



Food systems in a zero-deforestation world: Dietary change is more important than intensification for climate targets in 2050



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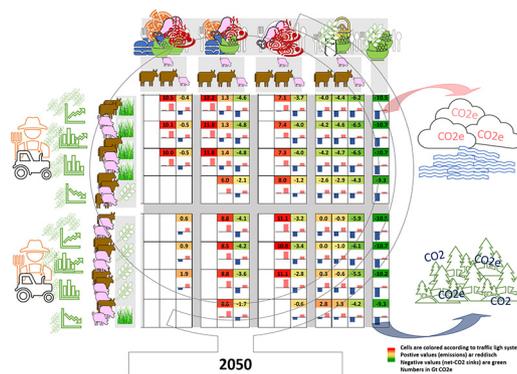
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HIGHLIGHTS

- We present an option space of 313 global food-system scenarios in 2050.
- The scenarios were feasible without deforestation.
- The net greenhouse gas emissions range from -10.7 to 12.5 Gt CO₂e/yr.
- Freed-up land that is left to regrowth shows huge carbon-sink potentials.
- Crucial are diets and livestock feed-intake, but not crop-yield gains to cut GHGs.

GRAPHICAL ABSTRACT



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ABSTRACT

Global food systems contribute to climate change, the transgression of planetary boundaries and deforestation. An improved understanding of the environmental impacts of different food system futures is crucial for forging strategies to sustainably nourish a growing world population. We here quantify the greenhouse gas (GHG) emissions of global food system scenarios within a biophysically feasible “option space” in 2050 comprising all scenarios in which biomass supply – calculated as function of agricultural area and yields – is sufficient to cover biomass demand – derived from human diets and the feed demand of livestock. We assessed the biophysical feasibility of 520 scenarios in a hypothetical no-deforestation world.

For all feasible scenarios, we calculate (in) direct GHG emissions related to agriculture. We also include (possibly negative) GHG emissions from land-use change, including changes in soil organic carbon (SOC) and carbon sinks from vegetation regrowth on land spared from food production. We identify 313 of 520 scenarios as feasible. Agricultural GHG emissions (excluding land use change) of feasible scenarios range from 1.7 to 12.5 Gt CO₂e yr⁻¹. When including changes in SOC and vegetation regrowth on spare land, the range is between -10.7 and 12.5 Gt CO₂e yr⁻¹. Our results show that 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, and lowest emissions for scenarios with vegan diets. Contrary to frequent claims, our results indicate that diets and the

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composition and quantity of livestock feed, not crop yields, are the strongest determinants of GHG emissions from food-systems when existing forests are to be protected.

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1. Introduction

As if providing sufficient food for a growing world population was not challenging enough, food systems are also expected to comply with climate-change mitigation goals. Today, the global food system is responsible for 14 ± 3.4 Gt CO₂e/yr, i.e., 25–30% of human greenhouse gas (GHG) emissions (IPCC, 2019; Smith et al., 2014). The future food system will have to substantially reduce emissions in order to comply with the 2°, preferably 1.5°, global warming limit of the Paris Agreement (Roe et al., 2019; UNFCCC, 2015). At the same time, pressures on land ecosystems are likely to increase, as land is expected to contribute to carbon (C) sequestration, thereby compensating C emissions from industrial processes and unavoidable emissions from agriculture (Roe et al., 2019), or provide substantial amounts of bioenergy, all of which may exacerbate competition for land (Haberl, 2015; Kalt et al., 2019).

It is commonly accepted that protecting forests is a key prerequisite for climate change mitigation (Foley et al., 2011; Griggs et al., 2013; UN General Assembly, 2015) because forests store considerable amounts of C (Erb et al., 2018; Pan et al., 2011), moreover, forests are biologically highly diverse and provide many important ecosystem services. Indeed, previous studies indicate that deforestation is not a biophysical necessity to feed a growing world population: in Erb et al. (2016), a plethora of different food systems were found to be biophysically feasible without deforestation compared to the land-use pattern observed in the year 2000, some even at low crop yield levels (e.g. at yield levels attainable through organic agriculture). Nevertheless, reducing emissions within the food systems as well as providing negative emissions is required while safeguarding today's forests. Thus, our analysis is based on the zero-deforestation principle in order to avoid trade-offs and even more C emissions from deforestation and other unintended outcomes.

Increasing agricultural productivity, in particular cropland yields, is widely assumed to alleviate trade-offs in the land system by creating synergies between increased food supply and enhanced land-use efficiency (measured in terms of land-area demand per unit of food), thereby contributing to “land-sparing” and helping to prevent land-use encroachment into remaining forests (Lamb et al., 2016; Valin et al., 2013). Some studies suggest that this land sparing effect of high yield agriculture is linked to reduced GHG emissions from land use change (Burney et al., 2010; Lamb et al., 2016).

These studies show that, under ceteris paribus conditions, raising crop yields can reduce cropland area, but this requires increased agricultural inputs of fertilizers or pesticides and increased use of machinery, raising associated emissions and increasing negative environmental effects (Bren d'Amour et al., 2016; Tilman et al., 2011a). The food system today is already related to immense methane (CH₄) and nitrous oxide (N₂O) emissions from agricultural activities most importantly from ruminants enteric fermentation and paddy rice production and livestock manure systems (5.3 Gt CO₂e in 2016; Tubiello, 2019) and fossil fuel use for soil cultivation (1.9–2.3 Gt CO₂e per year; Vermeulen et al., 2012).

Furthermore, it is claimed that achieving high yields would allow reducing cropland area (“spare land”). If spare land is afforested, it can contribute to achieving “negative emissions” (i.e. sequester C), which is commonly thought to be necessary to reach global climate targets. Most scenarios that comply with ambitious climate targets foresee considerable negative CO₂ emissions which may, among others, be achieved through afforestation or reforestation (Doelman et al., 2019;

Riahi et al., 2017). Other studies do not consider this effect (Muller et al., 2017; Searchinger et al., 2018; Springmann et al., 2018; Willett et al., 2019), even though C sinks from vegetation regrowth can be substantial (Erb et al., 2018; Kalt et al., 2019; Pugh et al., 2019). Improving the understanding of the systemic interactions between these essential elements of the land system is thus warranted in order to identify hot spots for intervention.

This also applies to the interactions and elements in the food system i.e. between yields and human diets, the efficiency of the production-consumption chains as well as the livestock system. Size and composition of food demand is crucial for the amount of primary biomass production, areas required for agriculture and thus spare land available for C sequestration (Bajzelj et al., 2014; Stehfest, 2014; West et al., 2014; Willett et al., 2019). Livestock plays a crucial role in this context. More than half of all biomass harvested globally for human purposes is fed to livestock (Krausmann et al., 2008), and grazing lands globally are two to three times larger than cropland areas. Furthermore, considerable dynamics are expected in the livestock sector: until 2050, rising affluence is anticipated to result in the adoption of richer diets with more livestock products, aggravating the effects of population growth (FAO, 2018). While recent scenarios (FAO, 2018) expect a growth of total food consumption of 45–52% until 2050, consumption of livestock products is expected to increase by 62–144% in the same period (Valin et al., 2014), predominantly in low- and middle income countries (Godfray et al., 2018).

Understanding the leverage effect of the composition of livestock feed (and thus livestock systems) and analyzing the effect of technological advances, such as changes in feed conversion ratios (Herrero et al., 2016; Lee et al., 2017; Zanten et al., 2015) is key in this context. Increased demand for roughage and the intensification of grazing areas as well as the use of “marginal land” for grazing will play a key role in future agriculture development (Garnett, 2009; Schader et al., 2015; van Hal et al., 2019; van Zanten et al., 2016) and is a key determinant of many environmental impacts, including but not restricted to, climate change (Herrero et al., 2013; Poore and Nemecek, 2018). This requires solid databases that enable researchers to consistently analyze the role of grazing systems and their production potentials, yet data remain surprisingly uncertain (Erb et al., 2018; Fetzel et al., 2017b). A focus on grazing lands, and in particular ruminant production, is especially important in scenario analyses that assume zero-deforestation, because cropland area changes directly communicate with the extent of grazing lands. For instance, keeping all other parameters constant, an expansion of cropland into grazing lands will result in an increased stocking density and thus grazing intensity increases on the remaining grazing land. Also the availability of spare land is strongly determined by grazing intensity (Kalt et al., 2020). Thus, the level of grazing intensity strongly determines the limits of the “biophysical option space” (Erb et al., 2016), i.e. the sum of all hypothetically feasible scenarios in combination of individual trends in agricultural area, yields, dietary developments and changes in the livestock production efficiency.

In this article, we present a systematic analysis of the GHG emissions, including fluxes resulting from land-use intensity changes and re-growth of vegetation, of global food system scenarios in 2050. We use the diagnostic modelling approach of the biomass balance model BioBaM (Erb et al., 2016) and extend this model with a comprehensive GHG module. The GHG emission module calculates emissions from upstream processes (e.g. production of mineral fertilizers), on-farm energy use (e.g. fossil fuels for field operations) as well as from agricultural

activities as defined by the Intergovernmental Panel on Climate Change (IPCC) guidelines (e.g. CH₄ and N₂O emissions from manure and fertilizers, enteric fermentation, paddy rice and residues). It also calculates C emissions and sequestration from land-use change (LUC), i.e. afforestation and soil C stocks in agriculture that result from land-use changes related to agricultural activities.

The main aims of the study are (1) to quantify GHG emissions related to a wide range of biophysically feasible food system scenarios for 2050 under a “zero-deforestation” assumption, (2) to comprehensively address systemic linkages between food demand, agricultural intensity and livestock feeding in the option space, and (3) to identify drivers of emissions as well as options for a low-GHG food system in 2050.

2. Material and methods

The biophysical accounting model BioBaM calculates agricultural biomass flows and land requirements of the global food system based on the analysis of 11 regions in the year 2050 in a hypothetical zero-deforestation world (see detailed description in the Appendix and SI of Erb et al. (2016)). One major asset of the model is that the potential (maximum) biomass supply for the food system is calculated based on spatially explicit (5 arc-min), consistent land-use and plant growth datasets (Erb et al., 2009, 2007; Haberl et al., 2007; Krausmann et al., 2008) that distinguish different productivities and yields on crop- and grasslands. Grassland areas are classified into different quality classes ranging from class 1 (highest productivity, very good grazing land and mowed meadows) to class 4 (very poor, low-productivity grazing land) which are characterized, among others, by different maximum sustainable intensive use levels (Erb et al., 2016, 2007; Fetzel et al., 2017a). Such a differentiation in extent and quality is also of major importance for the calculation of C emissions and sinks from land use change. While input data for the demand (human diets, livestock efficiency and feed composition) as well as supply side (agricultural areas and yields) were taken from Erb et al. (2016) for the sake of consistency, the original BioBaM model framework was expanded with a module that allows the comprehensive assessment of GHG flows associated with the global food system, which we describe in the next section.

2.1. The GHG module in BioBaM

We extended BioBaM using a new module that accounts for GHG emissions related to all relevant biomass flows (BioBaM-GHG). An overview of BioBaM-GHG is displayed in Fig. 1. BioBaM-GHG consists of three compartments that consider emissions from different sources: (i) agriculture, (ii) upstream processes, and (iii) C emissions and removals due to land use change (LUC). The agriculture compartment (i) accounts for all non-CO₂ emissions caused by agricultural processes, mostly based on IPCC Tier 2 in the case of CH₄ from enteric fermentation (IPCC, 2006). Upstream processes (ii) contain GHG emissions related to the production of agricultural inputs and the use of fossil fuels in agriculture, based on Life Cycle Assessment (LCA) input data (LCA; Frischknecht et al., 2005). The effects of LUC (iii) include C sources and sinks from changes in land use based on the stock-change approach (IPCC, 2006).

2.1.1. Agricultural activities and upstream processes

The accounting of non-CO₂ GHG emissions related to agricultural activities was based on IPCC guidelines, applying a Tier 1 or Tier 2 approach (IPCC, 2006), using additional emission factors and other relevant parameters from the Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) model (Amann et al., 2011). It included CH₄ emissions from enteric fermentation, manure management, paddy rice and the burning of residues, as well as N₂O emissions from the application of mineral fertilizers and livestock manure, manure management, droppings in the field, residues (including burning) and legumes. CH₄ and N₂O emissions were converted into CO₂ equivalents (CO₂e), using global warming potentials (GWP) with climate C feedbacks according to the IPCC 298 for N₂O and 34 for CH₄ (Myhre et al., 2014).

Emissions from residues and paddy rice were calculated by multiplying residue quantities and paddy rice areas from BioBaM-GHG with biomass N contents (INRA et al., 2018; Sauvant et al., 2002) and CH₄ and N₂O emission factors (Höglund-Isaksson, 2012; Winiwarter et al., 2018). The calculation of CH₄ from enteric fermentation was based on scenario dependent data for feed input calculated in BioBaM-GHG and feed specific CH₄ conversion rates (FAO, 2017a). N₂O and CH₄ from manure management and N₂O from manure application and droppings

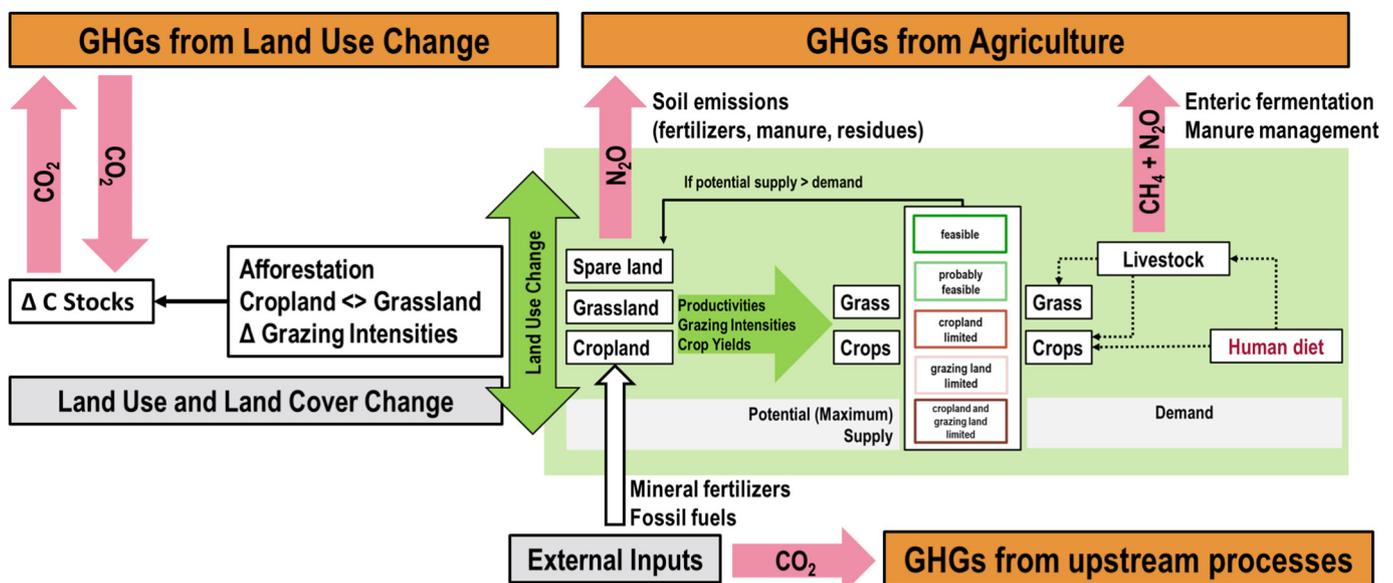


Fig. 1. Schematic representation of BioBaM-GHG's model architecture showing the nexus of biomass flows of the demand and supply side and the related GHG flows. Orange-colored boxes represent the three main GHG compartments and pink arrows represent emissions. In this analysis, we assume zero-deforestation in 2050, and therefore land-use and land cover changes affect only cropland and grassland areas.

were derived from livestock manure quantities for ruminants and monogastrics, calculated from scenario dependent feed inputs derived from BioBaM-GHG, feed digestibilities and nitrogen (N) content of feed (INRA et al., 2018; Sauvant et al., 2002). We took ratios for indoor and outdoor manure management systems as well as specific N₂O and CH₄ emission factors from the GAINS model (Höglund-Isaksson, 2012; Winiwarter et al., 2018) and multiplied them by manure quantities. N₂O emissions from the application of synthetic N fertilizers (for conventional scenarios) or N-fixing crops (for organic scenarios) were calculated by multiplying the quantity of N applied or contained in N-fixing crops by N₂O emission factors (Winiwarter et al., 2018). Future projections of N application rates were taken from FAO (Alexandratos and Bruinsma, 2012), adjusted according to the estimated changes of crop N demand resulting from scenario-specific yield levels, thereby also considering changes of nitrogen use efficiencies (NUE) reflecting yields (see Section 2.2).

Agricultural upstream processes consider the production of synthetic fertilizer and on-farm energy use from field operations using region-specific emission factors. We differentiated between urea and non-urea fertilizers (Frischknecht et al., 2005; Wernet et al., 2016; Wood and Cowie, 2004). Energy use of field operations from crop cultivation and grassland management was estimated based on recommendations for industrial countries (KTBL, 2015; ÖKL, 2017) and refined with region specific mechanization levels according to the global livestock environmental assessment model (GLEAM) framework (FAO, 2017a).

2.1.2. Carbon emissions from land-use change

C-stock changes resulting from transitions from grassland to cropland and vice versa, and from regrowing vegetation on grassland and cropland areas (agricultural abandonment) were calculated according to IPCC guidelines (IPCC, 2006). Depending on the biome type, vegetation regrowth implies regrowth of forests or other ecosystem types such as shrubland or steppe. Potential effects from human induced afforestation are excluded from our analysis. In the accounting of C stock changes, vegetation regrowth refers to values stated under the category “natural forests/natural vegetation” according to the IPCC (2006) guidelines. Due to the zero-deforestation assumption, transitions from forests to agricultural land do not occur. Loss of agricultural land to infrastructure and settlement areas was quantified using data in (Erb et al., 2016). C-stocks changes related to urban expansion were disregarded because they are identical in all scenarios.

Carbon emissions from land use change (LUC) were calculated with the ‘stock difference approach’ largely based on IPCC default data (IPCC, 2006). We calculated CO₂ emissions to or removals from the atmosphere (i.e. CO₂ sinks) by determining the C stock of vegetation on each unit area undergoing LUC at the beginning (2000) and the end (2050) of the considered period. Following IPCC (2006) accounting principles, we considered the C pools soil, biomass (above- and below-ground) and dead organic matter (litter; deadwood is disregarded). Fig. 2 schematically illustrates the relevant types of LUC, their drivers and the respective C stock changes. $\Delta C_{\text{soil}/\text{biomass}/\text{litter}}$ denotes stock changes in the respective C pool associated with each LUC class. Since litter is assumed to be zero on cropland as well as grassland under Tier 1 (IPCC, 2006), ΔC_{litter} is zero in case of LUC between these two land categories.

Following IPCC default methods, the values of ΔC_{soil} , $\Delta C_{\text{biomass}}$, ΔC_{litter} depend on various site-specific parameters. We used global raster data on the distribution of agricultural land (Erb et al., 2007) and site conditions (soils and climate zones: JRC, 2018, ecological zones: FAO, 2012), to determine C stock values for each raster cell. We calculated average C stocks for every land-use type and world region. This approach and the data used are consistent with previous applications of the BioBaM-GHG model (Kalt et al., 2020, 2019). The distributions of agricultural land types among climate zones, soil types and ecological zones are provided in the supplementary material to Kalt et al. (2020).

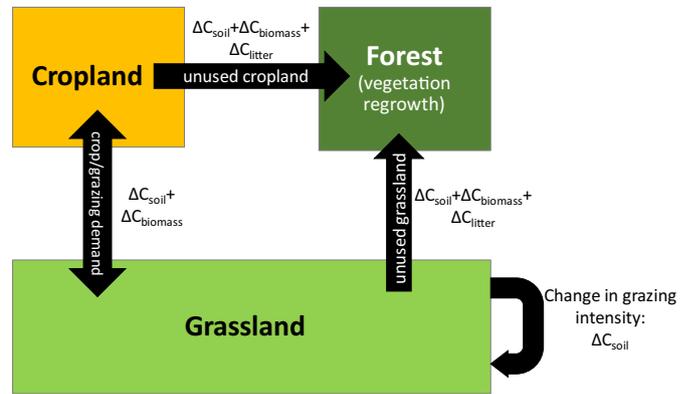


Fig. 2. Land use interactions and effects on carbon stocks as represented in BioBaM-GHG. Types of land use changes are specified with the black arrows and the associated C-stock changes calculated in BioBaM-GHG are specified in the formulas (IPCC, 2006). Note that, in dependence of the biome type, the component “forest” can also stand for other ecosystem types such as shrubland or steppe.

On grassland, soil C stocks are influenced by the level of degradation (IPCC, 2006). Here, we assumed that the level of degradation is correlated to the grazing intensity (grazed biomass as a fraction of actual net primary production; see Erb et al. (2016)) and supplementary material to Kalt et al. (2020).

Transition times from initial C stocks to a new equilibrium state extend over decades or even more than a century in case of forests. For soil and litter C stocks, we assumed the default 20 years according to IPCC Tier 1 methods. The decadal transition times imply that the emissions in 2050 depend on the timing of land-use changes during the whole timeframe from 2000 to 2050, and that the snapshot of land-use change emissions in 2050 is of limited significance. We therefore assumed constant annual rates of land-use change and considered cumulative C stock changes during 2000 to 2050 converted to average annual C emissions/sinks for scenario evaluation.

2.2. Scenario analysis

We build upon the permutations of all variants (number in brackets) for maximum cropland area (5), crop yields (4), human diets (5), type and proportion of livestock products in diets (3) and feed input-output efficiency (2), resulting in 520 scenarios from Erb et al. (2016; as a vegan diet is without livestock products, the number of scenarios is not 600 but 520). All scenarios except for BAU assume a globally converging calorific demand for all plant and livestock products (Erb et al., 2016), such that available diets per person become globally harmonized. More information about the parameters is provided in the Appendix (Table A.1).

It is important to note that the scenario-specific levels of maximum cropland expansion compared to the 2000 baseline (0% to a maximum potential of 70% expansion, the latter meaning a complete conversion of high-quality grazing land to cropland see Erb et al., 2016) must not be interpreted as the final cropland extent (use) in each scenario, but as the maximum allowed cropland expansion. BioBaM-GHG permits cropland into grazing areas only on high-quality grazing land (“grazing class 1” according to Erb et al., 2007), which is also assumed to be easily accessible for conversion (see Fig. A.4 for the actual used area of grazing and cropland in the respective scenarios). Cropland demand is a function of food demand and livestock feeding respectively its efficiency, and cropland demand can well be smaller than the assumed cropland maximum. In such cases, cropland that is not required to satisfy food, feed and other demands (including seeds and industrial uses) is assumed to be used to expand grazing land in cases where otherwise grazing intensity exceeds ecological limits, or for vegetation regrowth to create a C sink (see below). The area available for vegetation regrowth in most scenarios is thus the difference between cropland demand

(for producing food and feed according to the specific diet) and the specific cropland expansion variant (0%–70%). In scenarios where cropland demand declines compared to the year 2000, the area of potential vegetation regrowth is the difference between cropland demand of the respective scenario and the cropland area in 2000.

For grasslands, increased roughage demand results in an increase in grazing intensity, i.e. the % grazing harvest of actual net primary production (NPP_{act}). If intensification to the maximum sustainable levels, 70%, 55%, 40%, and 20% for the respective grazing classes 1 to 4 (see Erb et al., 2016) is insufficient to fulfill the demand, grassland expands into (freed-up/unused) cropland, if such is available in the respective scenario. If roughage demand still surpasses assumed ecological limits, the respective scenario is labeled infeasible due to grazing constraints and not further analyzed.

By contrast, if the demand for roughage decreases, we assumed that grazing intensities do not decrease below the (regionally specific) values estimated for the base year. Rather, we assumed grazing intensity remains stable and a commensurate fraction of the grazing land is abandoned and left to vegetation regrowth. Less productive areas (grazing classes 2 to 4 according to Erb et al., 2007) are assumed to be abandoned before class 1 areas. In grazing class 4, i.e. seminatural or natural grassland with low grazing intensity, abandonment is not considered to result in C stock changes because it is assumed that a reduction in livestock is compensated by an increase in population of wild grazers.

We use the NUE to quantify the needs for mineral fertilizer in our scenarios. NUE for the FAO scenarios have been taken from Alexandratos and Bruinsma (2012), who suggest a global improvement of the NUE of 4% in the period from base year to 2050 for cereals. Other scenarios sets deviate from that value. For our high-yield scenarios, we assume that this improvement is sacrificed in favor of higher yields, hence more fertilizer is added and the overall NUE decreases by 10%. Other scenarios reflect the general need to decrease environmental pressures from N fertilization (e.g. Kanter et al., 2020) and assume that NUE is improved. A 20% improvement of NUE was assumed for low yield organic scenarios where N application is below an economic optimum, which is a conservative assumption compared to the 50% improvement instigated by Zhang et al. (2015). For the yield gap closure scenarios, we assume that adoption of new technology and knowledge will improve soil fertility and decrease GHG emissions (Tilman et al., 2011b) and therefore use a 10% higher NUE for the high yield scenarios.

3. Results

3.1. Carbon emissions in the option space of the global food system in 2050

From the five diets analyzed in our study, a total of 313 options were feasible, i.e. biomass demand is lower than or roughly equal ($\pm 5\%$) to the maximum available supply (production). This means that 18% of western industrial calorie-rich, 63% of business-as-usual (BAU), 50% of high livestock proportion (MEAT), 96% of ovo-lacto based (VEGET), and 100% of all plant based (VEGAN) scenarios are feasible (for short descriptions for acronyms see Appendix table A.1). Greenhouse gas emissions were calculated for all feasible scenarios. These feasible food system scenarios were structured according to the respective predominant livestock feed intake category i) grain and ii) roughage. Fig. 3 represents the biophysical option space of the global food systems in 2050.

Results show that grazing and thus roughage supply is a constraint for many future food systems especially for BAU and RICH diet scenarios. If all countries would converge to western industrial diets for instance (scenario RICH), a 100% ruminant (rumi) share is unfeasible under the zero-deforestation assumption and thus excluded from the option space. However, RICH diets with a mix of ruminant and monogastrics are feasible, but only when fed on grain-dominated feedstuff in intensive livestock systems due to restrictions of roughage supply. A 100% monogastric (mono) based RICH diet is feasible for both grain and roughage (by-products) based livestock systems.

Ranges of total GHG emissions of the five diets are large. Within the option space, total GHG balances are between -10.7 Gt CO_2e/yr for scenarios with purely plant-based VEGAN diets based on FAO and closing yield gap projection and $+12.2$ Gt CO_2e/yr for scenarios characterized by rumiBAU diets with ruminant products only (milk, meat). In $>60\%$ (194) of the feasible scenarios, C sinks on spare land contribute to an overall negative GHG balance (for positive and negative emissions see the bar charts in Fig. 3). Negative emissions from vegetation regrowth amount to a C sink of up to 90% of total GHG emissions in scenarios with VEGAN and roughage based ovo-lacto vegetarian (VEGET) diets as well as for all grain-based VEGET and monoBAU diets at higher crop yields (bar charts in Fig. 3). Note that these C sinks represent a potential that occurs as a consequence of concentrated livestock grazing and hence grasslands become available for vegetation regrowth or, if cropland is required, because demand is lower than the potential supply and would not or only partially emerge if grazing intensities were to decline in scenarios with lower roughage demand.

Unsurprisingly, our results for 2050 show lowest GHG emissions for VEGAN and VEGET diets, and nearly all of them are related to the large C sinks generated by a lower demand for livestock feed. More importantly, the type of livestock products in diets as well as the type of livestock feeding system significantly influence GHG results. Many dietary pathways with a share of 100% ruminants in the diet, especially RICH, BAU, and diets with a high fraction of livestock products (MEAT) show GHG emissions above the 2000 baseline (>6.3 Gt CO_2e without land-use change). Interestingly, a 100% share of ruminant products was feasible in BAU grain-fed systems, but at very high emissions (around 12 Gt CO_2e/yr). In rumiVEGET diets, both grain and roughage dominated were feasible at low or even negative GHG emission.

Scenarios, with 100% monogastric products in the form of pig, poultry meat and eggs in BAU and MEAT diets, results in significant C sequestration potentials and negative emissions due to freed-up grasslands and thus strongly contribute to reducing overall GHG emissions between -1.7 and -4.8 Gt CO_2e , even with low organic yields (right column in RICH, BAU, MEAT, and VEGET in Fig. 3). This effect is slightly attenuated in grain based monoRICH and is related to very low GHG emissions in roughage (by-products) fed monoRICH. MonoRICH is however unfeasible with organic yields.

Yield improvements have less effect on GHG emissions of the option space, when it comes to calorie rich diets (RICH, BAU, MEAT) based on 100% rumi and the business-as-usual (bau) livestock composition (monogastrics and ruminants). On the one hand, our results especially for grain fed livestock systems show clearly that higher crop yields might contribute to up to -80% GHG reduction from organic low-yield (6.0 Gt CO_2e) to high-yields in bauBAU (1.3 Gt CO_2e) (Fig. 3). On the other hand, the effect of increased yields on total GHG emissions is rarely visible or considerably smaller in the other scenarios, for instance -15% in the grain based bauMEAT scenario.

3.2. Human diets as drivers of GHG emissions in the food system

From the results of the option space we already identified wide ranges of GHG emissions between the five diets. The differentiated analysis within diets and along the different GHG compartments is of major importance in order to identify the GHG reductions potentials and hot spots along the elements of the food system.

Results of the in-depth analyses show wide ranges for total GHG emissions within one diet and the different compartments, especially for diets with livestock products (Fig. 4, Appendix Fig. A.3). All VEGAN scenarios show negative C emissions (i.e. sinks), resulting in the maximum GHG mitigation potential within the option space (Fig. 4). Markedly, some scenarios within MEAT and BAU diets, i.e. those with livestock products purely from monogastrics (minimum and lower quartile), are associated with lower GHG emissions than the respective VEGET diets (75% quartile and maximum scenario in Fig. 4). Even BAU

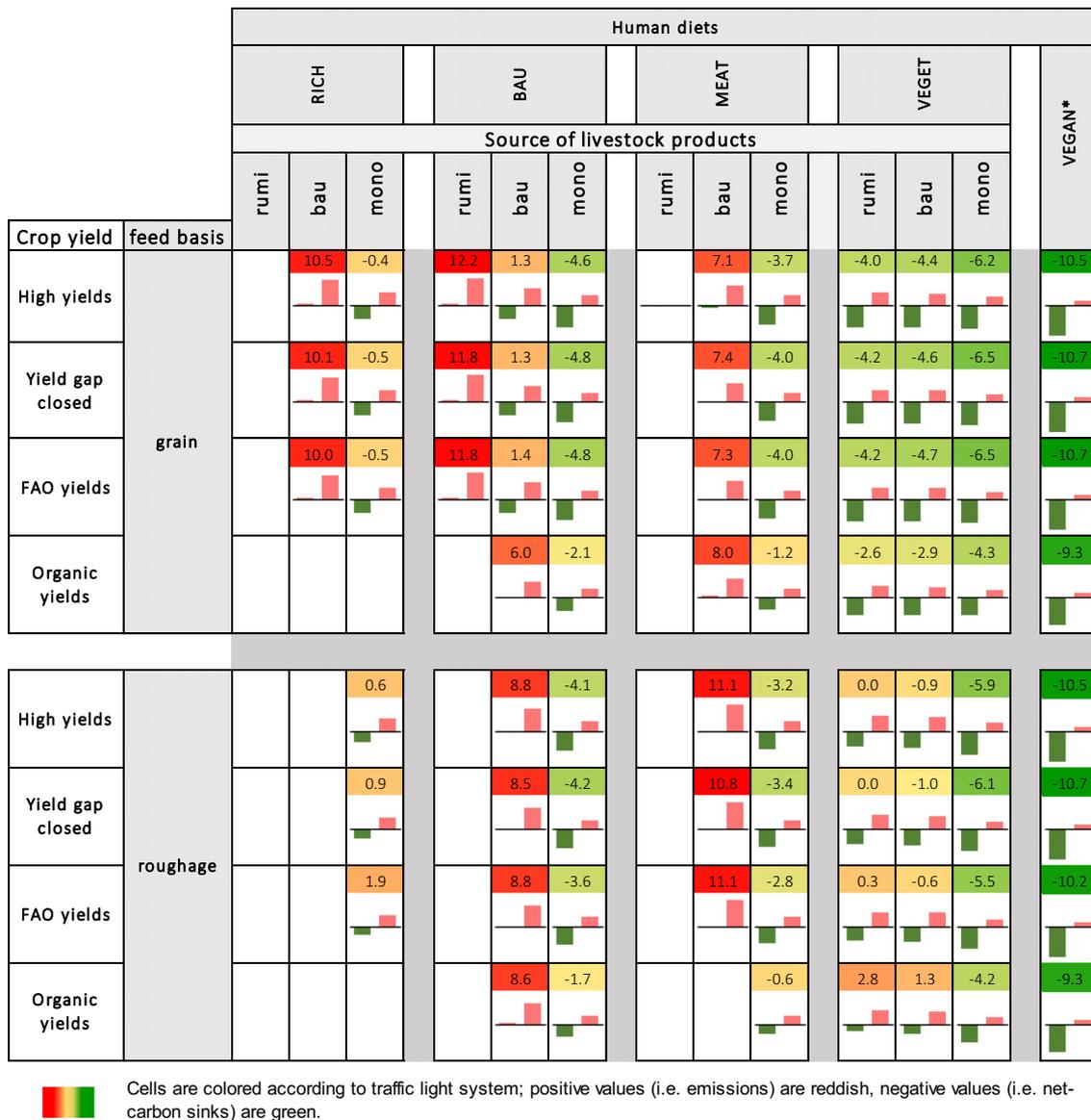


Fig. 3. Net GHG emissions in the option space. Numbers in each cell are the net emissions in Gt CO₂e yr⁻¹. The bars below show a break-down into emissions from agricultural activities including upstream processes (red bar) and sequestration by vegetation regrowth (green bar). Each scenario is a combination of possible variations of the demand side, i.e. human diets, proportion of livestock products in human diets (rumi = 100% ruminant meat and milk; bau = ruminant and monogastric product; mono = 100% pig and poultry meat and eggs), and the supply side, i.e. yields, cropland expansion, livestock feeding systems. Unfeasible scenarios, due to limited cropland or/and grazing land availability were excluded from the analysis (blank fields). All diet variants but BAU assume a global convergence of per capita diets. *VEGAN does not consider livestock products; RICH: calorie-rich diet, BAU: business-as usual diet, MEAT: healthy meat diet, VEGET: healthy vegetarian diet, VEGAN: healthy vegan diet.

and MEAT diets are in some scenarios associated with negative emissions, as opposed to the maximum of VEGET (see GHG net value MEAT min and 75% vs. VEGET max Fig. 4). RICH scenarios are generally consistently associated with very limited potentials for negative emissions.

A hot spot analysis of the food system compartments responsible for most emissions reveals that enteric fermentation dominates total GHG emissions in high emission scenarios. By additionally taking the emissions from livestock manure management into account, the share of solely livestock-related emissions increases drastically (blue parts of columns in Fig. 4 middle). These high emission scenarios are related to a simultaneous large increase in the use of grassland (dark green bar in Fig. 4) and thus to increased grazing. Current grazing areas are estimated at 3800 Mha (-39/+23%; Fetzel et al., 2017b). While the maximum RICH, BAU and MEAT scenarios are using about 5000 Mha, the maximum VEGET scenario uses about 3000 Mha in 2050. Grazing

intensities, i.e. the grazed biomass fraction of aboveground plant production, in roughage-based diets such as rumiVEGET (13–15%) are considerably lower than rumiMEAT (36–37% across all grassland qualities, the highest intensities of the option space), while grain-based rumiBAU diets (27–29%) are in between.

In terms of cropland use, RICH high emission scenarios increase cropland by 40% above 2000 levels (approx. 1523 Mha; Erb et al., 2007). Even the VEGET maximum scenario requires more cropland than in 2000, implying a conversion from grassland to cropland (i.e. emissions source), but emissions are compensated by freed-up grassland due to reduced feed demand and consequently show a C sink (bright green bar in Fig. 4).

Emissions from external fertilizer inputs and their application contribute strongly (20–25%) in scenarios where considerable amount of cropland area is cultivated (e.g. RICH scenarios; median to maximum BAU and MEAT, and maximum VEGET scenario in Fig. 4).

3.2.1. Key parameters driving GHG emissions of future food systems

We here systematically analyze two potential leverage points for GHG mitigation strategies: crop yields and feed intake. Different yield levels and feed intakes (demand) lead to different amounts of GHG emissions in dependence of the dietary composition of livestock products within a diet. When considering emissions from land-use change and vegetation regrowth, the resulting GHG emissions vary more strongly when different yields and feed intakes are assumed (a, b in Fig. 5).

Our results show no (5c) or only small (5a) reductions of GHG emissions when yields increase. Increased yields require increased N inputs, which are in turn associated with increasing GHG emissions from fertilizer manufacturing and application. In contrast to the effect of crop yields, the amount of feed intake and the total GHG emissions of the global food system show a strong positive correlation, with upstream emissions and emissions from LUC reinforcing this trend (5 b, d). The amount of GHG emissions is very sensitive to the type and composition of livestock feed stuff. Within one diet, grain dominated livestock systems (blank symbols in Fig. 5) tend to result in lower GHG emissions, while roughage dominated feeding was found to be very often related to higher GHG emissions due to

different feed digestibilities. This is clearly recognizable in RICH, BAU and MEAT diets. It is noteworthy that roughage dominated VEGET diets can result in higher emissions than monoMEAT and monoBAU diets if the livestock is fed a mixture of grain and roughage. But also meat based BAU diet scenarios can result in lower total GHG emissions in 2050 than in 2000, for instance if 100% of livestock products origin from monogastric livestock, or when the mix of monogastrics and ruminants livestock products is continued (bau scenario) but increasingly based on grain feed livestock (grey triangles and circles in Fig. 5b, d). In conclusion, our results show that GHG emissions are mostly affected by total amount of feed needed (concentrates and roughage) in the livestock sector (Fig. 5d).

4. Discussion

Our diagnostic modelling approach characterizes the biophysical food system option space 2050 in terms of the GHG effects of all feasible scenarios, thereby revealing trade-offs and systemic linkages in the food system. It is important to note that the model does not present an assessment of the plausibility or desirability of the biophysically feasible 313 scenarios. Rather, it includes extreme as well as plausible

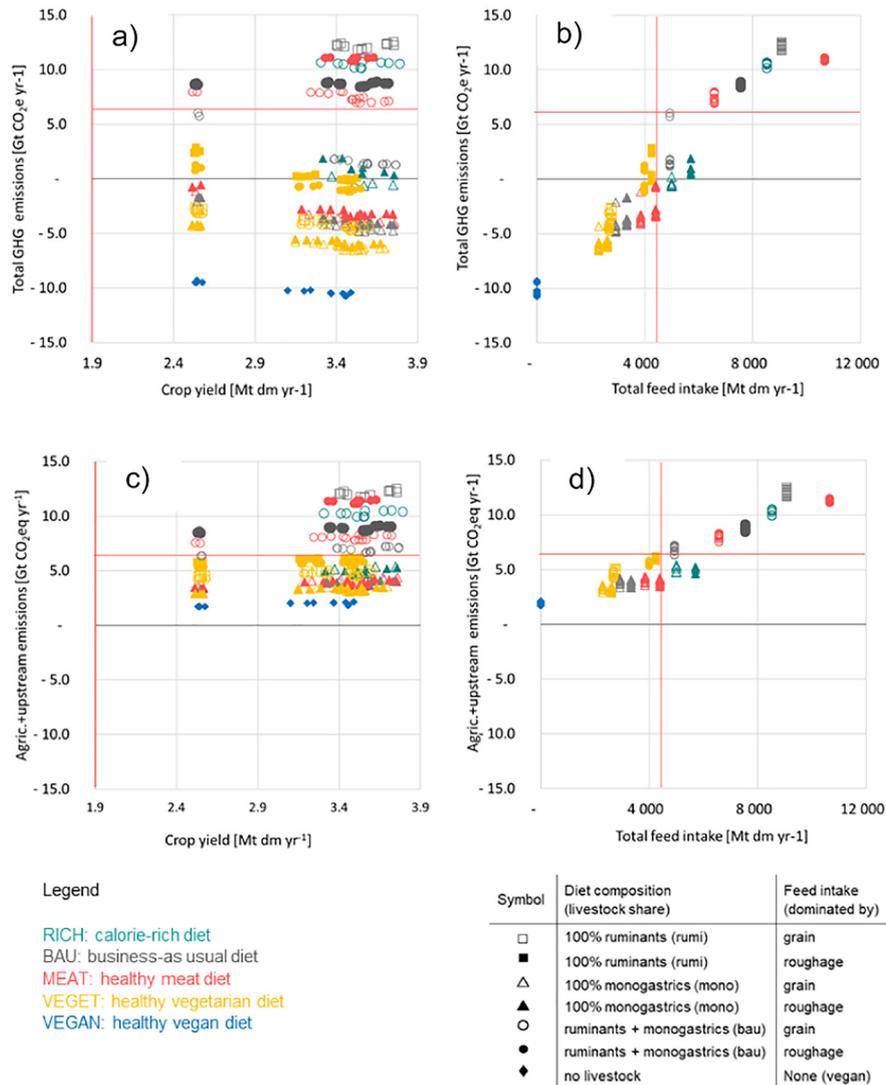


Fig. 5. Food systems of the option space as total GHG emissions including carbon stock-changes due to land-use change. (a, b) from agriculture and upstream emissions, (c, d) and in relation to crop yield projections (left) and total feed intake (right). Red intersecting lines represent the modelled baseline of the year 2000 (GHGs without emissions from land-use change, aggregated crop yield values according to FAO, feed intake based on Bouwman et al. (2005)).

combinations of individual variants within one analytical framework and assesses the biophysical feasibility as well as the full range of GHG implications. Already the basic no-deforestation assumption must also be seen in this context, revealing that deforestation is not a biophysical requirement for future food systems (Erb et al., 2016), but also that massive differences related to the climate implications within the option space exist. Also, we allow for cropland expansion into highly productive grazing areas only ("grazing class 1" according to Erb et al., 2007), which are assumed to be easily accessible and having sufficient soil quality for intensive cropping.

We found huge ranges of GHG emissions in the option space (-10.7 to 12.5 Gt CO₂e) of future food systems. There are few studies on the analysis of GHG emissions related to the global food system today and future projections. In general, our results are in line with findings from previous studies encompassing today's emission from the land system (9.4 Gt CO₂e/yr (2006–2015 average; Houghton and Nassikas, 2017; IPCC, 2019; Tubiello, 2019)). However, the comparability is hampered by the selective system boundaries of some studies that do not always include e.g. C-fluxes resulting from vegetation regrowth. A recent publication proposes a target of an allowable emission budget of 6.15–7.78 Gt CO₂e yr⁻¹ for agriculture in 2030 (Wollenberg et al., 2016). Our results suggest that such an ambitious climate target is biophysically feasible. However, we lack the information of the deceleration time from changing consumption and trade patterns, as well as establishing logistic and infrastructure particularly in developing regions like Sub-Saharan African countries. This study reveals that a systematic and comprehensive integration of all GHG-fluxes, explicitly including regrowth on potentially abandoned areas, is key for food system analysis and places previous insights into a new perspective. In particular, as in the future it is likely that the land system is required to provide negative emissions, including re- and afforestation compensating on for C emissions from the industrial sector (Roe et al., 2019; UNFCCC, 2015).

A closer inspection of different emission compartments reveals that GHG emissions results of the baseline scenario are well aligned with the emissions reported in the statistical database of the FAO (FAOSTAT, 2018). The BioBaM-GHG baseline in the year 2000 shows slightly lower GHG emissions from CH₄ and N₂O sources than FAOSTAT (-2% or -0.1 Gt CO₂e/yr, Fig. A.5). While FAO calculations of CH₄ from enteric fermentation follow Tier 1 approaches, we partly use Tier 2 for modelling the livestock systems yet on very aggregate livestock classification (total ruminants vs. total monogastrics). Other emission processes, such as CH₄ from the paddy rice sector or residue burning show differences not larger than 5% (Fig. A.5). A considerable difference, which nevertheless would not impact the interpretation of results, is found for N₂O emissions from manure application, and manure left on pastures due to a difference in allocation (FAOSTAT assumes that by far the largest share of emissions is due to grazing, while in BioBaM-GHG, the application of manure is also relevant). In general, assuming climate-carbon feedbacks likely overemphasizes GHG equivalent emissions from the livestock sectors but also used by others (FAO, 2017b), e.g. methane's global warming potential 34 instead 28 (Myhre et al., 2014) and does not affect the interpretation of our results.

Responsible for the resulting huge GHG ranges within the option space are the choice of diets, livestock systems and their demand for crop and grassland areas and yield levels. High agricultural yields are associated with emissions from upstream processes, and mechanization as well as from fertilization. While upstream emissions, e.g. energy embodied in fertilizer, and emissions from the use of fossil fuels in machinery play a subordinate role, emissions from fertilization (in the form of N₂O) play an important role. Nitrogen use efficiency in crop production is a key factor to determine the quantity of applied N fertilizer and GHG emissions caused by its production and application. Given constant agricultural technology, NUE declines with increasing crop yields (Lassaletta et al., 2014; Mueller et al., 2017; Seufert et al., 2012), implying that NUE in conventional production is lower than in organic production based on organic fertilizers (Lassaletta et al., 2014). Usually, N

response curves to N inputs (synthetic/organic fertilization and other N sources) have a high slope at low input rates and a plateau at high input rates (protein outputs do not respond to further N inputs; Mueller et al., 2017). Management shifts will have a distinct influence on such relationships (Bodirsky and Müller, 2014), which we expressed as NUE differences in the respective food system scenarios. In organic production, the main source of N is biological N fixation from legumes, which needs to be applied in rotation to supply required N for other crops (Muller et al., 2017). Additional area need were considered in this study (Erb et al., 2016), but it might result in a conservative estimate, i.e. result in a favorable assessment related to the feasibility of some or the organic scenarios. Improving the representation of N balances in food systems, e.g. through the explicit modelling of N response curves and taking the potentials of legume plants explicitly into account are necessary next step in identifying production constraints. Still, the effects of our assumptions on the resulting GHG emissions may remain rather limited (see the appendix material for further evaluation, Fig. A.6).

Previous studies indicated that past crop yield increases contributed to land sparing and avoided GHG emissions (Burney et al., 2010; Evenson, 2003; Lamb et al., 2016; Stevenson et al., 2013). Our results confirm that the land and GHG sparing effect of increasing yields (closing yield gaps) in the different world regions remains important in future scenarios, but effects from dietary changes are significantly larger. However, also relatively lower organic crop yields provide different future options to ensure a sufficient and healthy food provision for the future population. Furthermore, organic agriculture might have other environmental benefits that are beyond the scope of this paper, but nevertheless important (Mondelaers et al., 2009).

Analyzing the effect of dietary changes on freed-up land reveals a crucial hotspot for policy intervention and contribute to the land sharing/sparing debate. While the latter usually focusses on the beneficial effect of increasing yields (i.e. agricultural intensification) in terms of sparing land for biodiversity, nature conservation and GHG emissions (Balmford et al., 2018; Lamb et al., 2016; Tscharrntke et al., 2012), our results support the view that high crop yields are not necessarily linked to lower GHG emissions (Matson and Vitousek, 2006). High crop yields can translate into disproportional increases in demand for fertilizers that may be responsible for high GHG emissions during production and application. Demand for fertilizers can be decreased using organic farming or by using renewable energy sources during manufacture. This effect can be interpreted as a kind of rebound effect, where higher crop yields allow for diets with higher shares of livestock products, which in turn reduce the land-sparing effect. This rebound effect is potentially larger for scenarios with relatively higher crop yields, because lower (organic) crop yields require more land for production and the need for N fixation areas, but with a significantly reduced impact per unit of area. Changes in diets, in contrast, are not prone to this rebound effect. Our results show that a change in dietary demand has a large effect on sparing areas and can substantially help to increase C-uptake through vegetation regrowth (bright green bars in Fig. 4). Here, a trade-off exists if these freed-up areas are used for bioenergy production. Which of these options is preferable depends on site conditions (Kalt et al., 2019).

Our analysis is a hypothetical exploration with a strong biophysical land-systems backbone and with little, if any, consideration of existing constraints e.g. by consumer preferences or policy restriction such as free trade legislations on taxing meat, animal fat or vegetable oils. We do not consider downstream emissions, but they are important and could show important hot spots related to the food system. A fraction of the emissions from the transport sector (according to IPCC, 2019, these amount to 13.1% of total anthropogenic GHGs) stem from transporting goods produced in agricultural production systems. In this study, the aim was to understand the differences between the 313 food systems. Land competition within a region increases both, GHG emissions from agriculture and the need for long-distance transport,

which suggests that systems of low total GHG emissions would likely also have smaller associated transport emissions.

Climate change will very likely affect food systems considerably. By considering official UN or FAO projections (see Erb et al., 2016), we implicitly considered important climate drivers such as temperature changes, extreme weather events (droughts/floodings) change of atmospheric composition, decreasing ground water levels, as well as soil erosion due to unfavorable farming practices. Nevertheless, more research is necessary to better integrate our changing environment, or alternative ways of closing nutrient loops and feed in livestock (Muller et al., 2017; van Hal et al., 2019) especially in countries where yield gaps still have to be closed.

5. Conclusion

We quantified GHG emissions related to a wide range of biophysically feasible food system scenarios for 2050 under a “zero-deforestation” assumption in order to comprehensively address systemic linkages between food demand, agricultural intensity and livestock feeding in the option space, and to identify drivers of emissions as well as options for a low-GHG food system in 2050. The zero-deforestation option space 2050 includes 313 different food system scenarios with hugely varying total GHG emissions (−10.7 to 12.5 Gt CO₂e). Our results suggest that the choice and composition of future diets is highly important for GHG emissions of the food system, as well as for society-climate interaction in its entirety. A change in dietary demand has a large effect on sparing areas and can substantially help to increase C-uptake through vegetation regrowth. We show that today's business-as-usual and meat dominant diets would have the highest GHG emissions out of any dietary choice of the future option space. Adoption of a vegetarian diet helps, but does not guarantee low GHG emissions. Global conversion to monogastric based business-as-usual diets as well as diets with a high meat fraction is a feasible option to feed a growing world population in 2050 and may be compatible with relatively low GHG emissions to freed-up grasslands and thus strongly contributing to reducing overall emissions if grasslands are managed accordingly. The feeding system of livestock is a hotspot for reducing GHG emissions. The quantity and composition of livestock feed intake is strongly and unambiguously associated with the amount of GHG emissions of the food system. By contrast, agricultural intensification through yield increases did not necessarily result in reduced GHG emissions. Even low yield scenarios, such as a hypothetical complete switch to organic farming, can show C benefits from natural vegetation's regrowth, despite increased area demand. Thus, we conclude that diets and livestock feed intake are of prime importance for future GHG emissions from the food system, while raising crop yields does not necessarily result in low emissions.

Comprehensive assessments that link demand and supply side characteristics of the food system are crucial for providing information on the many trade-offs and systemic interlinkages in the food system and its key component, the livestock system(s). This is key for informed decision making and designing sustainable transformative pathways for reaching climate mitigation targets while preserving and enhancing human well-being.

CRedit authorship contribution statement

Michaela C. Theurl: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Investigation, Writing - review & editing. **Christian Lauk**: Conceptualization, Methodology, Formal analysis, Investigation, Writing - review & editing. **Gerald Kalt**: Methodology, Formal analysis, Investigation, Writing - review & editing. **Andreas Mayer**: Methodology, Investigation, Writing - review & editing. **Katrin Kaltenecker**: Investigation, Writing - review & editing. **Tiago G. Morais**: Formal analysis, Writing - review & editing. **Ricardo F.M. Teixeira**: Writing - review & editing. **Tiago Domingos**: Writing - review

& editing. **Wilfried Winiwarter**: Investigation, Writing - review & editing. **Karl-Heinz Erb**: Conceptualization, Methodology, Writing - review & editing, Supervision. **Helmut Haberl**: Conceptualization, Writing - review & editing, Supervision.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2020.139353>.

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