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Socio-economic, environmental and health impacts of dietary transformation in Bangladesh

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Supplementary material for this article is available online

Abstract

The transition to healthier diets might be accompanied by trade-offs that occur in other parts of the food system. In this study the trade-offs between socio-economic, environmental, and health indicators were analyzed in different dietary scenarios for Bangladesh between 2022 and 2050. We used a global economic simulation model with updated national food consumption data, extended with a footprint module to track environmental impacts through the food value chain in Bangladesh and its trading partners. This study compares a business-as-usual (BAU) diet with the EAT-Lancet diet and the Bangladesh food-based dietary guidelines (FBDGs). The BAU diet has a higher intake of animal products and sugar, and a lower intake of vegetables, fruits, legumes, and nuts than the EAT-Lancet and FBDG diets. We found that promoting a diet with more plant-based proteins has a strong positive impact on dietary health and an overall positive impact on the environment compared to the BAU scenario. This is due to the reduced impact of animal protein production on greenhouse gas emissions and the reduced impact of rice production on water use and nitrogen application. In addition, the transition to sustainable and healthy diets had minor impacts on the wages of low-skilled workers, Bangladesh's self-sufficiency, and the affordability of food and cereals. In particular, the FDBG diet scenario scored best on diet and cereal affordability, as well as freshwater use compared to the other two scenarios. The decrease in the self-sufficiency ratio was comparable to the BAU diet scenario and smaller compared to the EAT-Lancet diet.

1. Introduction

Over the last decades, Bangladesh has experienced strong economic growth and impressive poverty reduction. As a result, the country has made major progress in reducing malnutrition (Nguyen *et al* 2022). Like in other Asian countries (Reardon and Timmer 2014, Pingali and Abraham 2022), growing household income has led to an increasingly diverse diet (figure 1) with lower shares in starches in combination with an increase in meat, fruit, and beverages consumption (Waid *et al* 2018). However, there are still deficiencies in dietary diversity and micronutrient intake. The majority of the population consumes less than 75% of the recommended dietary intake for all food groups, with the exception of starches. Simultaneously, 22%, 17% and 14% of the population consume more than the recommended intake of sweets, oils, and meat, respectively (de Brauw *et al* 2020), which has led to a sharp increase in the prevalence of overweight and obesity (Nguyen *et al* 2022). This overconsumption has resulted in an

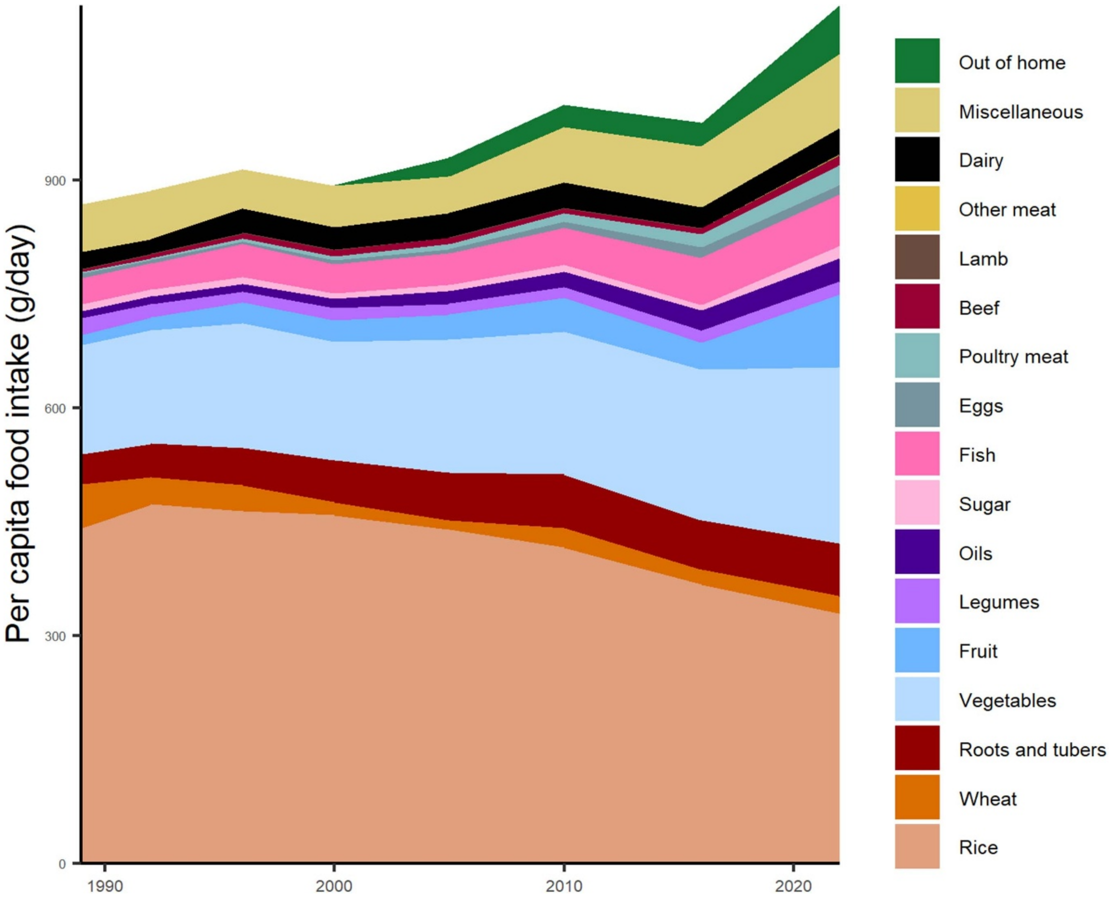

Figure 1. Daily per capita food intake in grams between 1989 and 2022 (Bangladesh Bureau of Statistics 1997, 2023).

increase in the incidence of non-communicable diseases like hypertension and diabetes over the last decades (Ahsan *et al* 2022, Nguyen *et al* 2022). Similar to other low- and middle-income countries, the prevalence of overweight, obesity, hypertension and diabetes were highest in wealthier households (Nguyen *et al* 2022). In addition to the health impact, changing food consumption patterns, coupled with population growth, affect land use by agriculture and have a significant impact on habitat loss and environmental degradation. This has led to deforestation and excessive use of agrochemicals, which threaten ecosystems and biodiversity due to their negative impact on both water and soil ecosystems (Hasnat *et al* 2018, Mukul *et al* 2018). In particular, increases in animal protein consumption leads to further biodiversity loss and an increase in greenhouse gas (GHG) emissions (Willett *et al* 2019).

The adoption of healthier diets is considered essential to halt the growth in obesity and negative environmental effects related to animal protein production. However, this adaptation process may yield negative consequences. In food systems, trade-offs between different dimensions of sustainability are inevitable and need to be made explicit when implementing or developing interventions (Béné *et al* 2019). The objective of the present study is to assess the potential trade-offs associated with a transition to healthier diets in Bangladesh. To this end, we will analyze the socio-economic, health, and environmental impacts of such a transition using a global computable general equilibrium (CGE) model in combination with an innovative approach for deriving environmental footprints.

There is a large body of literature on the health and environmental impacts of sustainable diets. A systematic literature review found that there are multiple health and environmental benefits of sustainable diets scenario compared to current or business-as-usual (BAU) diets (Jarmul *et al* 2020). However, the current literature on health and diet transitions has two limitations that we aim to address in this paper. First, most modeling studies focus only on the health and environmental impacts of diets, but do not address whether such diets are affordable (Biesbroek *et al* 2014, Springmann *et al* 2018, 2020, Clark *et al* 2019). Hirvonen *et al* (2020) pointed out that for at least 1.58 billion people, the cost of the EAT-Lancet diet is higher than their per capita income, and therefore the world's poor cannot afford this diet.

Thus, the inclusion of diet affordability in trade-off analyses is critical. If sustainable and healthy diets are not affordable, the transition to sustainable and healthy food systems will be severely hampered. We partially overcome this limitation by using a global CGE model with national detail that dynamically captures future changes in wages and food prices to measure food affordability. The second limitation is that most studies have used static footprint analyses, sometimes in combination with an economic modeling approach, to analyze the environmental impact of different diet scenarios (Biesbroek *et al* 2014, Irz *et al* 2016, Springmann *et al* 2018, 2020, Chen *et al* 2019, Clark *et al* 2019). While footprint analyses provide key insights into historical patterns, as behavioral responses are ignored (Rutherford 2010) their use in ex-ante analyses can be misleading. To overcome this limitation, we combined the CGE model results with an approach that uses the Leontief-inverse (Gatto *et al* 2023) to dynamically calculate the environmental footprints across different diet scenarios, while accounting for changes in global production and trade structures induced by the change in diets.

Bangladesh has experienced a strong transition in the economy resulting in dietary transitions, making it an interesting case study for trade-off analysis. This country case study is relevant given the limited available case studies on trade-off analyses of healthy diets in developing countries (Jarmul *et al* 2020). More than 100 countries, including Bangladesh, agreed to develop national strategies for transforming food systems during the UN Food Systems Summit 2021 (UN 2021). This study can contribute to informing policies supporting the national strategy of Bangladesh and it serves as a showcase for other countries who are in the same process of developing a national strategy. In addition, this method can also be applied on a global scale for broader policy analyses.

2. Methods and materials

2.1. Model setup

2.1.1. Modular Applied GeNeral Equilibrium Tool (MAGNET) model

We used the global CGE model MAGNET (www.magnet-model.org), to analyze the trade-offs between the diet scenarios for Bangladesh. MAGNET is a multi-regional multi-sector recursive dynamic equilibrium model built on neo-classical microeconomic theory (Woltjer *et al* 2014). The core of MAGNET is the GTAP v7 (Corong *et al* 2017) and the GTAPv10A database, base year 2014 (Aguiar *et al* 2019). The extension of MAGNET is mainly in the domain of agriculture and the bioeconomy (Woltjer *et al* 2014, Van Meijl *et al* 2018), and is used in various studies focusing on topics like biodiversity (Leclère *et al* 2020), food security (van Meijl *et al* 2020), climate mitigation (Frank *et al* 2019, Doelman *et al* 2020) or a combination (Hasegawa *et al* 2018).

MAGNET finds a new equilibrium in the global economy by adjusting prices to reach market clearing for all factor and commodity markets simultaneously. Producers adjust their input use in response to changes in input prices to maximize profits. As a result of constant returns to scale, the producers are operating under conditions of zero profit. Representative households respond to changes in income from factor sales and to fluctuations in commodity prices by maximizing their utility within their income constraint. Bilateral trade flows between all regions are modeled, with regional sourcing of imports based on the Armington assumption, allowing for two-way trade flows.

Key features of MAGNET relevant for this study are endogenous land markets, capturing the dynamics between agricultural land supplied and real land prices including the total potential suitable land available for agriculture (Dixon *et al* 2016, van Meijl *et al* 2006) and segmented factors markets in agricultural and non-agricultural labor and capital, given the empirical evidence that the mobility of labor is imperfect reflected by structurally lower wages in agricultural sectors (Herrendorf and Schoellman 2018). Other key elements of MAGNET include flexibly nested CES production trees, which provide greater substitution possibilities compared to the standard GTAP model, and a purchasing power adjusted CDE demand function. The latter allows for the adjustment of income elasticities in baseline projections, leading to more realistic patterns of food demand.

The main exogenous drivers of the model are based on shared socioeconomic pathway (SSP) projections (Riahi *et al* 2017), including population, technological change, and land productivity. Technological change is calibrated the GDP growth of the SSP projections. Additional information on the model settings, including an overview of the exogenous drivers used in this experiment, can be found in the Supplementary Information. As is common in global modeling studies (Stehfest *et al* 2019), we conducted a sensitivity analysis to examine the impact of changes in key drivers (e.g. population, technological change) using SSP1 and SSP3 compared to SSP2 (see table S1). These scenarios implicitly capture the impact of new technologies, such as new food (technologies) or agricultural technologies, within the SSP narratives. In SSP2, technological trends do not deviate significantly from historical trends, SSP1 represents a more sustainable path with high technological change towards lower material and reduced resource and energy consumption, while in SSP3 technological change is falling (O'Neill *et al* 2017, Riahi *et al* 2017).

2.1.2. Deriving environmental footprints and tracing food flows

Global multi-regional input–output (MRIO) databases provide detailed information on the global linkages between consumption and production. The use of global MRIO databases in combination with additional satellite accounts of various indicators, like land and water use and GHG emissions, allows the calculation of the footprint (direct and indirect) of consumption and is widely used in life-cycle studies (see for example Malik *et al* (2023), Wiedmann and Lenzen (2018)). By deriving the technical coefficients in the input–output analyses by computing the Leontief inverse (Leontief 1949), the amount of direct and indirect commodities used to produce one unit of a (final) product can be determined. These derived commodities used as input for final production are linked to indicators to calculate the footprints (see for example the method description in Lenzen *et al* (2021)). Prior to deriving the Leontief inverse, the physical flow in MAGNET needs to be traced to correct for non-material components like transport costs and export subsidies and create a regionalized material balance (Gatto *et al* 2023):

$$QO_i^p = \sum_{c,d} QI_{i,c}^{p,d} + \sum_{a,d} QF_i^{a,p,d} \qquad (2.1)$$

where QO_i^p is the production of commodity i in region p, $QI_{i,c}^{p,d}$ is the intermediate demand for commodity i from region p by production of c in region d, and $QF_i^{a,p,d}$ is final demand of commodity i from region p by agent a (private household, government and investment) in region d. The variables are updated with the percentage changes of the MAGNET model solution (excluding price or tax changes), thus enabling the material balance to be recalculated after each run. This method allows for the tracing of physical flows and, consequently, for the analysis of the footprint, including changes in production structure, including technological change. A detailed description of the tracing of the physical flows in combination with the Leontief inverse can be found in the Supplementary Information.

In addition to the ecological footprint, we used the Leontief inverse to derive the composition of primary food groups in processed foods, which allowed us to target diets at the food group level on which level dietary requirements in dietary guidelines are generally given. Unlike partial equilibrium models based on primary commodities, CGE models explicitly model food processing. This adds complexity to tracing nutrition as there are many indirect and cross-border flows. The Leontief inverse provides a summary of the direct and indirect primary contents allowing the trace of nutrition linked to primary content. Thus, we captured country-specific primary contents for processed food, by excluding the input used to produce primary food (such as cereals used as input feed inputs) and we can impose diet restrictions based on primary content irrespective of the channel (fresh, processed, services) through which they are consumed. For more information about tracking food flows, see the Supplementary Information.

2.1.3. Indicators

A set of indicators across three domains were defined to conduct trade-off analyses. In the socio-economic domain, we used the average wage of low-skilled workers, food and diet affordability, and the self-sufficiency ratio (SSR) (Beltran-Peña *et al* 2020). A country with an SSR of 1 or greater is considered to be self-sufficient in terms of food availability, while a country with an SSR of less than 1 is considered to be not self-sufficient.

The health domain was measured by the Sustainable and Healthy Diet Index (SHDI) (Ali *et al* 2022), which is a modification of the EAT-Lancet index developed by Stubbendorff *et al* (2022) and reflects the positive impact of adherence to the EAT-Lancet diet on a lower risk of mortality. Given the high level of aggregation of processed food in MAGNET, information on the consumption of sodium and fatty acids is lacking, making it impossible to use the commonly used indicators to evaluating the health outcomes of dietary patterns like the Healthy Eating Index (Krebs-Smith *et al* 2018) or the disability-adjusted life year (Afshin *et al* 2019). Nonetheless, the use of an index based on the EAT-Lancet score is a reliable proxy for the impact of consumed diets on health outcomes. Several studies have demonstrated that higher adherence to the EAT-Lancet diet is associated with a lower risk of several diseases, including type 2 diabetes (Knuppel *et al* 2019, Langmann *et al* 2023, Zhang *et al* 2023b), cardiovascular diseases (Knuppel *et al* 2019, Colizzi *et al* 2023, Zhang *et al* 2023a) and cancer (Stubbendorff *et al* 2022). Using the SHDI, we could indirectly compare the effects of the BAU diet and the food-based dietary guideline (FBDG) with the EAT-Lancet diet.

For the environmental domain, five environmental footprints were considered, including GHG emissions, land use, freshwater use, and nitrogen and phosphorus application. Further details on how the socio-economic indicators, the SHDI and the five environmental indicators were derived can be found in the Supplementary Information.

2.2. Diet scenarios

For the trade-off analysis we compared three diet scenarios: the BAU, EAT-Lancet and FBDGs of Bangladesh 2020. We imposed the diets in the MAGNET model by exogenously shocking the diets at the food group level highlighted in bold in table 1

Table 1. Baseline diet in 2022 and the food intake targets in grams for the BAU, FBDG and EAT-Lancet diet scenarios in 2050. The baseline diet is based on HIES 2022 data (Bangladesh Bureau of Statistics 2023) and the BAU, FBDG and EAT-Lancet diet scenarios are based on Bodirsky *et al* (2020), and Willett *et al* (2019) respectively. The numbers in bold present the food group targets that are used in the model.

Food group	Base year (2022)	BAU	FBDG	EAT-Lancet
Staples	453	**475**	336	302
Cereals	382		**254**	**254**
Roots and tubers	72		**82**	**48**
Vegetables, fruits, legumes, and nuts	343	**179**	618	625
Vegetables	229		**300**	**300**
Fruits	94		**200**	**200**
Legumes	18		**100**	**100**
Nuts	3		**18**	**25**
Oil seeds	32	**56**	**32**	**56**
Sugar	17	**66**	**38**	**31**
Animal source food	158	**357**	315	203
Meat, fish, egg	123		**175**	156
Red meat	14			**14**
Poultry	40			**42**
Fish	69			**100**
Dairy	36		**140**	**47**

until 2050 using preference shifts. The preference shifts allow a reallocation of private demand while maintaining the budget constraint. In this study, diets have been exogenously fixed, which means that non-food consumption must adjust to stay within the budget. A detailed description of the definition of the diet scenarios can be found in the Supplementary Information.

Comparing the BAU diet and the two diet scenarios with the diet in 2022 (Bangladesh Bureau of Statistics 2023), we found that the projected dietary intake of sugar and animal-source food increases in all three scenarios with the strongest increase in the BAU scenario (table 1). Also, in the FBGD and EAT-Lancet diet scenario there is a strong increase in the consumption of vegetables, fruits, legumes, and nuts, which is in contrast with the BAU scenario in which the consumption decreases. Comparing the FBDG and EAT-Lancet scenarios, we see that the targets of vegetables, fruits and legumes are similar. However, the consumption of nuts and oil seeds is lower in FBDG compared to the EAT-Lancet diet, while the intake of red meat and dairy is higher.

3. Results

No single diet performed optimally across all indicators when considering the relative impact of the change in diets between 2022 and 2050 (figure 2). In general, the impact of the diet scenarios was the strongest on health and the environmental indicators, while minor differences between the diets appeared in the socio-economic indicators. Comparing the EAT-Lancet and the BAU, trade-offs between environmental indicators like GHG emissions and land use became evident (figure 2(b)). These were accompanied by trade-offs in diet affordability and the healthiness of the diet (SHDI) (figure 2(a)). As mentioned earlier, we performed a sensitivity analysis using SSP1 and SSP3, in addition to the dietary scenarios using SSP2 presented here. The results are consistent with the main findings (see Supplementary Information).

3.1. Socio-economic effects

The wages of low-skilled workers were found to improve across all scenarios. The EAT-Lancet scenario showed the lowest increase in wages (see figure 2(a)). This relatively smaller increase can be explained by a decrease in rice production in the EAT-Lancet diet scenario. The labor used in rice production shifts to other sectors, resulting in an overall smaller increase in wages for low-skilled labor in the agricultural and non-agricultural sectors compared to the other scenarios. In the EAT-Lancet diet scenario the sectors with the highest wages to which labor can shift, such as the dairy sector, are smaller compared to the FBDG. Affordability of cereals improved significantly in all three scenarios due to lower cereal prices. The affordability of the diets also increased in all three scenarios, with the highest increase in the FBDG scenario. In all three scenarios, this increase in the affordability of the diet was the result of the increase in wages, while the price indices of the consumed diets changed only marginally between 2022 and 2050 (figure S3).

The SSR in Bangladesh was found to decrease across all three dietary scenarios with the highest decrease in the EAT-Lancet diet scenario. This decrease can be explained by a net increase in calorie imports, mainly from oilseeds in the BAU and EAT-Lancet diet scenarios, nuts and legumes imports in

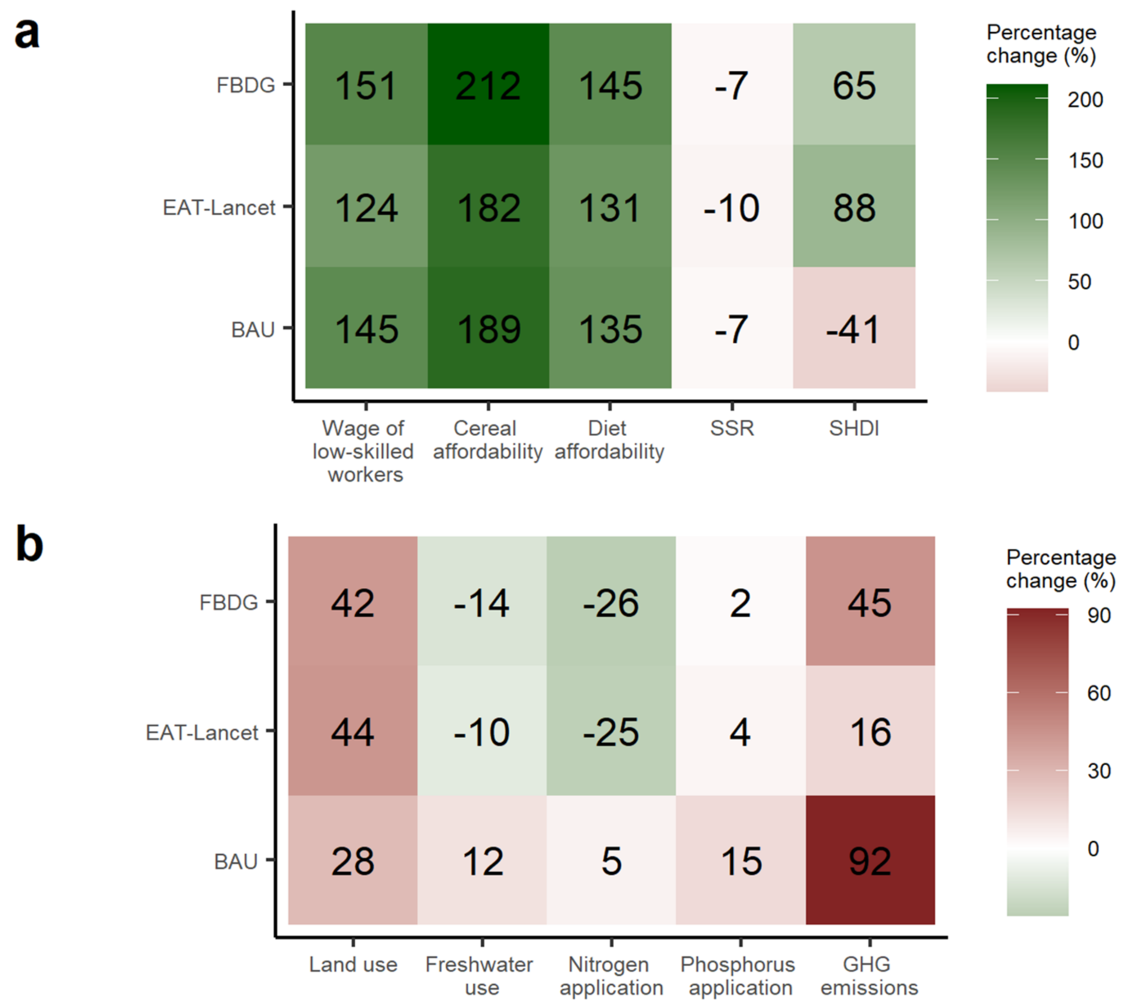

Figure 2. (a). Socio-economic, health and (b). environmental trade-offs for the BAU, EAT-Lancet and FBDG diet scenarios for the percentage change between 2022 and 2050. The socio-economic indicators and health indicator (a), including wage of low-skilled agricultural workers, affordability of cereals, affordability of food, self-sufficiency rate (SSR) and Sustainable and Healthy Diet Index (SHDI), and five environmental indicators (b), including land use, freshwater use, nitrogen application, phosphorus application, GHG emissions from the agri-food sector. The environmental footprint is the total footprint of food consumption from commodities produced in Bangladesh and abroad. The impact of the change in non-food consumption on the environmental indicators is excluded.

the EAT-Lancet and FBDG diet scenarios, and sugar imports in all three scenarios of different magnitude, while the net increase in calorie domestic production was substantially lower (figure S4).

3.2. Health effects

The healthiness of the diet (SHDI) was observed to improve substantially in the EAT-Lancet and FBDG scenarios, and worsen in the BAU scenario (figure 2). The decline in the healthiness of the BAU diet can be explained by excessive consumption of poultry, red meat and sugar, and a decrease in vegetable consumption (figure S5). The only positive change in the BAU diet was the increased consumption of oil seeds. In the EAT-Lancet and FBDG diet scenarios, the diet score improved due to increased consumption of fruits, vegetables, legumes, and whole grains, resulting in the highest scores for these food groups (figure S5). In comparison to the FBDG diet, the EAT-Lancet diet received a higher score due to increased consumption of nuts and oil seeds, and decreased consumption of sugar and refined grains. The FBDG diet scored higher in the consumption of roots and tubers, and dairy, because of higher minimum consumption recommendations.

3.3. Environmental effects

3.3.1. Trade-offs in environmental indicators

The environmental indicators revealed differences in the impact on the environment between the diet scenarios (figure 2(b)). The GHG emissions in the BAU scenario are higher compared to the alternative scenarios. Red meat consumption in the BAU diet scenario is responsible for most of the increase in GHG emissions from agricultural production (figure 3). Furthermore, the BAU diet resulted in an increase

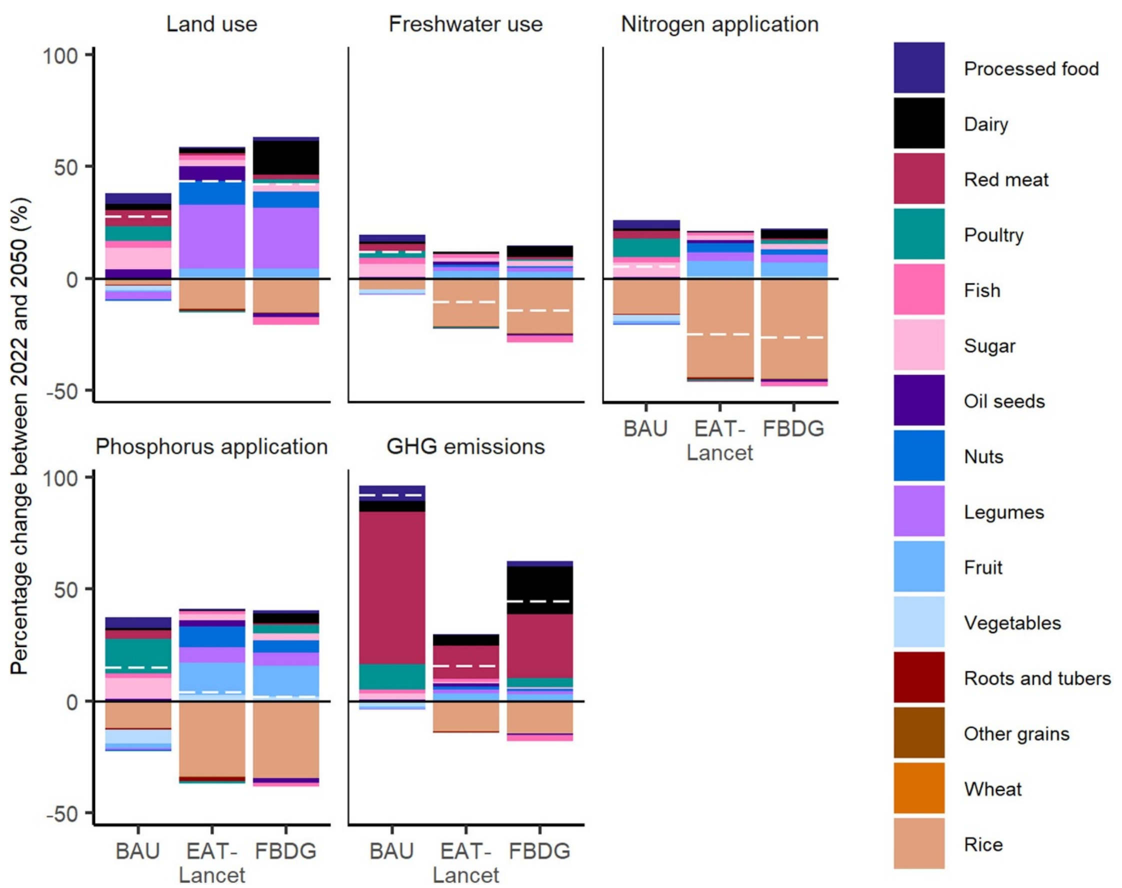

Figure 3. The percentage change in environmental footprints between 2022 and 2050 of total food consumption subdivided by commodity. The impact of the change in non-food consumption on the environmental indicators is excluded. The white dashed lines represent the total impact per footprint.

in freshwater usage, and nitrogen and phosphorus application, contrasting with the other two diet scenarios where freshwater use and fertilizer application decreased. The differences with the EAT-Lancet and FBDG diet scenarios were mainly caused by the lower reduction in rice consumption between 2022 and 2050. The disparity in nitrogen application compared to phosphorus between BAU and the EAT-Lancet and FDBG diet scenarios stem from the substitution of rice production for other crop production. As a result, nitrogen application decreases in the EAT-Lancet and FBDG diet scenarios because most legumes, nuts and fruits require a relatively higher proportion of phosphorus relative to nitrogen, unlike rice (Ahmmed *et al* 2018).

In the EAT-Lancet and FBDG diet scenario, land use was higher than in the BAU scenario and increased with similar magnitude. The majority of this higher increase is caused by the increase in legumes consumption compared to the BAU scenario (see figure 3). Focusing on the FBDG diet scenario, we can see that for most environmental footprints the impacts were comparable to the EAT-Lancet diet. However, GHG emissions are higher in the FBDG diet due to higher animal protein consumption.

3.3.2. The differing environmental impacts of changing diets domestically and in exporting countries to Bangladesh

In this section, we differentiate the impact of the five environmental indicators between domestic production and production in the countries exporting to Bangladesh. Major differences were found between the indicators in where the environmental impact took place (figure 4). Dietary change impacted almost exclusively land use in the exporting countries, while GHG emissions were mostly impacted in Bangladesh. The marginal changes in total land use in Bangladesh can be explained by the limited options to increase the total arable land in Bangladesh. However, major changes in land use in Bangladesh are a result of land used for rice production being substituted to produce other crops (figure S6). The increase in GHG emissions in Bangladesh resulted from an increase in the production of livestock (red meat and dairy) (figure S6).

In all scenarios, the water and nitrogen food prints of the diets decrease within Bangladesh while they increase outside Bangladesh. The highest positive impact on water use and nitrogen use within Bangladesh and the lowest negative impact outside

Figure 4. The percentage change in environmental footprints between 2022 and 2050 of total food consumption subdivided by the impact on Bangladesh or abroad. The grey dashed lines represent the total impact per footprint.

Bangladesh were found for the EAT-Lancet and the FBDG diet scenarios. The positive impact in Bangladesh was found to be the result of the reduced impact of rice production in all scenarios, as a result of technological change and the decrease in rice production in the FBDG and EAT-Lancet diet scenarios. The increase of the freshwater and nitrogen footprint outside Bangladesh resulted from the increase in production of oil seeds and feed production for animal protein production in the BAU and nuts and oil seeds production in the EAT-Lancet scenario.

4. Discussion

4.1. Comparison with other studies

Our results show that future consumer choices on food consumption in Bangladesh will have an impact on consumers' health and the environment in Bangladesh. This effect extends to countries exporting to Bangladesh. On health and most environmental indicators the EAT-Lancet and FBDG diets scored better than the BAU diet scenario. However, even under these more plant-based diets, land use, phosphorus application and GHG emissions increase between 2022 and 2050. In that sense, there is a trade-off between health/nutrition and environmental indicators. This is in line with the literature, showing that in low-income and, in one scenario, low-middle-income countries an improvement in diet might lead to improvements in health, but to deterioration in some environmental indicators including phosphorus application and cropland use (Springmann *et al* 2018). Furthermore, in line with Springmann *et al* (2018), dietary changes alone are not sufficient to reduce impacts on all environmental indicators and additional interventions to reduce food loss and waste, as well as technological improvements, are needed in order to reduce the impacts of food consumption.

Although there are explicit recommendations for legumes and nuts in the EAT-Lancet diet, most studies have not analyzed the two food groups separately (Hirvonen *et al* 2020, Bai *et al* 2021, 2022, Springmann *et al* 2021). However, our results show the importance of separating these food groups for analyzing the environmental impact. Although legume consumption increased more than four times compared to the nuts consumption in the EAT-Lancet and FBDG diet scenarios, the impact of the increase in nuts consumption on most environmental indicators was comparable or even slightly higher than the impacts of increased consumption of legumes. These strong differences we found in this study are in line with other studies. For example, Clark *et al* (2019) and Meier and Christen (2013) found a higher water footprint from the consumption of nuts and seeds compared to legumes. Potter *et al* (2020) compared the environmental impact of plant-based food and found that the overall impact of nuts on land use is the highest. Some types of nuts had also the highest water footprint depending on the geographical origin, namely whether the production relies on the use of irrigation water.

4.2. Policy implications

Promoting a diet with more plant-based protein in combination with a diet with a lower level of staples leads to positive health effects and has an overall positive impact on most environmental footprints compared to the BAU scenario. A transition to the FBDG diet recommendation has a negligible impact on socio-economic indicators. A comparison of the FBDG and EAT-Lancet diet scenarios reveals a trade-off between environmental impacts. The FBDG diet scenario yields a higher increase in GHG emissions, while the EAT-Lancet diets demonstrate lower increase in wages of low-skilled workers, as well as cereal and diet affordability. These findings suggest that there is no clear indication that Bangladesh should deviate from the FBDG in favor of the global EAT-Lancet.

A suggested improvement to the FBDG is to provide separate dietary recommendations for red meat, poultry, and fish instead of combining them into one. Our model results shows that red meat consumption is lower compared to poultry and fish. However, a different composition of red meat, poultry, and fish, such as higher red meat consumption, could substantially increase GHG emissions and possibly other environmental indicators. Therefore, adapting the red meat consumption recommendation of the EAT-Lancet diet will reduce GHG emissions in the FBDG diet. Additionally, the FBDG could be improved by setting a maximum limit for dairy consumption, rather than just a minimum target.

Between the scenarios, strong differences were observed in whether the impact takes place in Bangladesh or the countries exporting to Bangladesh. Opposite effects of the impact of the diet change on freshwater use and nitrogen application might occur in or outside Bangladesh. This illustrates that stimulating a consumption pattern with an overall lower footprint does not automatically lead to a reduction of the footprints regionally and spillover effects between regions might occur. In addition, spillover effects might appear between agricultural and non-agricultural sectors (Gatto *et al* 2023). Policymakers should be aware of these potential spillover effects from food imports.

Several consumer policies should be implemented in Bangladesh to facilitate the transition to a healthy diet. These policies can range from campaigns and dietary guidelines that allow a high degree of consumer choice to restrictions or limitations on consumer choice. Financial interventions, such as taxes and subsidies, appear to be effective policy measures (McGill *et al* 2015, Latka *et al* 2021). Nevertheless, a combination with non-financial measures, such as information campaigns and product labeling, may enhance consumer awareness and the effectiveness of the tax/subsidy, thus reducing the required magnitude of the tax/subsidy to achieve behavioral change (Latka *et al* 2021).

From the supply side, policy should focus on the diversification of agriculture transforming from rice production systems towards investments in horticulture. Additionally, investments in sustainable production practices are needed to reduce fertilizer use and pesticide use, like increasing the regulation of pesticide use and investing in the farmers' awareness and knowledge of pesticide use (Sarker *et al* 2021).

4.3. Strengths and weaknesses

One of the strengths of this analysis is the combination of a global CGE model with the Leontief inverse, which considers the changes in trade patterns resulting from changes in food demand in Bangladesh to analyze the environmental footprints. This allows us to identify the impact of different food groups and where environmental impacts occur, i.e. inside or outside Bangladesh. Another strength of this study is the addition of socio-economic indicators to our trade-off analysis, which provides new insights into the trade-offs between environmental and socio-economic impacts, especially for the EAT-Lancet scenario.

One of the limitations of using a global CGE model, as opposed to a partial equilibrium (e.g. GLOBIOM (Havlík *et al* 2018)) or national CGE models, is the lower level of granularity of the analysis concerning the agricultural sectors. The global CGE model also has limited detail on household structure (e.g. urban versus rural households), which is common in national CGE models (Thurlow *et al* 2012, Dorosh *et al* 2021). A more detailed breakdown of household types into rural farm, rural non-farm, and urban categories would be advantageous when examining the impact of dietary changes on food affordability.

4.4. Future research

Regarding stimulating a sustainable food system transformation in Bangladesh, further research should analyze which policy bundles are effective in stimulating consumers to adopt a healthy diet in Bangladesh. The differences in the effectiveness of these policies (like taxes or subsidies on consumers, producers, or import/export) will have different outcomes related to food affordability and the overall consumption patterns and inequality of the Bangladeshi.

In addition, the next step for future research would be to model differences in household income between household types and across regions in combination with global CGE models. This can be achieved by combining global CGE models with a microsimulation approach (van Dijk *et al* 2022). Such an approach would allow for the analysis of the impact of dietary change and related policy interventions on household poverty, undernourishment, and food affordability while considering the dynamics of the entire economy and trade.

In this study, we conducted a sensitivity analysis on the drivers of the model by using SSP projections of, among other drivers, GDP and population (Riahi *et al* 2017), and land and feed productivity from the land use model IMAGE (Doelman *et al* 2018) to capture the uncertainties of potential futures. A potential next step to improve the approach to perform sensitivity analysis in MAGNET is to use the novel approach informed rotations of Gaussian quadratures (GQs) (Stepanyan *et al* 2023) This approach is an improved approach of GQs and allows to perform a sensitivity analysis on parameters in CGE modeling with low computational cost compared to Monte Carlo.

5. Conclusion

This research provides insight into the potential trade-offs between different dietary scenarios in Bangladesh. Promoting a diet with more plant-based protein has an overall positive environmental impact compared to the BAU diet scenario. This is due to the reduced impact of animal protein production on GHG emissions and the reduced impact of rice production on nitrogen application and water use, while the socio-economic impact is limited. In addition, the adaptation to a more plant-based diet will lead to better health outcomes compared to the BAU diet. However, between 2022 and 2050, adapting to the EAT-Lancet or FBDG diets will still lead to an increase in GHG emissions, land use and phosphorus use because of population growth in Bangladesh and overall dietary improvements. Therefore, in addition to promoting dietary changes, additional interventions to reduce food loss and waste, as well as technological improvements, are needed in order to limit the increase in these environmental footprints. This research provides useful insights for other countries in terms of current levels of meat consumption, land pressure and demographics.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions

T d L, M v D, M K and W v Z conceived and designed the experiments. T d L, M v D, M K, W v Z, H B and A M contributed to the performed experiments and the analysis of the data. T d L wrote the initial draft and all authors contributed to the final manuscript.

Conflict of interest

The authors declare no competing interests.

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