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# Combining biophysical modeling and Polanyian theory pleads for a re-embedding of the agricultural system in 2050 in Austria

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## ABSTRACT

Land use faces a double challenge: to provide biomass to a growing population while contributing to climate-change mitigation. We here scrutinize this challenge by exploring the domestic option space for meeting the food demand of Austria in 2050 under the condition of no deforestation. To that end, we bring together a quantitative assessment based on biogeochemical models with a socio-political analysis based on the conceptual framework of (dis-) embeddedness derived from Polanyian thinking. We consider viable options by modifying four levers: (i) human diet and food waste; (ii) trade patterns; (iii) agricultural practices; (iv) technical climate change mitigation. Past and present policies in Austria have fostered an agricultural system rich in animal products, land-use specialization and the integration of biomass products within international markets, ultimately resulting in a loss of embeddedness in the sense of Polanyi. The biophysical analysis, however, highlights that a shift towards diets with less animal products would allow increasing self-sufficiency or a generalization of organic farming while turning the agricultural and forestry sector into a net GHG sink. Following a Polanyian perspective, we show that feasible scenarios require different types of re-embedding of the agricultural system: ecological, spatial and social, implying that land products should rather be common goods than mere commodities.

## 1. Introduction

The provision of food and other biomass such as fodder, fiber and wood is a central ecosystem service of the world agriculture and forestry sectors, accounting for 51% and 38% of global habitable land in 2018, respectively (Ritchie and Roser, 2021). Over the course of the 20th and early 21st centuries, expansion, intensification and specialization in the agricultural sector induced a tremendous increase in food production (Krausmann et al., 2009; Ramankutty et al., 2002) and facilitated reforestation in many industrialized countries (Mather, 1992; Meyfroidt and Lambin, 2011). However, these changes in the agricultural sector were enabled by an ever-growing dependence on fossil energy for machinery, fertilizer production and long-distance feed transportation enabling a surge in livestock production globally, and making the agricultural sector responsible for one-fourth of the global GHG emissions (Crippa et al., 2021; Gingrich et al., 2019; Tubiello et al., 2013). In 2015, out of the 18 Gt CO<sub>2</sub>eq. of GHG emissions linked to the global

food system, 40% were due to agricultural production and 32% to land use and land use change (Crippa et al., 2021). Meanwhile, between 2010 and 2019, global land surfaces provided a carbon sink of  $3.4 \pm 0.9$  GtC yr<sup>-1</sup> (Friedlingstein et al., 2020). In that context, the agriculture and forestry sectors face a double challenge in climate-change mitigation: by (1) reducing greenhouse gas (GHG) emissions from agricultural activities and (2) sustaining carbon sinks in agricultural and forest ecosystems to counteract emissions from other activities that are hard to decarbonize (Roe et al., 2019). Despite a controversial debate about the extent contributed by each, both processes are essential parts of National Determined Contributions (NDCs) to achieve the Paris Agreement (Walsh et al., 2017). Accordingly, the European Commission's goal is that agriculture and forestry in Europe should reach a budget of – 240 to – 475 Mt CO<sub>2</sub>eq./yr to meet respectively the < 2 °C and < 1.5 °C targets (Anon, 2018), while still providing food in quantity and quality. Understanding how this double challenge can be met requires exploring a large number of biophysical scenarios, their GHG budgets and

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socio-ecological contexts, i.e. their ecological implications on land systems, and the societal conditions accompanying them.

Since the Millennium Ecosystem Assessment in the 2000s (Alcamo et al., 2006), the literature on land ecosystem scenarios has been flourishing (Wiebe et al., 2018). In the 6th IPCC report, the combination of the Shared Socio-economic Pathway (SSP) with the Representative Concentrations Pathway (RCP) scenarios in the Integrated Assessment Models (IAMs) reflected possible futures for the socio-economic, land-use, and climatic systems (Popp et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017). These have, however, been vividly criticized (Anderson and Jewell, 2019; Kalt et al., 2021; Keyßer and Lenzen, 2021), mostly because of their unquestioned reliance upon economic profitability, growth, and self-regulative market-mechanisms, supposed to generate speculative technological break-throughs to solve environmental problems (Warszawski et al., 2021; Hickel et al., 2021). The predominance of the growth and free-market paradigms in IPCC scenarios may be encouraged by the dominance of conventional economic models, especially when these do not explicitly consider biophysical limits to economic growth. This omission indeed allows for unlimited growth and specialization for the sake of socio-economic benefits, but underestimates the non-linear environmental consequences of persistent unsustainable use of resources (Raworth 2017, Hickel 2020), a shortcoming with direct effects on the analysis of sustainable agri-food systems (McGreevy et al., 2022). Thus, recent research has brought forward complementary biophysical models to investigate sustainable option spaces, which are constrained by social thresholds on the one hand, that require meeting the livelihoods of people (e.g. food supply), and by the limits imposed by biophysical processes on the other (e.g. primary productivity of vegetation, agricultural yields) (Billen et al., 2021; Erb et al., 2016; Kalt et al., 2021; Le Noë et al., 2019; Muller et al., 2017; Theurl et al., 2020). So far however, these models have mostly focused on the biophysical dimensions of agriculture and forestry, falling short of integrating their results into broader social and economic contexts. Integrating biophysical models and socio-ecological theory is hence an urgent and promising step, needed to understand the social dimensions of sustainability transformations without systematically resorting to conventional market economic models (Brand et al., 2021; Meyfroidt et al., 2018; Otto et al., 2020; Pichler et al., 2017; Turner et al., 2020).

In the present study, we aim at leading off this research step, by answering two fundamental and interlinked research questions: (i) What are the future sustainable agricultural systems that contribute to both achieving a GHG neutral budget and providing healthy food for all? (ii) How can social theory be applied to articulate the societal implications of the different scenarios in terms of land-use management and food consumption? To answer these questions, we develop an interdisciplinary approach and apply it to Austria in the period up to 2050 to explore the results of a biophysical model in terms of GHG emissions from the agriculture and forestry sectors for a large number of agricultural scenarios, identifying a biophysical option space of feasible futures, and interpret these results through the lens of social theories. By focusing on an industrialized country, we explore the societal implications of reducing emissions, while continuously sufficient food provision allows a moderate reduction in agricultural production. We draw on the Polanyian concept of embeddedness, allowing for the economic system to be seen alternatively either as *an organizer of* or as *organized by* land-use systems (Polanyi, 2001). We use this conceptual framework to interpret path dependencies and political obstacles to be overcome when implementing various options of change in agricultural and forestry systems whose effect on the GHG balance is assessed by a biophysical modelling approach.

## 2. Concepts and methods

### 2.1. The Austrian case

Austria is a European, landlocked country in the temperate climate

zone, with a population of 8.9 million in 2019 and a total area of 83.9 thousand km<sup>2</sup>. As alpine mountains cover a large share of its territory, only 31% is used for agriculture, of which 52% are covered by arable land, 46% by grassland with mainly cattle, and 2% by perennial crops (vineyards and fruit orchards) (FAOstat). While most arable land can be found in the northern and eastern lowlands and plains, most grassland is situated in mountainous areas towards the West and South. As extensive pastures in high alpine areas exhibit a low profitability and depend strongly on state subsidies, there exists a trend towards an expansion of forest cover, especially in higher altitudes (Gingrich et al., 2016).

In the lowlands and plains, agricultural productivity as well as inputs of synthetic N fertilizers and pesticides are in the range of other industrialized countries, with average cereal yields of 6.2 t/ha, average mineral N fertilizer input of 89 kgN/ha of arable land and average pesticide use of 2.8 kg/ha of arable land in 2015. In 2015, 20% of all agricultural areas were cultivated with organic methods, a large part being extensive grassland due to pedoclimatic and relief constraints (Stolze et al., 2019). While average cattle density on grassland is comparable to other European countries of similar income, there is an above-average pig population in relation to total arable land (Billen et al., 2021). According to FAO data, the total calorific household food supply per person is, with 3768 kcal/pers/day in 2015, one of the highest worldwide, and 12% higher than the average of all high-income countries. This difference to similar countries arises from the exceptionally high per-capita supply of animal fats (such as butter and lard).

This current patterns in Austrian land-use and agricultural food systems are a consequence of the ‘modernization’ of agriculture. Started with the aid of the Marshall plan in 1947 and in an era of economic protectionism, national modernization policies sought to increase agricultural production, following the so-called “Grüne Plan” (Stolze et al., 2019). In the 1960 s and 1970 s, these policies aimed at reorganizing farming structure from integrated subsistence farming to specialized crop or livestock production, inserted in international markets and increasingly dependent on mineral fertilizers, animal feed, fuel, pesticides and antibiotics inputs (Fig. 1c) (Gingrich and Krausmann, 2018; Krausmann et al., 2008, 2003). The increased specialization of agricultural (and forestry) production was also accompanied with the expansion of international biomass trade (Krausmann et al., 2008, 2003), contributing to the disruptions of global nitrogen and phosphorus cycles (Lassaletta et al., 2014; Nesme et al., 2018) and to an outsourcing of the environmental burden toward exporting countries (Kalt et al., 2021; Kastner et al., 2011a, 2011b; Roux et al., 2021). Nevertheless, in Austria, biomass trade remained at a low level compared to biomass production until the 1970 s (Fig. 1d) because of protectionist and interventionist agricultural policies (Krausmann et al., 2003).

Since the 1990’s, Austrian agriculture has been subject to the Common Agricultural Policy (CAP), which strengthened the environmental regulation while facilitating greater deregulation of agricultural commodities on international markets (Kroll and Pouch, 2012). Following subsequent General Agreement on Tariffs and Trade (GATT) and World Trade organization (WTO) negotiations, Austrian farmers benefited less and less from government agricultural price supports, which were replaced by direct payments based on farm size. Food prices, however, still fell by 20–50% as a result of the further opening of food markets to international competition through lower customs protections (Sassatelli and Scott, 2001). Although these changes contributed to reduce agricultural overproduction, especially of livestock products, and avoiding environmental problems as overgrazing (e.g., Noll et al., 2020), they encouraged farmers to specialize their production in order to remain competitive (Krausmann et al., 2003). This paradox has materialized through the further integration of food commodities (Fig. 1d) into international markets while the Austrian government and the EU increased environmental regulation (e.g., through stopping the growth of livestock numbers and fertilizer use) (Fig. 1a & b).

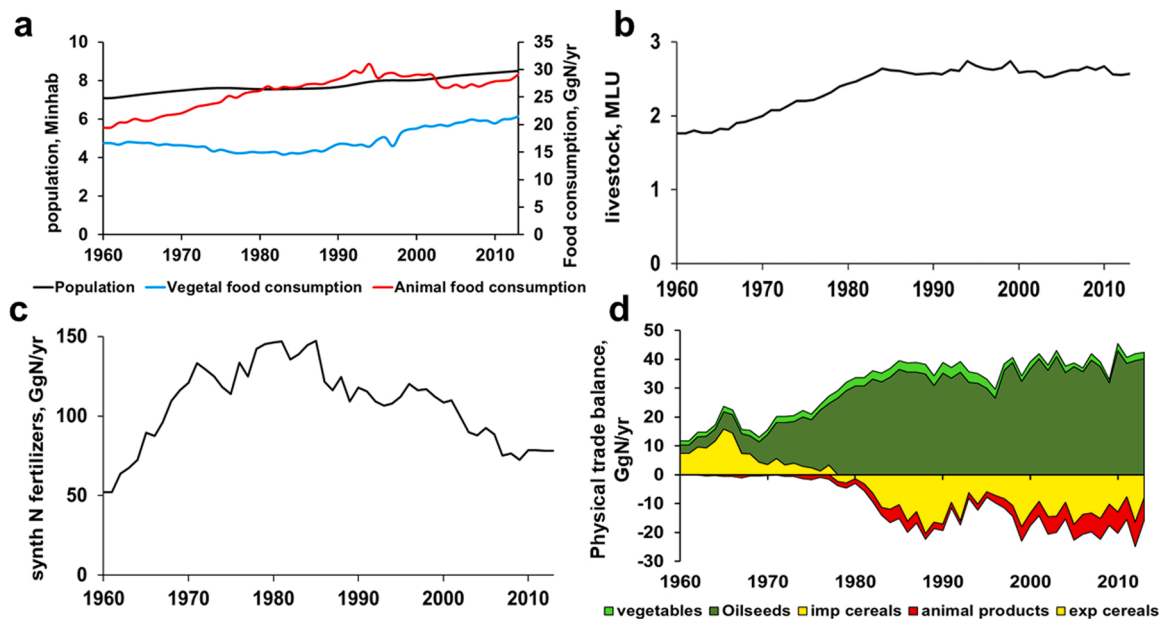


Fig. 1. Trajectories of agri-food systems in Austria through 4 main indicators: (a) population and food consumption, (b) livestock size, (c) inputs of synthetic nitrogen fertilizers and (d) Physical trade balance of agricultural products, with positive values referring to net import and negative values to net export. Data were extracted from the SI of Billen et al. (2021) after the FAOstat.

## 2.2. Conceptual framework

In order to account for the societal implications of the biophysical option space assessment, we employ the Polanyian concept of (dis-) embeddedness originally developed by Polanyi (2001) in his book “The Great Transformation”. Dis-embeddedness, according to Polanyi, describes the expansion of a market economy into all spheres of society, including production factors such as labor, land, and money which shall be mere commodities if they are to meet the market requirement of self-regulation (Fig. 1). However, according to Polanyi, production factors are fictitious commodities because none of them are actually produced in view of being sold. Dis-embeddedness of the economy thus refers to the movement of subordinating land, labor and money to the self-regulative economy. This marks an exceptional situation in the long-history of humanity which, according to Polanyi, has historically resulted in the destruction of land (soil fertility depletion caused by agricultural intensification and rural exodus) and the destruction of human livelihood conditions by exhausting and alienating the labor force treating labor as a commodity. Embeddedness, by contrast, describes a situation in which land, labor and money are not subject to market exchange, but are organized, used and regulated by political institutions, either at the level of state policy (e.g., public utilities) or at the local level by the rules of the local community (e.g., commons). Those concepts of embeddedness and fictitious commodity being defined, we argue that developing future scenarios by first considering the constraints set by a market economy implicitly accept the fictitious commodity of land and labor and the dis-embeddedness of the economy. By contrast, developing future scenarios by first exploring a biophysical option space implicitly adopts a Polanyian perspective by first considering environmental targets and social goals, thus tending to, at least epistemologically, re-embedding the economy in the environment and the society.

In land-use and agro-food studies, the concepts of embeddedness and dis-embeddedness have been widely applied, making these concepts more operational for analyzing contemporary land use changes and practices than Polanyi’s original work on the emergence of the market economy in late eighteenth century Britain. Penker (2006) identifies three types of embeddedness concepts in agricultural systems. The first form of embeddedness is that within the social context, including social

ties, social relationships in biomass production, producer-consumer relationships, and land ownership. The second form of embeddedness is the spatial scale of biomass production, which is best reflected in the intensity of biomass trade compared to local production. The third form of embeddedness is that of nature, including issues of nutrient cycling, greenhouse gas emission, water pollution, human and animal health. In the present study, we build on this distinction to interpret how recent trends and possible scenarios of agricultural systems are or could be tied to social, spatial and ecological embeddedness of Austrian agriculture and forestry. Applying these three dimensions of embeddedness allows us to articulate the Polanyian framework to different indicators driving or estimated by our modeling of the biophysical option space in Austrian agricultural and forestry systems (Fig. 2).

We considered that GHG budgets of agricultural systems, which is the main output of the modelling approach developed here (see Section 2.3) could be considered as an indicator of ecological embeddedness (Fig. 2&3). Trade pattern, which is a lever in the biophysical option space, reflecting the importance of food and feed net import for domestic consumption, is taken as an indicator of spatial embeddedness but can as well indicate social and ecological embeddedness as the integration of food within international market reveals its degree of commodification while trade also have environmental impact (Fig. 2&3). Last, as social practices, human diet and agricultural practices, which are also levers of the biophysical option space, can be considered as indicators of social embeddedness (Fig. 2&3). Although human diet and agricultural practices are mediated by many other social relationships and practices, including public policy, the processing, packaging, wholesale and retail industries, which make up the bulk of the economic profit of the agri-food industry sector in Austria (Anon, 2020), we could hardly include these social relationship in a biophysical modelling approach. This would indeed involve making hypotheses about the way society works being eventually at odds with the social embeddedness concept used to interpret the results and constrain these interpretations. However, we still discuss their historical and potential future roles qualitatively in Section 3.2.

Our interdisciplinary approach can be summarized as follows: Referring to (dis-) embeddedness enables us to qualitatively interpret the results of a biophysical modeling of option space in terms of their socio-political implications while considering the historical, political

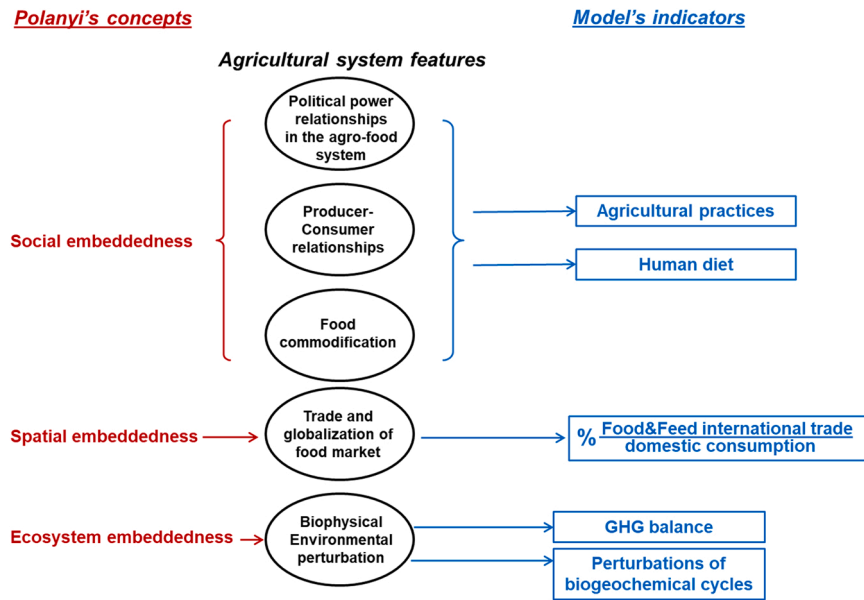


Fig. 2. Representation of the different conceptual fields used and their articulation for the present study.

and socioeconomic context of the Austrian agricultural and forestry systems. This allowed us to produce scientific knowledge with direct implications for ongoing debates and negotiations on how to use land, produce food and change eating habits.

2.3. Modeling approach and database

To evaluate the potential of climate change mitigation by the agriculture and forestry sectors while providing sufficient biomass resources for food, we developed a biophysical modelling approach relying on the coupling of the BioClim.at model and the CRAFT model (Le Noë et al.,

2020) (Fig. 3), representing quantitative operationalizations of the three dimensions of embeddedness outlined above. Model performance and robustness were evaluated against independent data, showing the reliability of our modelling approach (see Supplementary Information 1 and 2). This approach allowed us to: (i) characterize the functioning of the Austrian agricultural system in terms of land use, agricultural practices, human diet, dependence on foreign trade and implementation of climate-change mitigation techniques and, (ii) calculate the GHG budgets of the domestic agriculture and forestry sectors for the current situation and for prospective scenario of the agricultural system, and (iii) establish qualitative links to three dimensions of (dis-)

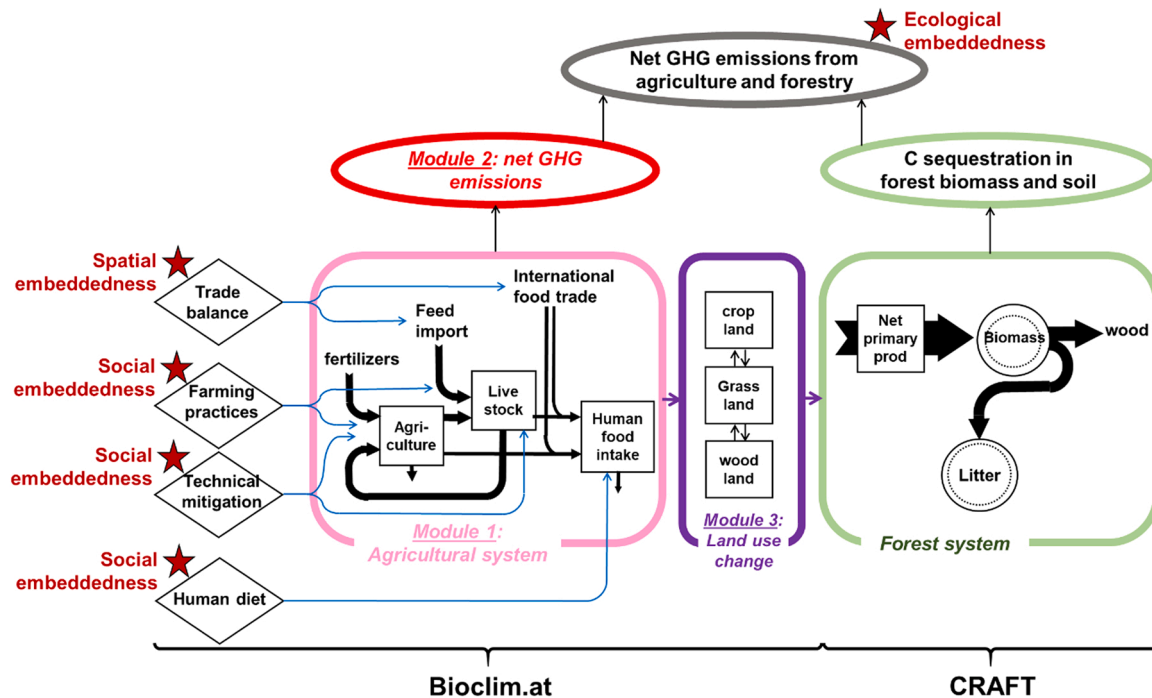


Fig. 3. Schematic representation of the accounting model BioClim.at coupled to the CRAFT model. Rectangles stand for processes governing carbon and other GHG fluxes, rhombuses stand both for forcing data used to represent the current situation and for the levers activated in the prospective scenarios, circles stand for carbon pools, ovals stand for GHG and carbon budgets, stars for embeddedness indicators. A more detailed description and representation of the BioClim.at model is provided in SI1.



embeddedness.

2.3.1. BioClim.at

For the calculations of agricultural biomass flows, land budgets and GHG emissions, we developed BioClim.at, a spreadsheet-based biophysical accounting model comprised of three modules (Fig. 3, see also the detailed model description in SI 1). The model was applied to the Austrian land-use sector, with 2010 (average 2009–11 to reduce yearly fluctuations) as base year. Following a territorial accounting approach, the model quantifies GHG emissions of domestic biomass production (including e.g. the emissions from livestock converting imported feed, or the emissions from products for exports), while upstream emissions from outside of Austria (e.g. from the production of feed imported to Austria) are outside the model’s system boundary. Key drivers of the agricultural system that are expected to change in the future (Table 1) are inputs to the model (see module 1 in Fig. 3): (i) diet and food waste, (ii) physical trade balance (iii) agricultural system, and (iv) implementation of technical mitigation measures. By varying these input parameters, the model calculates the impact of each scenario assumption on biomass flows, land demand and GHG emissions within Austria (see section scenario assumptions).

Module one depicts the structure and practices of agri-food systems and calculates the quantity of primary biomass required to produce a particular quantity of final products, including food products and products used by industries (bio-based energy and materials), based on conversion ratios and loss factors along the food supply chain. The baseline for 2010 was derived from national census data (BMLFUW, 2014; Statistik Austria, various years) and additional literature was used to account for all food losses and wastes in processing, retail and households (for references see Table 1). Within this module, per-capita diets and the relative amount of food waste were varied according to different scenarios (see Section 3.3).

Module two accounts for all GHG emissions from domestic agricultural activities. Activity data related to the production of biomass are provided by module one. GHG emissions caused by these activities are

calculated by multiplication with emission factors taken from Austrian inventory reports (Anon, 2021, 2014), the 2006 IPCC guidelines for national greenhouse gas inventories (Eggleston et al., 2006) and the EMEP-EEA emission inventory guidebook (Hutchings et al., 2013). For the conversion of N<sub>2</sub>O and CH<sub>4</sub> emissions into CO<sub>2</sub>-eq. we used global warming potential metrics for a time horizon of 100 years (GWP100) without inclusion of climate-carbon feedbacks according to the IPCC AR5 (IPCC, 2013) (GWP-CO<sub>2</sub> =1, GWP-CH<sub>4</sub> =34, GWP-N<sub>2</sub>O=298).

Module three accounts for land cover changes, including conversion of grassland into cropland and increases in forest areas from abandoned agricultural land (deforestation, which is rather irrelevant in Austria, is not allowed by the model). Land use changes are particularly important for the assessment of the GHG budget in the biophysical option space, because when the agricultural production target set by a given scenario is lower than what is produced on the available agricultural area, freed up land is systematically reallocated to re-forestation, which generates a carbon sink quantified here by the CRAFT model (Section 2.3.2). For this calculation, primary biomass demand (crops and roughage) from module one was converted into cropland and grassland areas on the basis of crop specific yields and grassland productivities. All food and fodder crops were further differentiated between conventional and organic agriculture in terms of average crop yield and demand for additional legumes for maintaining soil fertility in the case of organic agriculture. Potential demand for cropland and grassland was compared against a predefined area supply, assuming that total agricultural area cannot increase compared to the base year 2010 and that a maximum grassland area (set at 400’000 ha) can be converted into cropland. For the 2010 baseline, average crop yields, grassland productivities, shares of conventional vs. organic agriculture and agricultural areas were derived from national census data (BMLFUW, 2014). Areas not needed for agriculture in a given scenario were handed over to the CRAFT model (below) and allowed to regrow into production forests, sequestering carbon, thus offsetting emissions of the agricultural sector. Module 3, however, excluded changes in soil organic carbon (SOC) stocks associated to land-cover change because temporal changes in forest SOC stocks

Table 1

Variants of main food system parameters considered for this study and how they are derived. Each scenario shown in the option space is a unique combination of variants. A more detailed description of the variants and how they are derived is provided in SI1.

	Variant	Rationale/Characterization	Main Sources
Human diets and food waste	HighMeat	Continuation of past trends: Only slight changes in diets. Food wastes remaining constant on the level of 2010.	Historical data on food supply (Mao 2015) Food wastes according to (Beretta et al., 2013)
	EAT-Lancet	Transition to a healthy sustainable diet according to the planetary health diet of the EAT-Lancet commission and reduction of avoidable food wastes by 50%.	Diets: Planetary health diet of the EAT-Lancet commission (Willett et al., 2019) Food waste: Generic
	Vegan	Transition to a vegan diet (without animal products, including dairy) and reduction of avoidable food wastes by 50%.	Diets: US dietary guidelines (US Department of Agriculture 2010 and US Department of Health and Human Services, 2010) Food waste: Generic
Trade pattern	Constant	Import and export remain constant on the level of 2010 for all crops and livestock products.	National census data
	Zero	Import and export are set to zero in 2050 for all crops and livestock products.	Generic
Cropping system	Constant	<ul style="list-style-type: none"> <li>Share of conventional and organic agriculture remaining at 2010 production volumes (90% conventional, 10% organic).</li> <li>Crop yields remain constant at 2010 level</li> </ul>	
	Organic	<ul style="list-style-type: none"> <li>Full transition to organic agriculture until 2050.</li> <li>Crop yields in organic agriculture: Same growth rates as conventional crop yields, cross-checked with literature meta-studies on organic crop yields. Additional demand for legumes, based on crop rotations.</li> <li>Crop yields in conventional agriculture same as in the scenario “Conventional”.</li> </ul>	Meta-studies on organic crop yields: de Ponti et al. (2012); Seufert et al. (2012); crop rotations in organic agriculture: Freyer (2003).
	Conventional	<ul style="list-style-type: none"> <li>Share of conventional and organic agriculture remaining at 2010 production volumes (90% conventional, 10% organic). Crop yields in conventional agriculture: Linear extrapolation of past crop yield trends.</li> <li>Crop yields in organic agriculture same as in the scenario “Organic”.</li> </ul>	Linear continuation of past trend; Past and current crop yields: national census data
Technical GHG mitigation	Constant	Manure and pasture management shares remain constant. No implementation of technical GHG mitigation measures.	(Anon, 2014)
	Potential	Maximum implementation of technical mitigation measures targeting CH <sub>4</sub> and N <sub>2</sub> O emissions found in literature, with assumptions on dissemination (80–100%) and emission reduction rates in i.e., manure management, enteric fermentation, soil emissions, and fertilizer application.	(Bryngelsson et al., 2016; Winiwarter et al., 2018; Zethner, 2012)

are currently very poorly predicted by models (Mao et al., 2019; Zhang et al., 2020). We, therefore, considered that uncertainties would be too high to establish significant differences between scenarios.

### 2.3.2. CRAFT model

The CRAFT model (Le Noë et al., 2020) simulates the C stocks and fluxes in forest ecosystems, distinguishing coniferous and deciduous forests, at a national resolution and with annual time steps, based on inventory data and administrative statistics on forest management and land use. As assumptions of the model have been extensively presented and discussed previously (Gingrich et al., 2021; Le Noë et al., 2021, 2020), hereafter we briefly present the main features of the model and how it is implemented for the case of Austria (1994–2017) and for the scenario simulations while more details are provided in SI 1.

In the present study, harvested wood data were taken from FAOstat and converted from  $m^3$  to tC by applying specific coefficients following (Haberl et al., 2007). Data on area and standing biomass for coniferous and deciduous forests were provided by the national inventory report (<http://bfw.ac.at/rz/wi/home>). The estimation of the annual net primary production (NPP,  $tC\ ha^{-1}$ ) is based on a parabolic relationship between NPP and standing biomass (B, including aboveground and belowground biomass,  $tC\ ha^{-1}$ ), building on three parameters: r the annual growth rate ( $tC\ NPP\ tC^{-1}$  biomass), K the theoretical maximum carrying capacity in the absence of tree mortality ( $tC\ ha^{-1}$ ) and  $\alpha$  the annual change of the r parameter value (%). The values of these three parameters are calibrated with a routine using Macros in Microsoft Excel so that the simulation best fits the available observed data of standing biomass and minimizes the root mean square error (RMSE). In the present study, the CRAFT model was used to simulate forest C stock dynamics associated to different scenarios by applying the optimized value of r and K in 2017, thus considering that the relationship between NPP and forest biomass will remain constant until 2050.

### 2.3.3. Scenario assumptions

The biophysical option space for the agriculture and forestry sectors was explored by considering four main socio-ecological levers within the agri-food system: (i) diet and food waste, (ii) physical trade balance (iii) agricultural system, and (iv) implementation of technical mitigation measures. Within these four socio-ecological levers, ten variants were considered in the present study resulting in the exploration of 36 scenarios defined by specific combinations of these variants (Table 1, see also SI 1 for further details). The biophysical option space in this analysis is constrained by explicitly ruling out deforestation and the social threshold to provide food for the expected Austrian population in 2050, according to the forecast of the Austrian statistics agency (Statistik Austria, 2016), under diverging diets and levels of trade dependence. We coupled the BioClim.at model with the CRAFT model to simulate how these 36 scenarios would affect the GHG budget in the agriculture and forestry sectors, assuming a linear change of each variant until 2050. The BioClim.at approach allows to assess the GHG budget in the agricultural system as well as the agricultural land spared in each scenario. We considered that the spared agricultural lands were used for afforestation in the different scenarios and assumed that annual wood harvest levels remain constant so that the harvest rate ( $tC\ ha^{-1}$ ) mechanistically declines when afforestation occurs.

## 3. Results and discussion

### 3.1. The biophysical option space

Fig. 4 displays the biophysical option space of all 36 scenarios. Each cell shows the feasibility of a particular scenario in terms of land balances (i.e., all unfeasible scenarios would result in deforestation within Austria) and, for feasible scenarios, the corresponding GHG budgets. This quantitative assessment revealed a large range of possibilities to feed the Austrian population in 2050 while turning the agriculture and

forestry sectors from a net GHG source of 1.64 Mt  $CO_2$ -eq./yr in 2010 to a net GHG sink of 10.6–15.8 Mt  $CO_2$ -eq./yr in 2050 (Fig. 4). Nevertheless, 14 scenarios out of the 36 tested were not feasible as a result of land constraints. Among the 14 unfeasible scenarios, 10 were associated with a constant, meat- and dairy-rich diet, while the four others were found unfeasible when organic farming was combined with self-sufficiency (zero net trade). The finding that organic farming under the condition of self-sufficiency is not feasible is consistent with Billen et al. (2021), who found that under a reduced animal products diet and following a full transition towards organic farming, Austria has the potential to reach only 92% of self-sufficiency in terms of proteins. The only feasible scenarios resulting in a positive GHG balance were associated with the constant meat- and dairy-rich diet, while all others resulted in negative GHG balances. This result highlights that diet is the key driver allowing to reverse the agriculture and forestry sectors from a source to a sink of GHG emissions in Austria. Shifts in diets also open up a range of possibilities for the agricultural sector, including the possibility to transition towards full organic farming or reaching self-sufficiency. This finding is in line with previous studies at the European and global levels (Billen et al., 2021; Theurl et al., 2020). With the current meat- and dairy-rich diet, the only possibilities to feed Austria result in a net GHG source of 1.1–2.4 Mt  $CO_2$ -eq. in 2050 and requires to pursue a conventional agricultural system with further increased crop yields and the maintenance of food and feed imports as a result of increased population and higher agricultural land demand compared to the other scenarios with a shift in diet. By contrast, the implementation of technical mitigation measures in agriculture had no impact on the feasibility of scenarios and only a moderate impact on the net GHG budget. This suggests that the technical solutions currently available are insufficient in the face of the challenge of climate-change mitigation.

In all feasible scenarios with a shift in human diet, the positive GHG emissions in agriculture were overcompensated thanks to the large carbon sink generated by new forest areas and the thickening of existing forest. Focusing on the agricultural sector (Fig. 5a), we found that the lowest GHG emissions are associated with the implementation of organic farming systems as well as the vegan diet due to reduced fertilizer inputs, less agricultural land demand and animal products having impacts on enteric fermentation and manure management emissions. On the contrary, the conventional farming system and the current meat- and dairy-rich diet variants were associated with the highest GHG emissions in agriculture. Self-sufficiency and the implementation of technical mitigation variants were associated with slightly lower GHG budgets in agriculture compared to their alternatives, i.e., constant trade and no technical mitigation (Fig. 5a). This difference can be explained by a current net export of emissions embodied in agricultural products (Pendrill, Persson, 2020). While Austria currently is a net importer of oilseeds (Fig. 2d), it is a net exporter of cereals and animal products. As most of Austria's agricultural GHG emissions are  $CH_4$  from cattle (Fig. S3), self-sufficiency scenarios result in a significant reduction of cattle previously exported and the  $CH_4$  emissions associated with them. In forests, everything else remaining equal, the highest C sinks were associated with the continuation of the current net trade pattern and a shift towards vegan diets, while the continuation of conventional farming and the meat- and dairy-rich diet variants are associated with the lowest C sink in forests. The implementation of technical mitigation in agriculture had no effect on the C sink in forests as the considered mitigation measures (e.g. feed additives to reduce  $CH_4$  emissions) were by construction not related to agricultural area, i.e. forest regrowth.

### 3.2. Implications of scenarios for the embeddedness of the Austrian agricultural system

The option space shows that a vast range of biophysical possibilities exists to meet the double goal of a balanced GHG budget in the agricultural and forest sectors while feeding the population. However, it does not inform us about the socio-political implications and potential

		Self Sufficiency		Agricultural System					
				Constant		Organic		Conventional	
				Technical Mitigation					
Diets and Food Waste	Constant	Constant	Improved	Constant	Improved	Constant	Improved		
		100%							
	EAT-Lancet	Constant	-11.0	-11.5	-10.6	-11.0	-12.3	-12.8	
		100%	-11.4	-11.8			-13.3	-13.6	
	Vegan	Constant	-13.3	-13.7	-13.1	-13.3	-14.6	-15.0	
		100%	-13.6	-13.9			-15.6	-15.8	

Fig. 4. Land-use GHG emissions within Austria in 2050, in Mt CO<sub>2</sub>-eq./yr, with each field showing GHG emissions for one particular scenario. Scenarios not feasible due to land constraints are marked in black and excluded from further analysis. Negative values indicate a net sink of GHG (in orange, yellow or green) while positive values indicate net emissions of GHG (in red). Scenario circles in blue and named as S1 to S4 are discussed in more detail in Section 3.2.

a		Self Sufficiency		Agricultural System					
				Constant		Organic		Conventional	
				Technical Mitigation					
Diets and Food Waste	Constant	Constant	Improved	Constant	Improved	Constant	Improved		
		100%							
	EAT-Lancet	Constant	4.3	3.8	3.6	3.2	4.3	3.8	
		100%	2.8	2.4			2.8	2.4	
	Vegan	Constant	2.8	2.4	2.0	1.8	2.8	2.4	
		100%	1.3	1.1			1.3	1.1	

b		Self Sufficiency		Agricultural System					
				Constant		Organic		Conventional	
				Technical Mitigation					
Diets and Food Waste	Constant	Constant	Improved	Constant	Improved	Constant	Improved		
		100%							
	EAT-Lancet	Constant	-15.3	-15.3	-14.3	-14.3	-16.6	-16.6	
		100%	-14.2	-14.2			-16.0	-16.0	
	Vegan	Constant	-16.0	-16.0	-15.1	-15.1	-17.4	-17.4	
		100%	-14.9	-14.9			-16.9	-16.9	

Fig. 5. GHG emissions related to agricultural activities (a) and forest (b) within Austria in 2050, in Mt CO<sub>2</sub>-eq./yr, with each field showing GHG emissions (positive) or sinks (negative) for one particular scenario. Scenarios not feasible due to land constraints are marked in black and excluded from further analysis.

barriers of those biophysical potentials. We therefore interpret four contrasted scenarios (highlighted in Fig. 4) by relating their biophysical characteristics to the concepts of (dis-)embeddedness (Table 2).

Associated with the best score in terms of GHG budgets (15.8 Mt CO<sub>2</sub>-eq./yr), scenario S1 (Fig. 4) assumes a shift towards a vegan diet, the continuation of the conventional farming system and of the current net-trade pattern as well as the implementation of technical mitigation. In scenario S1, the shift from a rich meat and dairy products diet to a vegan diet can therefore be interpreted as an ecological re-embedding of the agricultural system where the suppression of livestock breeding results in considerable agricultural land abandonment, allowing to reach a negative GHG budget - thus contributing to climate change mitigation. However, some trade-offs with other ecological dimensions may emerge in this scenario, e.g. with biodiversity or other biogeochemical cycles, which are not considered in the present study. Such a radical shift in

human diet could be interpreted as an integration by citizens of the need to contribute to climate change mitigation (Judge et al., 2022). However, the implicit presupposition of a spontaneous shift in diet leaves aside the fact that the current diet in Austria is not the sum of individual habits but rather the result of past and recent public agricultural and food policies (see Section 2.1). These past public policies necessarily create a path dependency for future evolutions in the land-use sector with many techno-economic lockers, including a strong importance of the livestock sector, which would most certainly hinder a shift towards a vegan diet. Therefore, to shift diet from the current one to a vegan one would certainly require strong public policies, bypassing the pressure of the Agricultural Marketing Board (AMA), which is the central agency in charge of collecting agricultural market intelligence and administrating the agricultural support programs of the Common Agricultural Policy (Schermer, 2008). Such public policies would also severely impact



**Table 2**

Summary of the social, spatial and ecological (dis-)embeddedness of the scenarios as interpreted from the bio-physical model indicators and the scientific literature.

Scenarios	Social embeddedness (Model indicators: diet, farming practices, technical mitigation, trade balance)	Spatial embeddedness (Model indicator: physical trade balance)	Ecological embeddedness (Model indicator: greenhouse gas budget, farming practices, trade balance)
S1	<p><b>Ambivalent:</b></p> <ul style="list-style-type: none"> <li>- Vegan diet could severely impact peasant activities and Austrian landscapes,</li> <li>- The features of conventional farming (reliance on land-use specialization industrial inputs) are rooted in a logic of food commodification, arising from agricultural intensification and market integration of food products,</li> <li>- Technical mitigations indicate increasing concern regarding the environmental impact of agriculture,</li> <li>- Self-sufficiency shifts the production focus towards meeting domestic demand, representing a first step towards de-commodification.</li> </ul>	<p><b>Positive:</b></p> <ul style="list-style-type: none"> <li>- Self-sufficiency, by definition, relies more on local resources, thus being in line with the “food from somewhere” idea (by opposition to “food from nowhere”).</li> </ul>	<p><b>Positive with some ambivalence:</b></p> <ul style="list-style-type: none"> <li>- Most negative GHG budget, thus contributing to climate change mitigation,</li> <li>- Reforestation of permanent grassland on spared land following shift to vegan diet can lead to loss of habitat, and thus loss of biodiversity,</li> <li>- Conventional farming are less prone to agricultural biodiversity, improve water quality, locally closing biogeochemical cycles, resilience to extreme climatic events and human health than organic farming,</li> <li>- Self-sufficiency can help to meet the target of locally closing the nutrient cycles.</li> </ul>
S2	<p><b>Positive with some ambivalence:</b></p> <ul style="list-style-type: none"> <li>- The EAT-Lancet diet could allow a de-intensification of grassland and pasture, which can be expected to promote a de-commodification of food products since intensification were a key element of food commodification,</li> <li>- Organic farming are less intense production systems, which could favor a de-commodification of food,</li> <li>- However, organic farming products have since decades been integrated into lucrative food markets, so that it is not a panacea,</li> <li>- No implementation of technical mitigation can be seen as a lesser concern for the environmental impact of agriculture,</li> <li>- The continuation of the current trade balance maintains the status of food as a commodity integrated into international trade.</li> </ul>	<p><b>Negative:</b></p> <ul style="list-style-type: none"> <li>- The continuation of the current net-trade pattern results in the continuation of a lesser spatial embeddedness of the agricultural system.</li> </ul>	<p><b>Positive with some ambivalence:</b></p> <ul style="list-style-type: none"> <li>- Negative GHG budget contributes to climate change mitigation,</li> <li>- Organic farming are likely to promote to agricultural biodiversity, improve water quality, locally closing biogeochemical cycles, resilience to extreme climatic events and human health,- The continuation of the current trade pattern might fuel the externalization of negative environmental impacts (but this effect is not investigated in the present study).</li> </ul>
S3	<p><b>Ambivalent:</b></p> <ul style="list-style-type: none"> <li>- The EAT-Lancet diet contributes to social re-embedding in S3,</li> <li>- The features of conventional farming are likely to pursue food commodification,- Technical mitigations indicate increasing concern regarding the environmental impact of agriculture,</li> <li>- Self-sufficiency can be a first step towards de-commodification.</li> </ul>	<p><b>Positive:</b></p> <ul style="list-style-type: none"> <li>- Self-sufficiency, by definition, relies more on local resources, thus being in line with the “food from somewhere” idea (by opposition to “food from nowhere”).</li> </ul>	<p><b>Positive with some ambivalence:</b></p> <ul style="list-style-type: none"> <li>- Negative GHG budget contributes to climate change mitigation, - Conventional farming are less prone to agricultural biodiversity, improve water quality, locally closing biogeochemical cycles, resilience to extreme climatic events and human health than organic farming,- Self-sufficiency can help to meet the target of locally closing the nutrient cycles.</li> </ul>
S4	<p><b>Negative:</b>- The current rich-diet in Austria has adverse health effects according to the WHO and is inequitable as it cannot be generalized globally,- The features of conventional farming are likely to pursue food commodification,- No implementation of technical mitigation can be seen as a lesser concern for the environmental impact of agriculture,- The continuation of the current trade balance maintains the status of food as a commodity integrated into international trade.</p>	<p><b>Negative:</b>- The continuation of the current net-trade pattern results in the continuation of a lesser spatial embeddedness of the agricultural system.</p>	<p><b>Negative:</b>- Positive GHG budget contributes to increasing climate change, - Conventional farming are less prone to agricultural biodiversity, improve water quality, locally closing biogeochemical cycles, resilience to extreme climatic events and human health than organic farming,- The continuation of the current trade pattern might fuel the externalization of negative environmental impacts (but this effect is not investigated in the present study).</p>

peasant activities and Austrian landscapes (especially in Alpine regions) by a complete abandonment of grassland and breeding activities, which is hardly imaginable and would meet a strong resistance of interest groups, in particular livestock producers, tourism and local populations (Wending, 2016). Therefore, while the vegan diet corresponds to an ecological re-embedding of agri-food systems whose production activities would be oriented more by the need to limit the environmental impact than by the motive to secure profits, its social embeddedness is more ambivalent as it could be detrimental to rural livelihood conditions.

The ecological re-embedding of S1 would also be limited by the continuation of conventional farming system, as conventional farming, despite promoting land sparing (Lamb et al., 2016; Seufert et al., 2012), has other environmental drawbacks compared to organic farming systems. For example, organic farming has been shown to promote agricultural biodiversity (Leksono, 2017; Tuck et al., 2014), improve water quality (Benoit et al., 2014; Sivaranjani and Rakshit, 2019), allow better resilience to extreme climatic events (Borron, 2006) and improve human health (Mie et al., 2017). Conventional farming systems are also the results of past public policies, including land-use specialization and

dependence upon industrial inputs. These structural features of conventional farming are rooted in a common logic of food commodification, arising from agricultural intensification and market integration of food products (Friedmann, 2005; Langthaler and Schübler, 2019). This would be alleviated by shifting the production focus towards meeting domestic demand in S1, representing a first step towards de-commodification. Self-sufficiency would also help to meet the target of locally closing the nutrient cycles (Billen et al., 2021, 2015), which interruption have exceeded the limits for a safe operating space for humanity (Rockström et al., 2009) driven by international biomass trade, amongst others (Lassaletta et al., 2014; Nesme et al., 2018). Hence, self-sufficiency can be associated with a stronger ecological and spatial embeddedness. Overall, S1 would contribute to a re-embedding of the agri-food system in Austria, although it is prone to fuel conflictive situations, and this embeddedness might be weaker than suggested by the quantitative estimates of the GHG budget.

S2 represents a 33% lower carbon sink than S1, but still enables to significantly absorb carbon from the atmosphere. S2 assumes a shift towards the EAT-Lancet diet, a full transition towards organic farming, the perpetuation of the current level of trade and the implementation of

technical mitigation. Contrary to the vegan diet, the EAT-Lancet diet would have a less drastic impact on the activities of livestock farmers and the Austrian landscape. A transition towards the EAT-Lancet diet could allow a de-intensification of grassland and pasture, with beneficial effects on grassland ecosystems (Knudsen et al., 2019). Therefore, shifting towards the EAT-Lancet diet in S2 could contribute to a de-intensification of breeding activity and grassland ecosystems. As the intensification of land-use was historically a key process for food surplus production available for the market (Polanyi, 2001), the de-intensification of grassland and breeding activity promoted by a shift toward the EAT-Lancet diet can be expected to promote a de-commodification of food products and, as such, to contribute to an ecological and social re-embedding of the agri-food system in S2.

In S2, transitioning towards an organic farming system would promote long crop rotation with leguminous crops allowing symbiotic nitrogen fixation, resulting in less intense production systems (Billen et al., 2021), which could favor a de-commodification of food. This interpretation, however, warrants a caveat that organic farming products have since decades been integrated into lucrative food markets. However, some examples of local organic production and consumption systems have been shown to come with beneficial effects not only in ecological, but also in social terms (Milestad et al., 2010). Therefore, even though a full transition towards organic farming is not the panacea, it would still represent a further consideration of environmental concerns raised by citizens' movements, particularly in line with the 'food from somewhere' idea (Schermer, 2015). In Austria, such a transition would have to face many political and economic obstacles, mainly due to the deregulation policies of the agricultural markets leading Austrian farmers into a competitive logic which is not likely to ease conversions to organic farming (Kroll and Pouch, 2012; Sassatelli and Scott, 2001). However, the fairly strong tradition of organic farming production and consumption in Austria may be beneficial to further organic expansion (Schermer, 2015, 2008), which could be facilitated by bottom-up pressure from citizens upon policy-makers.

The continuation of the current net-trade pattern in S2 would result in the continuation of low spatial embeddedness of the agricultural system as well as maintaining the status of food as a commodity integrated into international trade. In our territorial-based approach, we were not able to quantitatively estimate the externalized GHG emissions of imported feed while the potential global optimization of greenhouse gas emissions by reallocating the production of land-based products is one of the most debated effects of international trade (Kastner et al., 2021). This idea originates from the adaptation of Ricardian economic reasoning of comparative advantage to environmental impacts on land (Lambin, 2012). Some empirical studies indeed found that the reallocation of production through international trade of land-based products reduced global land requirements (Kastner et al., 2014; Martinez-Melendez and Bennett, 2016; Xu et al., 2020) and associated material use (Dombi et al., 2021). Roux et al. (2021), however, found that this did not hold when looking at the pressure on ecosystem functions. Trade liberalization rather incentivizes countries with highly productive land as such in the tropics to specialize in exports of land-based products, increasing the pressure on tropical ecosystems and global greenhouse gas emissions of land use (Roux et al., 2021; Verburg et al., 2009). Therefore, in S2, transitioning toward a fully organic farming system concomitantly to a shift in diet toward the EAT-Lancet diet would increase ecological and social embeddedness of the agri-food systems while the continuation of the current trade pattern would limit the spatial embeddedness, mitigate the partial de-commodification effect of the shift in diet and transition towards organic farming, and might even fuel the externalization of negative environmental impacts (Fuchs et al., 2020).

Assuming a shift towards the EAT-Lancet diet, the perpetuation of conventional farming systems, a shift towards self-sufficiency of agri-food systems and the implementation of technical mitigation, S3 is associated with a score 14% lower than S1 in terms of GHG emissions.

Similarly, to S2, the shift towards the EAT-Lancet diet would contribute to an ecological and social re-embedding of the agri-food system in S3. However, this re-embedding would be restrained by the perpetuation of conventional farming systems, although these systems could be de-intensified in S3 since the EAT-Lancet diet could allow for a de-intensification of grassland and breeding activities. In S3, the search for food self-sufficiency would also contribute to de-commodify food and feed whose production would be intended for local consumption rather than for the global market, while the non-dependency on food and feed imports would help closing the biogeochemical cycles, thus improving the spatial embeddedness of food systems. In S3, reaching self-sufficiency while shifting toward the EAT-Lancet diet would thus increase social, spatial and ecological embeddedness of the Austrian agri-food system but the perseverance of the conventional farming systems would limit these effects.

Finally, S4 would have the worst score in terms of GHG emissions (2.4 Mt CO<sub>2</sub>-eq./yr). S4 assumes the perpetuation of the current agri-food system, including rich meat and dairy-based diets, conventional farming system, the current trade pattern and no implementation of the available technical mitigation. This scenario would therefore be in line with the pursuit of the historical trends (see Section 2.1), in which food and feed are further commodified through their integration within international markets, the continuation of intensive conventional farming systems as well as an inequitable rich meat and dairy products diet (Campbell, 2009; Friedmann, 2005). We understand S4 as the most-disembedded of all scenarios and also the one with the worst GHG balance.

### 3.3. Methodological contributions and limitations

Combining the exploration of a biophysical option space with a socio-political analysis based on Polanyi's thinking and the food regime theory offered here a complementary approach to the Shared Socio-economic Pathways (SSPs) in Integrated Assessment Models (IAMs) (Popp et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017), albeit at the national level and for the agricultural system only.

First, while the SSPs constrain the range of the biophysical possibilities by first defining socio-economic narratives and then implementing them into IAMs, the present approach pursues a reverse order by first evaluating a vast panel of options for the agricultural system constrained by biophysical feasibility and the objectives of food supply and non-deforestation, and second examining the socio-political implications of contrasting options. We thus follow a diagnostic approach to explore the biophysical future option space of the agri-food system in Austria. The SSPs provide quantifications of consistent, relevant and legitimate scenario narratives, however, leaving aside alternative development trajectories of biophysically possible options, leading to an implicit narrowing of the range of possibilities. This narrowing of the possible scenarios has been vividly criticized (Anderson and Jewell, 2019; Keyßer and Lenzen, 2021), mostly because of their unquestioned reliance upon economic profitability, growth, and self-regulative market-mechanisms (Hickel et al., 2021; Warszawski et al., 2021). At the national level and for a given sector, the approach implemented here allows to overcome this limit by analyzing the entire biophysical option space, without being constrained by ex-ante assumptions about the evolution of the economy (Brand et al., 2021; Otto et al., 2020; Pichler et al., 2017; Turner et al., 2020).

Second, IAMs often assume that commodities are distributed through markets, under "perfect" competition and information about the world (Clarke et al., 2014). These assumptions are however in direct contradiction with the social theories used in this article, which prone the de-commodification of food. Thus, even if IAMs would be calibrated to a wider set of scenarios than the SSPs (for example scenarios without economic growth), their interpretation through Polanyian social theories would be at odds with the assumptions of the models. Unlike IAMs, biophysical models do not rely on any assumption about the structure

and functioning of the economy. This leaves a high flexibility to interpret their results through the lenses of any social theory, without inducing any contradiction between the assumptions of the model and the theories at hand. The present study, therefore, highlights the importance of recognizing from the outset the bias associated with any socio-economic theory in constructing and assessing sustainability scenarios. Because systematically making explicit the socio-economic assumptions selected, as well as those left aside, is urgent to scientifically inform the debate on the possible future of land use systems, the present study contributes to this debate by offering an alternative approach to constructing scenarios, first exploring the biophysical option space and then examining their socio-political implications on the basis of referenced social theories and concepts. Hence, the approach presented here can help informing policy decisions and societal awareness about the feasibility and implications of future trajectories in the agri-food system.

The option space is as well so far focusing on biomass, and is hence isolated from other economic sectors. We do hence not model effects of material, monetary, or labor transfers between agriculture and other economic sectors, which may result from the studied transformations as dietary change. In this respect, the social, spatial and ecological embeddedness indicators we developed are necessarily reductive as they do not explicitly deal with the (dis-)embeddedness of the economic system. This limit could be overcome in future researches by coupling the biophysical modeling with an economic model of the food production and distribution chain. This would allow the development labor, land and food commodification indicators, indicating that the greater the commodification, the more the economy is disembedded from social ties and ecological limits. Last but not least, the present study is focused on the Austrian case, which is characterized by a very high level of animal protein intake and a lesser degree of international market integration compared to other European countries such as France or Spain. As a consequence, our results and interpretations regarding the implications of scenarios in terms of embeddedness can hardly be generalized beyond that case, although they have a heuristic value. Overall, these limitations only call for further interdisciplinary research integrating the multiple dimensions of agri-food systems: biophysical, environmental, social, spatial, economic, cultural, etc., of which the present research is already a first milestone.

#### 4. Conclusion

The interdisciplinary approach implemented in the present study allows to systematically and quantitatively assess the biophysical option space for land-use systems in Austria at the horizon 2050 and to appreciate the socio-political implications of different scenarios. The Polanyian and food regime theoretical frameworks used here highlighted that strong sustainability in land-use systems, prioritizing socio-ecological orientations such as climate-change mitigation and food provision, can only be reached by reducing the share of meat and dairy products in human diets. To enable re-embedding of the agri-food system, this necessary shift in diet, should, however, be understood as integral to a wider reconfiguration of land-use and agri-food systems aiming to preserve the environment while responding to social needs regarding food production and consumption.

#### CRediT authorship contribution statement

Conceptualization of the present research was conducted by JLN, SG, MP and CL. The Methodology was developed by CL and AM for the bioclim.at model and by JLN and SG for the CRAFT model. The Data Curation was checked by CL and JLN. JLN, SG, MP, NR, LK, AM and CL contributed to Writing - Original Draft and Writing - Review & Editing. Funding acquisition was made CL for the ZeAfolu project (*Zero Emission in Agriculture Forestry and Other Land-Use*) and by SG for the HEFT project (*Hidden Emissions of Forest Transition*). JLN supervised the whole

research.

#### 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.

#### Data Availability

Data are provided in SI 1&2.

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#### Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.envsci.2022.11.006](https://doi.org/10.1016/j.envsci.2022.11.006).

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