Bodirsky, B. L., Chen, D.-M.-C., Weindl, I., Sörgel, B., Beier, F., Molina Bacca, E. J., Gaupp, F., Popp, A., Lotze-Campen, H. (2022): Integrating degrowth and efficiency perspectives enables an emission-neutral food system by 2100. - Nature Food, 3, 5, 341-348.

DOI: https://doi.org/10.1038/s43016-022-00500-3

Integrating degrowth and efficiency perspectives enables an emission-neutral food system by 2100

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Abstract

Degrowth proponents advocate for reducing ecologically destructive forms of production and resource throughput in wealthy economies to achieve environmental goals, while transforming production to focus on human well-being. Here we present a quantitative model to test degrowth principles in the food and land system. Our results confirm that reducing and redistributing income alone, within current development paradigms, leads to limited greenhouse gas (GHG) emissions mitigation from agriculture and land-use change, due to nutrition transitions towards unsustainable diets already occurring at relatively low income levels. Instead, we show that a structural, qualitative food system transformation can achieve a steady-state food system economy that is net GHG-neutral by 2100 while improving nutritional outcomes. This sustainable transformation reduces material throughput via a convergence towards a needs-based food system, is enabled by a more equitable income distribution and includes efficient resource allocation through the pricing of GHG emissions as a complementary strategy. It thereby integrates degrowth and efficiency perspectives.

Main

Introduction

Proponents of degrowth propose an “equitable downscaling of production and consumption that increases human well-being and enhances ecological conditions at the local and global level”, to be undertaken voluntarily and democratically[1]. Degrowth proponents see this transformation as necessary to meet environmental goals, such as those laid out in the Paris Accord or the Planetary Boundaries[2], as degrowth would reduce demand-driven pressures on the environment[3]. Degrowth arguments also include a strong environmental and economic justice component: Downscaling and redistribution of the high-income economies of the Global North would allow for “more space” for countries of the Global South to develop and still grow within environmental limits[4,5]. A reduction of GDP is generally not seen as an objective per se, but rather as the expected consequence of the downscaling of material and energy throughput[4]Some practitioners may also target a reduced GDP as a means, given the strong association between GDP and certain ecological impacts[6].

While the theoretical debate around degrowth is emergent and lively[4,7,8], few studies have attempted to quantify degrowth propositions in modeling work, in order to assess how effectively such proposals meet stated goals. Integrated assessment modeling of future environmental scenarios without the precondition of economic growth, especially in the Global North, are needed[3,9].

Degrowth scenarios have been analyzed recently on a macro-economic scale and for the energy system[10,11], but not for the land and food system. A focus on the implications for the food and land system is long overdue as it is today the largest cause of biodiversity and ecosystem destruction[12,13] and as it emits one third of global greenhouse gas (GHG) emissions along the entire supply chain[14]. Furthermore, Land-Use and Land-Use Change (LULUC) emissions may alone preclude achieving the 1.5°C and 2°C climate targets as decided upon in the Paris Accord[15].

An assessment of degrowth scenarios for the land and food system should aim to cover the breadth of degrowth proposals and decompose the main dynamics that lead to GHG reduction and reduced economic activity. A review[16] structures the degrowth literature according to three economic policy objectives: (1) A sustainable scale of the economy, keeping the economy within the planetary boundaries of a “safe operating safe” with pollution remaining within environmental absorption capacity[2]; (2) “fair redistribution” between rich and poor, on both national and international scales; and (3) “efficient allocation” of resources in order to maximize well-being[17].

Here, we use a quantitative land system model[18] to decompose different dynamics behind a degrowth pathway and scrutinize the consequences of different viewpoints in the debate by constructing a range of scenarios, aligning with the policy objectives identified above.

Results

Scenario Set

Our set of exploratory scenarios of stylized socio-economic transformations covers different constituents of both degrowth proposals and efficiency-based approaches already theorized and modeled (Table 1). Two scenarios of ex-ante GDP reduction (GDP-CAP) or redistribution (GDP-FAIR) aim at discussing the potential and limitations of purposefully reducing or redistributing GDP, as opposed to the following scenarios, which address qualitative aspects of the food system with no prior assumptions of GDP - in line with current degrowth scholarship[4]. The food preference-change scenario (DIET) is oriented along a needs-based provision of food; the efficient allocation scenario (EFF) assumes a global greenhouse gas tax internalizing the costs of climate change stemming from food supply chains. Finally, the sustainable scenario combines GDP-FAIR, DIET and EFF.

The scenario assumptions serve as input to MAgPIE4, a modular open-source framework for modeling global land systems and their environmental impacts[18] (see Methods). Our scenarios focus exemplarily on greenhouse gas emissions as a central indicator for environmental sustainability. Further environmental indicators such as biodiversity intactness[19], nitrogen pollution[20], and water withdrawals have been shown to respond similarly[21,22].

There is extensive literature on the process of re-organizing the economy towards a degrowth-oriented system through democratic and participatory institutions[7,16]. We assume this a priori in this article and instead focus on the implications of such a transformation for the food and land system.

Table 1. **Scenario descriptions, decomposing proposals in the degrowth literature.**

Scenario	**Scenario settings**	**Literature analogue**
Baseline (BAU)	Baseline scenario along middle-of-the road development (SSP2 storyline), including moderate economic and population growth[29].	Default baseline scenario of many integrated assessment analyses of the land and food system[21,70].
Capped Income (GDP-CAP)	Total per-capita income decreases by 2030 to a limit of 12746 USD_{05PPP}, which is the World Bank threshold between middle- and high-income countries[71]. Countries below the threshold follow their normal growth path. See Supplementary Figure 1, for income trajectories of scenarios.	The selected threshold corresponds roughly to the income level where mean life satisfaction, life expectancy, infant mortality and participation in education begin to saturate[35,72,73,76]. This scenario does not include a qualitative transformation but rather simulates income reduction as measured by GDP, within the current economic paradigm.

Fair Redistribution (GDP-FAIR)	Like GDP-CAP, but increasing per-capita income to 12746 USD_{05PPP} for countries below this limit by 2030. In both FAIR and GDP-CAP, the historically observed relation between dietary patterns and income is maintained.	A fair and equitable economy in terms of income, where countries of the Global South have increased GDP per capita, given redistribution from higher-income countries[4,77] This scenario does not include a qualitative transformation but rather simulates income redistribution within the current economic paradigm.
Preference change (DIET)	A dietary shift towards the "Planetary Health Diet"[36] by 2030, which sees much lower animal-source food consumption, combined with a reduction of food waste[56].	A shift in diet has been proposed as part of any degrowth process in the agri-food sector, especially in a way that meets human needs for a good life, while remaining within planetary boundaries[78]. Such a shift should result in reduced consumption of emissions-intensive products[4].
Efficient Allocation (EFF)	GHG tax in line with the Paris Accord goal of 1.5°C warming. Non-CO_2 GHGs are priced according to their CO_2-equivalent warming potential.	An efficiency-based mitigation approach, reducing emission sources at the same marginal mitigation costs across emission sources by technical mitigation measures or relocation of resources and production factors. Achieved via a greenhouse gas price that internalizes externality costs of pollution into production costs[31]. Emission pricing is the key instrument in most integrated assessment analyses of the land and food system[24].
Sustainable Transformation (TRANS)	Combines GDP-FAIR, EFF and DIET	A sustainability transformation combining societal change and efficient taxing, as a combination of degrowth and efficiency perspectives[30].

Model Outputs

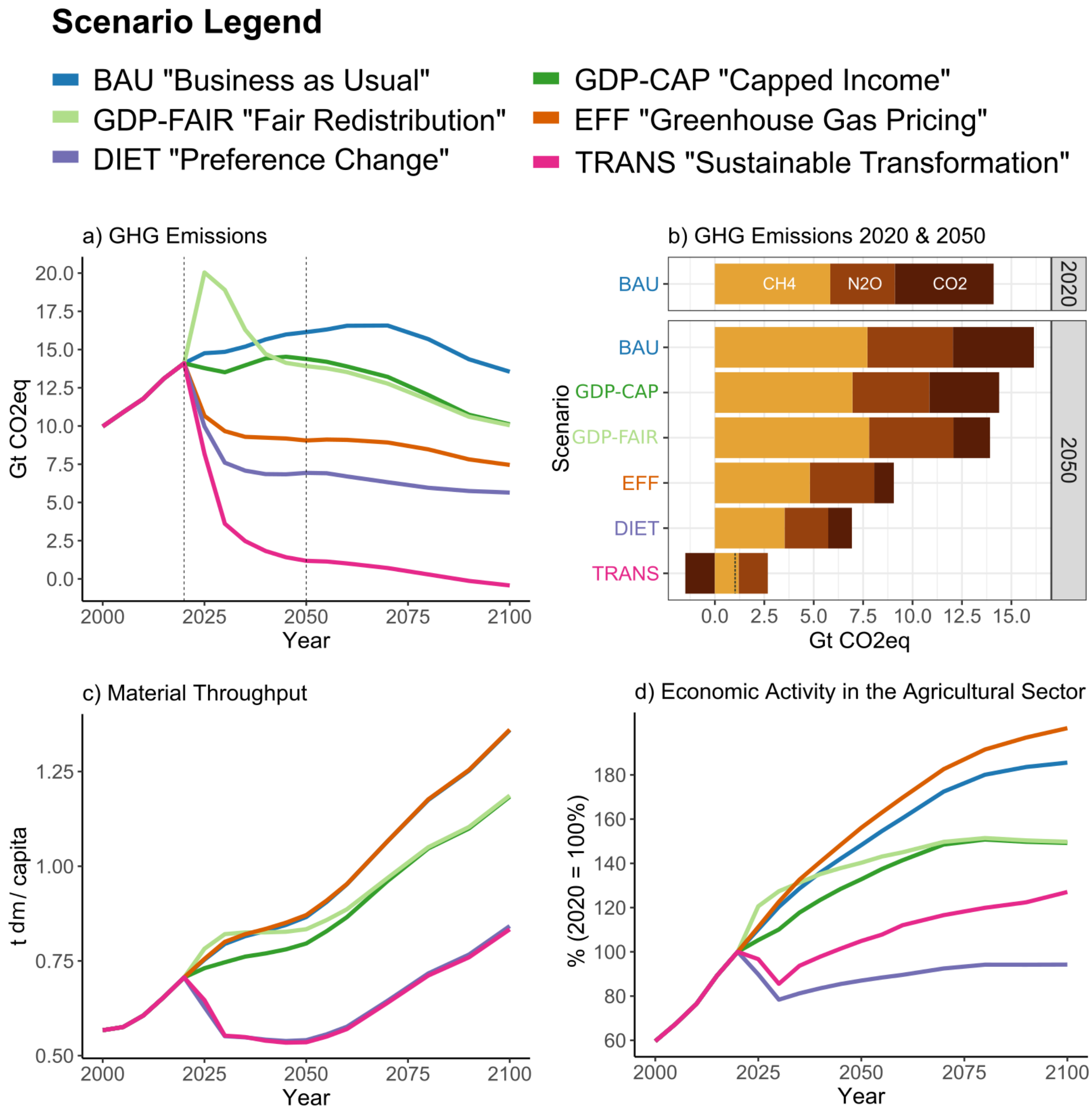

***Figure 1. Development of emissions, material throughput, and economic activity for 6 scenarios**. a) GHG emissions for 2020-2100 in CO2eq GWP100. Dotted lines indicate years of comparison in (b). **b)** shows the composition of GHG emissions in 2020 and 2050 as a stacked bar plot for, CH4, N2O and CO2 in Gt CO2eq GWP100. Dotted line in TRANS shows net total. **c)** Cumulative material throughput of food consumption, calculated as the demand for crop products in tons of dry matter (t dm) per capita. **d)** Percentage change of the economic activity in the agricultural sector (expressed as the factor costs of production at constant factor prices excluding land rents, water rents and emission taxes) as line-chart relative to 2020.*

Average yearly GHG emissions from agriculture and land-use change (LULUC) from 2020-2100 are highest in the SSP2 BAU baseline, at an average of 14.4 Gt / year of CO2-equivalents in 100-year global warming potential (CO2eq GWP100) emissions (Fig. 1a), and 16.1 Gt CO2eq in the year 2050. While the precise warming effect cannot be derived from the GWP100 metric, a comparable scenario[15] shows that business-as-usual emissions from the LULUC sectors alone would lead to global warming between 1.5 and 2°C. In the “Capped Income” (GDP-CAP) and “Fair Redistribution” (GDP-FAIR) scenarios, CO2eq emissions are reduced only modestly (14.4 Gt CO2eq for GDP-CAP and 13.9 Gt CO2eq for GDP-FAIR in 2050), as the reduced consumption in high-income countries is countered by a continued (GDP-CAP) or rapid (GDP-FAIR) increase in consumption in low-income countries. In fact, the redistribution in the GDP-FAIR scenario even results in higher food demand and increased emissions relative to the SSP2 baseline during the years when redistribution is implemented. Despite the substantial reduction in overall economic activity (global GDP in GDP-CAP is 44% and in GDP-FAIR is 51% that of BAU by 2050, see Fig. S1), cumulative emissions from 2020 to 2100 still are in excess of the remaining emission budget for achieving a 1.5° climate target with a probability of 66%[15], with 1024 Gt CO2eq (GDP-CAP) and 1077 Gt CO2eq (GDP-FAIR). The limited effect (in terms of a reduction of LULUC GHG emissions) for the GDP-CAP and GDP-FAIR scenarios compared to BAU stems from the fact that the main dynamic of the ‘nutrition transition’ – increasing demand for land- and emissions-intensive animal-sourced products as well as increased food waste – unfolds already at relatively low per-capita income levels[23].

The “Efficient Allocation” scenario (EFF) results in almost a halving of LULUC-related GHG emissions by 2100, with 9.05 Gt of GHG emissions in 2050. This price signal reduces emissions by incentivizing afforestation and less-polluting management practices, and incentivizing land-sparing and investments in yield-improving technological change[24] (see Methods). The consumer “Preference Change” (DIET) scenario as part of a degrowth pathway also leads to substantial emissions mitigation (6.93 Gt CO2eq in 2050), due to reduced demand-side pressures on the land system (i.e. a shift away from instead of towards animal-source products). Finally, a sustainability transformation scenario (TRANS) where fair redistribution is combined with efficient allocation and preference changes reduces cumulative emissions to 1.18 Gt CO2eq in 2050. In this scenario, land becomes available for increased afforestation and regrowth of natural vegetation, resulting in negative CO2 emissions that compensate for some of the residual N2O and CH4 emissions. By 2100, this scenario shows net-zero emissions for the food system.

The scenarios also show very different trends in their agricultural material throughput, defined here as the total demand for crops for food, feed, and other purposes (Fig. 1c). Both BAU and EFF show a continued increase, nearly doubling the per-capita footprint by the end of the century. The GDP-FAIR redistribution scenario leads to a slightly faster initial increase due to the acceleration of income-driven dietary changes in low-income countries but converges to the slower-growing value of the GDP-CAP scenario in the longer term. Finally, the DIET and TRANS scenarios project a strong initial reduction of the agricultural material throughput, and would only return to a per-capita footprint comparable to today towards the end of the century. Comparing material throughput with GHG emissions, there is no direct coupling between the two quantities in our scenarios. In the EFF and TRANS scenarios, we observe a partial but not complete decoupling of emissions from the material throughput; residual non-CO2 GHG emissions from agricultural production can be reduced but not completely avoided.

Changes in the material scale and efficiency of the agri-food system also impact economic activity, which we here define as the sum of global agricultural production costs, investments into agricultural R&D, and irrigation and land expansion costs. These costs correspond to production factors such as labor, capital, and input commodities that are required by the food system from the wider economy. In BAU, agricultural economic activity grows by 48% from 2020 to 2050 (Fig. 1d). When GDP is reduced in GDP-CAP and GDP-FAIR, agricultural activity is still 89% that of BAU in 2050, although GDP in GDP-CAP is 21% that of BAU by 2050 (Fig. S1). This can be traced back to food being a necessity good with an income elasticity smaller than unity. The efficient allocation scenario (EFF) with a GHG tax actually increases agricultural economic activity relative to BAU, as the implementation of mitigation measures increases costs, and as GHG-intensive land expansion has to be replaced by the intensification of existing croplands. In contrast, the structural change of the DIET scenario, in particular the reduction of animal-source foods, leads to a strong initial reduction and subsequent stabilization of economic activity to slightly below current levels. The TRANS scenario, combining GDP-FAIR, EFF, and DIET, shows a short-term decline of economic activity, and then a small but steady increase to a level 20% above current levels, also due to continuous population growth.

The dynamics driving the different scenario outcomes are further described in the Supplementary Text S1 and the Supplementary Data S2.

Discussion

Our study applies a set of quantitative scenario simulations in order to decompose the different constituents of both degrowth and efficiency-based visions for the agriculture and food system. We find that in order to reduce global LULUC GHG emissions, both a change of dietary preferences and a change of economic incentives by emission pricing are most crucial. A more equitable income distribution between countries only leads to very limited reductions in LULUC emissions if it remains within the current “nutrition transition” paradigm, i.e. the historically observed relations between income and dietary patterns[23,25].

Our results are in line with the arguments of degrowth proponents, who differentiate sustainable degrowth from economic recession in that degrowth proposals also transform the economy in a qualitative manner[1]. We show that a simple reduction of income in high-income countries, while maintaining the existing food system, is not very effective in mitigating GHGs; most importantly because the food system - in contrast to the energy system[26] - already produces relatively high emissions at low per-capita incomes[14]. The results from the GDP-FAIR scenario even indicate that the marginal pollution per unit of income is higher at lower incomes. Despite a lower global average GDP in the GDP-FAIR scenario (see Supplementary Figure 1), greenhouse gas emissions increase relative to the BAU scenario for the period of redistribution. Also, from the public health perspective, there is no sweet spot of economic development within the classical nutrition transition; the decline of undernutrition is paralleled by a simultaneous rise of malnutrition, the so-called "double burden of malnutrition" [23,27].

The food system thus needs to be transformed both in terms of its material scale and its qualitative structure: resource intensive and highly polluting industries, such as the livestock industry, would need to be downscaled along with a reduced consumption of animal protein. Other sub-sectors such as horticulture should in contrast even be expanded due to their role in preventing malnutrition and chronic diseases[23,28]. Furthermore, farmers need to adopt low-polluting management practices, and supply chains must shift towards low-polluting source materials.

Our study explores two distinct ways to change the qualitative structure of the food system: Emission pricing (EFF), which includes the hidden costs of GHG emissions into the decision-making at various stages of the food supply chain; and changing preferences of consumers (DIET), which influences the structure of the economy from the end of the supply chain.

While emission pricing and the resulting efficient allocation of resources has received a lot of attention in the integrated assessment modeling community[29], it is less prominent and indeed often criticized in the degrowth literature[16,30]. We thus consider it separately from the degrowth narrative, although some emission pricing schemes within a degrowth framework have been proposed[31]. Indeed, such schemes warrant further consideration as our model simulations show high mitigation potentials for the scenarios that introduce a price signal for GHGs into the agricultural and land system (EFF and TRANS). A GHG price does not only incentivize efficiency improvements and the implementation of mitigation technologies, as opposed to e.g subsidies for mitigation measures or more efficient technologies, a tax or cap-based policy circumvents rebound effects that can occur from efficiency-improvements and passes on the increased costs as mitigation incentive to upstream sectors and consumers. In these up-stream sectors, the price signal may lead to further mitigation, which is however not included in our assessment. For instance, higher raw material prices may incentivize food loss reduction or the replacement of emission-intensive animal-based ingredients by plant-based alternatives in the food processing sector[32].
GHG taxation would also translate into higher food prices (although the tax could be redistributed, discussed further on). Under cost-efficient CO2 prices, the low cost-share of agricultural products in total food prices[33], and observed price-elasticities, the resulting food price changes would however not have a transformative impact on dietary patterns (see Supplementary Text S2). Consumer tax levels to incentivize sustainable diets would thus need to be much higher than the signal that would reach consumers from a uniform emissions tax[34], and changing demand via prices would therefore constitute an inefficient alternative to production-side mitigation from an environmental cost-benefit perspective.

However, the potential of demand-side mitigation is substantial, as shown in the DIET scenario, and the pricing of GHG emissions only achieves minor impacts on this front. Transformative dietary change is therefore a key strategy. This approach is in line with the degrowth arguments that consumption should be oriented along with the satisfaction of basic human needs and provide living standards such that a "good life for all" is possible within environmental limits[35].

This diet-change is not a mere reduction of consumption, but a qualitative change that can be even considered an improvement with respect to the satisfaction of human needs, given the improved nutritional composition of the dietary shift[36].

Transformative dietary change, with its large mitigation potential, can also be achieved with different (non-price) mechanisms such as persuasion, access, empowerment, or nudging. Research has so far mostly focused on policy interventions to improve dietary health and compiled and evaluated a broad spectrum of interventions that target food preferences and food environments[37,38]. Mechanisms such as food labeling[39], advertisement bans[40], dietary counseling[41,42], and public food provision[43] have been identified as effective and often cost-efficient alternatives to fiscal instruments. In economic nomenclature, these policies target preferences (represented for instance by parameters such as demand-elasticities or floor demand shifters) which are usually assumed exogenous and constant. A consumer with the same income and faced with the same market prices will consume different quantities if she lives in a food environment with low marketing for highly processed foods, if the food availability in the canteen is modified, or if her awareness for environmental or health topics is raised. Research on the dynamics and drivers of preference change, on the influence of food environments, and their impacts on elasticities and floor demand shifters[44] is yet underdeveloped but would be the necessary bridge between a more holistic food system approach and standard economic models. The investigation would also be confronted with welfare economics paradoxes with regard to the evaluation of policy interventions, as the same individual may value a bundle of goods differently before and after the intervention[45]. Considering the strongly reduced burden of disease for both poor and rich consumers[36], the more modest and diverse consumption patterns of the EAT-Lancet diet could be considered an improvement of aggregate welfare, despite lower willingness-to-pay. Improved welfare indicators should therefore go beyond the aggregation of the individual willingness to pay, and could for example correct for differences in assets between individuals[46], or include further indicators that are oriented along outcomes of consumption such as health or subjective well-being[47].

Qualitative transformations of the food system lead to distinct outcomes for material scale, economic activity, and income distribution. Our simulations show that the emission pricing scenario EFF shows a partial decoupling between emissions and material throughput while leaving the material throughput largely unchanged compared to a BAU scenario. In contrast, the DIET scenario reduces environmental pollution along with material throughput. The results also show that reduced or stable economic activity in the agricultural sector is the consequence, and not the cause, of a sustainable food system. Economic contraction in high-income countries like in the GDP-CAP scenario does not lead to a strong reduction in material throughput or emissions in the food system; in contrast, the qualitative transformation of the DIET and TRANS scenarios leads to a strong reduction in economic activity in the agricultural sector during the transformation phase, resulting after 2030 in almost steady-state economic activities comparable to today's level (Fig. 1c).

While the environmental benefits of TRANS accrue mainly from the EFF and DIET levers, income redistribution from GDP-FAIR is furthermore a necessary though not sufficient condition for a sustainable transformation, as higher incomes will be required in lower-income countries to afford healthy diets, and to pay for the full price of food that includes the environmental externalities. Although the Planetary Health diet reduces dietary expenses in high-income countries and many middle-income countries, the average costs of 2-3 USD_{11PPP} per day would likely exceed available incomes in many lower-income countries[48]. Higher incomes in lower-income countries would not necessarily require global economic growth but could also be achieved by international redistribution. Furthermore, while the pricing of emissions may have a regressive distributional effect for lower-income populations, this could be reverted effectively via re-distributing tax revenue as per-capita dividends and via international transfers[49]. Indeed, in our EFF scenario, the revenues from emissions pricing collected in 2050 amount to $3.36 trillion USD05 by 2050, and would be available for redistribution or reinvestment in social policies. Emissions taxation with revenue-neutral redistribution has also been implemented in practice and resulted in improving public support[50].

Finally, mitigation activities of course require economic investment, e.g. to better monitor and control nitrogen flows on croplands, to invest in better animal waste management facilities, or to breed more efficient crops. Our simulation shows however that these additional costs are small in comparison to overall production costs, and a degrowth-informed shift from polluting to mitigation activities still results in a quasi-steady state land economy under a sustainable transformation. In reality, these investment costs may be further offset by the restoration of ecosystem services[51].

We identify four limitations in this study, pointing toward opportunities for further research. First, our model can only alter the income distribution between countries, but not change the income distribution within countries. Missing global data on the intersection between income distribution and diet distribution within countries still impedes such an assessment on the global scale. Yet, inequality between countries is still much higher than inequality within countries[52]. Given observed food demand patterns[23], it can be expected that reducing inequality within countries would have qualitatively similar impacts as reducing inequality between countries, reinforcing the dynamics observable in our study. Second, our study is a sectoral study for the food system. Macroeconomic trends such as per capita income are exogenously prescribed, and the economic activity in the agricultural sector does not further influence the wider macro-economy. Impacts on employment and wages may be high and require social and structural change policies[4]. Future assessments should investigate in more detail the interactions of the food system with the energy system and the remaining macroeconomy, for example to derive consistent bioenergy demand from an energy system running similar degrowth or emission pricing trajectories, or to account for agricultural labor costs given degrowth dynamics in the labor market. Moreover, energy emissions account for 21% of today's global food system emissions and stem in similar shares from energy use in agricultural production, food transport, processing, packaging, retail, and consumption[14]. These emissions are considerably higher in HICs due to longer supply chains and industrialized food processing. Carbon pricing would reduce these emissions via the decarbonization of the energy system[53], while diet change would reduce these emissions via a shift away from processed products. Similarly, food waste reduction could drastically lower methane emissions from wastewater and solid waste, which account for a further 9% of food system emissions[14].

Third, our scenarios focus on two central indicators: Greenhouse gas emissions and economic activity in the agricultural sector. Previous assessments came to similar conclusions also for an extended range of environmental indicators like nitrogen use, biodiversity loss, or freshwater withdrawals. The current global food system could only nourish 3.4 billion people sustainably, but a qualitatively altered food system could nourish up to 10.2 billion people[54]. The favorable impacts of diet change across environmental indicators has also been highlighted[28,22]. For a comprehensive welfare assessment of different pathways, further societal targets should also be included[22].

Finally, while our scenarios intend to aid in scrutinizing the desirability of goals and pathways, this study can not assess the psychological, economic, social, or political barriers that prevent such pathways. Future research should assess possible policy bundles to achieve such a rapid and radical transformation, as well the political economy, political institutions, and social movements that could enable such a change[55].

The food system should be more explicitly considered in the degrowth debate, as the basic need of food has to be fulfilled in any economy, and as the food system is a major source of GHG emissions and other environmental damages. We find that a sustainably transformed food system would align with a substantially reduced agricultural material throughput, thus shrinking the material scale of the global agri-food system. As a consequence, its economic scale may slightly shrink in the near term and would grow more slowly in the longer term. For the food system, our results quantitatively confirm that degrowth has to be qualitatively different from negative economic growth. The reduction of economic activity is not an a priori cause of a sustainable food system, but the consequence of it; negative growth or redistribution, if conceived of only as reduction and redistribution of GDP within the current economic development paradigm, contributes little to reducing environmental impacts of the food system while it likely reduces the provision of low-polluting goods and services. Indeed, a reduction in macro-level throughput as such does not guarantee a healthy and sustainable food system, for which bottom-up consumption changes are needed. Emission pricing is a complementary strategy that should receive further attention in the degrowth community, as it leads to more efficient resource allocation. The combination of preference change and efficient allocation integrates well into the concept of a sustainability transformation[30], and leads to the most stringent reductions of GHG emissions from the food system. International income redistribution, while not substantially reducing emissions by itself, may still be pivotal in its function to enable lower-income people to afford sustainable diets and to compensate for adverse distributional effects of emission pricing.

Methods

Model

We analyze the degrowth scenarios using the MAgPIE 4 *open-source framework for modeling global land system*[18]. The model is well-documented and available open-source (https://github.com/magpiemodel). MAgPIE combines socio-economic and biophysical data to simulate spatially explicit land use scenarios for the 21st century, along with resultant environmental impacts. At its core, the framework is a partial equilibrium economic model, with the objective function to minimize production and other costs while meeting food, feed and material demand.

The MAgPIE model is driven by a food demand module[23], which estimates final food demand and dietary composition based on population growth, demographic change, and per-capita income. It explicitly accounts for changes in caloric requirements by age, sex, physical activity and body height, and estimates body weight, food waste and dietary composition endogenously based on per-capita income. The model has been econometrically parameterized based on past country-level trajectories of body mass distributions, and food demand. Food demand is estimated for 4 product groups: Animal-source foods, empty calories (sugar, oil, alcohol), fruits and vegetables, and staples. For the scenarios that assume preference changes, we only use the information on caloric requirements and use exogenous assumptions for dietary composition and food waste[56], assuming a shift towards the healthy and sustainable Planetary Health diet as proposed by the EAT-Lancet commission[36].

The consumption of animal-based calories requires the cultivation of animal feed crops, estimated based on regional dynamic feed-baskets[57]. Similarly, the processing of empty calories requires primary crop commodities based on conversion efficiencies from FAOSTAT. Per-capita material demand for crops, processed products and livestock is assumed to grow proportional to food demand. Bioenergy demand is exogenous and the same for all scenarios simulated in this study. The cultivation of crops requires labor and capital inputs, land, nitrogen fertilizer, seed, and, in the case of irrigated crops, water. The location of crop and pasture production is spatially explicit on a 0.5° grid clustered to 200 production clusters. Production location is determined based on cost-competitiveness, considering the limited availability of land, irrigation water, organic fertilizers, and the differences in crop yield potentials, and transport costs. Yield potential patterns, irrigation water requirements and irrigation water availability are obtained from the dynamic crop and vegetation model LPJmL[54]. Moreover, the model can intensify crop production and achieve higher yields by investments into research and development as well as by scaling up fertilization to higher nutrient demands. Future technological change forecasts in MAgPIE have been estimated and validated based on historic trends and contemporary data[58,59]. These yield improvements do not take into account any “system-disrupting” future technologies, such as the production of food without land[60], and involve correspondingly higher fertilization needs per ha and corresponding emissions. The costs of additional yield gains were derived on relating past productivity developments to investments in research, technology and infrastructure[59].

Food can be traded internationally within certain self-sufficiency thresholds[61]. To satisfy increases in demand, the model finds an economic equilibrium between expanding croplands and expanding irrigated areas, relocating crop production to higher-yielding areas.

Emissions include CO2 emissions from land-use change, as well as non-CO2 emissions from agricultural production. Land-use change emissions are based on spatially-explicit cropland and pasture expansion and carbon stocks from the LPJmL model, including vegetation, litter and soil carbon[62].

When a price on emissions is activated, this incentivizes the preservation of currently existing forests, as well as the planting of new forests[63]. This afforestation is based on natural vegetation growth curves and carbon densities of regionally native species, as opposed to plantation forest curves[63]. The maximum carbon density achievable by afforestation is that of natural forests. Moreover, afforestation in our implementation can only take place in grid cells where carbon densities support greater than 20 tonnes C/ha, a commonly-used threshold for forest and non-forest land[64]. Finally, afforestation in the model does not take place in boreal zones, as the albedo effect would offset the climate effect of the CO2 sequestration[65]. This is implemented via an exogenous constraint[66], but results in similar outcomes as studies that directly include the albedo-effect within the optimization[67]

CH4 emissions from enteric fermentation are based on feed baskets[57] and the Tier-II methodology of the IPCC national reporting guidelines[68]. CH4 emissions of rice are estimated based on the Tier-I methodology of the IPCC national reporting guidelines[68]. N2O emissions are based on a nitrogen-budget model[20] that explicitly accounts for manure availability, crop residues, biological fixation and inorganic fertilizer application, as well as their direct and indirect N2O emissions based on IPCC reporting guidelines[68]. CH4 and N2O emissions can be reduced through marginal abatement cost curves[69]. These estimates are derived based on available mitigation technologies in the short-term, and extended for long-term mitigation scenarios to account for technological learning and removal of implementation barriers. For methane from enteric fermentation - the major CH4 emission source - a maximum reduction potential of 29-50% depending on world region is estimated for 2050, rising to 35-60% in 2100. Maximum reductions of N2O emissions from fertilization - the major agricultural N2O source - range from 21-35% in 2050 and 26-40% in 2100. The economic potential can also be smaller, depending on the level of the greenhouse gas price.

Scenario design

The business-as-usual scenario (BAU) follows the “middle-of-the-road” storyline of the Shared Socioeconomic Pathways SSP2. The scenario set-up is well documented and results have been compared with other land system models[70]. In this scenario, the total global income increases from 103 trillion $\text{USD}_{05\text{PPP}}$ to 231 trillion $\text{USD}_{05\text{PPP}}$ by 2050 (Supplementary Fig. S1), and average global per capita income from 13410 $\text{USD}_{05\text{PPP}}$ to 25179 $\text{USD}_{05\text{PPP}}$ by 2050. Additionally, population increases from 8 billion people to 9.5 billion in 2070 before decreasing again to 9 billion by 2100.

The GDP-CAP scenario, which limits the high-end of per-capita income and therefore the resulting food demand and dietary composition derived from past trends, reduces the per-capita income of all countries where per-capita income in 2020 is above 12746 $\text{USD}_{05\text{PPP}}$ to this value by 2030. 12746 $\text{USD}_{05\text{PPP}}$ is the threshold between a middle- and high-income country as defined by the World Bank[71]. This value also corresponds roughly to the income level where mean life satisfaction begins to saturate[72,73] and is furthermore very close to the current global average income of around 13 000 USD_{05PPP} in 2020. Countries where per-capita income remains below this threshold continue to grow along the SSP2 baseline until reaching the threshold level. Total income decreases from 103 trillion USD_{05PPP} to 77.7 trillion USD_{05PPP} in 2030, although further growth in lower-income countries means that global income then peaks in 2080 at 119.3 trillion USD_{05PPP}. Global average per capita income also decreases from 12 973 USD_{05PPP} to 9853 USD_{05PPP} by 2035, and only increases to 12696 USD_{05PPP} by the end of the century as lower-income countries catch up to the sustainably-scaled income (Figure S1).

The GDP-FAIR scenario implements the same reduction but concurrently implements a “catch-up” of countries where per capita income is below 12 746 USD_{05PPP}. These countries then see a linear increase of income until 2030 to 12 746 USD_{05PPP} per capita. This amounts to a slight increase of total GDP from 103 trillion USD_{05PPP} to 106 trillion USD_{05PPP} by 2030 (as opposed to 144 trillion USD_{05PPP} in BAU), and due to population increase, incomes peak in 2070 at 120 trillion USD_{05PPP} (Figure S1).

The DIET scenario implements a shift in consumer demand towards the Planetary Health diet as described in Willet et al[36]. The Planetary Health diet includes low amounts of animal-source foods, instead emphasizing fresh vegetables and plant-based sources of proteins. For instance, calories from livestock products are limited to 200kcal/capita/day. The shift from current diets to the Planetary Health diet also takes place by 2030, for comparability with the income-based scenarios. Furthermore, we limit food waste to 20% of caloric food intake, which is approximately half of the current levels in high-income countries[56].

The EFF scenario follows the socio-economic assumptions and dietary trends of the BAU scenario, but implements a GHG pricing on CO2, N2O, and CH4 emissions arising from Land Use and Land Use Change, as well as agricultural activities such as ruminant animal production. The price trajectory is calculated with REMIND-MAgPIE[74], an integrated assessment modelling framework that arises from the coupling of the MAgPIE model to the REMIND energy-economy model[75]. This enables the calculation of GHG prices to meet mitigation targets, here a price trajectory that limits warming to below 1.5 degrees Celsius in 2100 is used (globally uniform CO2 price of 140USD/ton in 2030, 371USD/ton in 2050, other GHGs are priced according to GWP100 CO2 equivalent). By internalizing the external costs, the tax leads to a more efficient allocation of resources within the food system: area expansion into natural vegetation is substituted by intensification of existing areas, trading routes source commodities from less-polluting world regions and livestock production systems with lower emissions gain a competitive advantage. Moreover, a range of explicit mitigation technologies are implemented at additional costs to reduce emission factors[69], and forests are planted to sequester CO2[63]. Bioenergy demand was not changed in the mitigation scenario, as the study is limited to the food system and cannot account for the emissions offset in the energy system by bioenergy.

The TRANS scenario is the combination of the scenarios GDP-FAIR, EFF, and DIET. The dietary impacts of the GDP-FAIR scenario however overlap with the exogenous diet-shift assumptions of the DIET scenario; the inclusion of the GDP-FAIR assumptions thus solely assures the consistency that people can also afford the sustainable diets.

Data availability

Generated data and replication scripts have been archived at: https://doi.org/10.5281/zenodo.5543427

Code availability

MAgPIE is an open-source model available at: https://github.com/magpiemodel/magpie. The model documentation for the exact version of MAgPIE used in this study (v4.3.4) can be found at https://rse.pik-potsdam.de/doc/magpie/4.3.4/.

Acknowledgements

DMC and FB are supported by the Deutsche Bundesstiftung Umwelt (DBU). BLB has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 776479 (COACCH), 689150 (SIM4NEXUS), 821010 (CASCADES), and from the Norwegian Research Council (Greenplantfoods). EMB acknowledges support from FABLE 2.0 Grant Agreement No: 94120, which is funded by FOLU Grant Agreement No: 94120. FB and FG receive funding from the Food System Economics Commission, which is funded by the Rockefeller Foundation (2020FOD008) and the Wellcome Trust (221362/Z/20/Z). SHAPE is part of AXIS, an ERA-NET initiated by JPI Climate, and funded by FORMAS (SE), FFG/BMWFW (AT), DLR/BMBF (DE, Grant No. 01LS19XXY), NWO (NL) and RCN (NO) with co-funding by the European Union (Grant No. 776608). Funding from the German Federal Ministry of Education and Research (BMBF) in the context of the project “FOCUS - Food security and sustained coastal livelihoods through linking land and ocean” (031B0787B) is gratefully acknowledged. Further support is provided by the Global Commons Stewardship (GCS) project, funded by the University of Tokyo.

Peer Review Information

We would like to thank the reviewers for their valuable contributions in improving this manuscript.

Author Contributions

BLB and DMC designed the study and drafted the manuscript. BLB, DMC, IW, EMB, HLC. contributed to core model development, DMC undertook the modeling and analysis, all authors contributed to discussing the results and writing the paper.

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Competing interests statement

The authors declare no competing interests.

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