Title
How dietary transition changed land use in Mexico

Journal
Ambio, 49(10)

ISSN
0044-7447

Authors
Tello, José
Garcillán, Pedro P
Ezcurra, Exequiel

Publication Date
2020-10-01

DOI
10.1007/s13280-020-01317-9

Peer reviewed

Ambio 2020, 49:1676–1684
https://doi.org/10.1007/s13280-020-01317-9

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

RESEARCH ARTICLE

How dietary transition changed land use in Mexico

José Tello, Pedro P. Garcillán, Exequiel Ezcurra

Received: 13 March 2019 / Revised: 28 August 2019 / Accepted: 3 January 2020 / Published online: 28 January 2020

Abstract The nutrition transition towards western diets in developing countries occurs at multiple levels, impacting health and society and also the environment. In Mexico, the shift in food consumption and production patterns, particularly in relation to animal source foods (ASF), has changed land use. We studied the consumption and production of ASF and change in agricultural land use in Mexico during the second half of the twentieth century and until 2013; using domestic and international data sources, our findings show an increasing proportion of farmed area devoted to the production of feed crops domestically, and also an increasing demand of farmed feed beyond national borders. We discuss how the intensification of livestock production is associated to major environmental threats and suggest that opportunities are available for sustainable and healthy food options.

Keywords Environmental impacts of agriculture · Food system · Land-use change · Livestock production · Nutrition transition · Sustainability

INTRODUCTION

Until the mid-twentieth century, the bulk of Mexican diet was largely based on corn, beans, and chilies grown under traditional farming methods. Corn-field weeds were harvested and consumed as greens, and the plots were intercropped with beans, tomatoes, green tomatillos, and squashes, among many other species. Corn grains were treated with lime before being ground into dough in a process that increased the amount of nutritional calcium and niacin. Avocados and cacao, together with a diversity of fruits both from perennial trees and annual crops, complemented this diet. Mexico is proud of its traditional diet and has successfully nominated Mexican cuisine to be inscribed on UNESCO's List of the Intangible Cultural Heritage of Humanity. Among other elements, the World Heritage Committee's nominating document underscored the importance of traditional cuisine as a means of sustainable development (UNESCO 2010).

Despite the scientific and cultural interest of the traditional Mexican diet, the reality is that everyday food consumption in Mexico has changed drastically during the second half of the twentieth century and continues changing today. Consumption of industrialized foods with added sugars and high in saturated fats together with food from animal sources has increased substantially, while that of plant-based dietary fiber has decreased. This transition towards more westernized diets (Popkin 1997) is driven by multiple variables such as food availability and supply, time needed to purchase and cook food, or affordability (Popkin and Gordon-Larsen 2004). In Mexico, Colchero et al. (2019) found that energy-dense, industrialized foods with lower nutrient quality were economically more accessible than healthier foods such as fresh produce, especially for lower-income population. Researchers in Mexico have been monitoring this transition because of concerns of the impact of the dietary change on public health. Flores et al. (2010), for example, reported that the

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s13280-020-01317-9) contains supplementary material, which is available to authorized users.

emerging new dietary patterns significantly increased the risk of being overweight or obese compared with traditional Mexican diets. Similar findings have been reported in other world regions (Popkin and Gordon-Larsen 2004; Rivera et al. 2014). According to the World Health Organization, obesity in Mexico increased from 9.5 to 29% between 1975 and 2016. The rising costs of the increase in diet-related diseases have triggered alarm: The incidence of diabetes increased from 6.7% in 1994 to 15.9% in 2015 (the highest in OECD countries), and is costing the Mexican health system 1.2 thousand million US dollars every year (Barquera et al. 2013).

In 1960, México was ranked as the 16th most populated country in the world and today it occupies the tenth place (World Bank 2018). Between 1961 and 2013, the human population increased from 32.4 to 116.6 million, a 260% increase at a mean annual mean rate of 2.5%. The urban population increased from 48% of the national population in 1961 to 78% in 2013, at a rate of 3.4% (INEGI 2017). In the same period, per capita income increased 148% at a mean annual rate of 1.7%, from 3751 to 9318 US dollars (World Bank 2018).

All these changes, especially rising consumption and shifting consumption patterns by the growing urban middle class, are occurring rapidly in emerging economies (Delgado 2003; Sans and Combris 2015). Consumer decisions responsible for nutrition changes are driven by social and demographic factors, and not only by economic forces (Drewnowski and Poulain 2018; Pingali et al. 2019). The consequences of nutrition changes are complex and impact social, economic, and natural systems. Indeed, agriculture and food production in general, and livestock production in particular, are major drivers of transformation in natural ecosystems (Turner et al. 1994; Vitousek et al. 1997) and impose pressures on ecological services (Herrero and Thornton 2013; Eshel et al. 2014).

The role of sugar-sweetened beverages in the nutrition transition in Mexico and its health consequences has been widely analyzed (Aburto et al. 2016; Sánchez-Pimienta et al. 2016), but the role of animal source foods (ASF) consumption and especially its ecological effects has been less explored. Some studies have examined aspects of this relationship (Barkin 1981; Galvan-Miyoshi et al. 2015; Narchi et al. 2015; Ibarrola-Rivas and Granados-Ramirez 2017), but none have analyzed it through the entire period in which it has occurred.

The research question we intend to answer is how land use has been impacted by the growing consumption of ASF in Mexico. Additionally, we will explore and discuss the key environmental impacts linked to this land-use change. Our aim was to analyze the relationship between the temporal dynamics of consumption of livestock products as a result of the nutrition transition in the late twentieth century and its effects on land-use change due to demand of feed crops.

MATERIALS AND METHODS

The time scope of our study is the 1961–2013 period, with the exception of two variables where we analyzed a different period: (1) harvested area (1950–2013), to show an extended tendency of agricultural land use in the twentieth century; and (2) pesticides (1990–2013), because data are available only since 1990. We built time series of the variables of interest by merging data from different official sources, and when necessary interpolating information gaps. When available, we compared different data sources to verify the reliability of the data.

Human population and consumption of livestock products

We used decadal population censuses (1960 to 2010) and surveys (1995, 2005 and 2015; INEGI 2017) to integrate the annual series of the human population of Mexico between 1961 and 2013. We estimated data for inter-census years assuming a continuous population growth (Appendix S1).

We used annual data of production, imports, and exports of animal products for human consumption (i.e., animal protein such as beef, pork, and poultry, as well as milk and eggs) between 1961 and 2013 from FAOSTAT (FAO 2017) to build annual series of total consumption (production plus imports minus exports), and per capita consumption of livestock products. Finally, based on FAOSTAT balance sheets (FAO 2017) we estimated the time series of animal product participation on the total energy intake and protein supply in the Mexican population.

Feed crops

Consumption. Following official Mexican statistics (SAGARPA 2016) we considered three types of feed crops (i.e., crops destined for animal consumption): (a) grains and oilseeds, (b) dry fodder (alfalfa, oats and barley hay), and (c) other cultivated grasses. We used annual data of livestock consumption of grains (sorghum, oats, barley, and wheat) and oilseeds (including byproducts of soybean, copra, cottonseed, peanut, rapeseed, and sunflower seed) from USDA (2017). Because dry fodder and grass-hay is not imported, national production was taken as an accurate estimate of consumption. In the case of maize, we compiled data from different sources to estimate consumption and production (Appendixes S2 and S3).

Production. We used data for sorghum from USDA (2017), wheat from SAGARPA (2016), and soybeans from FAO (2017).

Imports. We calculated feed crops imports as total consumption minus total production.

Exports. Mexican feed exports are very low or inexistent, and statistics are not available for all commodities and byproducts, so we did not integrate them into our database.

Harvested area

For 1950–1960, we used published data of total harvested area and feed crop area from Barkin (1981), and based on these data we estimated the harvested area of food crops. For 1961–2013, we compiled data from FAO (2017) and SAGARPA (2016) to estimate total harvested area in Mexico. We selected the main feed crops cultivated in Mexico (sorghum, maize, and soybeans; alfalfa, oats and barley fodder; and cultivated grasses). We used available data of annual harvested land of sorghum (FAO 2017), soybean (FAO 2017), and assembled different sources to elaborate time series of harvested land of maize; alfalfa, oats and barley fodder; and cultivated grasses. Based on total harvested and feed crops area, we estimated the harvested area devoted to food crops (see SEM for references and details).

Agricultural inputs and yields, and cattle extraction

The time series of nitrogen fertilizers includes data available in FAO (2017) for 1961–2001. We estimated data for 2002–2013 based on Tilman et al. (2001) (Appendix S5). We use data from FAO (2017) for area under irrigation and treated with pesticides. We estimated yields of maize, sorghum, soybeans, and alfalfa by dividing total production (tons) by total harvested area (ha) of each crop. Finally, we estimated the proportion of cattle slaughtered annually relative to the size of the national herd. For all these variables, we estimated the mean annual growth rates.

RESULTS

Mean per capita consumption of ASF, i.e., the five main types of livestock products combined (beef, pork, poultry, eggs, and milk), increased 73% between 1961 and 2013, from 104.8 to 181.4 kg year^{-1}. The main increment occurred in the consumption of poultry (658%), which grew from 4.2 to 31.6 kg year^{-1}, followed by eggs (396%), from 4.4 to 21.6 kg year^{-1}, beef (53%), from 10.5 to 16.1 kg year^{-1}, and pork (23%), from 13 to 16 kg year^{-1} (FAO 2017; see Fig. 1c, d). Finally, per capita milk consumption increased 31%, from 71.8 to 94.3 L year^{-1}.

Mean energy intake in Mexico increased 32% during the study period, from 2279 to 3023 kcal person^{-1} day^{-1}, and the proportion of this intake from animal sources grew from 11.6 to 19.3%. Similarly, total protein supply increased 34%, from 61 to 82 g capita^{-1} day^{-1}, and the animal participation in protein supply increased from 23.6 to 42.8% of the total diet.

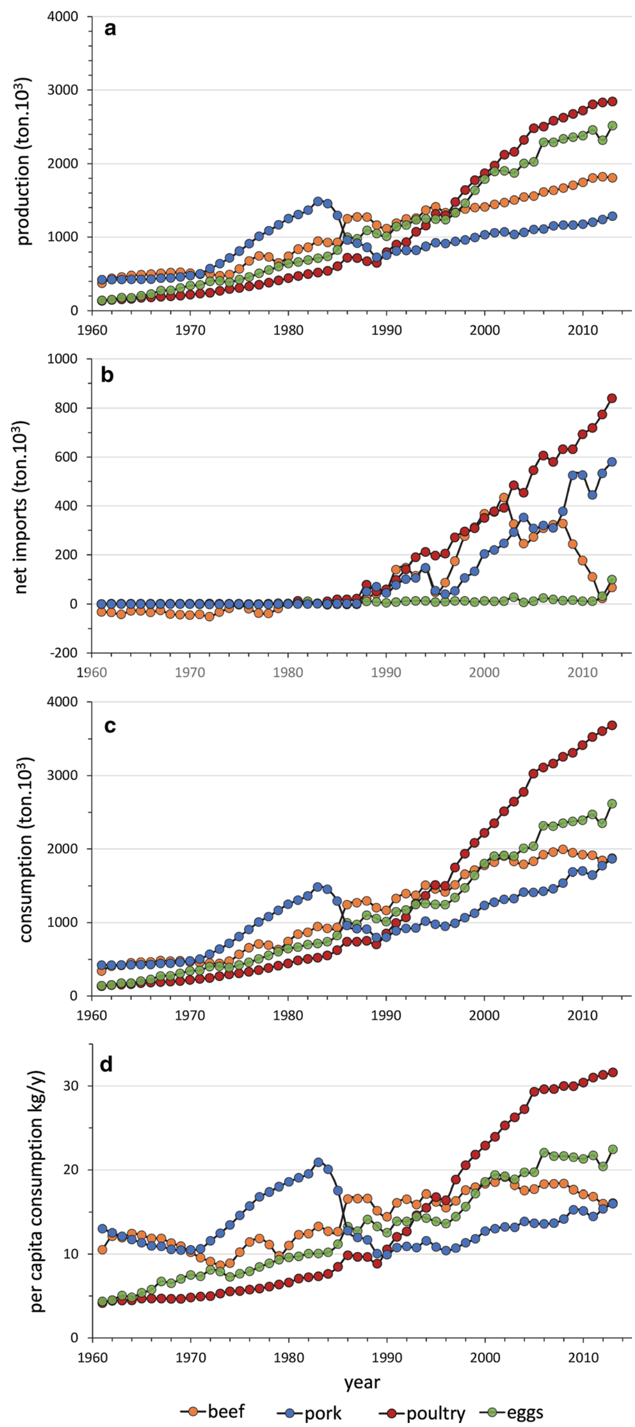

Fig. 1 Consumption of animal products (beef, pork, poultry, and eggs) in Mexico during the period 1961–2013. **a** Domestic production, **b** net imports (imports–exports), **c** total consumption (production + net imports), **d** per capita consumption

Total national production of poultry meat increased 2008% (from 0.14 to 2.8 million tons), eggs 1684% (from 141 to 2.5 million tons), beef 385% (from 0.37 to 1.8 million tons) , milk 371% (from 2.3 to 11 million tons), and pork 204% (from 0.42 to 1.3 million tons) (Fig. 1a). Pork imports increased sevenfold and poultry threefold between 1990 and 2103. Beef imports increased until 2001 and since then, they have been decreasing continuously (Fig. 1b). Nearly all consumed eggs and milk have been produced domestically.

In order to sustain this increase in per capita consumption while the Mexican population was also increasing at a 2.5% annual rate, the production of livestock products had to increase much faster than the population. National production has not been sufficient to meet demand and since the end of the 1980s meat imports (all types) have also increased, representing 24% of total consumed meat in 2013. Poultry production and consumption (including eggs), increased much faster than total population. The increase in beef production was less pronounced but still higher than population growth, while pork production increased at around the same rate as the population (Table 1).

Consumption of commodities and products to feed animals (cultivated grasses, fodder, grains and oilseeds, and byproducts) rose 2157% between 1961 and 2013, from 5.3 to 119.3 million tons, at a mean annual rate of 6%. The bulk of consumption is integrated by fresh biomass of cultivated fodder, which is produced domestically almost entirely. Cultivated grasses increased from 0.02 to 49.3 million tons and fodder (mainly alfalfa) from 4.2 to 42.8 million tons, at annuals mean rates of 14.7 and 4.5%, respectively.

Consumption of feed grains, oilseeds, and byproducts increased 2533% between 1961 and 2013, from one to 27 million tons, at an annual mean rate of 6.3%. Feed grains and oilseeds where mainly produced domestically during the 1960s but imports started increasing rapidly since the 1970s. In the 1980s imports of feed grains and oilseeds represented already 49% of total consumption and since 1992 the proportion of imports has settled around 60%. In 2013, most (90%) of total feed imports was made up of three commodities: corn (50%), soybeans (29%), and sorghum (11%; Fig. 2b).

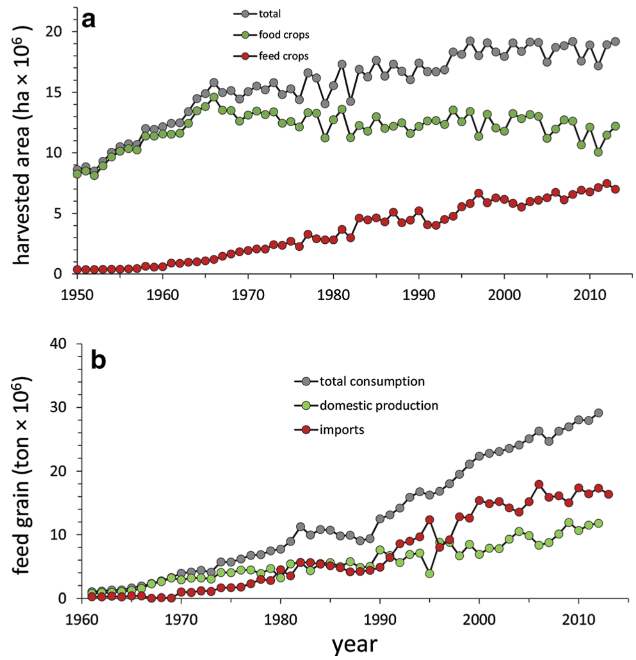

Fig. 2 Territorial expansion of the agricultural frontier in Mexico: **a** The development of technological intensification in the 1960s stopped the expansion of areas harvested for human consumption (green points), while the expansion of areas farmed for the production of feed (red points) continued at a mean rate of 3.9% (se ± 0.3). **b** The total consumption of feed in the country (gray points) has been increasing steadily since 1960 at a mean rate of 7.0% (se ± 0.2). This increase, however, has been supported mostly by imports, which have grown at a rate of 9.2% (se ± 0.6), twice as fast as the increase in domestic production, which was 4.2% (se ± 0.3) for the same period

Agricultural inputs and yields increased during the period of analysis (Table 2). Total area equipped for irrigation increased from 3 to 6.5 million ha and total use of synthetic nitrogen fertilizers increased sevenfold from a mean of 11.0 to 93.1 kg ha^{-1} (Tilman et al. 2001; FAO 2017). The use of pesticides rose between 1990 and 2013, from 2.0 to 3.6 kg ha^{-1} (FAO 2017). The mean yield of two of the three main feed grains increased continuously during the last half-century: maize (0.9 to 3.0 tons ha^{-1}) and sorghum (1.8 to 3.8 tons ha^{-1}). The third feed grain yield, soybeans, decreased from 2.0 to 1.5 tons ha^{-1}. The

Table 1 Mean annual growth rates (% value ± s.e.) in animal products (meat + eggs) during the 1961–2013 period in Mexico. Production refers to domestic production, consumption is domestic production + net imports, and per capita consumption is consumption divided by the national population size for the same year

	Beef	Poultry	Pork	Eggs
Production	3.10 ± 0.11	6.45 ± 0.08	1.86 ± 0.24	5.43 ± 0.13
Consumption	3.65 ± 0.13	7.00 ± 0.09	2.56 ± 0.21	5.46 ± 0.13
Per capita consumption	1.27 ± 0.11	4.61 ± 0.12	0.18 ± 0.18	3.07 ± 0.07

Table 2 Mean annual growth rates in agricultural inputs and yields in Mexico during the 1961–2013, except for pesticides (1990–2013). Inputs refer to (1) the ratio area equipped for irrigation/total harvested area (ha); (2) the ratio nitrogenous fertilizers used per harvested area (kg/ha); and the ratio pesticides used per harvested ha (kg/ha). Yields refer to tons produced per harvested ha per crop. Cattle extraction represents the ratio slaughtered animals/national cattle stock

Inputs	Mean annual growth rates (%)
Land equipped for irrigation/total harvested area	0.65
Nitrogen fertilizers (kg/harvested ha)	4.10
Pesticides (kg/harvested ha)	2.46
Yields (tons produced/ha of harvested area)	
Maize	2.44
Sorghum	1.41
Soybeans	− 0.51
Alfalfa	2.00
Cattle extraction	
Slaughtered cattle/stock heads	1.32

yield of alfalfa, the main forage for dairy cattle, increased from 28.9 to 80.7 tons ha^{-1} of fresh forage (equivalent to approximately 8 to 23 tons ha^{-1} of dry biomass; Rojas-García et al. 2017; Table 2). Finally, the number of slaughtered cattle increased almost tenfold from 0.9 million heads butchered in 1955 to 8.8 million in 2013 (3.2% annual growth rate). The national herd, however, did not increase so rapidly, shifting from 14.8 million heads in 1955 to 32.4 million in 2013 (1.4% annual growth rate). This shows that the proportion of cattle slaughtered annually relative to the size of the national herd (a ratio that measures the efficiency in the production system) increased threefold from 9 to 27% between 1955 and 2013.

One of the best indicators of the impact of the dietary transition on Mexican agriculture is the proportion of farmed area devoted to the production of food for direct human consumption (food crops) relative to the area devoted to the cultivation of feed crops: The area devoted to the cultivation of food crops expanded during the mid-twentieth century, from 8.2 million ha in 1950 to 14.6 million ha in 1966 (an increase of 77%). After 1966, however, the area under food crop cultivation stabilized and gradually decreased to the current value of 12.2 million ha. Feed crops, in contrast, started to rise quickly in the 1960s: The total area devoted to the cultivation of grains, oilseeds, and other forages including cultivated grasses (Appendix S4) rose from 0.9 million ha in 1961 to 7 million ha in 2013, and, as a result, the feed-to-food area ratio rose from 0.08 in 1961 to 0.57 in 2013 (Fig. 2a).

If we assume that the reduction of around 2.4 million hectares of food crops, between 1966 and 2013, shifted entirely to feed crop production, it leaves 3.4 million hectares of net expansion of the total harvested area in the same period, displacing natural vegetation in the agricultural frontier for feed crop farming. By 2013, 36% of the total harvested land was devoted to growing feed for livestock (Fig. 2a).

Between 1961 and 2013 total maize consumption increased 400% (from 5.4 to 27 million tons); however, consumption of maize for animal feed (mainly yellow maize or corn) rose 1700% (from 0.7 to 12.8 million tons; Fig. 3a). Demand for maize for animal feed exploded since Mexico opened to international trade at the end of the 1980s, and it has been met mostly through imports. While in the early 1990s imported maize constituted ca. 20% of all maize used for animal feed, in the late 2000s imports formed ca. 70% of maize consumed for feed (Fig. 3b). Finally, total domestic production of maize increased from

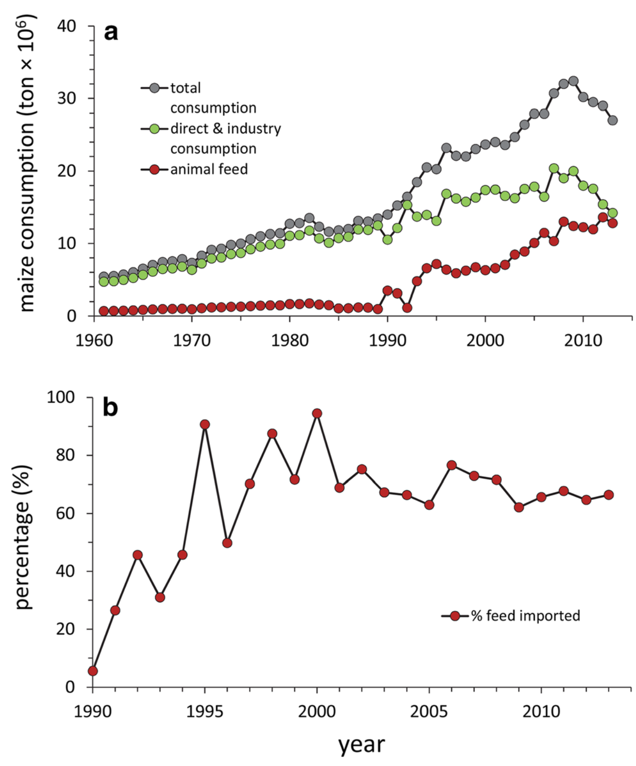

Fig. 3 Market transitions in consumption of maize: **a** The consumption of maize for feed in Mexico was small until the opening of imports in the 1989–1994 period. Before this period most of the maize consumed in Mexico was used for human food, mostly in the form of tortillas and nixtamalized maize flour (*masa*). After the opening of free trade, the percentage of maize used in Mexico for human consumption decreased gradually from 93% to 52% in 2013 (green points), while the proportion used for feed increased from 3% to 48% of the country's total consumption (red points). **b** The rapid increase in feed consumption was supported largely by imports; while in 1990 imported maize constituted only 6% of all maize used for animal feed, in the late 2000s imports formed ca. 70% of maize consumed for feed

6.2 to 22.7 million tons (363%) between 1961 and 2013, but the amount devoted to feed animals increased at a much faster rate, from 0.54 to 4.3 million tons (796%).

DISCUSSION

Our results highlight the important role of increasing consumption of animal protein during the last 50 years in Mexico as a driver of land-use changes. The first large-scale impact on land use due to increasing livestock production in Mexico was the clearing of tropical forests to open space for cattle grazing in the 1970s and 1980s (Bray and Klepeis 2005). Large governmental programs were established to promote agricultural and ranching settlements in the humid tropics, such as the Uxpanapa project in Veracruz, or the Chontalpa and the Balacán-Tenosique plans in Tabasco. A special governmental agency (*Comisión Nacional de Desmontes*) was created to promote land-clearing in the tropics (Toledo 1978; Moreno-Unda 2011). Deforestation rates throughout the tropics rose to 4–5% per year in all tropical lowland forests with the exception of the State of Quintana Roo (e.g., Dirzo and García 1992; World Bank 1995). The direct and clear link between tropical deforestation and cattle raising led the British ecologist Norman Myers (1981) to call the process "the hamburger connection," and public pressure started to grow against the loss of tropical biodiversity that was being driven by cattle husbandry. Clearings of the natural cover also affected large arid and semi-arid areas in the north of Mexico, where scrub ecosystems were transformed into buffel grass-induced grasslands (Narchi et al. 2015).

A second far-reaching effect of livestock production in Mexico, particularly since the 1990s, was agricultural intensification. As a result of international pressure, notably during the UN Summit of 1992 in Rio de Janeiro, the Mexican Government halted its efforts to expand agriculture into tropical forests and started promoting instead experiments in sustainable land use and restoration (Bray and Klepeis 2005). The efforts to halt deforestation coincided with the signature of the North American Free Trade Agreement (NAFTA) in 1994 and the opening of the Mexican economy to international trade, a period in which the most accelerated shift in the Mexican dietary habits occurred. In order to meet the increasing demand from the rapidly growing urban middle classes, the production strategy changed towards intensification of livestock production. At the same time, international trade allowed importing feed commodities and animal products. Industrialization of production and free trade contributed to reduce pressure on deforestation. Forest loss in Mexico, though still positive, is now less than 1% in most tropical regions. Finishing cattle on grain allows shortening the time to slaughter, which may reduce the rate of methane emissions from enteric fermentation (Swain et al. 2018) but increases energy consumption and greenhouse gas emissions from modern agriculture. Industrialized farming has intensified land use through the production of feed crops and concentrating feed-fed animals in massive enclosures. Despite some positive impacts of intensive farming, mostly related to the confinement of the agricultural frontier and the reduction of deforestation for new agricultural lands, industrialized production and land-use intensification can cause considerable environmental damages, as those related to manure and waste water mismanagement. Intensive feed crops demand high levels of pesticides, water, and fertilizers, while the massive concentrations of animals generate high amounts of nitrogen-rich waste, often close to urban centers, that after saturating the soils eventually pollute aquifers and surface water (Steinfeld et al. 2006). Although, globally, expectations have been generated around the industrial production of microbial proteins that could potentially reduce the demand for cropland area (Pikaar et al. 2018), this alternative is not yet a reality in Mexico nor are there any official plans for its promotion in the near future. During the last 50 years, livestock production has clearly changed agricultural land-use patterns in Mexico. The magnitude of the demand for animal products has turned the former extensive, grass-fed production system unviable, while, as a consequence, rearing animals in industrial barns and feedlots has rapidly gained relevance in the food system. Chicken and livestock have become a major consumer of cropland products through feed crop production, driving a 21.4% increase in the total harvested area of Mexico since 1966 (Fig. 2a), and also forcing the country to buy feed grains and other commodities abroad. In practice, Mexico is not only expanding its agricultural frontier domestically in order to meet the growing demand for feed but it is also consuming farmed feed from beyond its borders (mostly the USA), a phenomenon that seems to be increasing globally (Meyfroidt et al. 2010). Considering Mexican agricultural yields in 2103, it would have been necessary to add 5.6 million ha (i.e., and additional 29.4% of the total harvested area) to produce domestically the total feed production of maize, soybeans, and sorghum that were imported that year from the USA.

Recent predictions suggest that by year 2050 agricultural growth will be the major driver of land-use change (Mendoza-Ponce et al. 2019). Per capita area used by food crops shrunk between 1961 and 2013, from approx. 0.36 to 0.10 ha person^{-1}, while the harvested area for feed has been expanding during the last decades. Based on the observed trends, we estimate that by year 2027 agricultural land devoted to feed production will surpass that of food crops. Indeed, Ramankutty et al. (2002) warned on the vulnerability of the global food system that is caused by the sustained decrease in the land resource-base (i.e., population grows much faster than the every time scarcer cropland). These predictions trigger several questions about the viability of the food system in Mexico: How will future food consumption in Mexico be fulfilled, by increasing domestic production or through more imports of food and feed commodities? How much more can livestock production expand its share of land use? How much more agricultural and livestock production is it possible to reach? The answers to these questions should consider that changes in supply and demand are necessary to achieve a sustainable food system by improving supply and reducing demand and waste (Röös et al. 2017, White and Hall 2018). It seems, however, that production strategies, legislation, and public policies are not taking sufficiently into account the impact of the emerging modes of livestock production on land use and on the environment, as indicated by the scarcity of official information on these topics.

Land, irrigation water, reactive nitrogen, and greenhouse gases (GHG) emissions are key environmental metrics of the ecological impacts of feed production (Eshel et al. 2014). In Mexico, the intensification of agriculture relates to the increase of the area equipped for irrigation (more than doubled since 1961; FAO 2017). Synthetic fertilizers and pesticides are key inputs to high-yielding crops (De Walt 1985), but they contribute to nutrient loading, enabling eutrophication of surface water (Steinfeld et al. 2006). For example, Beman et al. (2005) have shown that nitrogen-rich agricultural runoff stimulates phytoplankton blooms in the Gulf of California as a consequence of high-input agricultural activity in the Yaqui Valley in the State of Sonora. In relation to GHG emissions in Mexico, GHG from livestock and manure increased during the period of accelerated increase of the cattle inventory (1961–1987) but leveled off during the 1990s, when cattle stocks stabilized (FAO 2017), confirming that the size of the cattle herd is a major factor to direct GHG (Eshel et al. 2014). Currently, livestock breeding contributes some 10–15% of the national GHG inventory (INECC 2018), less than the global average of ca. 15% (Rojas-Downing et al. 2017), possibly as a result of feed imports from the USA, which reduces the net environmental cost of agriculture in Mexico (Martinez-Melendez and Bennett 2016).

Projecting current trends, the population of Mexico may reach around 148 million by 2050 (CONAPO 2017). A conservative estimation of future demand, based on 2013 per capita consumption, shows that 26 881 million tons of livestock products may be consumed in Mexico by 2050, requiring an additional 5.2 million hectares of national agricultural area to produce feed crops equivalent to 27.1% of today's harvested area. Agricultural inputs will also have to multiply in order to catch up with production, increasing the environmental impacts of fertilizers, pesticides and fuel, among others. Additionally, animal stocks will have to increase in certain degree, generating more GHG emissions.

Maize (*Zea mays* L.) was domesticated in what is now Mexico around 7000 years ago (Piperno and Flannery 2001), and maintains in south-central Mexico its center of germplasm diversity (Vargas-Parada 2014). Maize is the most important crop in the diet of Mexicans, representing 85% of total grain production (SAGARPA 2016), and is an essential element in the national culture. Production of maize for feed has been evolving at high rates, but this has not affected the production of maize for food, which has been stable around 17 million tons (including around 4.5 million tons harvested for self-consumption). A similar shift in the production of maize from food to feed has been reported in India by Pingali et al. (2019). Our results suggest that there is enough production of grain for human consumption in Mexico, although there is an increasing dependence on corn imports from the USA, largely driven by the increasing consumption of livestock products.

CONCLUSION

The increasing consumption of ASF is deteriorating human and natural systems alike globally (Willett et al. 2019). In Mexico, the availability of animal protein as a component of the national dietary transition has been crucial to reduce malnutrition. However, this transition has had some unforeseen consequences: For example, in half a century Mexico reached first place in the world in childhood obesity (INSP 2016). Intensification of livestock production has also had impacts on land use and in the degradation of aquatic and terrestrial ecosystems. Although the stabilization of extensive livestock production has reduced the rate of conversion of tropical forests into induced grasslands, in Mexico, the agricultural production for feed for barn and feedlot rearing of animals has increased the demand for new croplands, expanding the agricultural frontier, putting pressure over food crop fields, and requiring more water and other agricultural inputs like fertilizers, linked to large-scale pollution processes. Increasing consumption of livestock products has also driven increasing corn imports, mostly from the USA.

Our analysis provides an insight at a national scale of land-use changes and large-scale environmental impacts induced by the increasing demand for ASF in the Mexican diet. Compared to the direct effects on human health, these environmental changes have been a less-discussed consequence of the transition that has occurred in the Mexican diet during the last half-century. We demonstrate that if these trends continue the environmental sustainability of

Mexican food production will be seriously challenged. The adoption of more balanced food diets by the majority of Mexicans, taking advantage of the country's rich culinary tradition, would contribute to an improvement of both public and ecosystem health. Human diets have transcendent ecological impacts that should be seriously considered at the individual and family level, and also by legislation and policy, in relation to the country's food system.

Acknowledgements This study is part of the first author's (José Tello Carrasco) PhD research, supported by a scholarship from CONACYT. We also appreciate the kind help of the workers of INEGI and the library Ing. José Luis de la Loma y de Oteyza (SIAP-SAGARPA). We are in debt with Associate Editor Linley Chiwona-Karltun and an anonymous reviewer for their helpful comments and very constructive criticism.

REFERENCES

Aburto, T.C., L.S. Pedraza, T.G. Sánchez-Pimienta, C. Batis, and J.A. Rivera. 2016. Discretionary foods have a high contribution and fruit, vegetables, and legumes have a low contribution to the total energy intake of the Mexican population. *The Journal of Nutrition* 146: 1881–1887. https://doi.org/10.3945/jn.115.219121.

Barkin, D. 1981. The use of agricultural land in Mexico. *Problemas del Desarrollo* 12: 59–85 (In Spanish).

Barquera, S., I. Campos-Nonato, C. Aguilar-Salinas, R. López-Ridaura, A. Arredondo, and J. Rivera-Dommarco. 2013. Diabetes in Mexico: Cost and management of diabetes and its complications and challenges for health policy. *Globalization and Health* 9: 1–9. https://doi.org/10.1186/1744-8603-9-3.

Bray, D.B., and P. Klepeis. 2005. Deforestation, forest transitions, and institutions for sustainability in Southeastern Mexico, 1900–2000. *Environment and History* 11: 195–223. https://doi.org/10.3197/096734005774434584.

Beman, J.M., K.R. Arrigo, and P.A. Matson. 2005. Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean. *Nature* 434: 211–214. https://doi.org/10.1038/nature03370.

Colchero, M., C. Guerrero-López, M. Molina, and M. Unar-Munguía. 2019. Affordability of food and beverages in Mexico between 1994 and 2016. *Nutrients* 11: 1–13. https://doi.org/10.3390/nu11010078.

CONAPO. 2017. Population projections 2010–2050. Retrieved June 4, 2018, from https://cutt.ly/lwklRQP (In Spanish).

Delgado, C.L. 2003. Rising consumption of meat and milk in developing countries has created a new food revolution. *The Journal of Nutrition* 133: 3907–3910. https://doi.org/10.1093/jn/133.11.3907S.

De Walt, B.R. 1985. Mexico's second green revolution: Food for feed. *Mexican Studies* 1: 29–60.

Dirzo, R., and M.C. García. 1992. Rates of deforestation in Los Tuxtlas, a neotropical area in Southeast Mexico. *Conservation Biology* 6: 84–90.

Drewnowski, A., and J.-P. Poulain. 2018. What lies behind the transition from plant-based to animal protein? *AMA Journal of Ethics* 20: 987–993. https://doi.org/10.1111/j.1753-4887.1997.tb01593.x.

Eshel, G., A. Shepon, T. Makov, and R. Milo. 2014. Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. *Proceedings of the National Academy of Sciences USA* 111: 11996–12001. https://doi.org/10.1073/pnas.1402183111.

FAO. 2017. FAOSTAT statistics database. Retrieved July 1, 2017, from http://www.fao.org/faostat/en/#data.

Flores, M., N. Macias, M. Rivera, A. Lozada, S. Barquera, J. Rivera-Dommarco, and K.L. Tucker. 2010. Dietary patterns in Mexican adults are associated with risk of being overweight or obese. *The Journal of Nutrition* 140: 1869–1873. https://doi.org/10.3945/jn.110.121533.

Galvan-Miyoshi, Y., R. Walker, and B. Warf. 2015. Land change regimes and the evolution of the maize-cattle complex in neoliberal Mexico. *Land* 4: 754–777. https://doi.org/10.3390/land4030754.

Herrero, M., and P.K. Thornton. 2013. Livestock and global change: Emerging issues for sustainable food systems. *Proceedings of the National Academy of Sciences USA* 110: 20878–20881. https://doi.org/10.1073/pnas.1321844111.

Ibarrola-Rivas, M.J., and R. Granados-Ramirez. 2017. Diversity of Mexican diets and agricultural systems, and their impact on the land requirements for food. *Land Use Policy Journal* 66: 235–240. https://doi.org/10.14350/rig.57538.

INECC. 2018. National inventory of greenhouse gases emissions. Retrieved September 15, 2015, from https://www.gob.mx/inecc/documentos/investigaciones-2018-2013-en-materia-de-mitigacion-del-cambio-climatico (In Spanish).

INEGI. 2017. Population and housing census of México, 1950–2010. Retrieved February 23, 2017, from https://www.inegi.org.mx/programas/ccpv/2010/ (In Spanish).

INSP. 2016. Encuesta Nacional de Salud y Nutrición de Medio Camino. Instituto Nacional de Salud Pública, México. Retrieved 23 June, 2018, from https://www.insp.mx/avisos/4576-resultados-ensanut-mc-2016.html (In Spanish).

Martinez-Melendez, L.A., and E.M. Bennett. 2016. Trade in the US and Mexico helps reduce environmental costs of agriculture. *Environmental Research Letters* 11: 2–13. https://doi.org/10.1088/1748-9326/11/5/055004.

Mendoza-Ponce, A., R.O. Corona-Núñez, L. Galicia, and F. Kraxner. 2019. Identifying hotspots of land use cover change under socioeconomic and climate change scenario in México. *Ambio* 48: 336–349. https://doi.org/10.1007/s13280-018-1085-0.

Meyfroidt, P., T.K. Rudel, and E.F. Lambin. 2010. Forest transitions, trade, and the global displacement of land use. *Proceedings of the National Academy of Sciences USA* 107: 20917–20922. https://doi.org/10.1073/pnas.1014773107.

Moreno-Unda, A.A. 2011. Environmental effects of the National Tree Clearing Program, Mexico 1972–1982. MSc Thesis. Cologne, Germany and San Luis Potosí, México. Universidad Autónoma de San Luis Potosí and Cologne University of Applied Sciences.

Myers, N. 1981. The hamburger connection: How Central America's forests become North America's hamburgers. *Ambio* 10: 2–8.

Narchi, N.E., A. Búrquez, S. Trainer, and R.F. Rentería-Valencia. 2015. Social constructs, identity, and the ecological consequences of *carne asada*. *Journal of the Southwest* 57: 305–336.

Pikaar, I., S. Matassa, B.L. Bodirsky, I. Weindl, F. Humpenöder, K. Rabaey, N. Boon, M. Bruschi, et al. 2018. Decoupling livestock from land use through industrial feed production pathways. *Environmental Science and Technology* 52: 7351–7359. https://doi.org/10.1021/acs.est.8b00216.

Pingali, P., A. Aiyar, M. Abraham, and A. Rahman. 2019. *Transforming food systems for a rising India*. Cham: Palgrave Macmillan.

Piperno, D.R., and K.V. Flannery. 2001. The earliest archaeological maize (*Zea mays* L.) from highland Mexico: New accelerator mass spectrometry dates and their implications. *Proceedings of* *the National Academy of Sciences USA* 98: 2101–2103. https://doi.org/10.1073/pnas.98.4.2101.

Popkin, B.M. 1997. The nutrition transition and its health implications in lower-income countries. *Public Health Nutrition* 1: 5–21. https://doi.org/10.1093/jn/133.11.3898S.

Popkin, B.M., and P. Gordon-Larsen. 2004. The nutrition transition: Worldwide obesity dynamics and their determinants. *International Journal of Obesity* 28: 52–59. https://doi.org/10.1038/sj.ijo.0802804.

Ramankutty, N., J.A. Foley, and N.J. Olejniczak. 2002. People on the land: Changes in global population and croplands during the 20th century. *Ambio* 31: 251–257. https://doi.org/10.1579/0044-7447-31.3.251.

Rivera, J.A., T.G. de Cossío, L.S. Pedraza, T.C. Aburto, T.G. Sánchez, and R. Martorell. 2014. Childhood and adolescent overweight and obesity in Latin America: A systematic review. *Lancet Diabetes & Endocrinology* 2: 321–332. https://doi.org/10.1016/S2213-8587(13)70173-6.

Rojas-Downing, M.M., A.P. Nejadhashemi, T. Harrigan, and S.A. Woznicki. 2017. Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management* 16: 145–163. https://doi.org/10.1016/j.crm.2017.02.001.

Rojas-García, A.R., N. Torres-Salado, S. Joaquín-Cancino, A. Hernández-Garay, M.D.L.A. Maldonado-Peralta, and P. Sánchez-Santillán. 2017. Componentes del rendimiento en variedades de alfalfa (*Medicago sativa* L.). *Agrociencia* 51: 697–708.

Röös, E., B. Bajželj, P. Smith, M. Patel, D. Little, and T. Garnett. 2017. Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. *Global Environmental Change* 47: 1–12. https://doi.org/10.1016/j.gloenvcha.2017.09.001.

SAGARPA. 2016. SIACON statistics database. Retrieved September 10, 2016, from https://www.gob.mx/siap/acciones-y-programas/produccion-agricola-33119 (In Spanish).

Sánchez-Pimienta, T.G., C. Batis, C.K. Lutter, and J.A. Rivera. 2016. Sugar-sweetened beverages are the main sources of added sugar intake in the Mexican population. *Journal of Nutrition* 146: 1888–1896. https://doi.org/10.3945/jn.115.220301.

Sans, P., and P. Combris. 2015. World meat consumption patterns: An overview of the last fifty years (1961–2011). *Meat Science* 109: 106–111. https://doi.org/10.1016/j.meatsci.2015.05.012.

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, and C. de Haan. 2006. *Livestock's long shadow: Environmental issues and options*. Rome: Food and Agriculture Organization of the United Nations.

Swain, M., L. Blomqvist, J. McNamara, and W.J. Ripple. 2018. Reducing the environmental impact of global diets. *Science of the Total Environment* 610–611: 1207–1209. https://doi.org/10.1016/j.scitotenv.2017.08.125.

Tilman, D., J. Fargione, B. Wolff, C. D'antonio, A. Dobson, R. Howarth, D. Schindler, W.H. Schlesinger, et al. 2001. Forecasting agriculturally driven global environmental change. *Science* 292: 281–284.

Toledo, V.M. 1978. Uxpanapa: Ecocide and capitalism in the tropics. *Nexos*. Mexico. Retrieved October 1, 2018, from https://www.nexos.com.mx/?p=3236 (In Spanish).

Turner, B.L., W.B. Meyer, and D.L. Skole. 1994. Global land-use/land-cover change: Towards an integrated study. *Ambio* 23: 91–95.

UNESCO. 2010. Document ITH/10/5.COM/CONF.202/6, 6 October 2010, United Nations Educational, Scientific and Cultural Organization, Paris. Retrieved October 1, 2018, from https://ich.unesco.org/en/lists.

USDA. 2017. Production Supply and Distribution (PSD) statistics database. Retrieved March 7, 2017, from https://apps.fas.usda.gov/psdonline/app/index.html#/app/home.

Vargas-Parada, L. 2014. GM maize splits Mexico. *Nature News* 511: 1–16.

Vitousek, P.M., H.A. Mooney, J. Lubchenco, and J.M. Melillo. 1997. Human domination of Earth's ecosystems. *Science* 277: 494–499.

White, R.R., and M.B. Hall. 2018. Reply to Van Meerbeek and Svenning, Emery, and Springmann, et al.: Clarifying assumptions and objectives in evaluating effects of food system shifts on human diets. *Proceedings of the National Academy of Sciences USA* 115: 1706–1708. https://doi.org/10.1073/pnas.1720895115.

Willett, W., J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett, D. Tilman, et al. 2019. Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* 393: 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

World Bank. 1995. Mexico-resource conservation and forest sector review. Washington, DC. Retrieved February 2, 2018, from http://documents.worldbank.org/curated/en/998301468757196117/Mexico-Resource-conservation-and-forest-sector-review.

World Bank. 2018. The World Bank open data. Retrieved June 8, 2018, from https://data.worldbank.org/.

AUTHOR BIOGRAPHIES

José Tello (✉) is a doctoral candidate at the Centro de Investigaciones Biológicas del Noroeste (CIBNOR). His research interests include land use change, food systems and environmental conservation policy.

Address: Centro de Investigaciones Biológicas del Noroeste (CIBNOR), Av. Instituto Politécnico Nacional 195, Playa Palo de Santa Rita Sur, 23205 La Paz, BCS, Mexico.

e-mail: jcarrasco@pg.cibnor.com; tellojos2@gmail.com

Pedro P. Garcillán is a Professor at the Centro de Investigaciones Biológicas del Noroeste (CIBNOR). His research interests include desert plant ecology and effects of human activities on dynamics of plant communities.

Address: Centro de Investigaciones Biológicas del Noroeste (CIBNOR), Av. Instituto Politécnico Nacional 195, Playa Palo de Santa Rita Sur, 23205 La Paz, BCS, Mexico.

e-mail: ppgarcillan@cibnor.mx

Exequiel Ezcurra is a Professor at the University of California, Riverside. His research interests include quantitative ecology, desert ecology and biogeography.

Address: Department of Botany and Plant Sciences, University of California Riverside, 900 University Ave, Riverside, CA 92521, USA.

e-mail: exequiel@ucr.edu