressures, and explore pathways in food and agricultural systems beyond the conventional. The explorative approach to scenario analysis supported by BioBaM is thus also particularly useful in connection with participatory processes, where it can assist stakeholders in thinking out of the box and considering unconventional scenarios and their possible implications. The presented scenarios on the expansion of agro-ecological innovations in the EU are an illustrative example, providing insight into how the GHG emissions and other environmental pressures of the EU agriculture and land sector could be reduced significantly. Through afforestation, the land sector could even become a strong net carbon sink if Europeans cut food wastes by 50% and switch to healthy diets with significantly less consumption of animal products, as assumed in the scenarios LfS and LAEsyst. In these local production scenarios, the livestock sector shrinks by 70% and total crop production can be reduced substantially without adverse effects on self-sufficiency.

The results from the second exemplary application (Section 3.2), on global afforestation potentials for climate mitigation, illustrate the basic idea of an option space approach, albeit with a relatively small option space (i.e. a small number of scenarios) in comparison to previous studies (e.g., Erb et al., 2016; Theurl et al., 2020b). We find a range for annual $CO_2$ sequestration from afforestation that compares well with ranges from previous studies: Considering FAO-based diets and zero to medium energy crop demand, the carbon sink in 2050 accounts for 0.5 – 4.4 Gt $CO_2$/yr without and 3.3 – 8.6 Gt $CO_2$/yr with grassland intensification (see SI); results from previous studies range from 0.5 to 7 Gt $CO_2$/yr (Fuss et al., 2018; Lenton, 2014). The option space further illustrates that the different crop yield projections according to FAO (2018) have relatively small influence on afforestation potentials, whereas the area used for energy crop cultivation (based on ranges found in literature), human diets, and intensity of grassland use are major influencing factors. While it is often difficult to identify the reasons for broad ranges in literature, the option space approach it suitable for putting them into perspective and discloses sensitivities to multidimensional uncertainties.

## CRediT authorship contribution statement

**Gerald Kalt:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Writing – original draft. **Andreas Mayer:** Conceptualization, Methodology, Investigation, Writing – review & editing, Project administration. **Helmut Haberl:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Lisa Kaufmann:** Methodology, Resources, Writing – review & editing. **Christian Lauk:** Methodology, Resources, Writing – review & editing. **Sarah Matej:** Methodology, Resources, Writing – review & editing. **Elin Röös:** Conceptualization, Methodology, Investigation, Writing – review & editing, Funding acquisition. **Michaela C. Theurl:** Methodology, Validation, Writing – review & editing. **Karl-Heinz Erb:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

## Declaration of Competing Interest

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

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## Supplementary materials

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