How different COVID-19 recovery paths affect human health, environmental sustainability, and food affordability: a modelling study

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Summary

Background The COVID-19 pandemic arrived at a time of faltering global poverty reduction and increasing levels of diet-related diseases, both of which have a strong link to poor outcomes for those with COVID-19. Governments responded to the pandemic by placing unprecedented restrictions on internal and external movements, which have resulted in an economic contraction. In response to the economic shock, G20 governments have committed to providing US$14 trillion stimuli to support economic recovery. We aimed to assess the impact of different COVID-19 recovery paths on human health, environmental sustainability, and food sustainability.

Methods We used LandSyMM, a global gridded land use change model, to analyse the impact of recovery paths from COVID-19. The paths were illustrated by four scenarios that represent different pandemic severities (including a single or recurrent pandemic) and alternate modes of recovery, including a transition of food demand towards healthier diets that result in changes to the food system: (1) solidarity and celery, (2) nothing new, (3) fries and fragmentation, and (4) best laid plans. For each scenario, we modelled the economic shocks of the pandemic and the impact of policy measures to promote healthier diets in the years after the COVID-19 pandemic, including the supply of and demand for food, environmental outcomes, and human health outcomes. The four scenarios use established future population growth and economic development projections derived from the Shared Socioeconomic Pathways 2. We quantified the outcomes from more societally cooperative pandemic responses that result in reduced trade barriers and improved technological development against less cooperative responses.

Findings Repeated pandemic shocks (the fries and fragmentation and best laid plans scenarios) reduce the ability of the lowest income countries to ensure food security. A post-pandemic recovery that includes dietary transition towards the consumption of less meat and more fruits and vegetables (the solidarity and celery scenario) could prevent 2583 premature deaths per million in 2060, whereas recovery paths that are focused on economic recovery (the fries and fragmentation scenario) could trigger an additional 778 deaths per million in 2060. The transition of dietary preferences towards healthier diets (the solidarity and celery scenario) also reduces nitrogen fertiliser use by 40 million tonnes and irrigation water by 400 km³ compared with no dietary change in 2060 (the nothing new scenario). Finally, the scenario with dietary transition increases the affordability of the average diet.

Interpretation The economic impact of the COVID-19 pandemic is most visible in low-income countries, where a reduction in growth projections makes a greater difference to the affordability of a basic diet. A change in dietary preferences is most impactful in reducing mortality and the burden of disease when income levels are high. At lower income, a transition towards lower meat consumption reduces undernourishment and diet-related mortality.

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Introduction

As COVID-19 infection rates increased globally in early 2020, governments implemented intranational and international movement restrictions with the aim of reducing the spread of SARS-CoV-2. Concerns arose about the resilience of the globalised food system to be able to feed the world under such restrictions.[1,2]

The closure of large parts of the global economy, to contain the spread of the virus, was projected to result in an annual contraction in gross domestic product (GDP) of 3·0–7·5% for 2020 and a return to growth of 2·8–5·8% in 2021.[3] The pandemic arrived at a time of stagnating malnutrition reduction and increasing rates of obesity due to faltering poverty reduction efforts, resulting in continued prevalence of deficiencies in key micronutrients and increased levels of diet-related non-communicable diseases.[4] The International Food Policy Research Institute estimated that an additional 90–150 million people could

Research in context

Evidence before this study

No formal literature review was done. Several previous studies have shown a relationship between economic recession or dietary changes and changes in the food system and global land use. Most previous studies considered only the relationship between health and dietary changes or only the economic and land use change. One study has shown the impacts of the COVID-19 pandemic on the Shared Socioeconomic Pathway projections, but did not include the different potential recovery paths depending on the global stimulus packages pledged by governments.

Added value of this study

To the best of our knowledge, this modelling analysis is the first to provide a global overview of the potential recovery paths post-pandemic, and the influence of the pandemic on health outcomes, economic impacts globally and at the country level, and the environmental changes after recovery from the

pandemic. We also explored the food affordability of the diet in the four different scenarios studied. We estimated the projected diet-related disease mortality burden in 2060, showing a disparity between countries according to income level.

Implications of all the available evidence

An improvement in global health, food affordability, and the environment was shown when stimulus packages were used in political cooperation, for promoting a healthier diet (fewer calories ingested, less meat and sugar, and more fruits, vegetables, and pulses). However, recovery to pre-pandemic dietary trends will exacerbate the impact of similar pandemics. Additionally, a fragmented response to the pandemic with greater protectionism will result in worse health outcomes and increased inequality between high-income and low-income countries. Our findings could help to develop policies and strategies for health protection, economic stability, and climate change mitigation and adaptation.

be pushed into extreme poverty due to the economic effects of the COVID-19 pandemic.[5] In response to this unprecedented economic downturn, G20 governments have committed to providing more than US$14 trillion in stimulus packages to support the recovery.[6] The nature of this recovery could provide an opportunity for a faster shift to a more environmentally sustainable economy and healthier populations.[7,8]

Poor diets are now the leading cause of all deaths globally, resulting in an estimated 11 million deaths in 2017.[9] Diet-related poor health outcomes typically come from diets high in sodium, low in wholegrains, low in fruit and vegetables, low in omega-3, and low in nuts and seeds. Each of these deficiencies was responsible for more than 2% of global deaths in 2017.[9] Reducing meat consumption is linked with reductions in premature mortality from diet-related and weight-related causes with up to 22% fewer deaths associated with a vegan diet and 12% fewer deaths in high-income countries following the environmental objectives diet.[10] Although research is still ongoing on the comorbidities and risk factors that cause severe COVID-19 symptoms and mortality, a connection has already been observed between diet and mortality. There is an increased risk of death or complications from COVID-19 for individuals with obesity or overweight.[11] Pooled analysis has shown that individuals with obesity were 73% more likely to have poor outcomes, including hospitalisation and mortality.[12] Furthermore, the mortality rate from COVID-19 in 93 countries showed a clear connection between certain pre-existing conditions—namely chronic obstructive pulmonary disease, Alzheimer's disease, hypertension, ischaemic heart disease, depression, lung cancer, asthma, and diabetes—and an increased likelihood of complications and mortality from COVID-19.[13] Healthier

diets as part of a COVID-19 recovery strategy could, therefore, reduce diet-related and weight-related deaths from non-communicable diseases while reducing mortality risk from COVID-19.

In addition to improving human health, healthier diets are also likely to improve environmental health. Models of the impact of dietary choices on land use and environmental indicators have shown that a reduction in meat intake reduces biodiversity loss, nitrogen and irrigation use, and the loss of natural land by reducing the expansion of grazing land and agricultural land for animal feed.[10,14,15]

Healthier diets can be difficult to define, due to differences in local and regional preferences.[16] There have been several attempts to define a healthy diet, most notably the *EAT–Lancet Commission on healthy diets from sustainable food systems*.[17] WHO and the UN's Food and Agricultural Organization have supported governments with general guidelines on key components of the diet that should be increased or reduced, taking into account regional and local contexts.[18] Previous food system studies have projected demand and the impact on agricultural resource use of different scenarios, using historically derived relationships between food demand and GDP.[15,19]

In this analysis, we aimed to assess the impact of changing to healthier dietary preferences using the EAT–*Lancet* diet.[17] To capture the impacts of different COVID-19 pandemic recovery paths on the food system, we used a state-of-the-art land use model, LandSyMM, to simulate the outcomes of four scenarios that represent different severities of the pandemic and alternative modes of recovery. For each scenario, we model the economic shocks of the pandemic and the impact of policy measures to promote healthier diets, in the years after the COVID-19 pandemic, including the supply of

and demand for food, and environmental outcomes and human health outcomes. This Article addresses the aforementioned gap of economic, environmental, and human health modelling consequences of the political changes described in this study's scenarios, through an assessment of the impact of prescribed dietary preferences while maintaining price dynamics as a key component of the demand modelling.

Methods

Overview

Using a scenario-based modelling approach to the food system, we studied the impact of different recovery paths from the COVID-19 pandemic on the environment, global health, and food affordability. Four scenarios (figure 1) were designed for this study and were run from 2019 to 2060 following scenario-specific parameters, which are detailed in this section and summarised in the appendix (p 3). The four scenarios—(1) solidarity and celery (SC),

(2) nothing new (NN), (3) fries and fragmentation (FF), and (4) best laid plans (BLP)—use established future population growth and economic development projections derived from the Shared Socioeconomic Pathways 2 (a middle-of-the-road pathway).

Scenario summary

Context: common to all scenarios

The onset of a global pandemic in 2020 resulted in widespread political actions. The restrictions put in place to reduce the propagation of the virus resulted in a sudden drop in economic output. Those countries most reliant on petroleum exports, tourism, international trade, and service sectors were hit hardest. Although most governments designated agricultural trade as essential, thus allowing it to continue, the need to test and quarantine at many borders caused some delays[2] and resulted in an increase in transport costs of goods. The increase in the time taken to transport fruit and
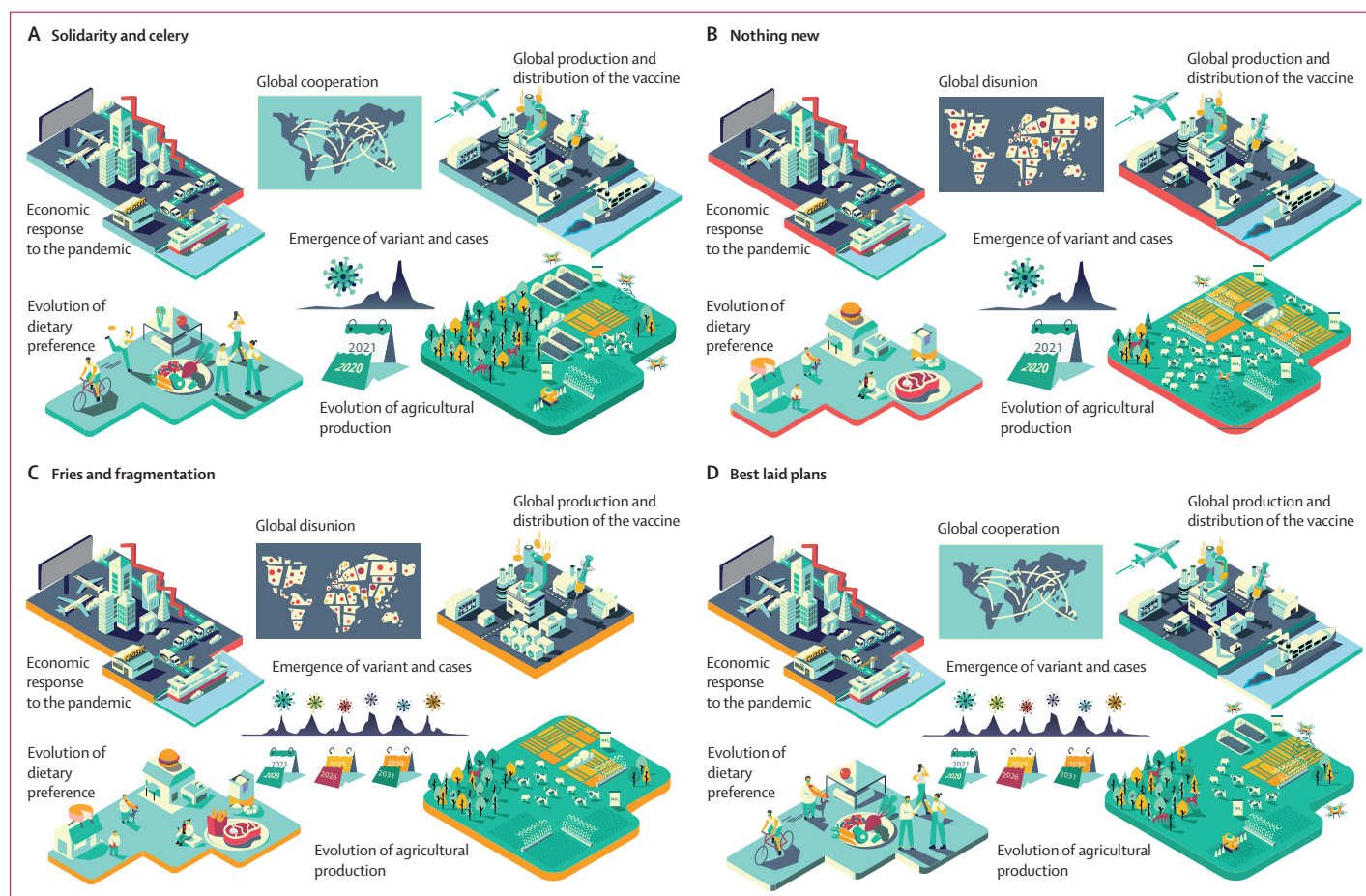
See **Online** for appendix

Figure 1: Schematic of the four modelled scenarios
(A) Solidarity and celery: a single pandemic shock in 2020–21 followed by high levels of global cooperation and a transition towards healthier dietary preferences in high-income countries (ie, those with a GDP per capita of >US$20 000). (B) Nothing new: a single pandemic shock in 2020–21 followed by low global cooperation and no change to dietary preferences. (C) Fries and fragmentation: a single pandemic in 2020–21 and repeated pandemics (due to new variants) every 5 years, resulting in a deterioration in global cooperation and no changes in historical dietary preferences. (D) Best laid plans: a single pandemic in 2020–21 followed by good levels of global cooperation. However, due to new vaccine-resistant variants or other transmissible diseases, new pandemics take place every 5 years. Dietary preferences change towards healthier diets in high-income countries (ie, those with a GDP per capita of >US$20 000).

vegetables also increased the quantity lost in transport. Both of these costs gradually reduce to pre-pandemic levels by 2025 as the severity of the pandemic reduces. The trillions of dollars of stimulus packages promised in 2020 and 2021 were a key tool for governments to invest in the post-pandemic recovery.

Solidarity and celery
In the first scenario, the pandemic creates an impetus for greater global cooperation, resulting in several successful vaccine candidates against COVID-19. International cooperation and an awareness that global immunity is required to reduce the risk of new vaccine-resistant variants results in efficient deployment of the vaccine globally between 2021 and early 2022. Affordable vaccines are made available for the lowest income countries before the end of 2022. The pandemic accelerates attempts to develop and implement global treaties and cooperation agreements to combat future pandemics, including prioritising One Health research and the management of risks from zoonosis. For example, less intensive meat production is deemed to be better for animal welfare and decreases the risk of creating new zoonotic diseases. National and international health institutions are supported in making ambitious proposals to improve health outcomes for everyone. As a result, increased education and a series of strong policy levers are used to promote healthier diets—eg, reduced meat and sugar consumption and increased fruit and vegetable consumption. Governments accept that there is a need to prioritise the dietary habits formed in childhood and work to protect children from fast food advertising and support them to build positive dietary habits. As a symbol of cooperation, and in an attempt to make healthier diets more affordable, governments agree to reduce import taxes (trade barriers) on agricultural products. Additionally, work continues to improve the productivity of farming practices, with the best technologies being made accessible to all. Due to the consistent and persistent policy interventions of governments and a greater global consciousness of both the environmental and health impacts of diets, between 2020 and 2040 on average, dietary preferences move pervasively towards a so-called healthy diet, reaching 50% of the way to that goal, from current trends.

Nothing new
In the second scenario, global cooperation deteriorates quickly in 2021 as countries impose vaccine export restrictions, and countries who funded vaccine development stockpile supplies. Commitments to help the lowest income countries are quickly forgotten, resulting in a slow roll-out across the Global South. However, the pandemic subsides in 2022 as a result of the virus mutating towards a less transmissible and virulent strain, which becomes dominant. Economic activity returns globally to pre-pandemic levels. Poor cooperation and widely varying mortality result in many countries exiting the pandemic with national growth in mind. Large industries, including in the agricultural sector, successfully lobby to maintain the status quo to not hinder growth. The health risks from the pandemic and the increased risks from COVID-19 posed to individuals with overweight or obesity are quickly forgotten, and result in no dietary preferences changes. Some efforts are made to reduce the risk of future pandemics and, as a result of that and pure chance, there are no pandemics for at least the next 40 years.

Fries and fragmentation
In the third scenario, early promises to cooperate globally on a vaccine are quickly forgotten when vaccines become available. All countries race to vaccinate their own populations, with the rich ordering multiple times more doses than they need and stockpiling excess doses for future vaccination campaigns. Vaccine producing countries impose export restrictions as a response to spikes in cases seen in 2021. Although there is scarce and deteriorating global cooperation, the pandemic naturally subsides, resulting in a return to pre-pandemic economic priorities. The meat industry successfully lobbies for increased investment in improving productivity, allowing them to increase efficiency through increased inten-sification practices. This intensification, they claim, will allow them to meet demand while reducing the impact on the environment. Recovery from the economic damage of the pandemic is a concern for all countries. However, this poor cooperation stretches into inaction on a strategy for future pandemics, the control of zoonosis, and coordinated efforts for improved diets. As a result, a new SARS-CoV-2 variant appears in 2025 and governments react with similar restrictions to those imposed in 2020. This response affects the global economy in a similar way. As global cooperation has deteriorated, distrust between countries grows and trade barriers are increased to try and provide domestic food security while increasing an advantage in the race to find a new vaccine. This deterioration results in repeated cyclical pandemics as the causes are poorly controlled in countries where wildlife trade and bush meat consumption is common.

Best laid plans (BLP)
In the fourth scenario, countries honour their commit-ments to pool resources to eliminate the virus, in the knowledge that anything less than global immunity might result in new vaccine-resistant variants. Consequently, the global vaccine programme is a success, and the global economy returns to pre-pandemic trends in 2023. This success encourages countries to strengthen international health organisations to develop common guidance and principals to reduce the risk of pandemics and improve health more generally. The strong link between poor diets and poor outcomes from COVID-19 along with the increased burden of diet-related diseases pushes healthy diets to the top of the priorities for the stimulus packages.

The stimulus packages are also used to improve the efficiency and technological development of meat production, with the aim of minimising the environmental impact of agricultural activities. Technologies are shared between countries in the spirit of cooperation and solidarity. There is a concerted effort to ensure that dietary habits of children are prioritised through clear and scientifically sound education on healthy diets. This approach is coupled with strong policy measures to promote healthier diets. However, global efforts to reduce the risk of pandemics starting or reappearing are inefficient and a new COVID-19-like pandemic returns in 2025. Repeated restrictions result in fewer people being able to make the transition to healthier choices. Most governments and populations react negatively to this outcome and impose some trade barriers on food imports to try and reduce the impact on their labour forces. The global cooperation does result in a gradual improvement in diets between 2020 and 2040. The pandemic returns every 5 years as the race to stay ahead of it fails.

LandSyMM

LandSyMM is a coupled, global-gridded land use, ecosystem, and food system model that uses the Lund-Potsdam-Jena general ecosystem simulator (LPJ-GUESS) and the Parsimonious Land Use Model version 2 (PLUMv2) to simulate land use change under different climate and socioeconomic projections.[20,21] LPJ-GUESS, a dynamic vegetation model, determines potential yields under climate projections for different crop functional types at different fertiliser and irrigation use levels. PLUMv2, a land use and food system model, uses calibrated potential yields from LPJ-GUESS, irrigation and fertiliser application rates, and other management intensities (eg, pesticides, lime application rates, and reseeding of grasslands) to meet demand for seven agricultural commodities—cereals, fruits and vegetables, oil crops, pulses, starchy roots, ruminant products, and monogastric products—for population and economic output projections. An increase in demand can be met by increasing management intensities, agricultural expansion (on unprotected land), or increasing net imports, with the combination selected based on the approach that has the least cost. PLUMv2 creates a surface representing annual yields based on different fertiliser and irrigation application levels that are defined by LPJ-GUESS for each grid cell of the model and year for each scenario. The food imports, land uses, crop types, and intensity levels are then selected on the basis of which meet domestic demand for the lowest cost. The model allows for over-supply and under-supply of commodities, with international stocks being used as a buffer. Commodity prices are calculated based on imports, exports, transport costs, transport losses, and trade barriers, and are adjusted to account for over-supply and under-supply.[22] Further details of the LandSyMM model can be found in the appendix (p 4).

The PLUMv2 demand system uses the modified, implicit, directly additive demand system (MAIDADS), extended for food demand by Gouel and Guimbard,[23] to define the relationship between food demand and GDP per capita, with price calculated as an endogenous variable. The MAIDADS model is modified to account for the differences in grouping between the Gouel and Guimbard[23] model and PLUMv2. We used 2010 FAOSTAT food balance sheets to determine the parameters in the MAIDADS model for PLUMv2. Food demand can be split into subsistence and discretionary spending. There is a key point of saturation, above which demand for each food group does not change with increase in GDP per capita. This saturation suggests a convergence of food demand towards diets that are typically seen in high-income countries, a model that has been observed as countries transition towards middle and high income.[23] These diets are characterised by overconsumption, increased animal product consumption, decreased fruit and vegetable consumption, and decreased staple consumption.

The key aspects of a healthy diet include increasing fruit and vegetable consumption and reducing intake of saturated fat, sugar, salt, and processed foods.[18] LandSyMM

For **FAOSTAT** see https://www.fao.org/faostat/en/

	EAT–*Lancet* caloric intake (kcal/day)	Historic caloric intake used for NN and FF (kcal/day)	SC caloric intake (kcal/day)	BLP caloric intake (kcal/day)	Example foods
Cereals	811	904	823	878	Whole grain rice, wheat, corn and others
Fruits and vegetables	204	188	720	622	All vegetables and fruits
Oil crops and pulses	989	492	41	48	Palm oil, unsaturated oils, legumes, and tree nuts
Sugar	120	368	325	267	All sweeteners
Starchy roots	39	56	151	244	Potatoes and cassava
Ruminant products	204	330	238	338	Beef, lamb, dairy, and lard or tallow
Monogastric products	96	286	125	213	Eggs, pork, chicken, and other poultry
Total	2463	2624	2423	2610	..

Fish is not included in the Parsimonious Land Use Model (version 2) and, therefore, is not accounted for here. Caloric intake is not replaced here; therefore, the diet used here will be lower in caloric intake than the EAT–*Lancet* Commission findings. BLP=best laid plans. FF=fries and fragmentation. NN=nothing new. SC=solidarity and celery.

Table: Worldwide saturation level (incomes [GDP per capita] >US$20 000 per year) used for various diets

does not include food processing, salt, or seafood. The table includes details of the saturation level diet used for each scenario in this study, which is based on the EAT–*Lancet* Commission and PLUMv2 food groups. Between 2020 and 2040, the saturation consumption levels of food groups are modified linearly from current levels to 50% and 25% of the difference between current levels and the EAT–*Lancet* diet in SC and BLP scenarios at high income (GDP per capita >$20 000) levels. Although there has been some criticism of the EAT–*Lancet* diet,[24] it was used in this analysis because this diet provides a universal healthy diet that can be produced sustainably. The relationship between dietary preference and income level is based on historic trends for NN and FF scenarios.

The model used GDP and population figures defined in the Shared Socioeconomic Pathways. Shared Socio-economic Pathway 2, the middle-of-the-road pathway, is used as a base for all scenarios. The shocks are modelled based on GDP growth rate projections for 2020 to 2022 as defined by the World Bank and Organisation for Economic Co-operation and Development. For the SC and NN scenarios, we modelled a single shock. For the

FF and BLP scenarios, we assumed a repeated shock every 5 years. More details on how the GDP was defined can be found in the appendix (p 4).

Monte Carlo runs for sensitivity analysis

To account for the high degree of uncertainty in the scenario design and modelling, we carried out 30 Monte Carlo runs for each of the scenarios. These runs included modifying key parameters in the PLUMv2 model around a central value. Examples of modified key parameters include population, GDP, trade barriers, technology, and transport losses. A full list of Monte Carlo runs, with details of modified parameters, is included in the appendix (p 10).

Health analysis

Using the methodology developed by Springmann and colleagues,[10] we analysed the impact of the changes in diet on mortality for each of the four scenarios. The methodology estimated the increase or decrease in mortality, due to changes in diet and weight class, through a comparison of a reference and a counterfactual. The reference case[10] (2019 in this analysis) used the mortality (by country and age group), average consumption of specific food groups, and the weight distribution for each country. Using relative risks for changes to meat, and fruit and vegetable consumption, and weight category, we calculated the impact of the diet change, in 2060, on mortality. More details of the health and mortality analysis can be found in the appendix (p 5).

Environment

Historical land use areas were taken from the Land-Use Harmonization 2 dataset.[20] Historical synthetic nitrogen fertiliser application and irrigation intensity levels were determined by the model and compared with Food and Agricultural Organization estimates during the calibration stage.[22] In the model, the level of nitrogen fertiliser application and irrigation level directly affects the management cost of the crop and the yield, changing the global market dynamic. In the LandSyMM model, as in real life, shifting diets drive land use for food production and the level of input necessary to meet the food demand. The food production evolution also drives the net global loss or gain of natural land area over the period of the scenario.

Economic analysis

To determine the impact of the different scenarios on the affordability of food, we calculated the percentage of GDP spent to meet demand. The food spending as a percentage of GDP per capita is calculated as:

$$E = \frac{\sum (D_{g,c,t} \times P_{g,c,t})}{GDP_{c,t}} \times 100$$

where E is the expenditure, $D_{g,c,t}$ is the demand for each food group for a given country, year, $P_{g,c,t}$ is the price for
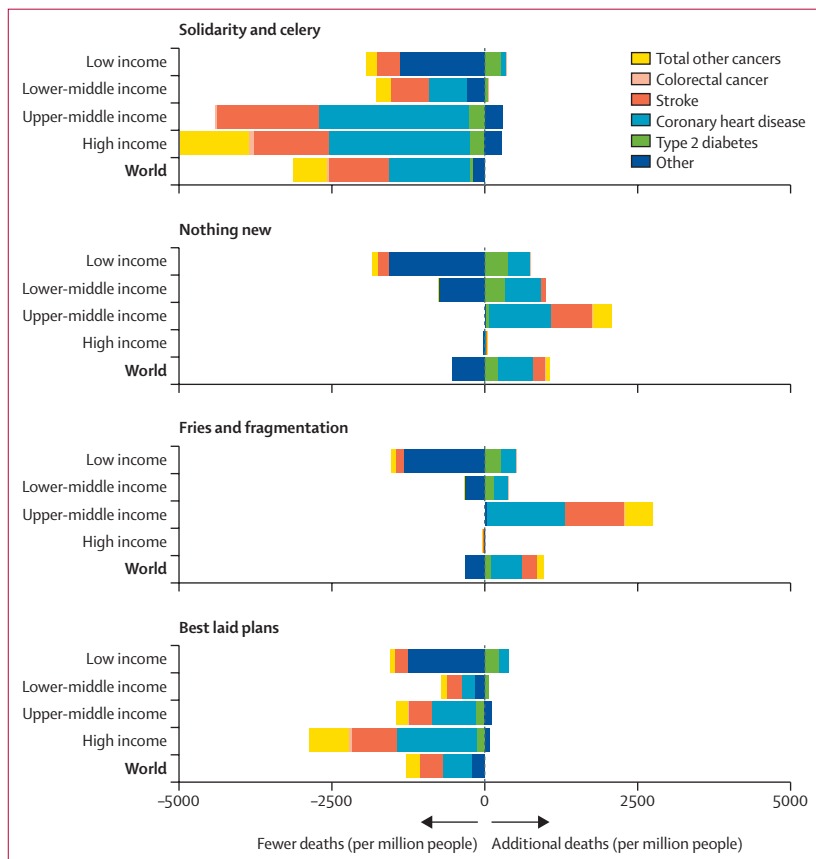

Figure 2: **The impact of scenarios on additional mortality, for each income level due to changes in diet**
The bars show the additional mortality per million. The reference is 2019 for each scenario and the comparison is 2060. The legend corresponds to different causes of death due to diet-related disease. Income levels are based on the World Bank grouping of countries based on their GDP per capita and are taken from July 1, 2014: low income <1035; lower middle income 1036–4085; upper middle income 4086–12 614; high income ≥12 615. Each country's group remains the same throughout the analysis.

each food group for a given country and year, and $GDP_{c,t}$ is the GDP per capita in the given country and year.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

For diet and global health, the changes in the prevalence of weight categories (underweight <18·5 kg/m², normal weight 18·5–25 kg/m², overweight >25–30 kg/m², obese >30 kg/m²) and underlying dietary changes result in an increase in global premature mortality in the NN (617 additional deaths per million) and FF (778 additional deaths per million) scenarios (figure 2). Additional deaths are greatest in upper-middle-income countries (NN: 2130 deaths per million, FF: 2991 deaths per million). The leading causes are coronary heart disease and stroke. There is a small difference in additional deaths in high-income countries in NN (48 additional deaths per million) and FF (15 fewer deaths per million) scenarios (figure 2). In scenarios where the dietary preference changes, there is a substantial reduction in deaths globally (SC: 2583 fewer
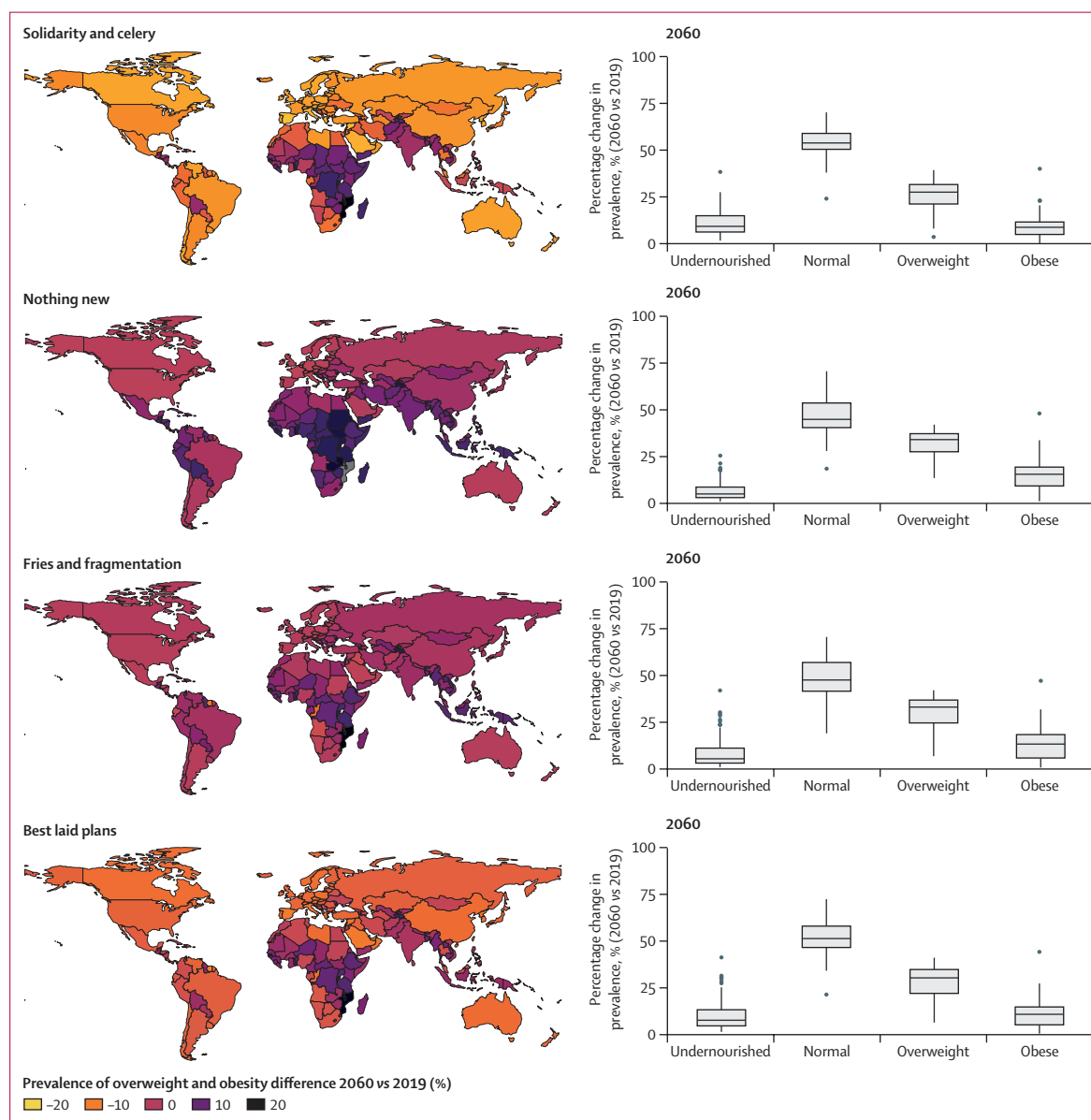

Figure 3: **Changes in the prevalence of overweight and obesity, 2060 *vs* 2019**
The map indicates the percentage change in the prevalence of overweight and obesity in each country between 2060 and 2019. Prevalence is the proportion of overweight and obesity in 2060 (in percentage) minus the proportion of overweight and obesity in 2019 (in percentage). Box plots indicate the global level of each weight category in 2060.

deaths per million, BLP: 1037 fewer deaths per million), and mainly in middle-income and high-income countries. This reduction in mortality is highest in upper-middle-income countries for the SC scenario (4099 fewer deaths per million) and in high-income countries for the BLP scenario (2400 fewer deaths per million), and as a result of the global reduction in coronary heart disease (SC: 1353 fewer deaths per million, BLP: 493 fewer deaths per million) and stroke (SC: 981 fewer deaths per million, BLP: 362 fewer deaths per million). There is an increase in the prevalence of overweight and obesity, in 2060 versus 2019, in low-income countries in all scenarios (figure 3).

The scenarios which included saturation consumption levels based on historical trends (NN and FF) result in an increase of prevalence by 10–20%. Undernourishment is most prevalent in NN (6%) and FF (8%) scenarios. Obesity prevalance is lower in the scenarios with a change in dietary preference (SC: 9%, BLP: 10%) compared with the scenarios without this change (NN: 15%, FF: 13%). The percentage of individuals with overweight in 2060 exhibits a similar pattern (SC: 26%, BLP: 28%, NN: 32%, FF: 30%).

The SC scenario results in a reduction of pasture area by 120 Mha and an increase in natural area of 119 Mha in 2040 (figure 4). In both land use types, this reverses to
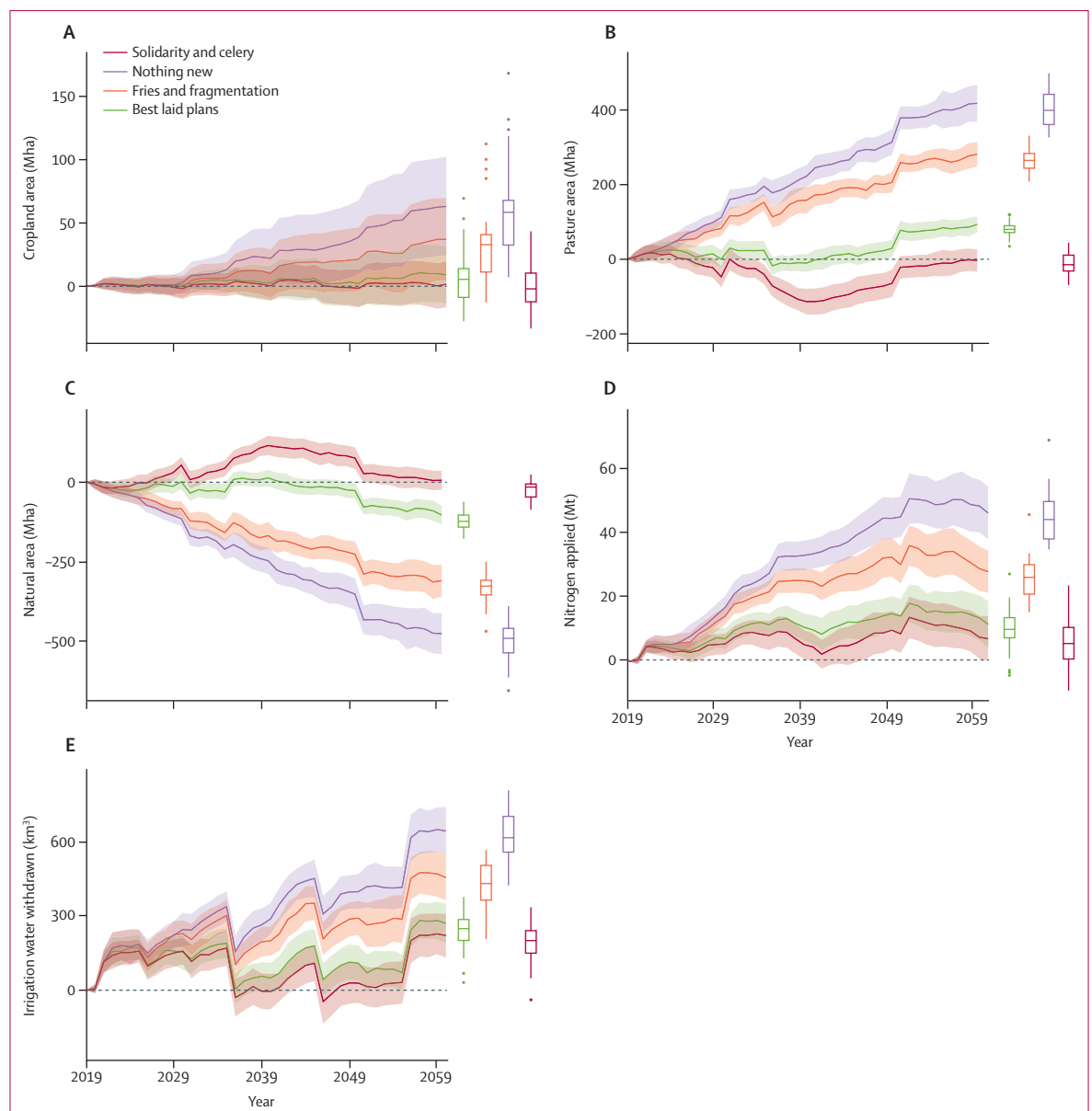

Figure 4: **Changes in land use, fertiliser application, and irrigation water withdrawal for each scenario, 2060 *vs* 2019**
The lines show the result of the median run and ribbons indicate the uncertainty associated with the 30 Monte Carlo runs. The box plots show the levels in 2060, including outliers.

reach similar quantities to 2019 levels by 2060 (increase of 10 Mha of pasture area and reduction of 1·5 Mha of natural land). Cropland area remains almost constant at 2019 levels, whereas pasture area increases by 100 Mha by 2060 (vs 2019 levels) for the BLP scenario. The increase of pasture area corresponds to an equivalent loss of natural land area. The NN and FF scenarios result in a loss of 481 Mha and 322 Mha, respectively, of natural land by 2060. This loss corresponds to an increase in cropland (NN: 48 Mha, FF: 29 Mha) and pasture area (NN: 424 Mha, FF: 292 Mha). In all scenarios, a loss of natural land is observed in the tropics and an increase of natural land (agricultural land abandonment) in more temperate regions (appendix p 9). The loss of natural land is greatest in the NN scenario and least in the SC scenario. Although nitrogen and irrigation use in

2060, versus 2019, increases in all scenarios, it is greatest in the NN scenario (2060 nitrogen use increase, SC: 6·45 million tonnes [Mt], NN: 46·05 Mt, FF: 27·8 Mt, BLP: 10·2 Mt; 2060 irrigation use increase, SC: 200 km³, NN: 630 km³, FF: 433 km³, BLP: 250 km³).

The percentage of income spent on food budget decreases in all scenarios and all income levels (figure 5). The most significant reduction is in low-income countries, where the percentage spent decreases from 60% in 2019 to 18% in 2060. The difference in scenarios can be observed in low-income and lower-middle-income countries, where scenarios with repeated pandemic shocks (the FF and BLP scenarios), resulting in reduced GDP, exhibit a lower reduction in food spending as a percentage in 2060.

The effect of the different scenarios on the production of the different commodity groups, in 2060, is high
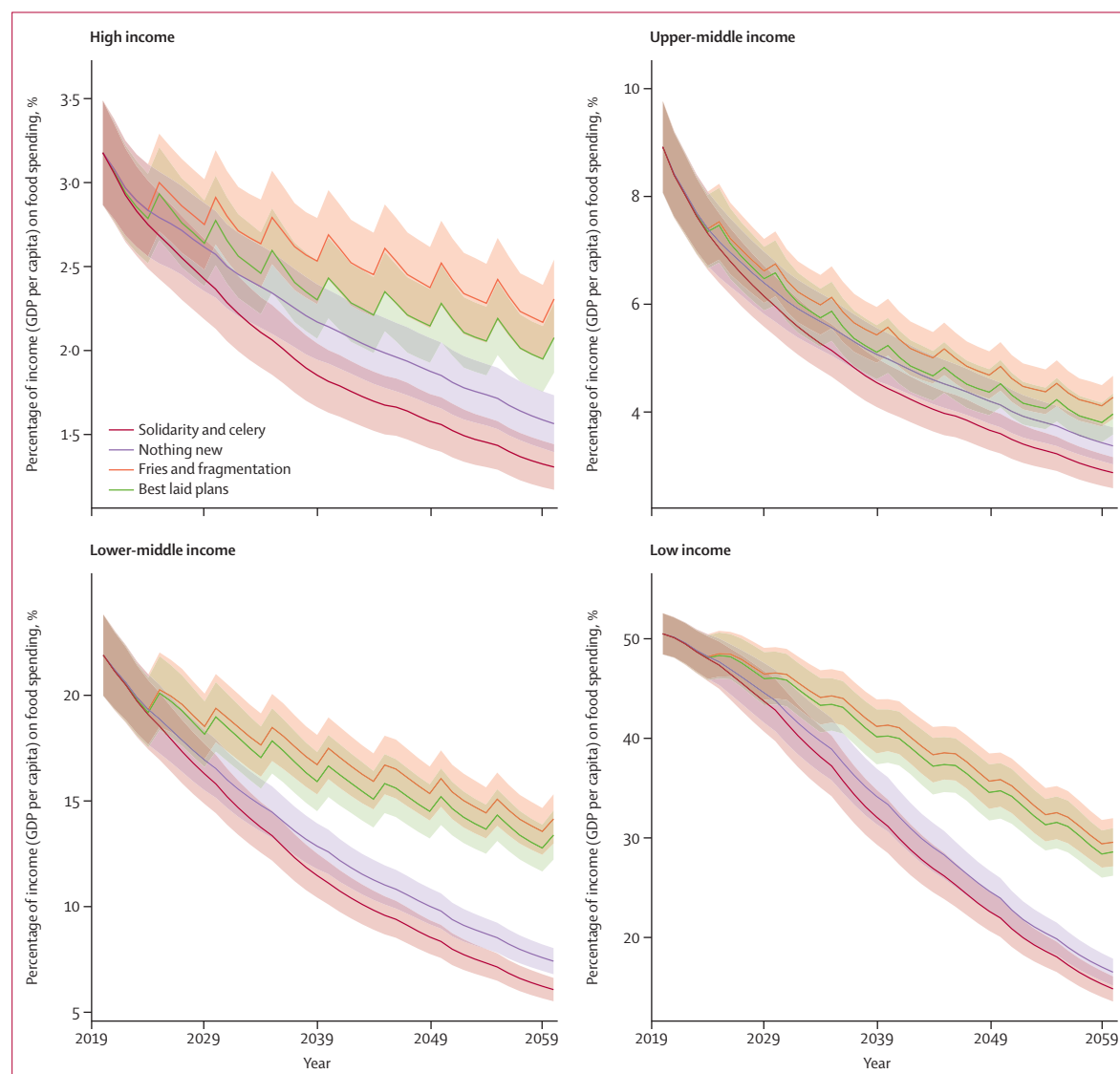

Figure 5: **Food spending percentage**
The graphs show percentage of food spending by income level. The lines show the median value and the ribbons show the sensitivity analysis.

(appendix p 10). Fruit and vegetable production is highest in the SC scenario and lowest in the FF scenario. Ruminant and monogastric production decreases from 6·6 Mt in 2060 for the NN scenario to 4·0 Mt in the SC scenario. For staples (such as starchy roots, wheat, and maize), the NN and FF scenarios result in higher production levels than those of the SC and BLP scenarios. In the SC scenario, the production of maize is lower than in other scenarios because of the change in livestock forage consumption. Food prices in the SC scenario are lower than in the other scenarios. The reduction of the price of the average diet, corresponding to an increase of its affordability, is due to the decrease in consumption of expensive commodities (such as animal products), which compensate in the SC scenario for the increased consumption of fruits and vegetables, another expensive commodity. Moreover, the FF and BLP scenarios—which include repeated pandemic shocks—are characterised by high variability in food affordability due to variable prices, which can cause food insecurity.

Discussion

The findings of this modelling analysis show that political decisions on recovery plans to the COVID-19 pandemic have a profound impact on the environment, global health, and food affordability. Land use change is dominated by the impact of the transition in dietary preferences, with the SC and BLP scenarios showing the lowest increase in cropland and pasture area, and the lowest loss of natural area. This result highlights the impact of a reduction in meat consumption, which would thus reduce the need for grazing land and cropland for animal feed. Similarly, nitrogen and irrigation application are lowest in scenarios with a dietary preference change towards lower meat consumption (ie, SC and BLP). These dietary preference changes also result in an overall reduction in calories consumed at higher income levels, which further reduces the pressure on agricultural land and management intensities. The areas with the greatest loss of natural land (figure 4) are tropical low-income and middle-income regions, such as central Africa and South America, with the greatest levels of biodiversity. This loss of natural land is due to the increases in both population and development that are expected in these regions.[14] SC and BLP scenarios also include a difference in trade barriers (a reduction of 20% for SC and an increase of 10% for BLP, vs the base case from 2025) and repeated increases in transported losses (increasing to 0·09 during the pandemic and gradually returning to base case once the pandemic recedes) during the pandemic period. It is not possible to disentangle the effect of these losses and barriers from the effects of the diet preference change and repeated economic shocks. The impact of repeated pandemics on GDP per capita affects land use change and input application, thus resulting in a slowing of the dietary transition process by stagnating economic development—as can be observed in the differences between the NN and FF scenarios.

The increase in the prevalence of overweight and obesity in all scenarios in low-income countries (figure 3) is an expected outcome for the scenarios. In all scenarios, the increase in the income level of low-income countries would result in greater consumption of animal products and total calories, as these countries move along the dietary transition process towards diets currently consumed in high-income countries. The dietary preference is defined for each scenario, and is used in conjunction with the income level and domestic commodity prices to project consumption.[15] Changes in food prices or incomes for high-income countries, where the population is already consuming close to the preferred diet, have a lower impact on the choices of food consumed than in low-income counties. The estimate of the prevalence of undernourishment is based on historical relationships and does not account for the possibility of a more equitable distribution of resources; therefore, scenarios NN and FF have greater levels of undernourishment when compared with scenarios in which the dietary preference is healthier at higher income levels. Bodirsky and colleagues[19] conducted an analysis of the dietary transition under different Shared Socioeconomic Pathway scenarios, including the prevalence of various weight categories. The Shared Socioeconomic Pathway 2 scenario in the Bodirsky and colleagues[19] study is relatively comparable with the NN scenario we use here, the biggest difference between the scenarios being the inclusion of the economic shock caused by COVID-19 (2020–23) in the NN case. The results for both studies are similar, with estimations of the reduction of undernourishment rates of 6% in both studies, and an increase in rates of overweight and obesity globally of 47% in 2060 for the NN scenario and of 45% in 2050 as estimated by Bodirsky and colleagues.[19] The mortality analysis indicates a strong connection between changes in dietary preference and a reduction in mortality. In the NN and FF scenarios, the restricted impact of the scenario on additional mortality in high-income countries is due to them already being at the saturation level of the diet–GDP trend, meaning that diets at these income levels do not change in the NN and FF scenarios. The increase in income globally results in greater mortality in lower income countries, whereas mortality in high-income countries remains unchanged in the NN and FF scenarios. This discrepancy between countries at different income levels is explained by the dietary transition; in lower income countries, as they go through the dietary transition, the population consumes fewer fruit and vegetables, more meat, and more calories in total, whereas higher income countries have already reached the saturation consumption level and their diets are not affected by increases in GDP per capita. National governments have developed their own dietary recommendations for their citizens with the aim of improving

diets within their population. However, these vary between countries and many would continue to pose a risk to health if followed.[16]

This modelling study shows a reduction in the cost of food in absolute terms and as a percentage of GDP per capita in all scenarios and all regions, between 2019 and 2060. The primary reason for this reduction is the increase in GDP per capita for all regions for 2019–60 in the scenarios modelled, indicating that the cost of the food basket is reducing relative to incomes over this period. However, the scenarios that include a transition towards healthier diets—ie, those low in animal products and staples and high in fruit and vegetables—are more affordable. This outcome is contrary to previous studies on the affordability of healthier diets,[25] which estimate that a healthy (nutrient adequate) diet costs 2·66-times more than an unhealthy (nutrient inadequate) diet. However, our modelling analysis is restricted to considerations of food production and, therefore, unable to consider micro and macro nutrient intake or food processing. Therefore, the reduction in dietary preferences for animal products results in a substantial saving due to reduced land use, fertiliser application, land for feed, and decreased total caloric intake, reducing the cost of diets in the SC and BLP scenarios. Additionally, there is evidence that a reduction in the rate of development, due to repeated economic shocks, reduces the extent of this reduction in costs. This analysis is supported by modelling carried out to estimate the impact of COVID-19 on poverty and undernourishment, which estimated 90–150 million individuals globally could fall into extreme poverty due to the pandemic.[5]

The LandSyMM model can provide credible global estimates and trends to support scenario analysis.[22] However, excess mortality during the COVID-19 pandemic has been estimated at 1·6-times higher than the reported mortality data implemented in this study,[26] with reported mortality at over 3·5 million (Johns Hopkins Coronavirus Resource Center, 2021). Moreover, there is large uncertainty in the predictions of the impact of the pandemic on population figures given that it is unclear how birth rates will be affected by lockdowns, returning migrant labour, or how long the pandemic will continue for.[27] The LandSyMM model simulates agricultural production to a greater level of detail than how it accounts for the supply system. Because the impact of COVID-19 has mostly affected the supply side of food production (such as delays in delivery due to border checks), disruptions in supply were only partially simulated in the scenarios with trade barriers and transport loss factors. Additionally, due to the grouping of pulses and oil crops in the PLUMv2 demand system, it was not possible to increase pulses in the healthier diets without also increasing the demand for oil crops. However, oil crops for bioenergy production are likely to increase.[28]

This modelling analysis considers the impact of four scenarios; however, it leaves open how these scenarios might materialise in practice. The improvements shown in this study require strong incentives to improve diets through a range of policy levers. Additionally, more data on the effect of diet on disease severity is necessary to consider the impact of the changes in diet on mortality from COVID-19, or similar pandemics. A reduced burden of disease would reduce mortality for both communicable and non-communicable diseases, which have been shown to be risk factors for severe diseases and mortality from COVID-19.

In summary, the COVID-19 pandemic arrived at a crucial time for the global food system. There is an urgent need to resolve sustainable development issues relating to the effects of the food system to reduce environmental degradation, reduce the burden of disease from malnutrition, low-quality diets and over-consumption, and improve food affordability. The unprecedented economic shock caused by measures to reduce the spread of SARS-CoV-2 created the pretext for extraordinary governmental support in the form of $14 trillion of economic stimuli. This intervention provides the opportunity to fast track a transition in the food system towards a healthy future within planetary boundaries and better global cooperation to orchestrate the transition. The four scenarios modelled in this study have shown that healthier diets would reduce the negative impact of the food system on the environment, reduce avoidable deaths from unhealthy diets, and increase the affordability of food. It is exigent that the COVID-19 pandemic is brought under control, especially for the lowest income countries that are already experiencing malnutrition and cannot afford the consequences of a further reduction in incomes. For middle-income and high-income countries, the focus and implementation of the recovery stimulus towards a healthier diet and international cooperation are key to a more sustainable food system.

For the **Johns Hopkins Coronavirus Resource Center** see https://coronavirus.jhu.edu/

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