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Does Mexico have the agricultural land resources to feed its population with a healthy and sustainable diet?

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ABSTRACT

Reaching healthy and sustainable diets for all people with the world's limited resources is one of the biggest challenges of humanity. The Healthy Reference Diet (HRD) is a recent proposal by the Eat-Lancet Commission for addressing this problem. Mexico has a high burden of obesity and persistent malnutrition. Recent national policies have focused on different strategies to transform the food system which include designing new dietary guidelines using the HRD adapted for the Mexican context and supporting small farmers to reduce food imports. The aim of the paper is to explore whether Mexico has enough land resources to produce food for a healthy and sustainable diet for its population, with no international trade, and what changes are needed to reach this in terms of diets, the food system, and in land use. Four scenarios are explored for changing the food system to reduce agricultural land use. The results show that Mexico has enough agricultural land to produce food for all its population to ensure healthy and sustainable diets with the current food supply chain. A healthy and sustainable diet demands 20 % to 50 % less agricultural land, depending on the type of dietary recommendation, than the present average diet of the Mexican population. But changes are needed in the food system in terms of land use such as exchanging pasture for cropland and changing the type of crop production like reducing cropland for sugar cane and feed for livestock, and increasing cropland for legumes and nuts. Furthermore, reducing losses in the supply chain and increasing crop yields reduces considerably the demand of agricultural land. Further research is needed to explore the socioeconomic issues and policies for reaching these changes. The insights of this paper should be considered when designing policy strategies and recommendations to reach a sustainable food system.

1. Introduction

One of the biggest challenges of humanity is to reach healthy diets for everyone with the world's limited natural resources (Brouwer et al., 2021; Davis et al., 2016; Rockström et al., 2020; Springmann et al., 2018; Willett et al., 2019). Land is one of the main resources for food production, and human's use is reaching its limits (Henry et al., 2019; Ibarrola Rivas and Nonhebel, 2016; Rockström et al., 2020). This challenge is a result of the current food system that promotes unhealthy diets and contributes to the global syndemic of malnutrition, obesity, and climate change, putting the food security and nutrition at risk for this and future generations (Swinburn et al., 2019).

In 2019, the Eat-Lancet Commission published The Healthy Reference Diet (HRD), a universal framework for a healthy and sustainable diet, rich in plant-based food such as legumes, fruits, vegetables, nuts, and whole grains, which should be adapted for each region of the world (Willett et al., 2019). Since then, many studies and organisations adapted this diet for local contexts, like for Mexico (Castellanos-Gutiérrez et al., 2021), or have adopted it as a reference or path for reaching a sustainable future (Brouwer et al., 2021).

The current COVID-19 pandemic compromised access to a healthy diet and increased the vulnerability of food security, especially among countries with high dependency of food imports (Barlow et al., 2021; Sers and Mughal, 2020). Therefore, ensuring a country's food sovereignty is crucial to be resilient to global shocks (Bicchietti et al., 2021).

Mexico is an example of these global challenges. The Mexican population faces an epidemic of obesity and chronic non-communicable diseases with persistent nutritional deficiencies. In 2020, 10.6 % of

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adults had diabetes and 13.4 % hypertension, overweight or obesity was present in 72.1 % of adults, 43 % of adolescents and 38 % of school aged children, while malnutrition persisted among 18.5 % of children 0–5 years in rural areas and 13.9 % nationally (Shamah-Levy et al., 2021). This epidemic is being fuelled by diets high in sugar, fat and sodium from ultra-processed products and sugary drinks, refined grains, and processed meat, and low on fruits, vegetables, nuts, whole grains and legumes (Gaona-Pineda et al., 2018; Pérez-Tepayo et al., 2020).

Mexico is a net importing country (D'odorico et al., 2014). The largest amount of food imported is maize, accounting for 15 million tons in 2019 (FAO, 2022b). Most of it is yellow maize which is mainly used as animal feed and for the food industry (SAGARPA, 2017). Also, Mexico is an important food exporter, in 2019, it was the 7th top exporter of agricultural products with beer, avocado, berries and tomatoes accounting the highest economic value (SIAP, 2020).

Present Mexican policies are focusing on promoting a fair, healthy, sustainable, and competitive agri-food system to facilitate the adoption of healthy and sustainable diets. These include taxes and a front-of-pack warning label for sugary beverages and ultra-processed products (White and Barquera, 2020), and promoting food sovereignty by supporting small farmers through guaranteed prices for food-staples and a ban on the use of glyphosate pesticide and transgenic corn by 2024, among others (DOF, 2020). Recently a new Food-Based Dietary Guidelines (FBDG) (SSA et al., 2022) has been developed to support these targets. The new FBDG include for the first-time considerations of the environmental impact of food using estimations developed for the most consumed foods in Mexico (Curi-Quinto et al., 2022), and recommend the consumption of fresh, minimally processed and preferably locally produced food, increase the consumption of fruits, vegetables, legumes, nuts, and whole grains, reduce red meat in half and avoid sugary drinks, ultra-processed products and alcohol. The guidelines were based on the EAT-Lancet HRD (Willett et al., 2019) adapted for the Mexican context (Castellanos-Gutiérrez et al., 2021), but with some differences to ensure macro and micronutrient adequacy and not to deviate so much from current consumption patterns. Reaching these guidelines is a challenge because the present food pattern of the population highly diverts from the healthy and sustainable diet, mainly among urban and middle- and high-income groups (Castellanos-Gutiérrez et al., 2021).

In this paper, we explore whether Mexico has enough land resources to produce food for a healthy and sustainable diet for its population in a context of no international trade, and what changes are needed to reach this in terms of diets, the food system, and in land use. Two references for a healthy and sustainable diet for the average adult population are used: the new FBDG 2022 and the HRD adapted for the Mexican context. First, we estimate how much food needs to be produced for these two dietary references and compare it with the present dietary pattern. Second, we estimate the agricultural land needed to produce this food and compare it with the present use of agricultural land. Third, we explore four scenarios of changes in the food system to reduce agricultural land use. Estimating the land required to comply with the recommendations for a healthy and sustainable diet will allow us to know if it is possible to achieve food sovereignty in Mexico and explore options to reduce the environmental pressure on land resources. The insights of this analysis are useful to make recommendations based on evidence to current health and food policies to achieve this goal.

2. Methods

2.1. System description: linking diets to land use

The food system analysed in this study is schematized in Fig. 1. The starting point is the food intake of the population (top) which is linked to the agricultural land use using the food supply chain shown in Fig. 1. In this way, we estimate how much land is needed to produce the food for those diets. The food supply chain of this study does not include international food trade, so we assume that all food supply of the country originates from the national food production. The food chain includes the food production (in green) and the domestic supply (in blue). The land use in the food supply chain is mainly associated with the national food production. The type of land (in yellow) is different for each food production category (in green). We analyse food intake for three Food patterns for which a different diet is used as a starting point. Food pattern 1 uses the "Present average diet" which is the present diet of the population, Food pattern 2 uses the FBDG 2022 for the Mexican population, and Food pattern 3 uses the "Healthy Reference Diet (HRD)" for the Mexican population.

The **food intake** is what people eat (top of Fig. 1). In Mexico, the National Health and Nutrition Survey (ENSANUT, 2016a) estimates the food intake of the population (Romero-Martínez et al., 2017). The average diet of this survey is used as a starting point for Food pattern 1. The health and nutrition survey underestimates the consumption of energy and underreports for some food categories such as sugar and alcohol (Guibrunet and Arnés, 2021; Kye et al., 2014). For example, compared with food supply reported by the Food Balance Sheets (FBS) (FAO, 2022b), food intake estimated from national dietary surveys is lower for fruits, vegetables, whole grains, red and processed meat, fish and seafood, milk, and total energy (Del Gobbo et al., 2015). Also, food is wasted along the consumption stage of the food chain. For instance, food that is wasted in supermarkets, in restaurants, or in households. The **food supply** includes these food wastes and underestimations and underreporting of dietary surveys (Fig. 1). We converted the food intake values into food supply by comparing the food intake of the dietary survey (ENSANUT, 2016a) with the food supply data of the Food Balance Sheets (FBS) (FAO, 2022b). Appendix 1 shows the details of the calculations.

The food losses along the food supply chain, from post-harvest to the consumption stage, are reported by the FBS of the FAO (2022b). Also, the FBS reports the amount for each food item which is used for "other non-food uses" (e.g. seeds for the next harvest, textiles, tobacco and cosmetics). We use the values of these losses and non-food uses, in addition with the food supply, to estimate the amount that needs to be produced. In this way, our results consider the present state of the food supply chain. Thus, the **domestic supply** includes the food losses, the other non-food items, and the food supply that is available in the country for human's consumption (Fig. 1).

The **national food production** includes three categories: crop production, animal products production, and processed crops production. A share of the crop production is used as feed for livestock, another share is used as inputs for crop processing, and the rest ends up as domestic supply (Fig. 1). The animal products production and the processed food production ends up as domestic supply. So, for this study, the domestic supply of the country includes the national production of crops (except feed crops and crops for processed crops production, to avoid double counting), animal products, and crops-based processed food (Fig. 1).

Each food production category includes different food items of the food intake, of the diets. The food items of the diets are grouped in 18 food categories to be analysed throughout the food chain. The grouping of the food items was based on the food categories reported by the FBS (FAO, 2022b) for Mexico in the period 2015–2019. Crop production includes cereals, vegetables, fruits, tubers, pulses, nuts, and stimulants and spices. Processed crops production includes vegetable oils, sugar, and alcoholic beverages. And animal products production includes beef, pork, poultry, other meats, eggs, milk and dairy, animal fats, and fish & crustaceous. Note that all animal food products are included in "animal products production" (including processed foods such as processed meat and cheese). Also, some crop-based processed food such as bread and pasta, is included in the "crop production" category because the FBS (FAO, 2022b) includes these processed foods in "wheat and products". Appendix 1 shows the food categories that are included in each production category.

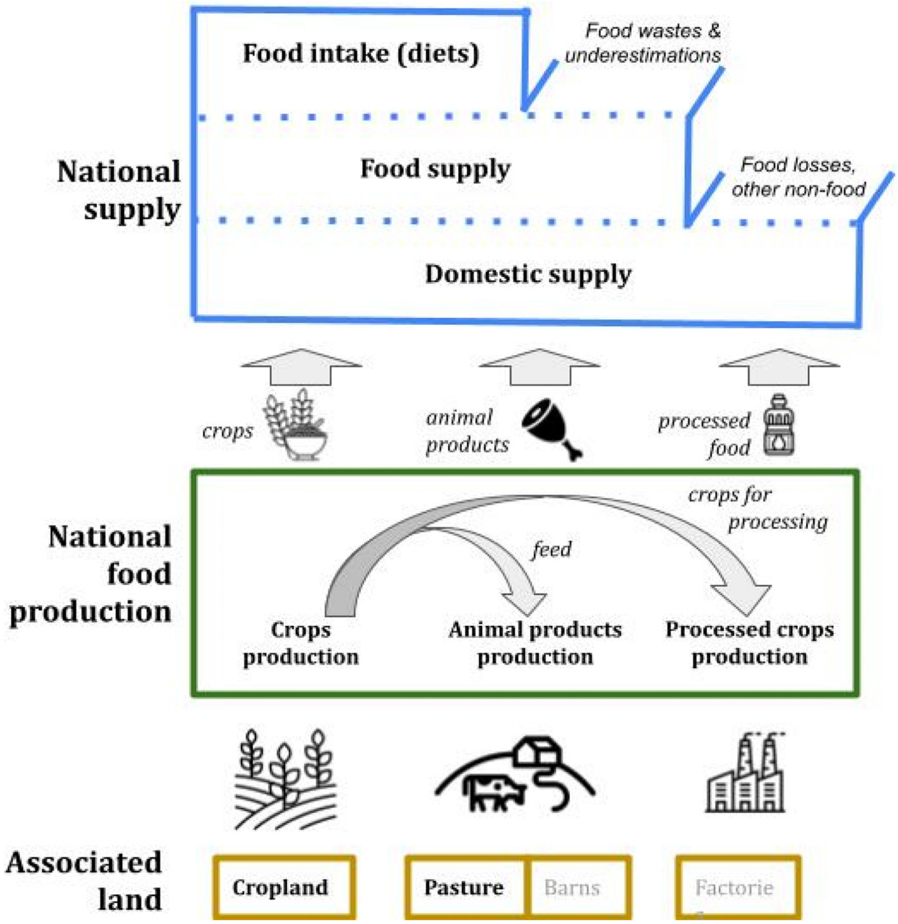

Fig. 1. System description for this study. It illustrates the food supply chain to link diets with its associated land use needed to produce the food. The land categories in grey (barn and factories) are not considered in this study because of its low relevance in magnitude compared with the agricultural land (cropland and pastures). This supply chain does not consider food trade. See text for details. Figure created by the authors using logos from The Noun Project (2022).

The choice of the production categories is based on the type of **land associated** with these production categories which require different types of land use (Fig. 1). Cropland is used for crop production; pastures and barns' area are used for animal products production; and area for factories is used for food processing production. However, as Fig. 1 shows, cropland is indirectly used in animal products and industrial food production by considering the cropland used to produce the feed and crops inputs for processed food. This indirect cropland for animal products production and processed food is the cropland used for the feed production and for the crop inputs for food processing which is considered in this paper. In addition, the pasture area associated with livestock production is also considered. The land use for barns and factories, which are shown in grey, is not considered in this paper because of its low relevance in the total land use. Ibarrola-Rivas and Nonhebel (2019) show that the barn area for animal products production is three orders of magnitude lower than the cropland and pastures associated with the production of that animal product.

2.2. Food supply data for the three food patterns

Three dietary patterns are analysed in this study: (1) the present average diet of adults in Mexico (Food pattern 1), (2) the Food-Based Dietary Guidelines 2022 (FBDG) recommendations for adults (Food pattern 2), and (3) the Healthy Reference Diet (HRD) adapted for the Mexican context for adults (Food pattern 3). Different data sources are used for each of these diets. For the present diet (Food pattern 1), data from the Mexican National Health and Nutrition Survey of 2016 (ENSANUT, 2016b) is used considering the average food intake for adults. The survey has information from a 24-hour dietary recall, within each population group (schoolchildren, adolescents, and adults), in a representative sample of the Mexican population ($n = 3646$). We used information reported by the National Institute of Public Health (ENSANUT, 2016b), who classified the food items from the survey into food categories and estimated average daily caloric intake (kcal/capita/day).

For Food pattern 2, the FBDG 2022 recommendations are used, which is the most recent recommendation for the Mexican population considering a nutritional adequate and sustainable diet (SSA et al., 2022). For Food pattern 3, we used data from the Healthy Reference Diet (HRD) developed by the Eat-Lancet commission adapted for the adult Mexican population (Castellanos-Gutiérrez et al., 2021). The values of the two recommendations (Food pattern 2 and 3) are "average food intake values". The reason for considering the recommendations as "food intake" is that they are estimated using as reference the values of the National Health and Nutrition Survey (ENSANUT, 2016a).

The food intake values of the three Food patterns are converted into food supply, and then into domestic supply by estimating the food wastes, losses, and non-food items, which are the two "flow losses" schematized in Fig. 1. Appendix 1 shows the values and the methods to calculate the food intake, the food supply, and the domestic supply of the three Food patterns.

2.3. Total food production estimations for the three food patterns

The amount of food that needs to be produced for the three Food patterns is estimated considering the complex food supply chain which is schematized in Fig. 1. The food intake and food supply values are in units of per capita calories per day. These values need to be converted into total tonnes demanded in one year. So, the food supply values are converted into kilograms per person per day, and then multiplied by the present population in Mexico. Appendix 1 shows the details on the conversion of food intake (kcal/person/day) to total domestic supply (million tonnes) considering the conversion of calories to grams for each food category. The domestic supply is the total amount of food needed to be produced. In addition to this amount, animal feed is needed for animal products production and crops are needed as inputs for crops processing production. Therefore, the production of these crops needs to be considered as well in the national production (feed and inputs for processing).

The amount of animal feed required is estimated using the methodology of Ibarrola-Rivas and Nonhebel (2019), who calculate the total amount of feed needed to produce one kilogram of animal product for an average medium-scale farm in Mexico using data from the Mexican Agricultural Survey of 2014 (INEGI, 2014). Appendix 2 shows the steps to calculate the amount of feed required to produce a kilogram of beef, pork, poultry meat, eggs, and milk. For fish, we used the average values of pork, poultry meat, eggs, and milk. Beef was not included in the estimations for fish because its value is much larger than the rest of the animal products. For animal fats and other meats we assume the same values as pork since most of the animal fats originate from pork.

Each country uses different types of feed for their livestock. To estimate the type of feed, we use the present distribution of feed used in Mexico reported by the FBS for the top four feed products. These four feed-products account for 96 % of the total amount of feed used in Mexico in the period 2015–2019 (FAO, 2022b) which are 65 % maize and products, 19 % sorghum and products, 11 % sugar cane, and 5 % soybeans. Table A6 in Appendix 2 shows the distribution of feed crops for Mexico which is used to calculate the feed crops for all animal products.

The amount of crops needed for the crops processing (Fig. 1) is calculated for vegetable oils, sugars, and alcoholic beverages. A conversion factor is calculated for each of these three food categories by dividing the present supply of crop input used for “processing” by the present production of the processed food category reported by the FBS (FAO, 2022b). For each processed food category, we used the values of the food items most largely produced in Mexico. Table A7 in Appendix 2 shows the food items used and the conversion factors to calculate the crops input for each food category.

2.4. Agricultural land use estimation for the three food patterns

In Section 2.3, the total amount of food production required is estimated for the three scenarios. Whether it is possible to produce this amount within Mexican territory depends on how much agricultural land is available and on the crop yields (food produced per hectare) that can be expected from the various crops and livestock production. So, the amount of land associated with the three Food patterns is estimated and compared with the available agricultural land in Mexico.

The cropland associated with each crop production category is calculated by dividing the amount produced (in tonnes) by the crop yield (in ton/ha). FAO (2022a) data for Mexico was used for estimating the average crop yield of each food category in the period 2015–2019 (Table 1). The crop production category reported by FAO is linked with the crop categories used in this paper (Table 1).

The pasture associated with the livestock production is estimated using published data for beef production (351 m2-yr/kg) and milk production (8.6 m2-yr/kg) in Mexico (Ibarrola-Rivas and Nonhebel, 2019, Table 9). Note that the rest of the livestock products do not use pastureland.

The cropland and pastureland calculated for the three scenarios are compared with the present use of cropland and pastureland for Mexico during the period 2015–2019 reported by the FAO (2022c).

Table 1
Crop yields values for each food category to estimate the cropland used for the crop production. Source of data: average values for Mexico for the period 2015–2019 (FAO, 2022a).

Food category of this study	Crop production category of FAO	Crop yield [ton/ha]
Wheat	Wheat	5.4
Rice	Rice, paddy	6.3
Maize	Maize	3.8
Barley	Barley	2.8
Sorghum	Sorghum	3.3
Other cereals	Cereals nes	1.7
Tubers	Roots and tubers, total	29.1
Fruits	Fruit primary	15.2
Vegetables	Vegetables primary	21.9
Pulses	Pulses, total	0.9
Nuts	Tree nuts, total	1.7
Oil crops	Soybeans	1.7
Sugar cane	Sugar cane	72.5
Stimulants	Coffee, green	0.3

Furthermore, the calculated cropland for each food category is compared with the present harvested area of each food category in Mexico during the same period. Note that the harvested area is lower than the present use of cropland because of several reasons such as harvest loss and fallow periods which are included in the present use of cropland area, but not in the harvested area. This comparison allows us to identify whether land use changes are needed in terms of the type of crop production.

2.5. Exploring changes in the food system to reduce agricultural land use

Finally, changes in the food system are explored to reduce agricultural land use and, at the same time, reach healthy and sustainable diets for all people. To do this, four scenarios are compared with our results of Section 2.4. These scenarios include increasing the efficiency in the food supply system in terms of increasing crop yields and in reducing food losses in the supply chain. Table 2 describes the changes of the four scenarios.

The first row shows the Business As Usual (BAU) scenario which is the Food System analysed in this paper (Section 2.4). The first scenario explored is the “(1) Moderate crop yields increase” which assumes an increase in the crop yields (Table 1) based on the projections FAO (2018, Table 4.9) for crop yields increase for Latin America. The second scenario is “(2) High crop yields increase” which assumes that all crop yields, except for sugar cane, increase by 50 %. The third scenario is “(3) Reducing Losses” which assumes that the food losses in the food supply chain (first lost flow of Fig. 1) reduces by 75 % of its present value. The fourth scenario is “(3) Reducing losses & high crop yields” which assumes the increase of crop yields by 50 %, except sugar cane, and the reduction of food losses by 75 % of its present value. Appendix

Table 2
Changes in the food system to explore scenarios for agricultural land use reduction. Source of data: [a] Table 1 of this paper, [b] Appendix 1 of this paper, [c] Table 4.9 in FAO (2018); [d] Appendix 4.

Scenarios	Crop yields	Food losses
BAU: present food system	Same as present system[a]	Same as present system[b]
(1) Moderate crop yields increase	Projections of crop yields increase for Latin America[c]	Same as present system[b]
(2) High crop yields increase	Increasing crop yields by 50 %[d]	Same as present system[b]
(3) Reducing losses	Same as present system[a]	Reducing losses by 75 % in all food categories
(4) Reducing losses & high crop yields increase	Increasing crop yields by 50 %[d]	Reducing losses by 75 % in all food categories

4 shows the details on the estimations of the food system changes for each scenario.

3. Results

3.1. Domestic supply: food production required

The food intake of the three Food patterns is 1823 kcal/cap/day, 1882 kcal/cap/day, and 1878 kcal/cap/day respectively (Appendix 1). The food supply, which consider the underestimations of the survey and the food wastes, for the three Food patterns is 3117 kcal/cap/day, 3287 kcal/cap/day, and 3420 kcal/cap/day respectively. The conversion of food intake to food supply is different for each food category (see Table A2 in Appendix 1).

The per capita food supply values are converted into total domestic supply values which are 100 million tonnes, 106 million tonnes, and 97 million tonnes per year respectively for each Food pattern. These are the total amount of production needed to feed the Mexican population in one year for the three Food patterns (Fig. 2). The three Food patterns have significant differences on the amounts of the various food categories. Table A3 in Appendix 1 shows the values of Fig. 2.

For some food categories, the amount in the present diet is larger than what is recommended for a healthy and sustainable diet. The present consumption of sugars is twice than in both Food patterns 2 and 3 than the present consumption. The consumption of beef is 60 % larger in Food pattern 2, and 5 times larger in Food pattern 3 than the present consumption. The present consumption of milk is 40 % larger than Food pattern 3 and it is the same in Food pattern 2. The consumption of cereals is 24 % and 20 % larger in Food pattern 2 and Food pattern 3 respectively than the present consumption. For other food categories, the amount in the present diet is smaller than the two recommendations. The present consumption of pulses is only one fourth and one fifth of the consumption in Food patterns 2 and 3 respectively. The present consumption of nuts is only one tenth or less of the consumption in Food pattern 2 and 3. The present consumption of fish is half and one third compared to Food pattern 2 and 3 respectively. The present consumption of vegetable oils is also half than Food patterns 2 and 3. The present consumption of fruits and vegetables is 50 % and 20 % lower than Food pattern 2 and 3 respectively. The present consumption of chicken meat, eggs and animal fats is slightly smaller than Food patterns 2 and 3. So, to reach a healthy and sustainable diet for all Mexicans the consumption of sugars, beef, pork, and cereals need to be reduced, and pulses, nuts, fish, vegetable oils, nuts, fruits, and vegetables need to be increased.

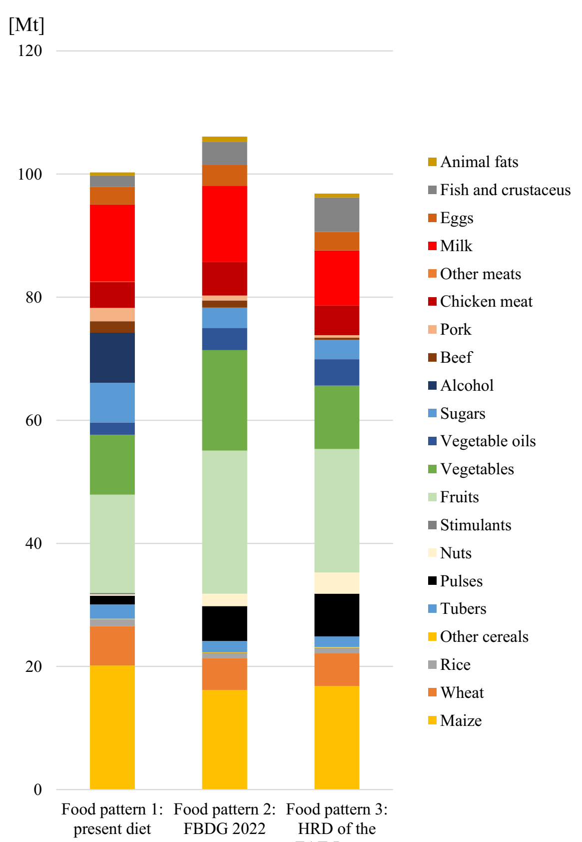

Fig. 2. Domestic supply for the three food patterns: total amount of food production needed to feed the entire Mexican population in one year. Values in millions of tonnes. Source: calculations by the authors.

In addition to the total domestic supply (Fig. 2), the animal products and processed foods require crops to produce them (Fig. 1). Table 3 shows the crop production requirements for the three Food patterns considering the feed crops to produce the animal products, and the input crops to produce the processed foods. In the second column, the crop equivalent for each animal product and processed food is indicated. Feed includes maize, sorghum, sugar cane, and soybeans. Appendix 3 shows the specific amount required of each feed crop for each animal product production.

3.2. Agricultural land demand and present use

The agricultural land demand for each Food pattern includes cropland to produce the crops and pastureland to produce the beef and milk products (Fig. 1). The amount of cropland required to produce the food for each Food pattern depends, for each food category, on the amount of crops required (Table 3, and Appendix 3) and on the crop yield of the crop (Table 1). The differences in crop yields determine the amount of cropland needed to produce a kilogram of crop, and therefore, a kilogram of food (also for animal products and processed foods). Crops with higher crop yields require less land to produce a

Table 3
Total crop production requirements for the three Food patterns.
The amount of crop inputs for animal products and for crops processing is indicated.
Source of data: Calculations by the authors.

Food category	Input crops for national food production (Feed & crops for food processing)	Total demand of crop production [Million tonnes] Food pattern 1: Present diet	Food pattern 2: FBDG 2022	Food pattern 3: HRD of the EAT-Lancet
Maize		20.15	16.18	16.80
Wheat		6.39	5.13	5.33
Rice		1.10	0.89	0.92
Other cereals		0.13	0.10	0.11
Tubers		2.30	1.85	1.72
Pulses		1.42	5.64	6.95
Nuts		0.19	2.02	3.46
Stimulants		0.24	0.00	0.00
Fruits		15.99	23.25	20.05
Vegetables		9.73	16.31	10.30
Vegetable oils	Soybeans	8.57	15.56	18.42
Sugars	Sugar cane	45.14	23.10	21.94
Alcohol	Barley for beer	1.18	0.00	0.00
Beef	Feed for beef	25.10	15.61	4.75
Pork	Feed for pork	10.07	3.71	1.91
Poultry	Feed for poultry	10.73	13.77	12.24
Other meats	Feed for other meats	0.39	0.00	0.00
Milk	Feed for milk	13.80	13.73	9.92
Eggs	Feed for eggs	6.52	7.63	6.81
Fish and crustaceans	Feed for fish	4.92	9.88	14.82
Animal fats	Feed for animal fats	2.29	4.15	2.91

ton of food than crops with lower crop yields. So, a kilogram of maize requires 4 or 6 times more cropland than a kilogram of fruits or vegetables respectively (Table 1).

The total agricultural land demanded is 112 Mha for Food pattern 1, 94 Mha for Food pattern 2, and 62 Mha for Food pattern 3 (Fig. 3). The large difference among the Food patterns is mainly driven by the different demand for pastureland which is mostly because of the consumption of beef. 86 %, 79 % and 62 % of the total demand of pastureland is for beef production, respectively for the three Food patterns (Fig. 3).

The present use of pastureland and cropland in Mexico is 74 Mha and 23 Mha respectively (FAO, 2022c), so 97 Mha in total. Food pattern 1 demands more pasture and cropland than what is presently used in the country. In contrast, Food pattern 2 and 3 demand less, Food pattern 2 demands 4 % less agricultural land, and Food pattern 3 demands 36 % less agricultural land. However, note that the difference between demand and present use differs between pasture and cropland. The three Food patterns demand more cropland than what is presently used: Food pattern 1 demands 53 % more cropland, Food pattern 2 and 3 demands 81 % more cropland. The cropland required for each food category and each Food pattern is shown in Fig. 4.

The cropland to produce the feed for the animal products accounts for 52 % of the total cropland in Food pattern 1, 41 % in Food pattern 2, and 32 % in Food pattern 3. Most of it is for beef and milk production. Cropland for cereals for food accounts only for 19 %, 13 % and 13 % of the total cropland respectively. Cropland for pulses and nuts is higher in Food pattern 2 and 3 (8 Mha and 10 Mha respectively) compared with Food pattern 1 (2 Mha). This is because of the low consumption of pulses and nuts in the present diet, which is lower than the recommendation for a healthy and sustainable diet.

The cropland to produce stimulants is relatively high in Food pattern 1 (1 Mha) accounting to 3 % of the total cropland, and for vegetable oils is relatively high in Food pattern 2 and 3 (9 Mha and 11 Mha) compared with Food pattern 1 (5 Mha). In contrast, the cropland demand for sugars is relatively small in the three Food patterns accounting to 2 % in Food pattern 1 and 0.8 % in Food pattern 2 and 3 of the total cropland compared with its higher role of caloric consumption in the diet. The relatively low demand of land for sugars, and higher demand of land for vegetable oils, pulses, nuts, and stimulants is driven by the differences in crop yield among these food categories, with sugar cane with the largest crop yield (Table 1).

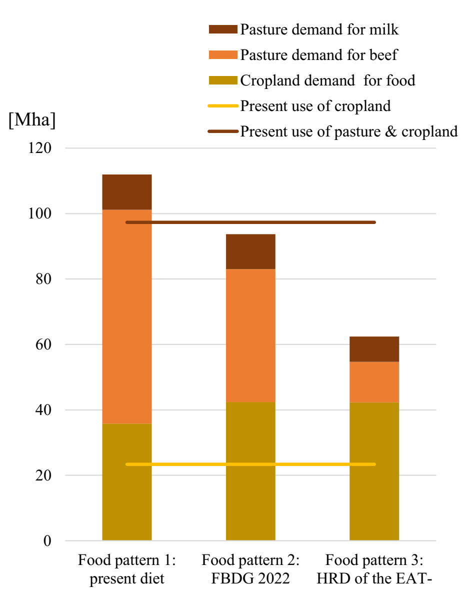

Fig. 3. Agricultural land demand for the three food patterns. The demand for pasture is divided by beef and milk demand. Data sources: demand for cropland and pasture: Calculations by the authors; Present use of cropland and pasture: FAO (2022c).

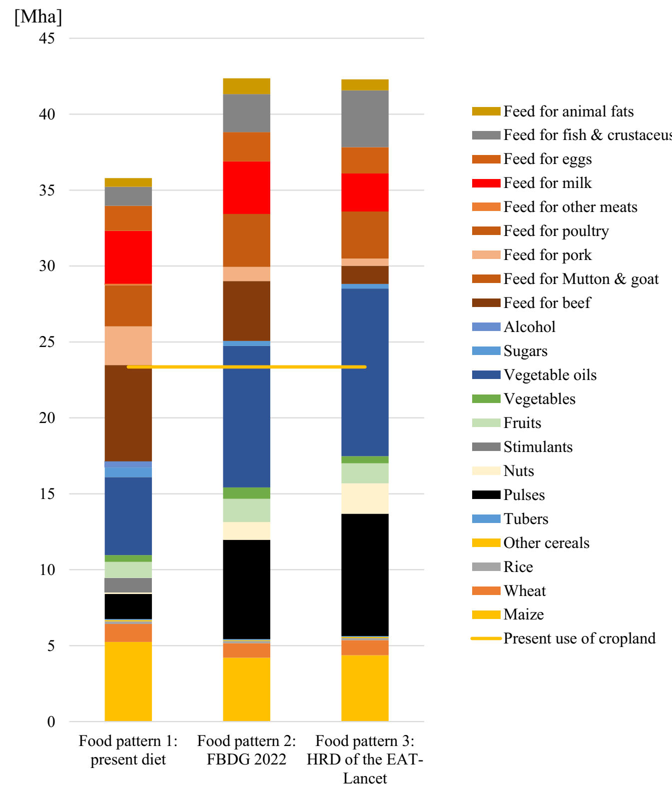

Fig. 4. Cropland demand by type of food consumed. Data sources: demand of cropland for each food category: cropland demand: calculations by the authors; present use of cropland for Mexico in the period 2015–2019: FAO (2022c).

Fig. 5 shows the cropland requirements for each Food pattern by the type of crop, and the present use of cropland (harvested area) by type of crop produced (in yellow). The differences between the land demand of each Food pattern and the present harvested land indicates whether the present production in Mexico can fulfil the food demand of each Food pattern for each food category. This figure shows that the present harvested cropland, for the three Food patterns, is not enough for the demand of sorghum, maize, and soybeans for vegetable oils, and other cereals for food. This is mainly driven by the large demand for feed (sorghum and maize) and soybeans for which the present supply mainly comes from imports. Note, that we assumed that all vegetable oil is produced from soybeans. For pulses and nuts, the present harvested area is smaller than the demand of Food patterns 2 and 3 but is enough for the demand of Food pattern 1. The reason is that presently the consumption of pulses and nuts is smaller than the recommendation for a healthy and sustainable diet.

In contrast, the harvested cropland of vegetables, fruits, sugars, and barley is larger than the demand of the three Food patterns. This is mainly driven by the large exports of vegetables, fruits, and beer (made from barley). For sugars, the exports are not that large, but this difference is driven mainly by the large present consumption of sugars which is higher than the recommendation.

3.3. Exploring changes in the food system for land reductions

Four scenarios for reducing the agricultural land demand were explored by increasing crop yields or/and reducing food losses in the food system (Table 2). These scenarios were compared with the present food system analysed in this study to discuss pathways for reducing agricultural land demand and reaching healthy and sustainable diets. The results are shown in Fig. 6.

The three Food patterns of all scenarios demand less land than the Food pattern 1 of the BAU scenario. Table 4 shows the ratios of the

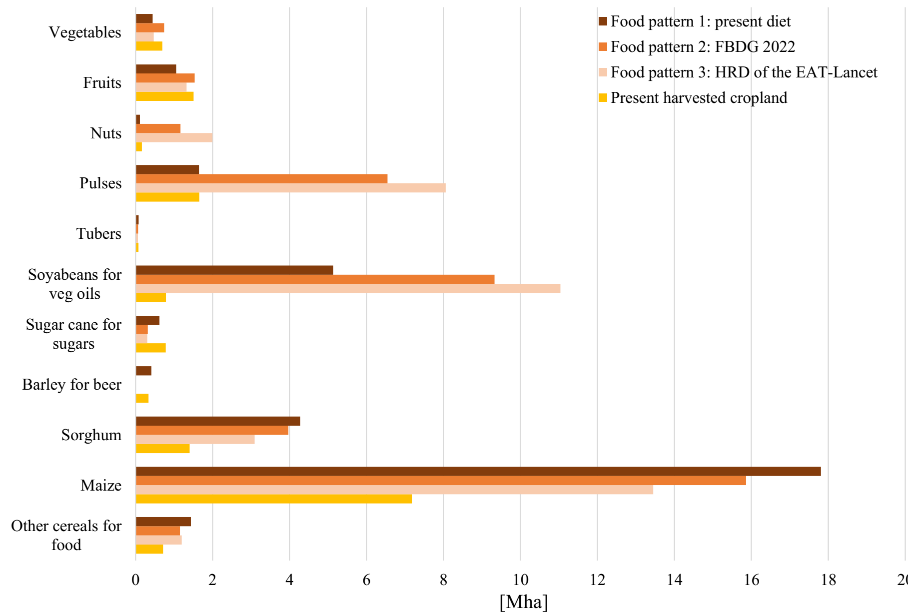

Fig. 5. Cropland requirements by type of crop and compared with the present harvested land for each crop. Data sources: use of cropland for each food category: Calculations by the authors; present harvested cropland from FAO (2022a) using the crop category of Table 1.

total demand of agricultural land for each scenario and Food patterns compared with Food pattern 1 of the BAU. This shows that the changes in the food patterns (horizontal differences in Table 4) have a stronger effect on land demand reduction than the technological changes assumed in this study (vertical differences in Table 4).

For all scenarios, except scenario 4 (reducing losses by 75 % and high crop yields increase), the cropland demand is higher than the present use of cropland. Though, considering the total agricultural demand (including pastures), for Food patterns 2 and 3 in all scenarios, the demand is much lower because of the low demand of pastures. This suggests that to produce enough food for a healthy and sustainable diet in Mexico land use changes are needed from pastures to crop land. Note that in all scenarios explored in Fig. 6, the cropland demand for food (excluding feed) is enough for Food patterns 2 and 3. Thus, the large demand of

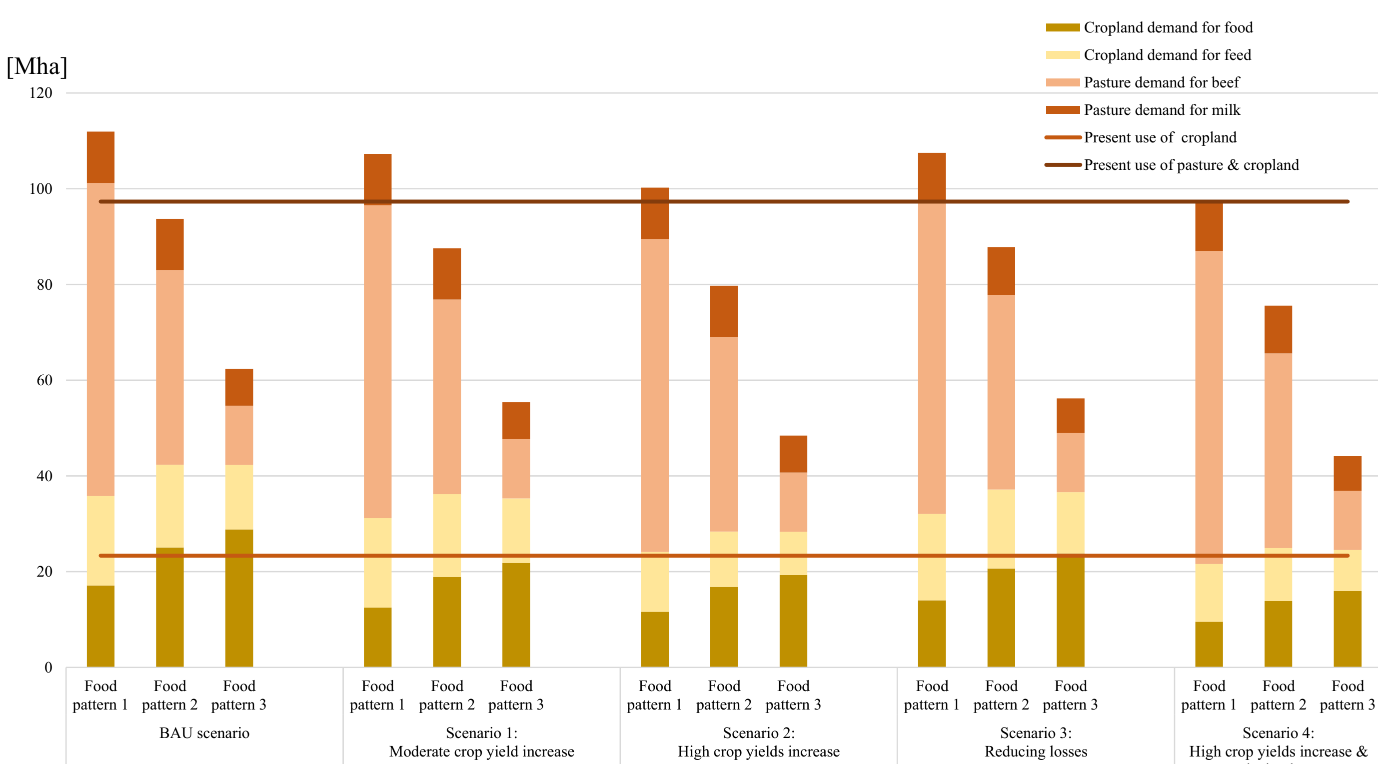

Fig. 6. Agricultural land demand and present use for four scenarios of technological changes in the food system to increase efficiency and to reduce land use. The agricultural land demand is shown in the bars, and the present agricultural land use is shown in the lines. See text for details.

Table 4
Share of total agricultural land demand for each scenario and Food pattern compared with Food pattern 1.
Source of data: calculations by the authors.

	Food pattern 1	Food pattern 2	Food pattern 3
BAU	1.00	0.84	0.56
Scenario 1	0.96	0.78	0.49
Scenario 2	0.90	0.71	0.43
Scenario 3	0.96	0.78	0.50
Scenario 4	0.87	0.68	0.39

agricultural land, even with changes in the food system (reducing losses and increasing crop yields), is to produce animal products in all dietary scenarios analysed in this paper.

Also, a large share of the present use of pastureland is not needed to reach healthy and sustainable diets. This is different for each scenario and each Food pattern explored in Fig. 6, see the difference between the bars and the top line. This amount is the one that can be converted into nature area or other uses, which is considering the changes of pastureland to cropland, to fulfil the demands of the four scenarios. For Food pattern 2, the pastureland that can be used for other land uses ranges from 4 Mha (BAU) to 22 Mha (scenario 4); and for Food pattern 3, it ranges from 35 Mha (BAU) to 53 Mha (scenario 4). This shows the large potential for agricultural land reductions by changing to healthy and sustainable diets, and by improving the Food System (increasing crop yields and reducing losses in the food chain).

4. Discussing the implications of our results

This study assessed the land demand for the present diet and two dietary recommendations for a healthy and sustainable diet, to assess whether Mexico has enough agricultural land to be able to be food self-sufficient. Then, some scenarios were explored for changing the food system to reduce land use. The results show that, in principle, Mexico has enough available agricultural land to produce healthy and sustainable diet for all people following either the new Food-Based Dietary Guidelines (FBDG) (SSA et al., 2022) or the EAT-Lancet HRD adapted for the Mexican context (Castellanos-Gutiérrez et al., 2021). However, the demand for cropland and pastureland must be considered separately. For pastureland, the demand for a healthy and sustainable diet is smaller than the present use of pastureland. For cropland is the opposite, the demand for cropland is larger than what presently is used. So, pastureland should be converted to cropland to supply the demand with the present food system (considering present crop yields and food losses). The demand of agricultural land by a healthy and sustainable diet can be very different depending on the type of dietary recommendation. We show that the FBDG demands 50 % more agricultural land than the EAT-Lancet HRD, but the FBDG demands 20 % lower amount of land than the present diet. The large difference is mainly driven by pastureland, mainly by the amount of beef in each diet. It is important for nutritional recommendations to try to reduce the recommendation of beef as much as possible and replace it with other protein-source products that are healthy and sustainable, to fulfil the nutritional requirements with lower land use and other environmental impacts.

In addition, the extension of agricultural land by the type of crop production needs to be changed from the present food system to produce the food for the healthy and sustainable diet. The main changes include producing more pulses and nuts, and less cereals (for feed) and sugar cane (to produce sugars). The high consumption of refined grains from cereals, and sugar used in processed food and sugary drinks such as sodas, is one of the main health problems in Mexico, contributing to obesity and chronic diseases (Rodríguez-Ramírez et al., 2022). In addition to agriculture changes, some of the present policies in the country to tackle obesity are focusing on strategies to reduce the consumption of sugary drinks (which indirectly can reduce the production of sugar cane). First, taxes on sugar beverages (Colchero et al., 2017) and high-energy density processed products (Batis et al., 2016) were implemented in 2014 (10 % of price). Second, a front of package warning labelling system was recently implemented for all processed products including sugary beverages (White and Barquera, 2022). Third, the ban of selling high energy processed products and sugary drinks in schools (Alianza por la salud alimentaria, 2022).

Furthermore, the consumption of stimulants and alcoholic beverages uses a relatively large extension of land, accounting for 4 % of the total cropland in our results. These items should be considered when discussing production potentials for food sovereignty or the modification of the food system, although the FBDG 2022 recommendation for alcoholic beverages is to avoid its consumption, and stimulants such as coffee and tea are not considered in the dietary recommendations.

Thus, the present program of the Mexican government (DOF, 2020) that focuses on reaching food sovereignty and improving nutrition of all people can be achieved if the agricultural changes mentioned above are done and ensuring that all people have a healthy and sustainable diet.

4.1. Trade-offs by land reduction

The amount of land for different food systems scenarios depends on the type of food consumed, the amount of food losses in the systems, and on the value of the crop yield to produce that food (Table 1). This opens possibilities for land savings which were explored: (a) modifying dietary patterns by changing to a low land-demand diet (such as the healthy and sustainable diet), (b) reducing food losses in the system, and (c) increasing crop yields of current food production. However, these changes have trade-offs for health, the economy, and the environment.

In terms of **health**, focusing on increasing the consumption of food products with low land demand can result in nutritional deficits. For example, sugars have low land demand but promoting its consumption is linked with increased risk of obesity, hypertension, and diabetes (Bray and Popkin, 2014; Malik and Hu, 2022). Therefore, the change in production should be to high crop yields that are also nutritionally adequate foods. For example, the production of legumes should be increased, though they generally have low crop yields. For this case, the strategy should focus on identifying the legume crops and production system with higher crop yields, and identifying the region which can reach the highest crop yields.

In terms of the **economy**, changes in the type of crop production (e.g. sugarcane to beans production) could mean reducing economic gains for farmers. Specially for cash crops such as sugar cane or others which are currently used for exports. For example, in 2021, the average national prices at the farm of sugarcane and beans were $850 MXN (approx. US$42) per ton and $15,900 MXN (approx. US$792) per ton respectively (SIAP, 2022). But the crop yields were 68 ton/ha for sugar cane and 0.77 ton/ha for beans (SIAP, 2022). Based on these values, a farmer gains approximately US$2900 per hectare of sugarcane production compared with US$600 per hectare of beans production (SIAP, 2022). Thus, the farmer that produces sugar cane gains 4.7 times more than the farmer that produces beans. Note, that these values do not include production costs. However, sugar cane is one of the most subsidised agricultural crops in the country, costing the government 16,000 MXN (857 USD) per individual farmer in 2017 (OECD, 2021). This subsidy could be reallocated to incentivise the production of more nutritionally adequate and lower environmental impact crops such as pulses (Springmann and Freund, 2022).

In terms of the **environment**, increasing crop yields can result in a higher use of other natural resources and environmental impacts. For example, a higher use of water, including groundwater depletion by using unsustainable irrigated systems (Dalin et al., 2017; Tuninetti et al., 2019), a higher use of energy e.g. including machinery, fertilisers and pesticides (Pimentel, 2009), and a higher emission of greenhouse gases (Poore and Nemecek, 2018). Therefore, the increase of crop yields should be done with a sustainable intensification of agriculture

(Godfray and Garnett, 2014; Rosa et al., 2018). These trade-offs for human and planetary health should be considered in further research.

4.2. Limitations of this study and the need for further research

This study shows a national analysis of average diets and average agricultural production systems (average crop yields). However, diets and crop yields vary largely throughout the population and the territory, respectively. Therefore, the changes in terms of diets and in production system might be different for each social group and each territory. The differences within the population and the territory should be considered in further research.

Whether the changes explored in this study (1: land use changes to produce other crops, 2: modifying present dietary patterns for a healthy and sustainable diet, and 3: reducing food losses or increasing crop yields) will take place depends on complex socio-economic conditions: are people willing to change diets? Can people afford these diets? Are farmers willing to change production practices? Are farmers able to change production practices, in terms of economic and physical access to technology? These socio-economic and policy issues are outside the scope of this paper and should be explored in further research.

However, the present projections indicate that dietary changes can go in the opposite direction than a "healthy and sustainable diet" if policy measures are not implemented. The projection for the coming years is that, in general, the Mexican population will have an increase in socioeconomic development. Castellanos-Gutiérrez et al. (2021) shows that the Mexican population with the highest income level has a "less sustainable diet" mainly because of a larger consumption of red meat. So, the increase in socioeconomic development of the Mexican population can lead to these food patterns. This can result in food patterns demanding more land than the present use of agricultural areas. Therefore, urgent actions are needed to explore avenues towards dietary changes for a more sustainable and healthy diet.

5. Conclusions

This study shows that Mexico has enough agricultural land to produce food for a healthy and sustainable diet for all its population, but changes in the food system are needed. First, changes in consumption patterns following the healthy and sustainable diet solve the strong nutritional problem of the present Mexican population and reduce pasture demand. Second, changes in the type of agricultural land use are needed such as pasture to cropland to produce foods which are presently lacking in the diet of the population in Mexico.

Authors' contributions

All authors conceptualize the study, participated in the writing and editing. Ibarrola-Rivas did the data analysis and coordinated the project.

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Declaration of competing interest

The authors state no conflict of interest.

Appendix 1. Values of "Food intake", "Food supply" and "Domestic supply" for the three scenarios analysed in this paper

The starting point of our calculations is the food intake of the three scenarios analysed in this study. Then, food wastes and underestimations of these values in the individual-dietary survey need to be estimated to calculate the food supply of the diets. Then, food losses and non-food uses need to be estimated along the food chain to estimate the domestic supply for each scenario. The domestic supply is the total amount needed to be produced in each scenario. Fig. 1 illustrates these steps. In this appendix, we describe the estimations of the food intake, the food supply, and the domestic supply. The food categories of the data sources for food intake used for this study are different for each of the three diets. Table A1 shows the values that we used. For Food pattern 1 (the present diet) the results of the National Health and Nutrition Survey of 2016 is used (ENSANUT, 2016b). For Food pattern 2, the Food-Based Dietary Guidelines 2022 is used (SSA et al., 2022), and for Food pattern 3, the Healthy and Sustainable Diet framework by the Eat-Lancet Commission adapted for the Mexican population is used (Castellanos-Gutiérrez et al., 2021). The two dietary references (Food pattern 2 and 3) group all cereals as "grains" category, and Food pattern 2 includes tubers in the grains category. Food pattern 3 groups pork and beef as "red meat", and Food pattern 2 groups vegetable oils and animal fats into one category. To compare the diets of the three Food patterns, we allocated the values of Food pattern 2 and 3 into the food categories of Food pattern 1 using the allocation of food items in the present diet for each grouping category. For instance, the total grains value of Food pattern 3 is divided into maize, wheat, rice and other cereals using the distribution of these cereals of the present diet. This allocation is shown in Table A1.

The Food intake (Table A1) does not consider food wastes of consumers, and it includes underestimations for specific food categories for different reasons (Guibrunet and Arnés, 2021). The food supply values include these underestimations and consumers food wastes. The consumers' food wastes and the underestimations can be estimated by comparing the values of the average Food intake reported by the National Survey of Health and Nutrition (ENSANUT, 2016b) with the food supply values of the Food Balance Sheets (FAO, 2022b). Table A2 shows a conversion factor calculated by dividing, for each food category, the per capita food supply of the FAO (2022b), shown in column 4 of Table A2, by the Food intake used in this study (column 3 of Table A1). For the categories with a conversion factor larger than 1, the values of Food intake are underestimated by the ENSANUT survey. For example, the Food intake of maize is underestimated 2.4 times compared with the available food supply of the country. In contrast, wheat and beef meat is overestimated by 25 % and 19 % respectively. In short, the food intake compared with the food supply is underestimated for maize, rice, other cereals, pulses, fruits, vegetable oils, sugars, alcoholic beverages, pork, poultry, eggs, fish, and animal fats. In contrast, the food intake is overestimated for wheat, stimulants, vegetables, beef, and other meats. The reasons for the underestimations and overestimations might be different for each food category (e.g. not reported in the survey, large food wastes at home, consumption outside home) which have been reported in other studies around the world (Del Gobo et al. 2015). The reasons for the overestimations and underestimations should be studied in further research.

To calculate the amount of food needed to be produced (in tonnes), we need to convert the Food supply values from calories to grams. To do this, a conversion factor of "calories per 100-gr" is used to convert the values from calories to grams. This conversion factor is calculated using the per capita food supply values in kilograms (kg/cap/yr) and in calories (kcal/cap/day) for Mexico during the period 2015–2019 given by the Food Balance Sheets (FAO, 2022b). This conversion factor is shown in Table A3 indicating the food items used to calculate it. These values are used to convert the Food

supply values (Table A2) from calories to grams. In this way, we use specific conversion factors for the type of food supply consumed in Mexico in this study period.
The Food supply (Table A2) does not consider losses throughout the food chain (from harvest to consumers) and non-food items (seeds for the next harvest and non-food items like cosmetics). The Food Balance Sheets of the FAO (2022b) reports these amounts for each food item. We have added these values for each food category to estimate the "Domestic Supply" for each scenario. To do this, we calculated the share of these components (Losses, Seeds and Non-Food) compared to the Food Supply component for Mexico in the period 2015–2019 (FBS). This is shown in column 3 of Table A3. Then, we use this value to calculate the domestic supply for each scenario and each food category using the Food Supply amount of Table A2. Finally, these values are multiplied by the Mexican population to have the total values of the domestic supply in million tonnes. The Mexican population is 124,747,000 people, which is the average value in the period 2015–2019 given by the United Nations (2022).

Table A1
Food intake for the three Food patterns. Values in kcal/cap/day.

Data sources: [1]National Health and Nutrition Survey of 2016 (ENSANUT, 2016b), [2]Food-Based Dietary Guidelines 2022 (SSA et al., 2022), [3]Castellanos-Gutiérrez et al. (2021), [4]Calculations by the authors. *Mutton & goat is added to "other meats".

Type of production	Food categories[1]	Food pattern 1: present diet[1]	Food pattern 2: FBDG 2022		Food pattern 3: HRD of the EAT-Lancet	
			Original data[2]	Data used in this paper[4]	Original data[3]	Data used in this paper[4]
Crops	Maize	419	639	336	640	349
	Wheat	310	(Grains)	249	(Grains)	259
	Rice	36		29		30
	Other cereals	2		2		2
	Tubers	27		22	20	20
	Pulses	51	203	203	250	250
	Nuts	7	73	73	125	125
	Stimulants	21	–	–	–	–
	Fruits	80	116	116	100	100
	Vegetables	61	103	103	65	65
Processed food	Vegetable oils	116	247 (Veg. oils & animal fats)	211	250	250
	Sugars	195	100	100	95	95
	Alcohol	23	–	–	–	–
Animal products	Beef	61	38	36	28	12
	Pork	87	32	36	(red meat)	16
	Poultry	70	90	90	80	80
	Other meats	11*	–	–	–	–
	Milk	167	166	166	120	120
	Eggs	48	56	56	50	50
	Fish & crustaceous	10	20	20	30	30
	Animal fats	20	–	36	25	3
	Total	1823	1882		1878	

Table A2
Food supply for the three food patterns. Values in kcal/cap/day.

Data sources: * food supply reported in the Food Balance Sheets of the FAO average values in the period 2015–2019 (FAO, 2022b); ** calculations by the authors.

Type of production	Food categories[1]	Conversion factor** $\left[\frac{\text{Food supply}}{\text{Food intake}}\right]$	Food supply [kcal/cap/day]		
			Food pattern 1: present diet*	Food pattern 2: FBDG 2022**	Food pattern 3: HRD of the EAT-Lancet**
Crops	Maize	2.40	1005	807	837
	Wheat	0.75	231	186	193
	Rice	1.63	59	48	50
	Other cereals	7.54	17	14	15
	Tubers	1.16	31	25	23
	Pulses	1.90	97	386	475
	Nuts	1.86	13	135	232
	Stimulants	0.58	12	0	0
	Fruits	1.40	112	163	140
	Vegetables	0.78	48	80	51
Processed food	Vegetable oils	2.55	297	538	637
	Sugars	2.36	460	236	224
	Alcohol	3.04	69	0	0
Animal products	Beef	0.81	49	31	9
	Pork	1.83	159	58	30
	Poultry	1.83	128	165	146
	Other meats	0.65	2	0	0
	Milk	0.98	164	163	118
	Eggs	1.50	72	84	75
	Fish & crustaceous	2.91	29	58	87
	Animal fats	3.08	61	110	77
	Total	–	3117	3287	3420

Table A3
Conversion of calories to 100 g for the diets.

Source of data: calculations by the authors using FAO (2022b). These values were calculated with the per capita food supply values of calories and grams for Mexico in the period 2015–2019 using the food items.

Food category for this study	Food items from the Food Balance Sheets (FAO, 2022b)	Calories (per 100 g)
Maize	Maize and products	309
Wheat	Wheat and products	264
Rice	Rice and products	255
Other cereals	Rye and products; oats; millet and products; cereals, other	680
Tubers	Cassava and products; potatoes and products; sweet potatoes; roots, other	68
Pulses	Beans; peas; pulses, other and products	348
Nuts	Nuts and products	331
Stimulants	Coffee and products; cocoa beans and products; tea (including mate); pepper; pimento; cloves; spices, other	254
Fruits	Oranges, mandarins; lemons, limes and products; grapefruit and products; citrus, other; bananas; plantains; apples and products; pineapples and products; dates; grapes and products (excl. wine); fruits, other	36
Vegetables	Tomatoes and products; onions; vegetables, other	26
Vegetable oils	Soya bean oil; groundnut oil; sunflower seed oil; rape and mustard oil; cottonseed oil; palm kernel oil; palm oil; coconut oil; sesame seed oil; olive oil; maize germ oil; oil crops oil, other Butter, ghee; fats, animal, raw	1042
Sugars	Sugar non-centrifugal; sugar (raw equivalent); sweeteners, other; honey	351
Alcohol	Wine; beer; beverages, fermented; beverages, alcoholic; alcohol, non-food	41
Beef	Bovine meat	120
Mutton & Goat	Mutton & goat meat	201
Pork	Pig meat	333
Poultry	Poultry meat	138
Other meats	Meat, Other	116
Milk	Milk - excluding butter; cream	65
Eggs	Eggs	132
Fish & crustaceous	Freshwater fish; demersal fish; pelagic fish; marine fish, other; crustaceans; cephalopods; molluscs, other; aquatic animals, others	71
Animal fats	Fats, animals, raw; butter, ghee	898

Table A4
Domestic supply for the three food patterns. Values in million tonnes.

Data sources: * food supply reported in the Food Balance Sheets of the FAO average values in the period 2015–2019 (FAO, 2022b); ** calculations by the authors.

Type of production	Food categories[1]	Share of losses, seeds, non-food from food** $\left[\frac{Losses+Seeds+Non\ foods}{Food\ supply}\right]$	Domestic supply [million tonnes]		
			Food pattern 1: present diet*	Food pattern 2: FBDG 2022**	Food pattern 3: HRD of the EAT-Lancet**
Crops	Maize	0.36	20.15	16.18	16.80
	Wheat	0.60	6.39	5.13	5.33
	Rice	0.04	1.10	0.89	0.92
	Other cereals	0.09	0.13	0.10	0.11
	Tubers	0.10	2.30	1.85	1.72
	Pulses	0.12	1.42	5.64	6.95
	Nuts	0.08	0.19	2.02	3.46
	Stimulants	0.08	0.24	0.00	0.00
	Fruits	0.12	15.99	23.25	20.05
	Vegetables	0.15	9.73	16.31	10.30
Processed food	Vegetable oils	0.54	2.00	3.63	4.29
	Sugars	0.08	6.46	3.30	3.14
	Alcohol	0.04	8.12	0.00	0.00
Animal products	Beef	0.00	1.86	1.16	0.35
	Pork	0.00	2.17	0.80	0.41
	Poultry	0.00	4.22	5.42	4.82
	Other meats	0.00	0.08	0.00	0.00
	Milk	0.09	12.49	12.43	8.98
	Eggs	0.15	2.85	3.34	2.98
	Fish & crustaceous	0.00	1.86	3.74	5.60
	Animal fats	0.60	0.49	0.89	0.63
	Total	–	100.25	106.08	96.82

Appendix 2. Type and amount of feed required to produce animal products

1. Feed required for animal products production

The amount of feed required to produce a kilogram of beef, pork, and poultry is estimated by dividing the total amount of feed consumed by the animal during its lifetime (second column Table A5) by the final amount of food product per animal (column 5 Table A5). The final weight of food product per animal (5th column) is the final live weight of the animal when slaughtered multiplied by the dressing factor. For milk and eggs, the feed requirements to produce one kilogram of food is estimated by dividing the total amount of feed consumed per animal per day by the daily productivity of the animal. For animal fats, the values of pork were used because most animal fats are pork-based. For fish, the average values of feed required (kg-feed/kg-food) of pork, poultry, eggs and milk were used. Beef was not included because its value is much larger than the rest of the animal products.

Table A5
Variables to calculate the amount of feed required to produce one kilogram of animal product.

Data source: Ibarrola-Rivas and Nonhebel (2019).

Type of animal product	Amount of feed during lifetime [kg-feed/animal]	Live weight of animal when slaughtered [kg/animal]	Dressing factor	Final weight of food product [kg-food/animal]	FEED required [kg-feed/kg-food]
Beef	2836.0	539.0	0.39	210.0	13.5
Pork	368.0	88.0	0.90	79.0	4.6
Poultry	4.5	2.3	0.77	1.7	2.5
	Amount of feed per day [kg-feed/animal]	Daily productivity [kg-food/animal/day]			FEED required [kg-feed/kg-food]
Milk	7.40	6.70			1.1
Eggs	0.16	0.07			2.3
Fish	Average of the values for: pork, poultry, milk and eggs				2.6

The type of feed varies among countries and among type of livestock animals. In this study, we assume that all animals consume the same mixture of feed. This mixture is calculated based on the average supply of feed for Mexico reported by the FAO (2022b) during the period 2015–2019. The total amount of feed and its share is shown in Table A6. These amounts account to 96 % of the total feed supply of the country during that period.

Table A6
Feed products used in Mexico. These values account to 96 % of the total feed supply in Mexico in the period 2015–2019.

Data source: feed category of "domestic supply" in Mexico Food Balance Sheets (FAO, 2022b).

Food category	Total supply used for feed [Mt]	Share of total feed
Maize and products	16.9	65 %
Sorghum and products	5.0	19 %
Sugar cane	2.9	11 %
Soybeans	0.9	5 %

2. Crops required for crops processing

In this study, we considered three food categories as "processed foods" which are vegetable oils, sugars, and alcoholic beverages. To estimate the amount of "input crops" (Fig. 1) needed to produce a kilogram of these processed crops, we calculated a conversion factor (Table A7). The FBS reports, for each food item, the supply that is used for "Processing", and the "national production" of each food item. The conversion factor is calculated by dividing the "processing" supply of the "input crop" by the "national production" of the "processed food item".

For each food category, we selected the input crop and the processed food item that is the largest produced and supplied for processing in Mexico during the period 2015–2019. For vegetable oils, soybean is selected as input crop and soybeans oil as the processed food item. For sugars, sugar cane is selected as input crop and "sugars (raw equivalent)" and "sweeteners, other" are selected as processed food items. For alcoholic beverages, barley is used as input crop and beer is used as the processed food item. Table A7 shows the values of the supply and production of input crops and processed food items respectively, and the conversion factor calculated with those values.

Table A7
Conversion factors: crops to processed foods. The values show the domestic supply of crop inputs (processing category of the FAO) and the production of the processed foods in Mexico in the period 2015–2019.

Data source: Food Balance Sheets (FAO, 2022b).

Food category	Input crop and supply for "processing" [Mtones]		Processed food item and "national production" [Mt]		Conversion factor [kg-crop/kg-processed-food]
Vegetable oils	Soybeans	3.2	Soybean oil	0.7	4.3
Sugars	Sugar cane	52.5	Sugar (raw equivalent) & sweeteners, other	7.5	7.0
Alcoholic beverages	Barley	1.6	Beer	11.1	0.14

Appendix 3. Demand of feed

Table A9
Total demand of feed per type of crop required to produce the total amount of each animal product for each scenario. Values in million tonnes.

Animal product category	Feed crop	Scenario 1: present diet	Scenario 2: FBDG 2022	Scenario 3: HRD of the EAT-Lancet
Beef	Maize	16.43	10.21	3.11
Beef	Sorghum	4.86	3.02	0.92
Beef	Sugar cane	2.85	1.77	0.54
Beef	Soybeans	0.96	0.60	0.18
Pork	Maize	6.59	2.43	1.25
Pork	Sorghum	1.95	0.72	0.37
Pork	Sugar cane	1.14	0.42	0.22
Pork	Soybeans	0.39	0.14	0.07
Poultry	Maize	7.02	9.01	8.01
Poultry	Sorghum	2.08	2.67	2.37

Table A9 (*continued*)

Animal product category	Feed crop	Scenario 1: present diet	Scenario 2: FBDG 2022	Scenario 3: HRD of the EAT-Lancet
Poultry	Sugar cane	1.22	1.56	1.39
Poultry	Soybeans	0.41	0.53	0.47
Other meats	Maize	0.26	0.00	0.00
Other meats	Sorghum	0.08	0.00	0.00
Other meats	Sugar cane	0.04	0.00	0.00
Other meats	Soybeans	0.02	0.00	0.00
Milk	Maize	9.03	8.98	6.49
Milk	Sorghum	2.67	2.66	1.92
Milk	Sugar cane	1.57	1.56	1.13
Milk	Soybeans	0.53	0.53	0.38
Eggs	Maize	4.27	4.99	4.46
Eggs	Sorghum	1.26	1.48	1.32
Eggs	Sugar cane	0.74	0.87	0.77
Eggs	Soybeans	0.25	0.29	0.26
Fish & crustaceous	Maize	3.22	6.47	9.70
Fish & crustaceous	Sorghum	0.95	1.91	2.87
Fish & crustaceous	Sugar cane	0.56	1.12	1.68
Fish & crustaceous	Soybeans	0.19	0.38	0.57
Animal fats	Maize	1.50	2.72	1.90
Animal fats	Sorghum	0.44	0.80	0.56
Animal fats	Sugar cane	0.26	0.47	0.33
Animal fats	Soybeans	0.09	0.16	0.11

Appendix 4. Exploring changes in the food system to reduce agricultural land use demand

Scenarios 1, 2 and 4 assume an increase in crop yields. Scenario 1 assumes a moderate increase in crop yields using the projections of FAO for Latin America (2018, Table 4.9). These assumptions are shown in the second column of Table A10. Therefore, the crop yields for scenario 1 calculated by multiplying the present crop yields (Table 1) by this increase. The crop yields values of scenario 1 are shown in the 3th column of Table A10. Scenario 2 and 4 assumes a high crop yield increase by 50 % for all crops, except sugar cane which has already a high crop yield. The crop yields for these 2 scenarios are shown in the 4th column of Table A10.

Table A10
Crop yields values for scenarios 1, 2 and 4.

Source of data: [(a)] Values for "all crops" from FAO (2018, Table 4.9); [(b)] Values for each type of crop from FAO (2018, Table 4.9); [(c)] Calculations by the authors multiplying the crop yields values of Table 1 by column 2 of this table; [(d)] Calculations by the authors assuming an increase by 50 % for all crops except sugar cane based on the values of Table 1.

	Scenario 1		Scenarios 2 & 4
	FAO's projection increase by 2050	Crop yield (ton/ha)[(c)]	Crop yield (ton/ha)[(d)]
Wheat	1.25[(a)]	6.7	8.1
Rice, paddy	1.25[(a)]	7.8	9.4
Maize	1.65[(b)]	6.3	5.8
Barley	1.25[(a)]	3.6	4.3
Sorghum	1.25[(a)]	4.2	5.0
Cereals nes	1.25[(a)]	2.1	2.6
Roots and tubers, total	1.25[(a)]	36.4	43.7
Fruit primary	1.30[(b)]	19.7	22.7
Vegetables primary	1.32[(b)]	28.9	32.9
Tree nuts, total	1.25[(a)]	2.2	2.6
Pulses, total	1.25[(a)]	1.1	1.3
Sugar cane	1.20[(b)]	87.0	72.5
Soybeans	1.30[(b)]	2.2	2.5
coffee, green	1.25[(a)]	0.3	0.4

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