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A time-quantitative analysis of calorie flows within the global food supply and the calorie footprint of nations - opportunities for increasing food availability and enhancing food security.

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CONTENTS

Summary:

Motivated by the interest in finding ways to increase the availability of food in order to feed the population in 2050 while also meeting the growing global demand for crops for other purposes, the present work presents a temporal and quantitative analysis of the global food supply, taking into account how the production of edible calories has been allocated among different competitive uses – food, feed livestock and non-food. Calorie allocation to non-food activities increased significantly during the study period. However, it was found that animal-related losses account for the majority of edible calorie losses from the food system. Thus, in order to assess the influence of animal-based food consumption and dietary preferences on the current structure of the food system, five eating patterns were analysed - current pattern, EAT-Lancet, Mediterranean, Vegetarian and Vegan. The result shows that only substantial changes in the consumption of animal-based products will enable the current food system to feed the estimated 10 billion people. Furthermore, while performing the temporal analysis of the nation's footprint, it was identified that there has been an increase in countries reliant on imports to meet domestic demand. High-income countries with high consumption of animal-based food and developing countries, known for their large and extensive meat and dairy production, have an amount of calories embedded in their products that is up to 5 times higher than their final consumption. The analysis showed that food security and the sustainability of the food system are dependent on shifts in crop allocation and a more egalitarian distribution of world production.

Keywords: Food security, diets, animal-based food, livestock, feed-food conversion, footprint, MRIO, FABIO.

1. INTRODUCTION

Human societies have employed increasingly larger amounts of agriculture yields to satisfy their needs, that range from food production to livestock feed, energy generation and other bio-based materials manufacture (Muscat et al., 2020; Muscat et al., 2021)

In line with this upward trend in crops requirement, in the coming decades, it is estimated that the demand for food will increase 70%-110%, (Tilman et al., 2011), boosted not only by population growth, but particularly by the changes in dietary patterns, with larger consumption of meat, dairy, and higher calorie diets (Godfray et al., 2018). Yet, considering the necessary strive to curb global warming, it is also foreseen a more extensive use of biomass, including edible crops, for bioenergy and other biomaterials production (IEA,2017).

Together, population growth, dietary patterns shift, and energy transition place a massive claim on globally available crops. Posing a challenge to the agri-food system, which will need to cope with (i) the expansion/intensification of production to meet the growing demand to feed 10 billion of human beings, while providing them the resources needed for other purposes, and (ii) the sustainable management of natural resources and the environmental impacts related to the agri-food sector (Foley et.al., 2011; Poore and Nemecek 2018).

Agri-food system is frequently seen as a major source of human-induced environmental strain. However, part of this is a result of increased demand for animal feed production (Springmann et al., 2018). Several studies describe the direct connection between the greater consumption of animal-based food products and the soaring burden on the planet and its natural resources, given that the animal-based food production processes use land, water, and energy resources less efficiently than the crop production for direct human consumption (Davis et al., 2016; Lovarelli et al., 2016; Mekonnen & Gerbens-Leenes, 2020). In addition, studies also describe the recent transition in global livestock production, which has become a more industrialised system and requires greater amounts of edible calories to feed confined animals. Even though it still has a considerably low caloric yield, evidencing that the use of edible calories to feed animals has not proved to be an efficient way to provide calories to humans (Cassidy et al., 2013; Shepon et al. 2016).

Still addressing the competition among the multiple uses for crops, International Energy Agency (IEA) indicates that despite the escalation of global biofuel production in the early 2000s, it did not resume after the drop observed in 2010 (IEA, 2019). Current production figures are still lower than those preceding the fall, and since 2011 the average annual growth rate has slowed, with prospects of further reduction in the coming years (IEA, 2017). This meets the predictions of the US Energy Information Administration, which projects a slowly increasing US production through 2050 compared to 2010 figures (EIA, 2020). However, regardless of slowing growth rates, it is worth bearing in mind that the great majority of biofuel feedstocks are composed of edible biomass (maize, sugarcane, sugar beet, soybean, rapeseed, sunflower), hence, it is possible to project greater demand for crops for bioenergy generation (Muscat et al., 2021).

Within this context, the picture emerging in the medium term highlights the limited production capacity of our planet. Raising the concern with the maintenance or expansion of current consumption patterns and the potential transgression of planetary boundaries that may restrict the ability to expand food yield or even mean a decline in it (Springmann et al., 2018; Bowles et al. al., 2019, IPCC, 2019; Hasegawa et al., 2021).

In this regard, understanding how the crop production has been allocated among the competing uses, as well as identifying which nations consume the most edible calories, are central factors to obtain insights into the opportunities of how increase food availability, and design strategies aiming at more efficient use of agriculture yield to ensure global food security and the sustainable progress of the agri-food sector.

Conducting this analysis became even more relevant in the current global geopolitical context, in which food security has been called into question. Russian products have been embargoed worldwide. Ukraine is unable to dispense its grains. Part of Brazil's production was impacted by weather events. As a result, fearing shortages and rising commodity prices, India and other countries banned the export of their agri-food products. (Reuters, 2022).

Motivated by these factors, the present study explored the recent Food and Agriculture Biomass Input-Output Model (FABIO) (Bruckner et al., 2019) to:

(i) perform a temporal analysis of the allocation of edible calories provide by the global crop production among three competing uses - food for human consumption, animal feed, and other non-food products, which includes biofuels. Thereby, it was possible to identify the yearly amount of human-consumable calories produced, the amount of calories delivered as food for human consumption, and the potential number of people that could be fed per hectare of cropland yield.

(ii) perform a temporal analysis of the calorie footprint of nations. Footprint is an indicator which makes use of the multi-regional input-output (MRIO) model to capture information about the direct and indirect flows of resources within and between economies, providing information related to the required resource to meet a given final demand, hence, presenting a consumption-based perspective (Wiedmam et al., 2013; Tukker et al., 2016).

(iii) develop scenarios that considered the adoption of different eating patterns. With this, it was possible to acquire a sense of the order of magnitude of the upcoming global food demand, taking into account how different diets influence the allocation of calories between human consumption and feed livestock. In addition to identify whether the agri-food system would be able to feed more or fewer people per hectare in each alternative adopted.

2. GOALS

The goal of the present study is to provide insights into aspects that make the agri-food system inefficient and how these aspects have evolved over the last few decades. It also aims at identifying opportunities to shore up food security by adopting more sustainable eating patterns, as well as indicate the potential of the current global food system to feed the world population in 2050.

To accomplish this task this study seeks to answer:

- In a time series perspective:
  - How much of the global primary production of calories has been consumed as food and what is the fraction used to feed animals or employed in other uses?
  - What is the fraction of human calorie intake that has been provided by primary crops, and animal-based products?
  - How many people could be fed per hectare of cropland, assuming that the production of edible crops was directly consumed by humans and considering the ideal daily calorie intake (2500kcal/capita/day)?
  - What has been the progress in the feed-food efficiency conversion over the past few decades? And how much agriculture land has been used to feed farmed animals?
  - Have there been changes in the nation's calorie footprint? What are the possible factors that influenced the changes?

- Considering the different eating patterns and the expected growth of the human population:
  - Are the current crop yields sufficient to meet human caloric needs in 2050?
  - Under the scenarios for 2050, would be required more hectares of cropland to provide the required daily calorie intake?

3. MATERIALS AND METHODS

3.1. MATERIALS

The development of this work was based on secondary data.

- Scientific papers and official public documents contributed to the formation of the theoretical foundation of this study.

- FABIO - provided the multi-regional physical input-output tables covering the global agri-food commodities trade, used to perform all analyses on crop allocation and calculate the nation's calorie footprints.
- The World Bank database supplied the population size data (The World Bank, 2022). Since the database does not provide aggregated information on the population size of the former socialist blocs (USSR, Czechoslovakia, and Yugoslavia), in order to obtain the size of their populations, it was necessary to add the number of individuals from each of the member states. The same procedure was applied for Belgium-Luxembourg, Serbia and Montenegro, and the "Rest of the world" region.

Furthermore, to handle and process the large amount of data, MatLab R2021 was used. It is a software developed by MathWorks Inc. A popular programming language used for numerical computations.

3.1.1. FABIO - FOOD AND AGRICULTURE BIOMASS INPUT-OUTPUT MODEL

FABIO was the database selected to carry out the analyses of this study since it is the most recent MRIO available designed exclusively for food and agriculture commodities. When compared to other existing models, FABIO provides the highest resolution in terms of the number of agri-food products and countries participating in the global trade of these commodities (see table 3.1). This reduces, even if partially, the classic problem of homogeneity, common to all MRIO models.

Also, FABIO differs from other MRIOs as it provides information in physical units. The lack of information with this characteristic has motivated objection about the robustness of MRIO-based calculations of biomass flows. Up to the present time, the most recurrent has been to use of economic data in an attempt to track global physical biomass flows from producers to final consumption. However, this practice can lead to an incorrect estimation since prices may vary between transactions (Bruckner et al., 2019).

According to Bruckner et al., 2019, data available in FAOSTAT – the Statistical Services of the Food and Agriculture Organization of the United Nations - were the main source of data used to build the model. Information not covered by FAOSTAT was obtained from other databases. FAO's fishery division provided information on fish capture and aquaculture production. International Energy Agency (IEA) and US Energy Information Administration (EIA) supplied information on biofuel production. While UN Comtrade and BACI provided data on bilateral trade in fish and biofuels.

Relying on this information they defined the physical supply and use tables. While supply table describes all products delivered by all industries in a region and products provided by the international market (imports), the use tables represent the products used by industries in this region, as well as those used by its final consumers. Following, these two tables were conjoint and harmonized to obtain an input-output table, which is composed of 4 components: a square intermediate demand matrix **Z**, a vector of total output **x**, a final demand matrix **Y**, and a **S** matrix (environmental-extensions), which informs the direct socio-environmental impacts of production. This version of FABIO contains 4 environmental-extensions - biomass, land use, blue water, and green water. Further details about FABIO and its building process can be found in Bruckner et al. (2019).

In short, FABIO offers a set of multi-regional physical input-output tables on the global agriculture trade. It accommodates information about 191 countries plus one aggregated region "Rest-of-World", covering 121 processes and 125 commodities, between the years 1986 and 2013.

TABLE 3.1: Resolution - number of countries, commodities and temporality - of the main MRIO databases. Source: Bruckner et al. (2019).

	GTAP	EXIOBASE	EORA	WIOD	OECD-ICIO	FABIO
Regions	140	49	190	43	69	192
Agri-food products	21	27	2-80	2	2	127
Other products services	35	172	24-936	53	34	0
Units	USD	EUR	USD	USD	USD	ton/heads
Years	2004, 2007, 2011	1995-2011	1990-2015	200-2014	1995-2015	1986-2013

As described by the authors, the original set of FABIO tables are expressed in tons of biomass or in thousands of heads in the case of live animals. Later, the tables were translated to calories. The calorie supply of edible product was estimated using mainly the FAO food energy conversion factors (FAO, 2001), and where not available from Berners-Lee et al. (2018).

3.2. METHODS

3.2.1. LITERATURE REVIEW

A traditional literature review was undertaken to identify and examine publications on the topic, with the aim to provide (i) a clearer picture of the research gaps, (ii) define the scope and (iii) ground the theoretical basis of this work.

At first, data collection was carried out exploring the scientific literature databases *Scopus* and *ScienceDirect* using a set of keywords - (i) global food security; (ii) food production; (iii) food supply; (iv) dietary patterns; (v) dietary changes; (vi) international food trade; (vii); efficiency (viii) sustainability; (ix) footprint.

To select the publications (peer-reviewed) from international journals, it was used the criteria (i) most recent year of publication; (ii) relevance; and (iii) cited by highest number.

Following, the works were screened within abstracts and conclusion under another set of criteria - (i) relevance to identify trends and drivers in food nutrition consumption; and (ii) relevance to understand how efficiently the agri-food sector has been using natural resources.

Those that met the criteria were selected for more detailed analysis and contributed to the construction of this work.

3.2.2. INPUT OUTPUT ANALYSES AND MATHEMATICAL FUNDAMENTALS

The application of Input-output analysis (IOA) in studies related to the strain imposed by the final demand on the global production activity and environment finds its roots in the model developed by Russian economist Wassily Leontief (1970), known as "The Leontief inverse".

IOA is a macroeconomic method that depicts the economic transactions of a given year in a tabular form, describing the production and final consumption in an economic interlinked structure. This accounting framework illustrates how the output of one industry/country becomes the input of another while unveiling supplier and demander interdependent network along the production chain (Miller and Blair, 2009).

The application of IOA allows identifying (i) the intermediate inputs associated with one unit of final demand, (ii) inputs needed to meet the total final demand, and (iii) tracing the influence caused by changes in final consumption on production structures and environmental aspects (Murray & Wood, 2010; Schaffartzik et al., 2015), thereby it has become one of the most applied methods in economics (Miller and Blair, 2009).

Figure 3.1 illustrates a generic multi-region input-output table and its components, similar to those offered by FABIO and used in this work. Where:

- **Z** represents the intermediate demand matrix, which records the inter-industry flow of products. This matrix has dimension $n \times n$, and each element zij represents the total flow of products from industry i as inputs to production of industry j. Yet, the **Z** matrix shows each industry j described in the IOT as producer ($z_j{}^P$) and consumer ($z_j{}^C$).

$$\begin{bmatrix} Z11 & \cdots & Z1n \\ \vdots & \ddots & \vdots \\ Zn1 & \cdots & Znn \end{bmatrix} \tag{1}$$

$$z_J^P = \sum_{i=1}^{N} z_{Ji} , Z_J^C = \sum_{\bar{J}=1}^{N} Z_{ij} \tag{2}$$

- **Y** refers to the final demand matrix. It shows the total demand of products by all f final consumers and has dimension $n \times f$.
- Vector **x** represents the column sum of both intermediate consumption from the inter-industry matrix **Z** and final demand consumption matrix **Y**, that is, the total outputs of the n industries addressed in the IOT. Its dimension is $n \times 1$.

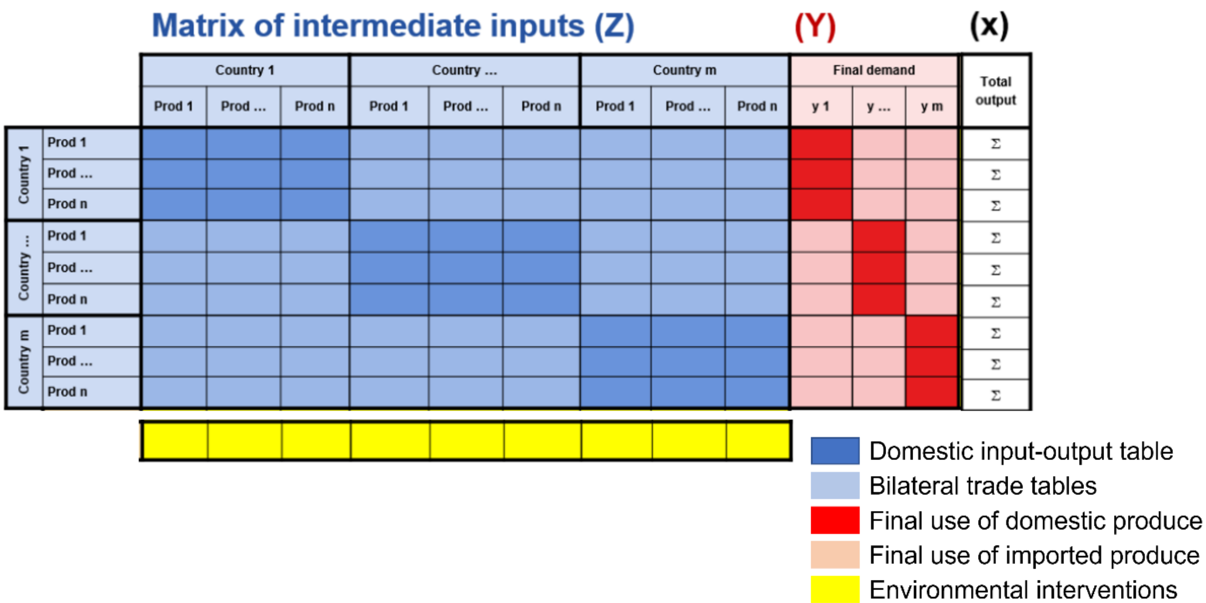


FIGURE 3.1 - Representation of a typical MRIO similar to those of FABIO. Source: Wieland & Giljum (2019).

The matrices **Z** and **Y**, as well as the vector **x** from FABIO that bring information about biomass, are represented in tons and 1000 heads in the case of live animals. These components, when referring to calories, are expressed in Giga calories.

From these numbers provided by FABIO, a series of calculations was performed to find the calorie footprints of nations.

$$A = Z * \hat{x}^{-1} \tag{3}$$

$$L = (I - A)^{-1} = (I + A + A^2 + A^3 \ldots + A^n) \tag{4}$$

$$F = L * y \tag{5}$$

Where:

- Matrix **A** represents the requirements of inputs from other industries to produce one unit of output in each industry (also called technical coefficient matrix). It has dimension $n \times n$. Each element in **A** (a_{ij}) represents the amount of inputs from industry i required to produce one unit of output in industry j.
- $\hat{\boldsymbol{x}}$ represents the diagonalization of vector **x**. Its dimension is $n \times n$.
- **L** is the Leontief inverse matrix that describes the total inputs needed to produce one unit of final demand in each industry. It has dimension $n \times n$. Each element of **L** (l_{ij}) represents the sum of the direct and indirect (upstream supply chain) requirements associated to industry i to produce 1-unit final demand of industry j.
- **y** is a final demand category vector. Its dimension is $n \times 1$. Each element represents the final consumption of products from industry i. In the case of FABIO, there are 6 final demand categories, food item, other industrial uses, stock addition, losses, unspecified and balancing;
- F is the footprint, represents direct and indirect requirements to meet the total final demand of an industry. It indicates the effects embodied in consumption, that is, in the upstream supply chain of final consumption of products.

Through these calculations, it was possible to determine the:

- **Production-based accounting impacts** (**PBA**) of a nation, which refer to the effects happening in a country c that are associated with all domestic production from this nation c, including impacts related to domestic consumption and exports.

$$PBA^c = L^{cc} * x^{cc} + \sum_{s \neq C} L^{cc} * y^{cs} \quad (6)$$

- **Consumption-based accounting impacts** (**CBA**) or **footprint** of a nation, which refers to impacts happening in all countries (including country c) along the entire supply chain of final consumption of country c.

$$CBA^c = L * y^c \quad (7)$$

Yet, two points worth to mention:

- In this study, the Leontief inverse was calculated through Taylor power series expansion ($\mathbf{L = I + A + A^2 + A^3 + ... + A^n}$), because, as warned by Bruckner et al. (2019), there is some degree of linear dependency between the columns of table **Z** that impedes its inversion. Tests were previously performed to verify the minimum number of tiers ($\mathbf{A^n}$) to be used and not affect the result. It was found that numbers greater than 5 did not lead to significant changes. Then, as a precaution, it was adopted the number of tiers equal to 15.
- Here, only the calories consumed as food items and other uses were considered when calculating CBA and PBA.

3.2.3. CALORIE ALLOCATION

The **Z** and **Y** matrices provided by FABIO were also used to determine the allocation of edible calories among the multiple uses - food, feed, and non-food - as well as losses.

The **Y** matrix was employed to point the supply of edible calories to human's food consumption provided by edible crops, animal-based products, and processed products (sugar, oils and alcohol), separately. For each nation, its respective column corresponding to food consumption was selected. From the selected columns, the rows were split among the three groups of products mentioned above. Finally, the rows belonging to each group were added up to obtain the total amount of calories provided by each group.

A similar approach was performed to find the edible calories delivered to non-food uses or the losses. However, this time, the columns of **Y** corresponding to other uses consumption or losses were selected, respectively.

Using the **Z** matrix, calories delivered to animal-based and processed products were calculated, regardless of the end use of animal-based products. For each nation, its respective column associated with animal-based and processed products were selected separately. Then, the inputs were split between edible and non-edible classes and, finally, summed the classes individually. With regard to edible calories, an extra procedure was performed, subdividing the sources between edible crops and other edible calories, such as sugars and fats used in animal-based and processed products production.

At this point, it is worth mentioning that, despite not being directly consumed by humans, oilseed cakes are, in general, produced from edible crops after their oil extraction. Therefore, it was assumed that cakes also represent human-edible calories. They correspond to edible crops that could be allocated directly to feeding humans.

3.2.4. CALORIE FEED-TO-FOOD CONVERSION EFFICIENCY

While measuring the efficiency of the animal-based food production processes the focus on edible calories outcomes was maintained. With matrix **Y,** the sum of all animal-based edible products delivered (regardless of their use) was found. Using matrix **Z,** it was possible to find the sum of all inputs (edible sources + non-edible sources). To find the efficiency, a straightforward mathematical approach was used, by dividing the outputs by the inputs.

3.2.5. DEALING WITH TWO UNITS IN THE SAME TABLE

As previously mentioned, the original FABIO tables contain information expressed in tons, however, in the particular case of live animals, especially in their **rows**, the unit used is thousands of heads, following the convention used by FAOSTAT.

This fact prevented the direct use of the matrixes in the planned calculations. Therefore, as described below, previous processing of the data was necessary.

Firstly, it is important to say that FABIO assumes that live animals are not consumed directly by humans, but rather their derived products, such as meat, fats, eggs, and milk. Also, it should be noted that other rows of the table already inform the quantities of animal-based products produced, traded, and consumed. Thus, the approach performed aimed at proportionally redistributing the inputs (feed livestock), initially delivered for live animals, among their derived products.

The procedure consisted of the following steps:

1) Select the rows and columns corresponding to live animals. For the sake of clarification and understanding of steps 3 and 4, the rows of the Z matrix indicate where a product *i* represents an input for a product *j*. While the columns represent a “recipe” of all the inputs needed to produce the amount of product *j* that meets the final demand.
2) Split up the selected rows and columns from the table; - Thus, the original table, which contained 125 products per country, now has 112, after excluding the 13 live animals.
3) Using the selected rows, identify the ratio in which each live animal products served as input for the other commodities. Thus, each element of a selected row was divided by the sum of all elements of this same row.
4) Redistribute all products that originally represented inputs for live animals (selected columns) among the commodities identified in the previous step, following the found ratios. In this way, those commodities for which live animals originally represented inputs (animal-based derived products) turned to present a more voluminous "recipe", as the corresponding proportion of the live animal "recipe" was added to their initial "recipe".

This procedure was undertaken for both the calorie and biomass tables, with the aim of homogenizing data, once biomass information was applied to decompose the factors behind changes in agricultural land-use.

3.2.6. IPAT EQUATION AND INDEX DECOMPOSION ANALYSES

The IPAT equation is widely accepted for analysing factors associated to the impacts induced by human activities on the environment. This equation expresses the environmental impact, (I), as the result of population (P), affluence (A), and technology, (T) (Ehrlich and Holdren, 1971).

Bearing in mind that land-use conversion is closely related to biodiversity loss, emission of greenhouse gases, and changes in the water regime and ecosystem services. Also, taking into account that the goals of this work have to do with land-use and agricultural productivity per hectare. Agriculture land was the impact selected to be studied. In this way, here, the interest is to identify how much land has been used by the agri-food system and the factors that have impacted its growth.

The approach described below was carried out to investigate changes in four agricultural powers - China, USA, Brazil, and India.

For this, the following variables were considered:

- I = impact
- P = population
- Land = agricultural land-use
- CalP = total calorie production
- CalC = total calorie consumption
- ABmP = Animal-based biomass production
- ABmC = Animal-based biomass consumption
- mP = total biomass production

$$I = L/CalP * CalC/P * ABmP/CalC * CalP/ABmP * ABmC/mP \quad (8)$$

The analysis of the difference between land use emission in time ‘t^0’ and ‘t^1’ was performed for three distinct periods, using the decade's average of calorie consumption:

- 1980s-1990s
- 1990s-2000s

Using the LMDI decomposition technique as described by de Boer & Rodrigues (2019), the total variance in land-use over a period, as well as the individual effect of the variables on changes, was decomposed.

$$\Delta I = \Delta Land/CalP * \Delta CalC/P * \Delta ABmP/CalC * \Delta CalP/ABmP * \Delta ABmC/mP \tag{9}$$

$$\prod_{i=1}^{N} \left(\frac{Land^0}{CalP^0}, \frac{Land^1}{CalP^1}\right)^w \tag{10}$$

$$\prod_{i=1}^{N} \left(\frac{CalC^o}{P^0}, \frac{CalC^1}{P^1}\right)^w \tag{11}$$

$$\prod_{i=1}^{N} \left(\frac{ABmP^o}{CAlC^0}, \frac{ABmP^1}{CalC^1}\right)^w \tag{12}$$

$$\prod_{i=1}^{N} \left(\frac{CalP^o}{ABmP^0}, \frac{CalP^1}{ABmP^1}\right)^w \tag{13}$$

$$\prod_{i=1}^{N} \left(\frac{ABmC^o}{mP^0}, \frac{ABmC^1}{mP^1}\right)^w \tag{14}$$

Where:

$$w = \frac{L\,(t^1,t^0)}{\sum^{N} L(t^1,t^0)} \tag{15}$$

And L refers to the logarithmic mean.

3.2.7. DIETARY PATTERNS SCENARIOS. SUPPLYING FOOD TO THE HUMAN POPULATION NOW AND IN 2050.

This study explored five eating patterns to identify how individual dietary calorie intake influences the global food availability and land occupation by the agricultural sector.

The diet **QUO** represents the current average world diet, as provided by FABIO's 2013 data. This diet was taken from matrix **Y**. Combining all columns referring to food consumption in a single vector (***v***) that informs the total global calorie supplied by each edible product.

The other patterns, EAT-Lancet (**EAT**), Mediterranean (**MED**), Vegetarian (**VEG**) and **Vegan**, which are diets described as more sustainable and healthier by experts (Tilman & Clarck, 2014; Schader et al, 2015; Broekema et al, 2020; Reinhardt et al., 2020), were obtained through the compilation of information from the work of Tukker et al. (2009), USDA & HHS (2015), Orlich et al. (2014), Blackstone et al. (2018), Willey et al. (2019), and Blackstone & Conrad (2020).

Together, these works provided information on the calories provided by different food groups - fruits, vegetables, grains, vegetable-based protein foods, animal-based protein foods, dairy, oils, and discretionary calories - in each diet studied.

Then, calories from a group were distributed equally among products from that group included in FABIO. For example, the EAT diet indicates a daily consumption of 811 kcal from grains. These 811 kcal were equally distributed among all the grains presented on FABIO's table - rice, wheat, barley, maize, rye, oats, millet, sorghum, and other cereals. Details on the distribution of calories between FABIO products for each of the diets can be found in Supporting Information (SI 4).

This new redistribution of the calorie supply involved the reconfiguration of the previously mentioned vector ***v***. Establishing, in this way, a new final food demand for each diet ($\boldsymbol{v}_{diet}$). Subsequently, these new vectors were used to find how changes in final demand affect the matrix **Z** and the vector **S** (land-use).

In this approach, the following steps were followed:

- Identify the fraction of the **Z** matrix exclusively related to food production. Multiplying the **Z** matrix by the result of dividing the total food consumption by the entire **Y** matrix

$$Znew = Zoriginal \times (v \div Y)$$

- Divide the new vector by the original one. Thus, it was possible to identify the consumption variation of each product in the different diets.

$$Rdiet = vdiet \div v$$

- Multiply the new Z matrix by the variance found between the final demands.

$$Zdiet = Znew \times Rdiet$$

A similar application was employed to define the land use associated with each diet. However, of course, instead of the **Z** matrix, the **S** matrix was used.

Further, the ***Zdiet*** matrix and **S*diet*** vector were used to identify, respectively, (i) how the allocation of calories between food and feed occurs, and (ii) how many hectares of cropland and grassland would be needed to provide the ideal daily intake of kcal for the current population and for the 10 billion inhabitants in 2050.

Two important points to mention about this procedure:

- It was not taken into account possible crop yield changes resulting from new technologies or farming practices, rather it was maintained the 2013 crop yield levels per hectare.
- There was no consideration of cultural matters or food taste. It was assumed that any edible product is appropriate human food and can be consumed by any individual anywhere on the planet.

It is important bearing in mind that studies indicate different amounts of daily calorie intake, depending on their assumptions about the population's sex, age, height, and level of physical activity. World Health Organization recommends that men and women consume, on average, 2500 and 2000 kcal/capita/day, respectively. USD, in turn, presents a list of recommendations, but, on average, it represents about 2800 kcal/capita/day for men and 2200 kcal/capita/day for women. Hiç (2016) found that the global average calorie intake is about 2370 kcal/day. Cassidy et al. (2013) considered 2700 kcal/capita/day to be an adequate daily consumption. Willett et al. (2019) used 2500 kcal/day as the basis for their study, indicating that this corresponds to the average energy needs of a 70-kg man aged 30 years and a 60-kg woman aged 30 years whose level of physical activity is moderate to high. Following Willett and his partners, the present study assumes a daily per capita consumption of 2500 kcal as the ideal average amount to be ingested, applying it in the comparative analysis of the scenarios.

4. BACKGROUND - THEORICAL FOUNDATION

4.1. DIETARY PATTERNS SHIFT, ENVIRONMENTAL IMPACTS, AND GLOBAL FOOD SECURITY.

Global food demand has been shaped by population growth and dietary habits shift, which is characterized by the transition from traditional diets, including fresh and unprocessed foods, towards affluent diets, abundant in calories, added sugars, saturated fats, highly processed products, and, specially, animal-based products (Popkin, 2002; 2003; Godfray et al., 2018; Bodirsky et al., 2020).

Statistical data indicates that from 1951 to 2013, meat consumption per capita increased by nearly 75%, reaching 51 kg/capita/year on average, that represents roughly fourfold growth in global meat production. At the same time, crop production used for feed have tripled (FAO, 2015; FAOSTAT, 2017). Furthermore, compared to the previous decade, meat consumption is projected to rise about 12% by the end of the current decade (OECD-FAO, 2021). A similar picture is pointed out for the consumption of milk and dairy products, trends indicate a probable world growth rate at 1,6%/year to reach 977 Mt through 2030 (OECD-FAO, 2021).

With these changes in consumer structures the agri-food system has been under pressure to increase its productivity, and as a result, higher environmental stress has been observed (Foley et al., 2011; Tilman & Clark, 2014; Clark & Tilman, 2017).

As argued by Pimentel (1996), the benefits arising from technological development, mechanisation, as well as the use of fossil fuels and chemical fertilizers in agricultural production are undeniable. These factors enabled the unparalleled increase in yields and contributed to reductions in hunger.

However, this progress has been at the expense of natural land conversion (de Ruiter et al., 2017), biodiversity loss – including sharp reduction in global fish stocks (Machovina & Feeley, 2014), soil degradation (Kopittke et al., 2019), massive use of water (de Vries et al., 2021), overuse of fertilizers (Chaudhary & Krishna, 2019), and intensification of greenhouse gas emissions (Poore and Nemecek 2018).

Additionally, Foley et al. (2011) report that, in recent years, the pace of agriculture yield improvements has slowed, and the necessity for agricultural expansion in order to meet higher demand became imminent. The undesired new conversion of natural landscapes into agricultural land would intensify all these impacts, while the expansion over lands already anthropized would limit their use for other purposes (de Ruiter et al. 2017).

Nevertheless, as highlighted by Herrero et al. (2016), part of this environmental burden is due to dietary choices, since global livestock production occupies about one-third of terrestrial land for grazing and others 33% of arable land is dedicated to grow feed-crop, it consumes 32% of withdrawal freshwater, and contribute with 15-20% of all global greenhouse gas emissions.

Moreover, in the current food system, regardless of the practice, the production of livestock feed competes with food production, with adverse implications for total food supply (Karlssoon & Röös, 2019). While the extensive practice of livestock production uses pastures and crop residues for animal feed, it does not pose direct competition for edible crops (Makkar, 2018). However, as forage is not as nutritious as animal feed, larger areas are required to produce the same number of animal calories (Krausmann et al., 2008). On the other hand, industrialized livestock, characterized by large outputs within small areas, represents a competitor for edible crops. According to Makkar (2018), currently, approximately one-third of total cereal production is used in livestock feed, besides he claims that, by 2050, about 37,5% more resources will be required.

This leads to trade-offs with food supply, since food provision through animals results in remarkable losses due to metabolic conversion factors (Davis & D'Odorico, 2015). In this regard, addressing the USA context, Shepon et al. (2016) found that the growing demand for edible crops to feed animals comes with a trivial return on investment. On average, the efficiency of calories and proteins conversion in the animal-based food production is 7% and 8% respectively. So, reallocation of arable land and edible crops from feed production to direct human food production would considerably increase global food availability (Foley et al., 2011).

In this way, in the future, food production may be limited by the availability of natural resources (Haberl, 2015) and food security threatened by the competitive and inefficient use of agriculture yields (Muscat et al., 2020). Therefore, to meet the demand and feed the human population in the coming decades, agricultural yields must increase significantly, decoupling its growth from inefficient use of natural resources (Tilman et al., 2011), whilst diets have to shift to consume fewer resource-intensive products (Tilman & Clark, 2014; Erb et al., 2016; Springmann et al., 2016).

To these ends, the concept of sustainable eating patterns, which entails the interdependence among diets, human health, and environmental sustainability, has become a central element of discussions on food security (Lucas et al, 2021).

According to FAO (2012).

"…Sustainable diets are those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources."

In this context, there is a myriad of studies that investigate environmental and health impacts related to classic diets such as mediterranean, vegetarian, vegan, pescetarian or flexitarian diets (Orlich et al., 2014; Springmann et al., 2016; Rosi et al, 2017; Green et al, 2018; Hallström et al., 2018; Springmann et al., 2018; Chai et al, 2019). In addition, efforts have been made to identify nutritionally adequate eating patterns with a lower environmental strain (Tukker et al., 2009; USDA & HSS, 2015; Smith et al., 2016; van Dooren, 2018; Willett et al., 2019; Lucas et al., 2021). Overall, their results explicit the reduced environmental burden and healthy gains with the replacement of animal-base food with plant-based products.

Among the diets, those that have received the most attention among specialists are vegetarian, vegan, mediterranean and EAT-Lancet. Therefore, they were selected to compose this study.

Based on the facts described - dietary patterns shift, greater consumption of meats, intense use of natural resources, and inefficient conversion of feed-food – and supported by the recent FABIO MRIO model, the present work found the opportunity to contribute to this discussion by exercising a temporal analysis of the allocation of edible calories between competing uses and, in addition, to assess how the adoption of sustainable diets could benefit the food supply and land sparing in the future.

4.3. ENVIRONMENTAL-EXTENDED MULTI-REGION INPUT-OUTPUT MODELS AND AGRI-FOOD SECTOR.

With the growth in trade, supply chains have been transformed and organized at the international level in such a way that there has been a progressive disconnection between the place of production and the place of final consumption. In other words, consumption elsewhere abroad has become a major driver of local environmental and social strain in countries, where raw materials are extracted, biomass is produced or products are manufactured. As a result, conventional national accounting approaches, focused on what happens within the frontiers of a country, have become insufficient to measure the whole impacts of a product's consumption (Plank et al., 2018; Tukker et al., 2018).

This is also true in the case of the agri-food sector, which industrialized, intensified, and commoditized its production (Lucas et al., 2019). Over the past three decades, the global agri-food trade has more than doubled, with average annual growth rates equal to 8% since 2000, representing U$1,75 trillion in 2021 (FAO, 2022). According to FAO (2015), even self-sufficient countries import some sort of food product. According to Bentom (2017), this phenomenon can be attributed in part to the concentration of principal commodities production in a few countries.

Furthermore, Weinzetel et al. (2013) claim that global cropland growth has been driven mainly by the production of commodities to meet international demand. In 2004, 24% (1,8 billion Gha) of the global land footprint was displaced through international trade. In 2010, this number grew, corresponding to 31% of cropland cultivation (Tramberend et al, 2019). Makkar (2018) exemplifies this context bringing the Chinese numbers on livestock production and feed imports. According to the author, China produces half of the world’s pork, 20% of the world’s poultry, and 10% of the world’s beef. In this way, China has become the world's largest importer of soybeans. Likewise, the country also imports barley, wheat, and sorghum to feed its animals. These crops have different origins but come mainly from Brazil and USA.

In this new world order, EE-MRIOs became a key tool. These models connect the economic structure of a country or region to the structures of others through bilateral trade data, providing a detailed representation of the global economy transactional flows and environmental accounts for a specific time frame. Thus, enabling the calculation of total direct and indirect (intermediate product) inputs requirements for satisfying final demand (Tukker & Dietzenbacher, 2013, Wiedmann & Lenzen, 2018).

Input–output analysis has been applied to economic impact analyses since the 1930s. In the 1960s, it began to be used to analyse the binomial relation economy–environment. However, we have seen the number of publications increase only after 1995, and gaining greater notoriety in the past decade, when more MRIOs models became available. Thereafter, IOA has been widely employed to express and trace production and consumption responsibility for environmental and socio-economic impacts along the global value chain (Dietzenbacher et al., 2013; Tukker & Dietzenbacher, 2013).

The production-based accounting (PBA) considers environmental pressures caused by economic activities within the country's territory, encompassing all resources extracted from the domestic environment. In another perspective, in the consumption-based accounting (CBA) - also known as footprint - environmental strains generated at different tiers of the supply chain in order to produce the final products are all allocated to final demand, including the domestic extracted resources and those embodied in imports, excluding the resources extracted and exported (Wiedmann et al, 2013).

Concerning the agri-food sector, many works have applied IOA to calculate its ecological footprint. Galli et al. (2017) explore the Global Trade Analysis Project (GTAP) and report the land footprint related to food consumption in Mediterranean countries. Cederberg et al. (2019) document carbon, land, and agrochemicals footprints from Swedish food consumption through EXIOBASE. Liu et al. (2021) used EORA data to track the land footprint of the global food trade. Kucukvar et al. (2019) compare WIOD, EXIOBASE, and EORA models when investigating the carbon, energy, and employment performance of agri-food sector.

It is also true that in many cases, regional input-output table had to be built in order to make up for the lack of resolution of MRIOs (Cazcarro et al., 2020; Sun et al., 2021; Chen et al., 2022). In this regard, referring exclusively to the agri-food sector, the current MRIO databases differ in relation to the number of countries, sectoral detail, time series, and units as table 4.1 shows. Addressing the sectorial details, GTAP (Global Trade Analysis Project) comprises 21 agri-food products. World Input–Output Database (WIOD), EORA and OECD-ICIO provide only 2 products. While EXIOBASE coverages 27 agricultural sectors. In turn, the number of countries ranges between 43 to 192,

Addressing this issue, Majeau-Bettez et al. (2016) discuss how aggregating products and regions affects environmental analysis, clarifying that the low level of detail limits the comparison between sectors or regions, leads to aggregation errors, as well as results in variation of relevance of sectors or regions depending on the socio-environmental indicator. Other authors who also exercise this reflection conclude that aggregations of regions or sectors can result in different outcomes, depending on the indicator analysed (Giljum & Hubacek, 2004; Bjelle et al, 2020). This can be partly explained by (i) the lack of detail in the global south, a region with substantial share of global material extraction and extensive land use, (ii) the aggregation into a single category of products very distinct in their composition and (iii) the intensity of material use or emission in the aggregate activities. For instance, de Koning et al. (2015) attest that the variability of carbon emissions between sectors is smaller than the variability in material extraction. Carbon emission occurs in every sector, but biomass or material extraction is a very specific activity that occurs in the primary sectors, as agriculture. This statement is supported by studies conducted by Bouwmeester & Oosterhaven (2013) and Stadler et al. (2014), which indicate that greater regional detail does not imply significant changes in carbon footprints, however, notably affects water or land footprints.

TABLE 4.1: Resolution - number of countries, commodities and temporality - of the main MRIO databases. Source: Bruckner et al. (2019).

	GTAP	EXIOBASE	EORA	WIOD	OECD-ICIO	FABIO
Regions	140	49	190	43	69	192
Agri-food products	21	27	2-80	2	2	125
Other products services	35	172	24-936	53	34	0
Units	USD	EUR	USD	USD	USD	ton/heads
Years	2004, 2007, 2011	1995-2011	1990-2015	200-2014	1995-2015	1986-2013

Referring to units, three main approaches of IOA can be distinguished - MONETARY - which extends Monetary Input–Output Tables (MIOTs) by environmental data in monetary units; HYBRID - that incorporates both monetary and physical information within the inter-industry table; and PHYSICAL (PIOTs) – express all economic transactions in physical terms (Giljum & Hubacek, 2004).

With tremendous differences, understanding the advantages and drawbacks of each of these models is essential to determine the most suitable one for the wanted analyses.

A PIOT differs fundamentally from other IOTs in two respects: (i) they represent flows without market value. PIOTs are built based on the principle of mass conservation and using physical units, being the ideal framework to study the physical structure of an economy; and (ii), they include the environment both as an input source (raw material or biomass) and as a sink (solid waste, air and water emissions). In other words, whereas other IOTs hold a single final product (final goods), PIOTs store both final products along with waste derived from their production. (Giljum & Hubacek, 2004; Suh, 2004; Altimiras-Martin, 2014). In this way, as cautioned by Giljum & Hubacek (2004), a PIOT cannot be derived by merely multiplying MIOT by a vector of prices per ton for each sector.

In addition, when comparative analyses focus their attention on the differences between MIOT and PIOT, they find a significant difference between the (high) intensity of resource use by primary sectors (agriculture, forestry, mining, and energy supply) and (low) value of its products. The picture is inverted when we refer to the services sector, where the monetary value per unit of outputs is substantially higher, but with lower resource intensity. As consequence, final demands for the service are higher in MIOTs than in PIOTs. On the other hand, the primary sector takes the lead in PIOTs. Furthermore, fluctuations in currency, inflation, and commodity prices can be a challenge when trying to unify international data on a temporal scale. Therefore, applying IOA for the calculation of the ecology footprint, based on the monetary units, will likely cause distortions of results (Tukker & Dietzenbacher, 2013; Kastner et al., 2014).

Finally, Hubacek & Feng (2016) clarify the main difference between MRIOs and the unidirectional trade approach. While the first distinguishes intermediate and final products, including inter-sectoral flows within and between countries, the second captures only the final product numbers, ignoring materials used as inputs along the value chain (intermediate products), thus cannot comprehensively describe the supply chain and identify the driving forces.

That said, FABIO emerges as an alternative to resolve such issues in the context of the agri-food sector. As told earlier, when compared to other existing models, FABIO is the model that accommodates greater detail in terms of product (125), covers a higher number of regions (192), and presents a long time series (1986-2013). In this sense, FABIO offers the best framework available to solve, even partially, the problems with the aggregation of products and regions.

FABIO is the first global MRIO dedicated exclusively to the agri-food sector that records the links between the economy in physical units, tracking biomass and calorie flows across sectors and regions. In addition, FABIO provides information on land and blue and green water required in agriculture production.

Recalling the works cited above, which recorded the footprints of the agri-food sector, all of them used non-physical IOTs or unidirectional trade approach in an attempt to track water and land embodied in the agricultural trade. However, as discussed, the use of these tables induces noise in the result.

On this issue, FABIO represents a response to those who questioned the accuracy of MIOT measurements in calculating agri-food footprints. At the same time, it meets Giljum & Hubacek (2004) recommendation that it is more appropriate to use PIOT in the quantification of resource requirements by the primary sector due to its resource-intensive industries and low products value.

In the present work, FABIO becomes extremely important since it allowed the identification of the total amount (footprint) of calories consumed by each nation. To the best of my knowledge, this differentiates the present work from other studies carried out to date, which provided information regarding final consumption, not considering the calories embodied in intermediate products.

FABIO's PIOTs also constitutes a single point of entry for information on the production, import, export and uses of agri-food products, distinguishing intermediate and final products. Therefore, it was crucial for the calculations regarding the resource's allocation between competing uses, define the land required for agri-food production, and provided physical insight into opportunities for improving resource use efficiency.

5. RESULTS AND DISCUSSION

5.1. GLOBAL CALORIE ALLOCATION

The temporal analysis of the global caloric content allocation among competitive uses showed that between 1986 and 2013, despite the yield growth, there was a slight reduction in the fraction of calories provided by edible crops directly for human consumption. In 1986, 43.5% (3.07E+09 Gcal) of the total caloric content of edible crops was delivered direct to human consumption. While in 2013, this fraction was reduced to 40.1% (4.62E+09 Gcal)*[1], decreasing 8.5%.

When we look at Figure 5.1, which illustrates the changes in the allocation of the caloric content of edible crops among the multiple uses, we find that since 1995, when the peak was reached (44.9%), the fraction of edible crops delivered directly to humans has been reduced by 0.25%/year on average.

[1] The numbers in parentheses represent the total quantity of calories delivered to each use in the respective year. It is worth clarifying that the amounts for 2013 will always be higher but **not** necessarily represent the higher share.

The ratio of edible crops grown for animal feed decreased 10% in the same period, going from 38% (2.65E+09 Gcal) to 34% (3.95E+09 Gcal). Despite this, animal husbandry consumed, in absolute numbers, 49% more edible crops in 2013 than in 1986. Alongside, animals consumed 20% more non-edible calories in 2013 (5.27E+09 Gcal) than at the beginning of the records (4.39E+09 Gcal).

The figure 5.1 indicates that the drop in the proportion of edible crops allocated to animals occurred mainly in the early 1990s. From 1993 onward, the percentage slight varied from year to year, but there was a consistent average of 34%.

On the other hand, Figure 5.2, which provides a breakdown of the different caloric sources of livestock feed, reveals the growth of the share of edible calories in farm animal feed over the 30 years. Edible crops have accounted for 43% of feed livestock in 2013 compared to 37% in 1986. Other edible sources always corresponded to 1 or 2% over the years. Together in 2013, these two sources amounted to 44% of the calories delivered to farmed animals. This information is in line with the findings of Davis & D'Odorico (2015), who point out that the global increase in demand for resources to feed animals was supplied by edible sources, with a gradual reduction in the share of non-edible sources over the last five decades (from 73% to 56% in terms of biomass).

The reduction in the percentage of allocation of edible calories to the animals, but the greater share of these calories in the feed is a result of changes in the animal production system. The works of Pimentel & Pimentel (2003, Pellegrini & Fernández (2018), and Lucas et al. (2019) corroborate this information. According to authors, world livestock has been industrialized, production has intensified, animals have been raised in confinement (at least for some period of life), and a greater amount of feed has been being required. Otte et al. (2007) also describe the turn in raising animals and trends towards industrialization of livestock production, pointing out that, over recent decades, high-income countries have breed animals in confinement mainly. While developing countries are replacing the traditional extensive model in an accelerated way. In this regard, Polaquini et al. (2006) portrays the situation in Brazil, the second largest producer and leader in beef exports, reporting that between the 1990s and 2000s the country witnessed the tripling of the number of cattle for beef fed in confinement.

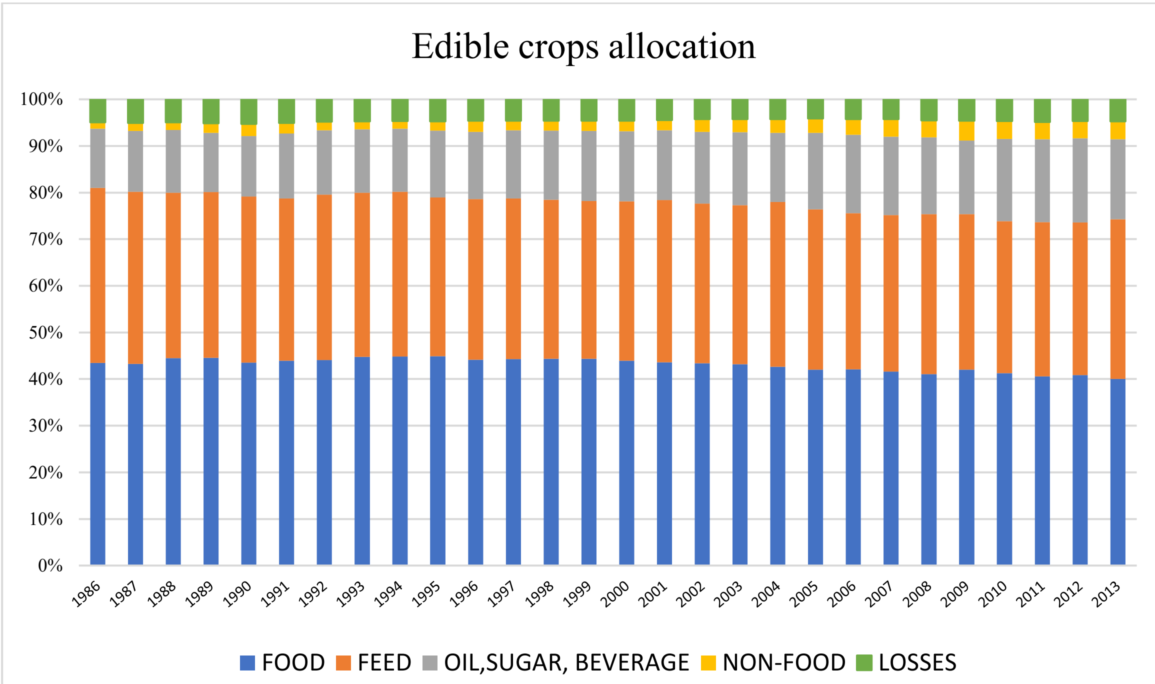


FIGURE 5.1: Respective fractions of the caloric content of edible crops allocated among the multiple uses over the studied period

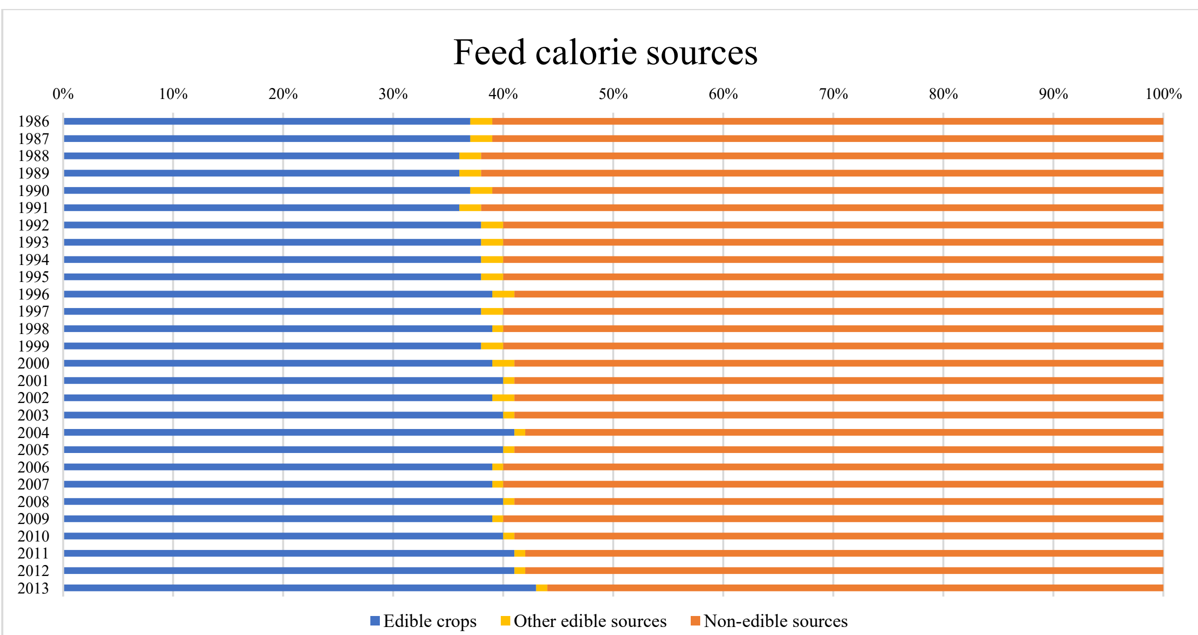


FIGURE 5.2: The caloric sources that compose the animal feed and their respective fractions over the period studied.

With regard to losses, in 1986, 3.46E+08 Gcal (4.9% of total production) were lost, while in 2013, 5.42E+08 Gcal became waste (4.7% of total production).

The energy content of edible crops allocated to non-food use, despite representing only 4% (4.45E+08 Gcal) of total production in 2013, was the category that showed the highest growth (354%) over the time, seeing that in 1986 it represented only 1.5 % (9.78E+07 Gcal). In addition, in both years, as well as over the entire studied period, approximately twice as many other edible calories (sugars, oils, crop cakes, and animal-based sources) were also delivered to non-food uses.

Non-food uses comprise applications in chemical, pharmaceutical and cosmetics industry, but mainly the production of biofuels. In this way, the results are in line with what was presented by the EIA and IEA, which highlight the growth of biofuel production in the early 2000s. It also aligns with the statements by FAPRI (2011), who reported increases in consumption of edible calories to produce ethanol in Brazil and USA. Europe, despite being dependent on imports of raw materials, has become the main producer of biodiesel in the world, and has seen its production grow over recent decades, allocating larger amounts of grains in the production of biodiesel and ethanol. Furthermore, this meets the movement spurred forwards by the Kyoto Protocol, in force at the time, seeking to combat global warming. Together, the USA Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007, fostered the production by providing various financial incentives and expanding the necessary infrastructure. EU Directive on Biofuels for Transport (2003/30/EC) set indicative biofuel proportion targets of 2% by the end of 2005 and 5.75% by the end of 2010. Regulation similar to the European one was established by the Brazilian National Program for the Production and Use of Biodiesel of 2004, which foresaw, at that time, minimum additions of biodiesel in common diesel equal to 2% and currently requires 11%. To gasoline is expected to be added 27% of ethanol.

Complete information on all calorie allocation analysis can be found in the supporting information SI 1.

5.2. CALORIE COMPOSITION OF FOOD SUPPLY

Figure 5.3 illustrates how the caloric composition of human food evolved. It is evident that throughout the period, calories consumed directly from edible crops have formed, by far, the majority of human calorie intake, followed, respectively, by other edible sources (oils, sugar, beverages) and animal-based products.

However, the previously mentioned changes in dietary patterns are also exposed here. The bars in Figure 5.3 show that between 1986 and 2013, the share of calories provided by edible crops decreased by 4%, from 65.7% to 63.2%, and there was a tendency to increase consumption from other origins. Other edible sources came to represent 20.4% of the food caloric composition in 2013, a growth of 3.5% compared to 1986. Animal-based sources had a significant increase of 11.20%, given that its share in the human diet jumped from 14.6% to 16.4%.

With the support of the lines in figure 5.3, which show the variation in the global average daily calorie intake per capita (kcal/capita/day) from each source, we can undoubtedly see the movement toward diets richer in sugars and animal-based products. It is possible to observe that the growth of calorie intake directly from edible crops was the smallest (2%) among the three sources. Since the mid-1990s, the increase of ingestion from other origins has overtaken the one related to the per capita consumption of edible crops. Coming to 2013 and comparing it with the numbers of 1986, it is identified that the increment in the intake from other edible sources was 11.4%, while the rise of the consumption of calories from animal-based products was 21%.

Still in this regard, figure 5.4 depicts in greater detail the evolution of the share of calories provided to humans exclusively by animal-based products, establishing a relationship with the growth of the world population, PIB per capita, and the global yield of calories from crops and animal-based sources.

It is possible to argue that the trend towards greater consumption of meat, eggs and dairy products was accentuated and consolidated at the end of the 1990s. What can be described as the result of (**i**) industrialization, intensification and commoditization of production that took place exactly in this period, as discussed above and claimed by Lucas et al. (2019), Otte et al. (2007) and Polaquini et al. (2006), and (**ii**) the raise in the world per capita income, also more pronounced in this period. People with higher incomes and facilitated access to food started to demand more animal products (Tilman et al., 2011; Folley et al., 2011; Davis & D'Odorico, 2015; Clark & Tilman, 2017; Poore & Nemececk, 2018).

In addition, we found that the growth rate of global crop production followed the population growth rate until the early 2000s, when the former surpassed the latter. The growth rate of animal-based calories yields surpassed the others in the mid-1990s and accelerated in the early 2000s. As previously reported, the increase in crop production did not mean a higher fraction of this resource being delivered directly to humans or feed production. Hence, with this is possible to claim that the crop production raise was mainly drive by the population growth until early 2000s, however, thereafter, the surplus was mainly allocated to for non-food uses. This meets the rise in biofuels production after 2000. This fact also indicates the optimization of the animal-based food production promoted by the intensification of its process between mid-1990 and early 2000s. The animal-based products growth rate was higher than the grow of crops or population, even not demanding larger fractions of edible calories.

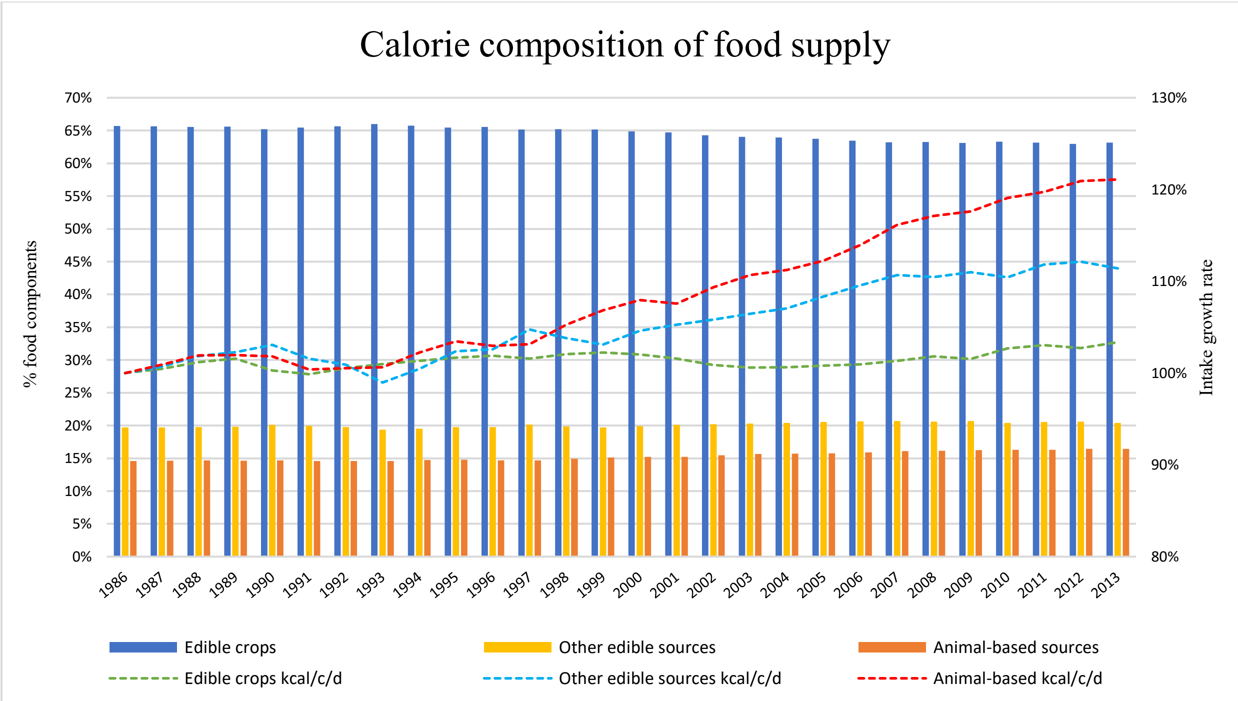


FIGURE 5.3: Share of calories supplied to humans by each of the sources (bars). And the variation of kcal/capita/day provided per each source (lines).

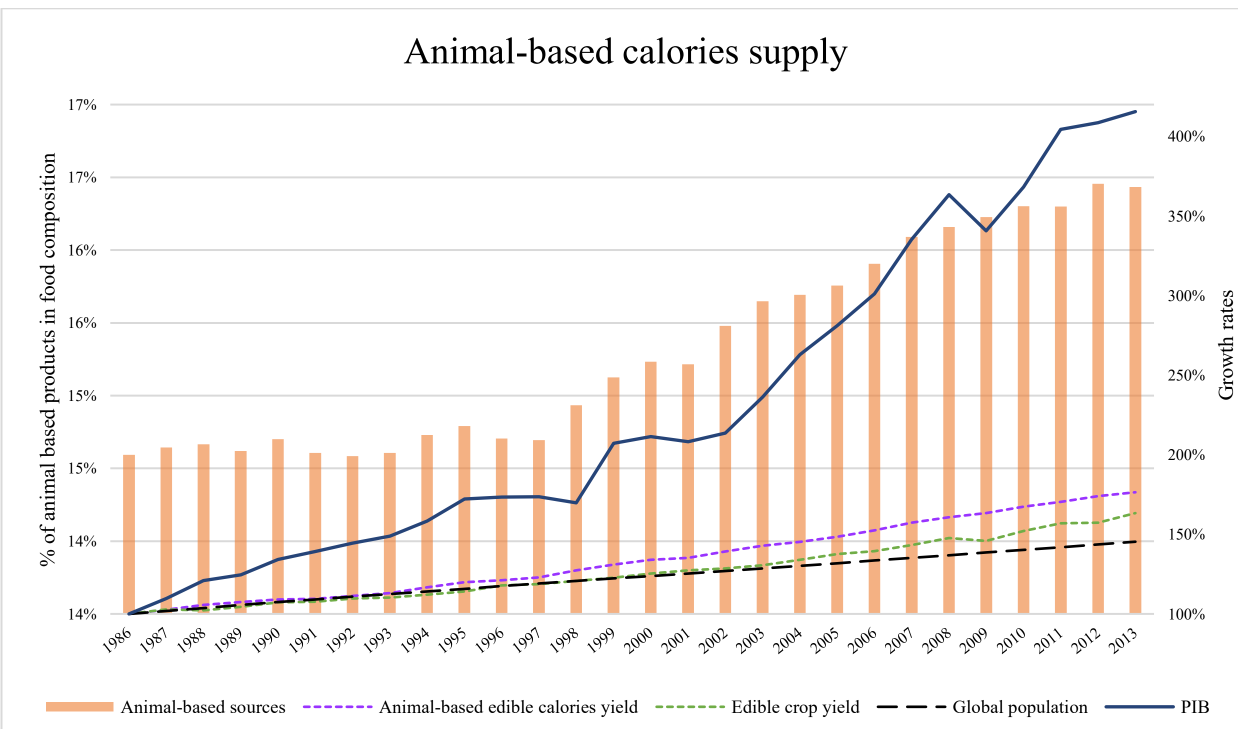


FIGURE 5.4: Share of calories provided by animal-based products to humans (bars). And variation in the yield of calories from animal-based and crops, population, and PIB per capita (lines).

5.3. THE CALORIES LOSSES IN THE WORLD FOOD SYSTEM

Figure 5.5, comparing data from 1986 and 2013, illustrates how the global flow of food calories changed, and highlights where calories have been lost from the food system. For the sake of clarification, the concept of losses here does not refer exclusively to FABIO's losses (waste), in this section losses are more comprehensive and encompasses all calories that somehow leave the food system - waste, non-food use and animal-related.

In 1986, edible crops produced 3925 kcal/capita/day. Of this total, 193 kcal/capita/day were wasted. Through non-food uses, 54 kcal/capita/day were taken from the global food supply. The sugar, beverage and oil industries received 499 kcal/capita/day. Of the remaining, 1473 kcal/capita/day were invested to feed animals. Farmed animals also consumed 67 kcal/capita/day from other edible sources (oils, sugar) and 2441 kcal/capita/day from non-edible crops (grazing and fodder crops), totalling 3981 kcal/capita/day. Finally, only 1705 kcal/capita/day of crop production were delivered for human consumption. The total edible calories available for human consumption was complemented by animal-based products (379 kcal/capita/day) and other edible sources - oils, sugars and beverages - (511 kcal/capita/day), thus, accounting for 2595 kcal /capita/day.

The 2013 frame shows that there was a 63% gain in the primary production of edible calories, that is, edible crops produced 4400 kcal/capita/day. Along with the rise in production there was an absolute increase in waste, reaching 207 kcal/capita/day. As previously mentioned, non-food use was the category that proportionally showed the greatest growth in edible calories consumption, so that, in 2013, 170 kcal/capita/day were allocated to the production of biofuels and biomaterials. Calories consumed by animals totalled 3569 kcal/capita/day, with 1507 kcal/capita/day from edible crops, 48 kcal/capita/day from other edible sources and 2014 kcal/capita/day from non-edible crops. Humans had at their disposal 2791 kcal/capita/day, 1763 kcal/capita/day from edible crops, 569 kcal/capita/day from other edible sources and 459 kcal/capita/day from animal sources.

Overall, these findings are similar to the numbers of other studies. For instance, regarding the total edible calories available for human consumption, the number presented here is only 2% lower than that indicated by Berners-Lee et al. (2018) and 8% higher than that of Cassidy et al. (2013). The only incongruity between this work and Berners-Lee's is the amount of energy given by non-edible crops to animals. This is likely due to the different methodological assumptions. This means the references used to convert the energy content of non-edible crops and cakes.

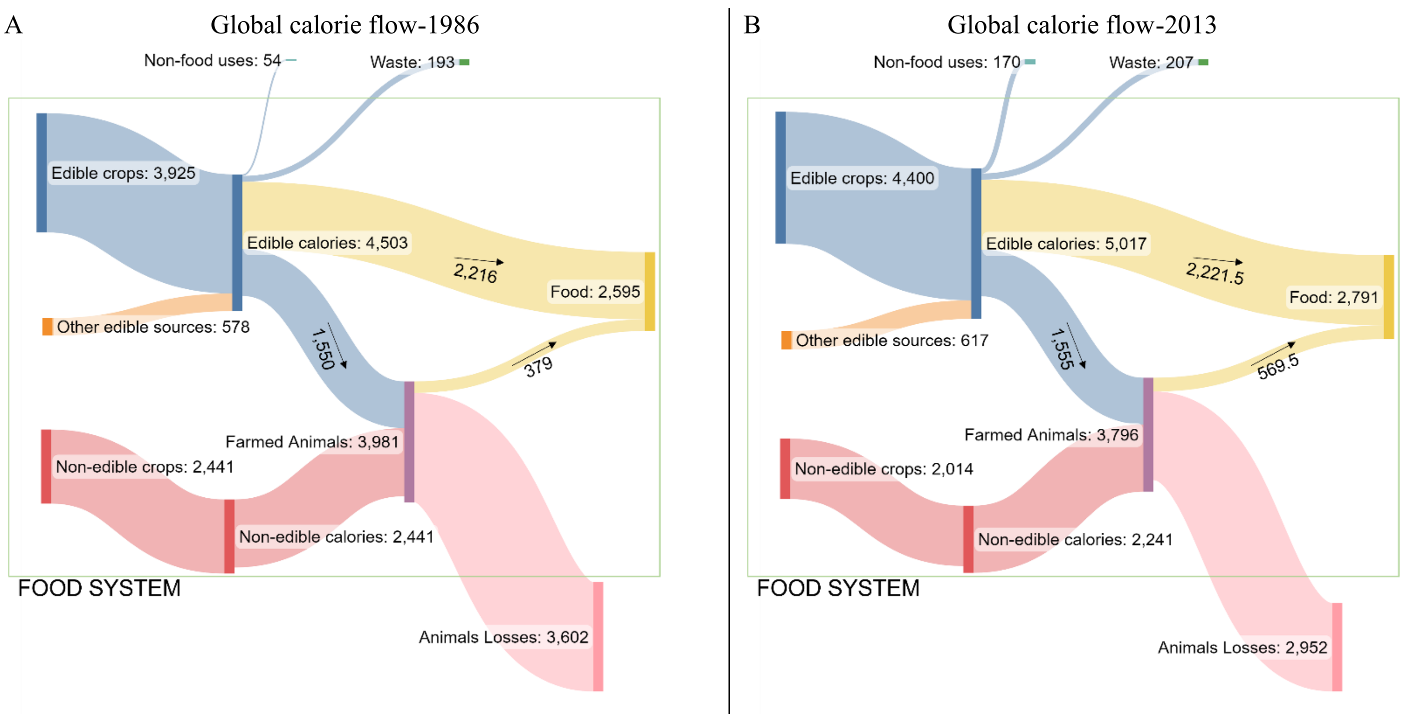


FIGURE 5.5: Calorie flow (kcal/capita/day) from the different sources to the food supply, including the losses from the food system. (**A**) In 1986. (**B**) In 2013.

In this manner, we identified that the most significant loss from the world food system comes from crop-feed-food conversion.

For instance, in 2013, farmed animals consumed the equivalent of 9.35 E+09 Gcal, whereas delivered only 1.2E+09 Gcal for human consumption, a fraction slightly higher than 12%. This conversion factor is similar to that pointed out by Berners-Lee et al. (2018) and Tilman and Clark (2014). However, it is lower than the average of 7% found by Shepon et al. (2016), who portrayed exclusively the American context, and of 4% by Cassidy et al. (2013), who used 2003 data and assumed that the entire crop cake production is consumed by animals, unlike FABIO.

At this point, an important distinction must be made. Despite the increasing share of edible calories, non-edible sources still make up most of the caloric value of animal feeds. In 2013, this accounted for 5.27E+09 Gcal, or 56% of calories supplied to herds and shoals. Notwithstanding their importance to the food system, grazing and fodder crops cannot be directly digested by humans and, therefore, cannot be utterly understood as calories available to humans. So, from this point onward, the analysis of caloric losses in the food system will only look at the ratio of edible calories delivered to animals and the return they give to the system.

Based on figure 5.6, we find that the losses from the system decreased from an average of 35%/year in the 1980s to 32.2%/year in the 2010s. In spite of the system's optimization, due to the absolute increased production of crops, animal-based products and biofuels, the volume of total losses grew by almost 50% to reach 3.86E+09 Gcal in 2013.

Throughout the period, animal-related losses continuously accounted for more than 70% of the calories leaving the food system. However, animal-related losses share has decreased (from 82% to 74%). At the same time, the non-food share has increased (from 4% to 12%), and the waste share has remained pretty constant (14%). As argued previously, these changes result from refinements in animal husbandry and increased production of biofuels, both of which intensified between end of 1990s and 2010.

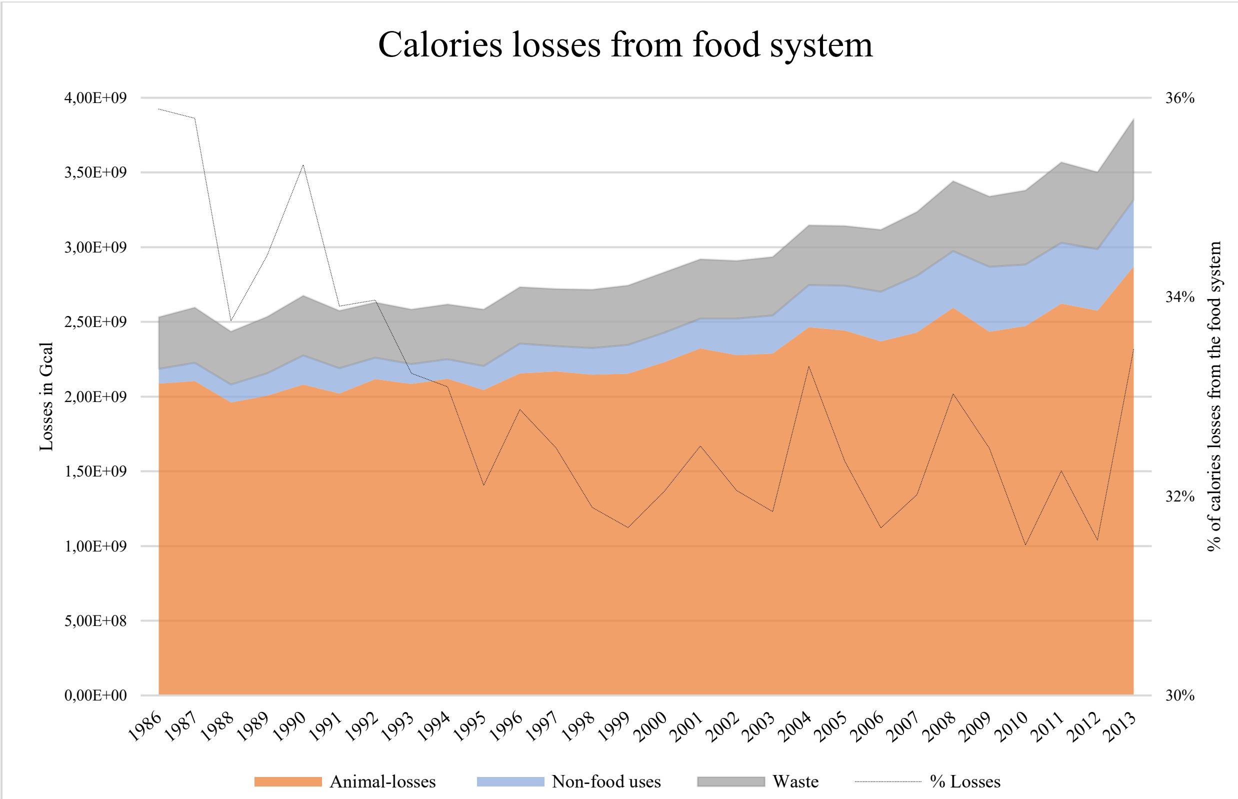


FIGURE 5.6: Calories (Gcal) losses from the food system by each of the sources (areas). And the share of calories losses from the food system (line).

Turning the attention to regional characteristics, it is noticed that the allocation of edible calories among the multiple uses differs considerably. Consequently, the calorie losses from regional food systems also vary. Due to the current agricultural model, which is characterized by the concentration of the production in just a few countries (Bentom, 2017), it was selected Brazil, China, India, Russia, and USA to further analyse the differences. Together these countries accounted for 49% of the production of edible calories in 2013. They are the largest producers and exporters of several commodities such as rice, wheat, maize, soybean, milk, eggs, and meat. However, they have dietary and cultural peculiarities that distinguish them from each other with regard to the use of their crops.

The regional analysis focused on some specific grains – maize, wheat, soybeans, sugar cane and barley. Together, in 2013, these crops accounted for 46% of the global production of edible calories. Additionally, they are the main crops allocated to animal feed or biofuel production.

Further, as can be seen in Figure 5.6, the percentage of losses fluctuates between the years. Due this fact, averages were chosen as a means of presenting the results. Therefore, as illustrated in Figure 5.7, the most relevant points for the 1980s, 1990s and 2000s (including 2011-2013) are presented as averages per decade. Finally, in the case of Russia, of course, only the 1990s and 2000s appear in the figure.

It is possible to noticed greater similarities between Brazil, Russia and the USA. These countries allocate a small fraction of the national production of edible crops to their domestic food markets. These fractions varied between 9% and 25% over the three decades. In these countries, most of the national production was destined to feed domestic herds. In the case of Brazil, this fraction varied between 28.9% and 36.5% of national production. On average, 71% of the national production of maize and 37.8% of soybeans fed Brazilian herds. In addition, approximately 46% of Brazilian exports, made up mainly of soybeans, were also allocated to animal feed in other parts of the world. A similar figure emerges from the analysis of the USA, more than 50% of corn, soybean, sorghum, and wheat exports were destined for animal feed production. Russia stands out due to the fact that it increased its exports by approximately 700% between the 1990s and 2000s, and more than 60% of its exports of barley and maize, together with 12% of wheat exports were directed to animal consumption.

In the Brazilian and American contexts, we also evidence the highest consumption of edible crops by non-food uses. They are the two leading countries in the production of ethanol fuel. The USA have applied increasing fractions of the national production of maize to produce ethanol. In the 2000s, this fraction represented 27.4%. Throughout the decades, at least 40% of Brazilian sugar cane production was converted into fuel ethanol. And in the 2000s, 24% of soybean production was employed for biodiesel production. Yet about Brazil, in the 1990s, edible calories directed to non-food consumption declined mainly because of the collapse of the national ethanol program (Pro-Alcool) and the fall in the price of a barrel of oil, which motivated drivers to consume gasoline. However, in the early 2000s, after the oil price recovered, the country returned to encourage the production of ethanol and developed the national program for soy-based biodiesel.

China has seen its animal-based food production nearly triple over the past three decades, yet much of the population adopts vegetarian or low-meat diets. In this way, China allocated, on average, 49% of its national crop production for direct human use. Despite the growth trend, the country has not delivered more than 30% of its national yield for feed production. From what was allocated, maize is the most used grain. On average, 64% of the national production of maize was utilised to feed animal. It is worth noting that China was the second largest producer of maize in the world in that time, behind USA. The country still used, on average, 46.5% of imports of edible crops, mainly maize and soybean, to feed animals. It is also worth mentioning that the main Chinese animal product is pigmeat. Pigs are known to be more efficient in processing feed-food than ruminants (Shepon et al. 2016).

India has one of the largest cattle herds in the world, however, because it is considered a sacred animal by the Hindus, who make up almost 80% of the population, the consumption of bovine meat is low in the country. Most of the population adopts vegetarian diets. Thus, India is the country that has shown the least edible calorie loss in its food system. On average, 65% of national production was consumed internally by humans. Of the imports, only 6% on average were used for feed production.

In this way, it is possible to note that among the top producers of those crops that provide the greatest amount of edible calories to the global food system, those which also stand out for the production and consumption of animal-based food, especially ruminants-based, are allocating large fractions (above 50%) of their national production to feed animals and produce biofuels. Revealing, here, a major point of calorie leakage from the food system.

1980s

- 25% of national production of edible crops was destined directly for Brazilian human consumption.
- Brazil used 1.07E+08 Gcal, or 33.2% of its national production of edible crops to feed animals in the country. 74.3% of its maize production accounted for 61% of this fraction. And 42% of the production of soybeans added 26% to this fraction.
- 14.4% of national production was consumed by the non-food industry. 62.25% of sugarcane production made up 96% of this fraction.
- Another 6% of national production was wasted.
- Of edible crop imports, 19.75% of calories (2.77E+06 Gcal) fed Brazilian herds. 75% of maize imports make up 83% of those calories. 54.4% of soybean imports added up to another 12.8%.
- 39% of Brazilian exports were used in animal feed elsewhere in the world. 55% of soybean exports accounted for 97.5% of this fraction.
- Domestic production of animal-based products amounted to 2.52E+07 Gcal. Milk accounted for 26% of this total, beef 18%, pigmeat and poultry meat accounted for 10% each.

1990s

- 9.12% of national production of edible crops was destined directly for Brazilian human consumption.
- Brazil used 1.32E+08 Gcal, or 36.5% of its national production of edible crops to feed animals in the country. 78% of its maize production accounted for 63.5% of this fraction. And 42% of the production of soybeans added 26.21% to this fraction.
- 6% of national production was consumed by the non-food industry. 56% of sugarcane production made up 89% of this fraction.
- Another 2.46% of national production was wasted.
- Of edible crop imports, 44% of calories (4.62+06 Gcal) were allocated to feed Brazilian herds. 98.6% of corn imports made up 59% of those calories. 55% of soybean imports made 20% of those calories. 66% of wheat imports added another 12.4% to that amount.
- 46% of Brazilian exports were used in animal feed elsewhere in the world. 55% of soybean exports accounted for 96.5% of this fraction.
- Domestic production of animal-based products amounted to 3.52E+07 Gcal. Milk accounted for 24% of this total, beef 18%, poultry meat 14% and pigmeat 13%.

2000s

- 16% of the national production of edible crops was destined directly for Brazilian human consumption.
- Brazil used 1.86E+08 Gcal, or 28.9% of its national production of edible crops to feed animals in the country. 63% of its maize production added up to 60% of those calories. And 29.3% of the production of soybeans amounted to 30%.
- 12.7% of national production was consumed by the non-food industry. 46% of sugarcane production made up 86% of this fraction. And 24% of the production of soybeans accounted for 14% of this fraction.
- Another 5.3% of national production was wasted.
- Of edible crop imports, 11% of calories (3.72+06 Gcal) were allocated to feed Brazilian herds. 76% of maize imports made up 53% of those calories. And 52% of soybean imports accounted for 11% of calories.
- Of Brazilian exports, 55% of calories were used in animal feed elsewhere in the world. 54% of soybean feed exports accounted for 67.5% of this fraction. And 72% of maize exports accounted for 32% of that fraction.
- Domestic production of animal-based products amounted to 5.87E+07 Gcal. Milk accounted for 22% of this total, pigmeat 20%, beef 17%, and poultry meat 14%.

1980s

- 56% of the national production of edible crops was destined directly for Chinese human consumption.
- China used 2.83E+08 Gcal, or 21.5% of its national production of edible crops to feed animals in the country. 58.3% of its maize production accounted for 60.5% of those calories. And 42% of sweet potato production and 9% of rice production made up 10.3% and 13.4%, respectively.
- 3.15% of national production was consumed by the non-food industry. 11.15% of maize production made up 70.84% of this fraction.
- Another 6% of production was wasted.
- Of the edible crop imports, 22.44% of the calories (1.92E+06) were allocated to feed the Chinese herds. 48.5% of corn imports made up 64% of those calories. Imports of cassava (50%), rice (33.5%) and soybeans (28%) added about 10% each.
- Of Chinese exports, 58% of calories were used in animal feed elsewhere in the world. 75% of maize exports accounted for 64% of this fraction. And 50% of soybean exports accounted for 12% of this fraction.
- Domestic production of animal-based products amounted to 8.78E+07 Gcal, pigmeat corresponding to 58% of this total.

1990s

- 43% of national production of edible crops was destined directly for Chinese human consumption.
- China used 4.15E+08 Gcal, or 26% of its national production of edible crops to feed animals in the country. 66% of its maize production accounted for 62% of this fraction. And 9.5% of rice production added 10.4% to this fraction.
- 3% of national production was consumed by the non-food industry. 8% of maize production made up 53% of this fraction.
- Another 5% of national production was wasted.
- Of edible crop imports, 44% of calories (5.36+06 Gcal) were allocated to feed Chinese herds. 98% of maize imports made up 29.5% of those calories. 56% of soybean imports made up 27.4% of those calories. 46% of rape and mustardseed imports added another 16.3% to that amount.
- Of Chinese exports, 50% of these calories were used in animal feed elsewhere in the world. 70% of maize exports accounted for 78.5% of this fraction.
- Domestic production of animal-based products amounted to 1.52E+08 Gcal. Pigmeat made up 50% of that total, and eggs 12%.

2000s

- 46.3% of national production of edible crops was destined directly for Chinese human consumption.
- China used 5.78+08 Gcal, or 30.3% of its national production of edible crops to feed animals in the country. 67.6% of its maize production accounted for 64.3% of those calories. 9% of rice production amounted to 7.2%. And 50% of soybeans added just over 4%.
- 9% of national production was consumed by the non-food industry. 14% of maize production made up 44% of this fraction and soybeans accounted for another 21%.
- Another 4% of national production was wasted.
- Of the edible crop imports, 48.9% of the calories (7.6E+07 Gcal) were allocated to feed the Chinese herds. 53% of imported soybeans made up 78% of these calories.
- Of Chinese exports, 36% of calories were used in animal feed elsewhere in the world. 70% of maize exports made up 84% of this fraction.
- Domestic production of animal-based products amounted to 2.6E+08 Gcal, pigmeat represented 44% of this total, and eggs 12%.

1980s

- 75% of the national production of edible crops was destined directly for Indian human consumption.
- India used 2.83E+07 Gcal, or only 3.9% of its national production of edible crops to feed animals in the country. 27% of its groundnut production accounted for 28% of that fraction. And 35% of rape and mustard seed production added 20% to that fraction.
- 0.5% of national production was consumed by the non-food industry.
- Another 3.2% of production was wasted.
- Of the edible crop imports, only 4% of the calories fed the Indian herds.
- Domestic production of animal-based products amounted to 3.97E+07 Gcal. Milk totaled 58% and butter another 15%.

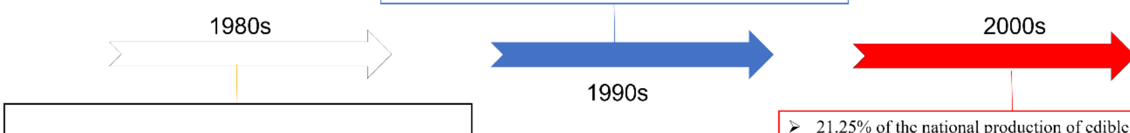
1990s

- 54% of the national production of edible crops was destined directly for Indian human consumption.
- India used 5.41E+07 Gcal, or 6.2% of its national production of edible crops to feed animals in the country. 36% of its snuff and mustardseed production accounted for 18% of that fraction. 26% of maize production added 17% to this fraction. And 49% of soybean production amounted to 15%.
- 0.5% of national production was consumed by the non-food industry.
- Another 2.6% of national production was wasted.
- Of the edible crop imports, 9.2% of the calories (2.59+06 Gcal) fed the Indian herds. 86% of maize imports account for 18% of those calories. And 23.5% of wheat imports accounted for 11%.
- Domestic production of animal-based products amounted to 5.39E+07 Gcal. Milk made up 57% of that total, and butter 18%.

2000s

- 68.6% of the national production of edible crops was destined directly for Indian human consumption.
- India used 7.44E+07 Gcal, or only 7% of its national production of edible crops to feed animals in the country. 28.5% of its maize production accounted for 23% of those calories. And 50% of soybeans added just over 20%.
- 0.7% of national production was consumed by the non-food industry.
- Another 4.1% of production was wasted.
- Of the edible crop imports, only 5.4% of the calories fed the Indian herds.
- India exported 3.5% of its national production of edible crops. 19% of these calories were used in animal feed elsewhere in the world. 67% of maize exports made up 68% of this fraction.
- Domestic production of animal-based products amounted to 9.05+07 Gcal. Milk totaled 56% and butter another 24%.

- 18.5% of the national production of edible crops was destined directly for Russian human consumption.
- Russia used 1.1E+08 Gcal, or 46% of its national production of edible crops to feed animals in the country. 72% of its barley production accounted for 33.5% of this fraction. 33% of wheat production added 29% to this fraction. And 65% of oats production accounted for 16% of that fraction.
- 0.56% of national production was consumed by the non-food industry.
- Another 1.2% of national production was wasted.
- Of the edible crop imports, 73% of the calories (1.4+07 Gcal) were allocated to feed Russian herds. 72% of wheat imports made up 42% of those calories. 97.5% of cornmeal imports made up 33.5% of those calories. And 77% of barley imports added another 16% to that amount.
- Russia exported 1.9% of its national production of edible crops. 38% of these calories were used in animal feed elsewhere in the world. 65% of barley exports accounted for 52% of this fraction. 26% of sunflower seed exports accounted for 14% of this fraction. And 16% of wheat exports accounted for 13.6% of this fraction.
- Domestic production of animal-based products amounted to 3.5E+07 Gcal. Milk accounted for 43% of that total, and pigmeat 12%.



- 21.25% of the national production of edible crops was destined directly for Russian human consumption.
- Russia used 5.78+08 Gcal, or 30.3% of its national production of edible crops to feed animals in the country. 67.6% of its maize production accounted for 64.3% of those calories. 9% of rice production amounted to 7.2%. And 42% of sweet potato production and 50% of soybean production added just over 4% each.
- 1.2% of national production was consumed by the non-food industry.
- Another 1% of production was wasted.
- Of the imports of edible crops, 38% of the calories (4.87E+06) were allocated to feed the Russian herds. 71% of imported barley made up 30% of those calories. 33% of wheat imports made up 21% of those calories. 80% of corn imports made up 20% of those calories. And 61% of soybean imports made up 17% of those calories.
- Russia exported almost 14% of its national production of edible crops. 24% of those calories were used in animal feed elsewhere in the world. 66% of barley's exports made up 43% of this fraction. 12% of wheat exports accounted for 38% of calories. And 66% of maize exports accounted for 11.3% of calories.
- Domestic production of animal-based products amounted to 3.89E+07 Gcal, milk represented 40% of this total and pigmeat 13%.

1980s

- 11.62% of the national production of edible crops was destined directly for American human consumption.
- USA used 5.57E+08 Gcal, or 44% of its national production of edible crops to feed animals in the country. 60% of its maize production made 72% of those calories. And 32.4% of soybean production added 10.3% of those calories.
- Approximately 4% of national production was consumed by the non-food industry. 6.7% of maize production accounted for 84.5% of this fraction.
- Only 0.6% of production was wasted.
- Of the edible crop imports, 42% of the calories (8.22E+06 Gcal) were allocated to feed the American herds. 74% of oats imports accounted for 32.2% of that amount. 84% of barley imports accounted for 22%. And 95% of corn imports accounted for 18%.
- USA exported 29.5% of its national production of edible crops. 48% of these calories were used in animal feed elsewhere in the world. 68% of maize exports made 60% of those calories. 51% of soybean exports accounted for 18.5%. And 95% of sorghum exports accounted for 11%.
- Domestic production of animal-based products amounted to 1.37E+08 Gcal. Milk, Pigmeat, Poultry Meat and Bovine Meat accounted for 23%, 13%, 9% and 9%, respectively.

1990s

- 9.1% of the national production of edible crops was destined directly for American human consumption.
- USA used 6.06E+08 Gcal, or 43% of its national production of edible crops to feed animals in the country. 58.7% of its maize production accounted for 59% of this fraction. And 32.7% of the production of soybeans represented 11.4%.
- 3.9% of national production was consumed by the non-food industry. 8% of maize production accounted for 81.4% of this fraction.
- Only 0.65% of production was wasted.
- Of the edible crop imports, 65% of the calories (2.26E+07 Gcal) were allocated to feed the American herds. 87% of barley imports accounted for 30% of this amount. 94% of oats imports amounted to 23%. 96% of maize imports accounted for 20% of those calories. And 91.5% of wheat imports accounted for 15.4% of this fraction.
- USA exported 27.4% of its national production of edible crops. 49% of these calories were used in animal feed elsewhere in the world. 68% of maize exports, 53% of soybean exports, and 95% of sorgum exports, represented, respectively, 62.5%, 19.5% and 10% of the exported calories that were allocated to livestock feed.
- Domestic production of animal-based products amounted to 1.52E+08 Gcal. Milk, Pigmeat, Poultry Meat and Bovine Meat accounted for 22%, 14%, 11% and 9%, respectively.

2000s

- 12% of the national production of edible crops was destined directly for American human consumption.
- USA used 5.97E+08 Gcal, or 35.6% of its national production of edible crops to feed animals in the country. 45.5% of its maize production represented 78.5% of that amount. And 32.4% of the production of soybeans represented 15%.
- 16.5% of national production was consumed by the non-food industry. 27.4% of maize production represented 96% of this fraction.
- Only 0.6% of production was wasted.
- Of the edible crop imports, 44.4% of the calories (2.32E+07 Gcal) were fed to American herds. 72% of wheat imports made up 42% of those calories. 85% of maize imports made up 30% of those calories. 77% of barley imports added another 22.5% to this amount. And 36.5% of wheat imports added another 13% to that amount.
- USA exported 25.4% of its national production of edible crops. 49% of these calories were used in animal feed elsewhere in the world. 56% of wheat imports represent 60% of this amount. And 51% of soybean imports represent 27%.
- Domestic production of animal-based products amounted to 1.78E+08 Gcal. Milk represented 22% of this total, pigmeat, pultry meat and bovine meat accounted for, respectively, 15%, 13% and 8%.

FIGURE 5.7: Timeline of edible calorie allocation among the multiple uses in Brazil, China, India, Russia and USA.

5.4. GLOBAL FOOD PRODUCTION AND ITS POTENCIAL TO MEET THE HUMAN CALORIC REQUIREMENTS IN 2050.

With the previous analyses, it was possible to identify three main points that indicate the potential of the current agri-food sector to feed a bigger number of people. That is, opportunities to increase food availability and relieve the pressure on the food system that needs to find ways to feed 10 billion people by 2050.

As discussed, the feed-food conversion has not been shown to be an efficient way of providing calories to humans. Even so, the food system has allocated significant fractions of its edible calorie yields to feed herds and shoals.

The competition between the food system and non-food uses has intensified. Over time non-food uses have received rising fractions of edible calories, mainly to produce biofuels.

Finally, it was also identified that the food system has provided, on average, each human being with quantities greater than the ideal daily intake of calories (2500 kcal/capita/day). This surplus could also be used to feed a larger population.

In this way, in the hypothesis of rearranging the current distribution, whether the calories delivered to farmed animals and non-food uses were reallocated directly to human consumption, we would have, in 2013, an addition of 5.49E+09 Gcal available. This amount represents 75% of all edible calories delivered to humans (7.31E+09 Gcal). Adding these calories to the surplus supplied to humans (7.61E+08 Gcal), we would have enough to feed an additional 6.84 billion people.

This number is quite bigger than the 4 billion presented by Cassiy et al. (2013). However, it is thought that it makes sense because the author used data from 2004 and assumed the ideal intake to be 2700 kcal/day.

Figure 5.8 illustrates the number of extra people fed by the calories from each of the identified points over time. It is clear that the yields are more than sufficient to meet 2050s demands for food. However, profound changes in dietary patterns are imperative. As illustrated, in 2013, solely with the amount of edible calories allocated to animals (4,07E+09 Gcal), it would be possible to feed 4.46 billion people, or 65% of the potential additional people fed by changes in the system. Animal-based products delivered 1.2E+09 Gcal to the system that same year. These calories could only feed 1.32 billion people. Ratifying, in this manner, the huge gap between return on investment and the finding that this is the biggest reason for calorie losses from the food system.

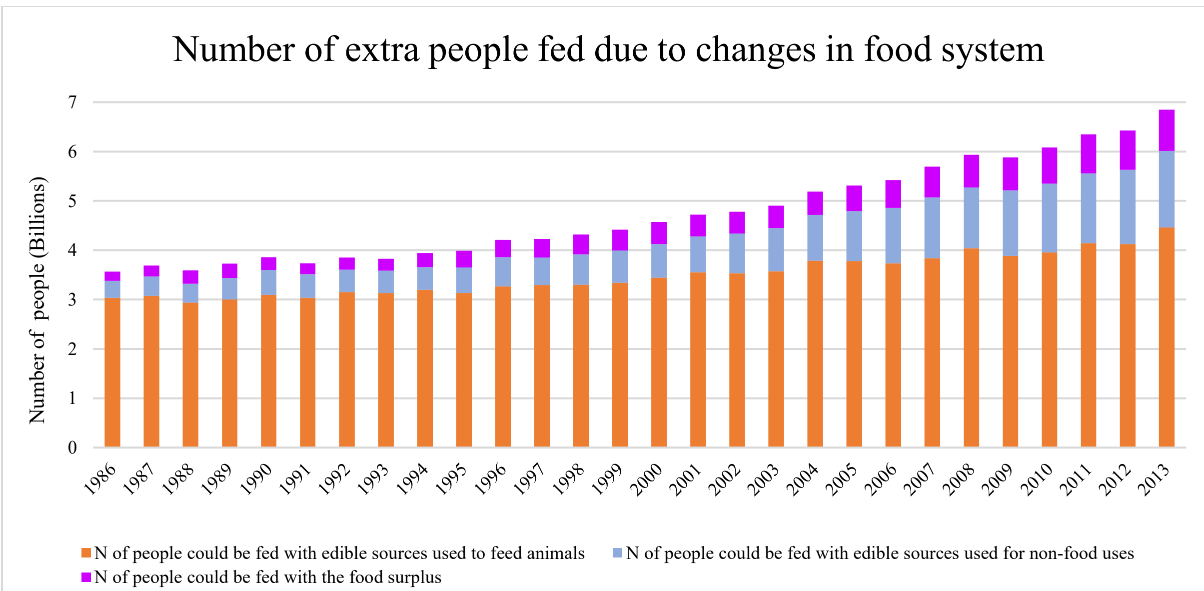


FIGURE 5.8: The number of people that could be fed by the calories provided by each point identified as a factor of calorie loss from the food system or by the supply surplus.

Figure 5.8 also supports the argument that the gains in calorie yields did not exclusively meet the demand imposed by the larger population but were also driven by increased calorie consumption by animal husbandry and applications in non-food uses.

Translating the agri-food calories yields into the number of people that could be fed per hectare of cropland, we identified that the gains can be attributed to the expansion of cropland, as well as the optimization of the production system (see figure 5.9). In 1986, 10.9 people could be fed with 2500/kcal/day per hectare of cropland. With an increase of 42% by 2013, this number reached 15.5 people, indicating the optimization that occurred in the system. However, if the losses related to the feed-food conversion and the calories allocated to non-food uses are considered, this ratio would be reduced to 7.7 people fed/hectare in 1986 and 11.2 people fed/hectare in 2013, a reduction of approximately 38% in both years.

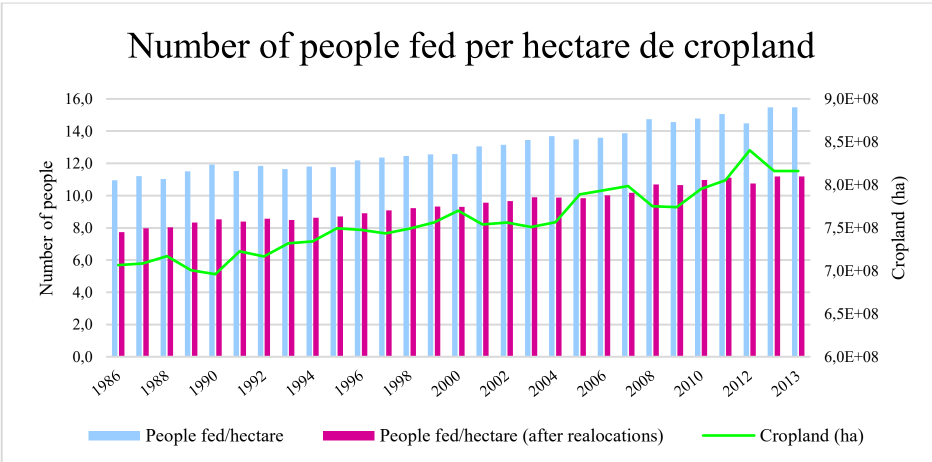


FIGURE 5.9: Number of people fed per hectare de cropland if all yield were allocated direct to human consumption (blue) and after losses related to feed-food conversion and calories allocated to non-food uses (pink). Green line indicates de extension of cropland (ha).

Returning the focus to the regional characteristics, it is possible to identified that, in 2013, Brazil, China and the USA had a ratio of people fed/hectare higher than the world average (see figure 5.10). However, after subtracting losses, only China still had this ratio higher than the world average. The Brazilian ratio dropped from 15.75 people fed/hectare to only 5 people fed/hectare. The American ratio, which was the highest before the reallocations (19.2 people fed/hectare), fell to 6.2 people fed/hectare after the losses. The Russian ratio decreased by almost 50%, from 7.5 to 4 people fed/hectare. India, in turn, was the country that showed the smallest drop after losses, going from 8.35 to 6.75 people fed per hectare.

The reasons for these differences are the same as those presented in the previous section. Brazil and the USA allocate more than 50% of their maize, soybean, and sugar cane production, for example, to produce biofuel and feed animals around the world. China also allocates relevant parts of its production to animals, but the focus on pigmeat production and the fact that a large part of the population is vegetarian, put a brake on the decline in the relationship. India is the country with the least loss from its food system thanks to the low production and consumption of meat in the country and the fact that it exports a small portion of its national production.

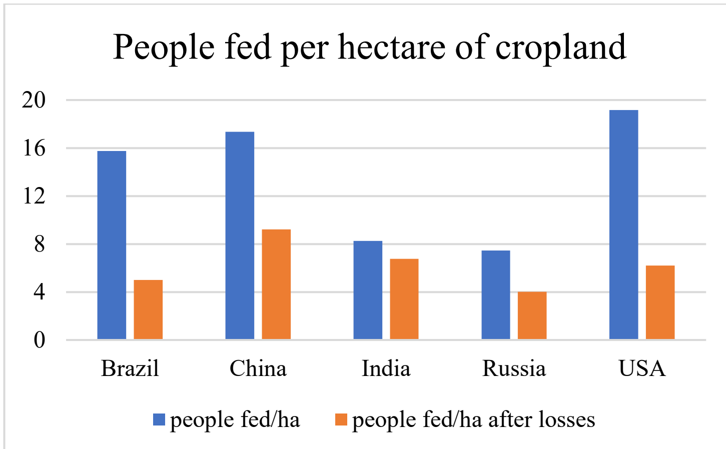


FIGURE 5.10: Potential number of people fed per hectare of cropland before the of edible calories among the multiple uses (blue) and after the losses from food system (orange).

With this translation exercise, it was possible to explore an extra factor that could also increase edible-calories available in the food system. It is about converting grassland areas into croplands. Grasslands cover more than one-third of continental surfaces, representing, in 2013, 62% of the land used by global agriculture. Yet, they do not produce calories that can be fully understood as human-edible. In such a way, the conversion of these areas could mean positive returns for the food system.

It is necessary to keep in mind that shares of grassland occupy areas that are not exactly suitable for the cultivation of grains, either due to fertility, terrain conditions or other environmental factors. Therefore, a complete usage conversion would be unrealistic and impossible.

However, considering the cropland productive capacity of 2013 (15.5 people fed/hectare) and the territorial extension of grassland (1.43E+09 hectares), the conversion of a mere 10% of these areas would mean a caloric increase sufficiently to feed 2 billion people.

5.5. CALORIE FEED-FOOD CONVERSION EFFICIENCY AND LAND DEDICATED TO ANIMAL HUSBANDRY

First, it should be emphasized that animals produce edible calories that are also consumed by other uses, such as fats applied in industries. This fraction that has been lost from the system was constantly around 10% of all the edible calories produced by the animals. For example, in 2013, the animal-based calorie loss from the food system was 1.29E+08 Gcal. Enough calories to feed approximately 150 million people. Therefore, in this section, although all outcomes are taken into account regardless of their final use, it was adopted the term *'feed-food'* conversion, since practically 90% of production is consumed as food and due to the idea that the losses could mean more people fed. It should also be said that the inclusion of losses had low influence on the results. Efficiency would decrease by an average of 0.6% if leaks were excluded.

Figure 5.11 illustrates the evolution of feed-food conversion efficiency over time. It is possible to observe the continuous optimization of the process, which reached its peak, around 13%, after 2010. Further, figure 5.11 also highlights the percentage of global cropland used to grow crops to feed farmed animals. It is observed that the downward line of cropland share crosses the upward line of efficiency in the mid-1990s, and they distanced themselves more sharply after the beginning of the 2000s. It is argued that this is due to the progress achieved by agriculture practices, which has invested in genetic engineering to select seed lineage and breeding animals, better management of irrigation and fertilizer application, and production automation (Pingali, 1992; Bailey-Serres et al, 2019). As the processes intensified, higher crop yields per hectare was obtained and a smaller amount of calories was needed to produce the same volume of meat, dairy, and egg. This culminated in the reduction of the percentage of cropland used to grow crops intended for animal feed. Yet, this picture reinforces the information that the optimization in crop production was followed by refinement in raising animals, which took place in the mid-1990s and expanded in the 2000s (Polaquini et al., 2006; Otte et al. 2007).

It is noteworthy that the husbandry intensification process also involved pasture intensification. From 1986 to 2013, 13% less grassland was used to animal feed. Through improved fodder grass selection, the incorporation of leguminous, tillage reduction, fertilization of rotationally grazed pastures, and the introduction of mixed systems, occurred the reduction of grassland area occupied to farm animals (Strassburg et al., 2014; Erb et al., 2016). A certain decoupling of yield growth from land dependence, promoted by the intensification of the animal husbandry and the pasture, brings benefits not just to the food system but also has the potential to contribute to the solution of other challenges humanity faces. Several works indicate that spare land is crucial for the conservation of natural ecosystems and mitigation of the greenhouse effect (Tilman et al., 2002; Defries & Rosenzweig, 2010, Godfray et al., 2010, Herrero et al., 2010).

To demonstrate the relationship between food supply and the area dedicated to animal raising, figure 5.11 also brings the fraction of animal-based calories that make up human caloric consumption. Even with progress in all production practices, the production of animal-based products remains a land use-intensive process. In 2013, grassland corresponded to 62% (1,31E+09 ha) of the entire area occupied by agriculture (2,3E+09 ha) and 35% (2,88E+08 ha) of the cropland was dedicated to growing edible crops to feed animals. In return, animal-based calories made up just 16.43% of the food supply. In 1986, these percentages were 71%, 39%, and 15% respectively.

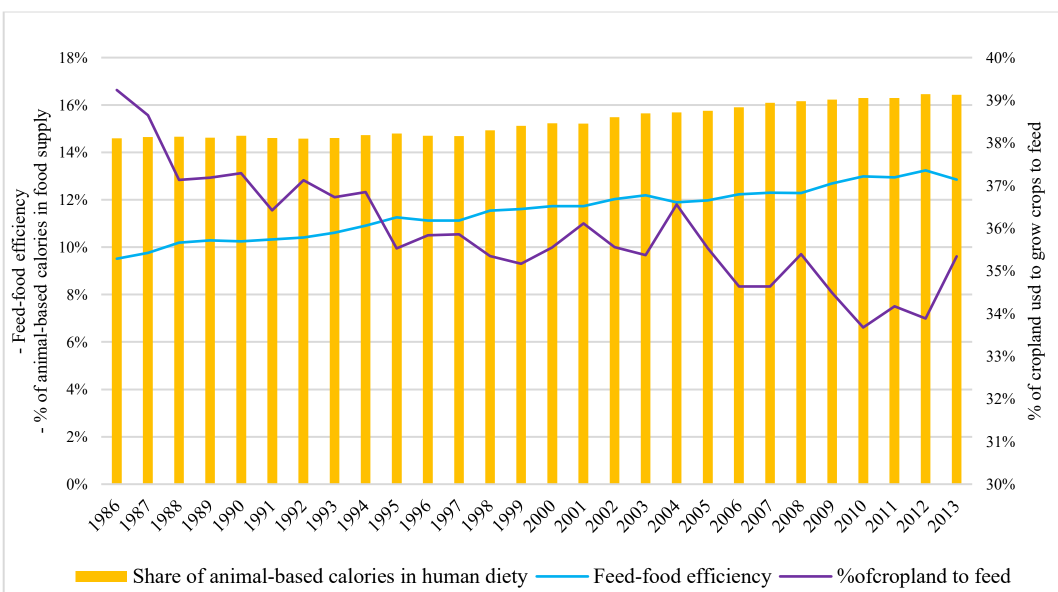


FIGURE 5.11: Global feed-food conversion efficiency (blue), and share of cropland used to grow crop to feed animals (purple)

Analysing the feed-food conversion efficiency of each animal-based product individually, we found that milk and pigmeat are the those that have consistently provided more calories for the multiple uses. Throughout the period, milk steadily delivered 24%-25% of the total energy supplied by animal-based products. Pigmeat share always corresponded to 21%-23%. Another major contributor is fat, which contributed 17% on average. It is also worth remarking that the share of poultry meat doubled over the period. In 1986, it corresponded to 5% of the energy provided by animals, while, in 2013, it represented 10%. On average, the stakes of eggs, butter, and bovine meat were 6%.

In contrast, the analyses of the inputs required by each animal reveals that the system has been investing more resources in those that do not contribute with proportional returns. On average, fats and bovine meat production consumed, respectively, 32% and 22% of all calories supplied to the animals. Milk and pigmeat consumed 15% on average. While poultry meat and egg consumed, on average, 4% and 3% each.

Thus, as illustrated by Figure 5.12, it is remarked that the feed-to-food conversion efficiency rate of beef and fat production are extremely low. Over time, feed-food conversion of bovine meat and fat remained constant at 4% and 7%, respectively. Poultry meat efficiency also remained pretty constant, but at a rate of 24%, considerably higher than the two mentioned above. Pigmeat, milk, and egg production were optimized, and conversion efficiency increased. Among the most relevant products for the system, the egg is the one with the best feed-food conversion efficiency.

While the bovine meat efficiency presented here meets the claimed by the literature, the other rates vary. With regard to dairy products, the result of this work is in line with the conclusions of Shepon et al. (2016) and Alexander et al. (2016). However, it is considerably lower than the 40% efficiency reported by Cassidy et al. (2013). Yet, the ratio presented here and associated with pigmeat, poultry meat and eggs are considerably higher than those reported by other authors. It is argued that this possibly results from the different ways the feed conversion was calculated especially in the case of monogastric animals. For example, Cassidy et al. (2013), in order to allocate the feed, assumed that (i) livestock consuming feed grains is proportionate to their production, (ii) dairy cow feeds have 60% grassy fodder component, while beef cattle feed has 15%, (iii) monogastric are fed exclusively with grains, excluding fodder crops from their feed, and (iv) counted only the inputs while dairy cows and monogastric animals are being fed with grains (in many countries, this is not a standard). The FABIO model, in turn, uses the detailed data on feed supply from FAO and estimates the feed demand of animals based on the amount of feed needed to produce 1 kg of product, as provided by Bounwman et al. (2013). FABIO does not make a direct distinction between the dairy cow and beef cattle feed and assumes that pig feed contains fodder crops. Further, FABIO is input-output model, built from the balancing and harmonization of supply and use tables, hence, differs slightly from food balance sheets employed by all other authors.

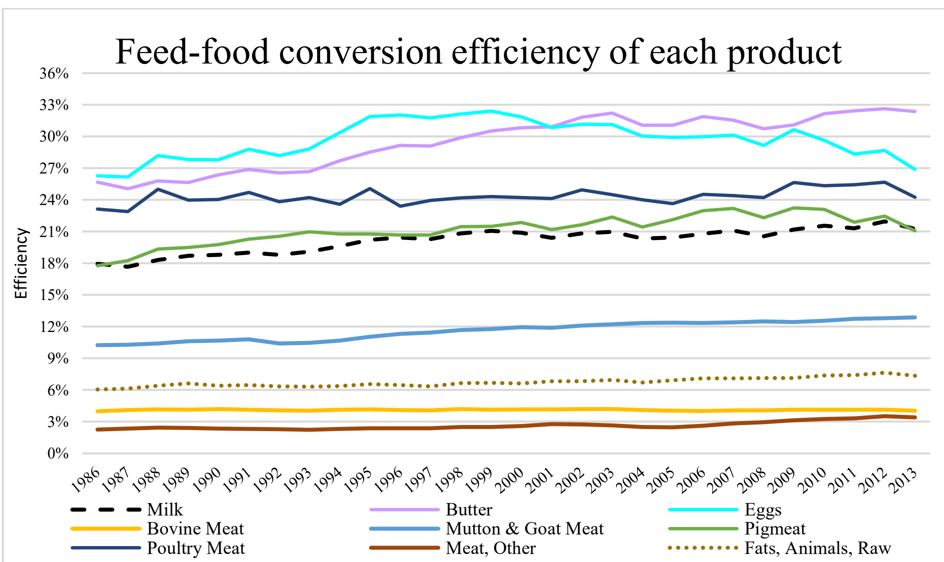


FIGURE 5.12: Evolution of food-feed conversion efficiency by products over the years.

Differences between specific feed requirements and composition are large in different regions of the world (Herrero et al., 2010). This fact, combined with dietary preferences and other characteristics of animal husbandry, influences the efficiency of local production.

To illustrate the variations, Brazil, China, India, and the USA were selected. These countries are the world's top dairy and meat producers, and together they provide 49% of all animal-based calories. Again, the average of the decade was adopted to present the information.

India is the world's largest milk producer, with roughly 19% of global production in 2013. Milk production in India has always been more efficient than the world average. The Indian rate has remained around 45% efficiency over the three decades. This aspect can be attributed to the fact that the country directs a tiny portion of its crops to feed animals. The large milk production is due to the country's large foraging herd.

China is the biggest pigmeat producer in the world, accounting for 53% of global production in 2013. In all decades, pigmeat corresponded to more than 45% of all animal calories produced and consumed in the country. Therefore, pigs were the animals that consumed the most feed. On average, 56% of all edible calories supplied to the animals were destined for pigs. China was able to optimize the pigmeat production process over time thanks to the industrialization of production. In the 1980s, the average efficiency rate was 33%. In the 2000s, the rate increased to 38%, the best performance among the countries analysed. It is important to highlight that the share of edible crops in pig feed has increased over the decades, making up 99% of its calories (mainly maize). Something expected because it is a monogastric animal, but it also exposes a considerable factor of edible calorie losses.

Brazil and USA have varied productions. Furthermore, fractions of animal-based calories produced by each product are similar across the countries. Milk, pigmeat and poultry meat correspond to about 24%, 14% and 13.5%, respectively, in both countries. The main difference is found in bovine meat production. In Brazil, over the three decades, bovine meat represented, on average, 18% of the production of edible animal-based calories. In the US, beef added up to 10% on average. With regard to the intensification of production, the distinctions between both countries are in line with what is claimed by Otte et al. (2007). The USA, a rich and developed country, has a long-standing, more sophisticated production system. Most of the animals are fed in confinement, which results in a larger share of edible calories in the composition of more nutritionally complex feed and greater yield. Referring to bovine meat production, USA allocated, on average, 14% of all calories offered to animals to beef cattle, 36% of these calories were edible, and the average yield was 10%. In Brazil, 35% of all energy delivered to animals is destined for beef cattle. Despite the growth, the share of edible calories in the feed composition is only 7% on average. And its average yield is 3%.

Complete information on all analysis regarding feed-food conversion efficiency can be found in supporting information SI 2

5.6. DRIVERS OF DIET-RELATED LAND USE IMPACT

The expansion and intensification of agricultural production have environmental consequences (Tilman et al., 2002; Steinfeld et al., 2006). Land use is one impact that deserves special attention as it is intrinsically connected to a cascade of other environmental consequences. (Erb et al., 2007). Therefore, it was the impact selected to understand how dietary choices affect the ecosystem and what factors have driven the evolution of this impact. The results presented reflect the domestic calorie consumption, accounting for the total amount of calories produced in the national territory, plus imports minus exports.

Figure 5.13 shows, by time intervals, the trends of the driving factors in the selected countries land-use impact, according to the IPAT identity and the index decomposition analyses (LMDI or Additive Sato-Vartia decomposition). The changes in the impact (**Δ land-use**) are presented as the result of: ratio of agriculture land (hectares) to unit of calorie output (**e**); ratio of total consumption of animal-based products (in tons of biomass) to total food consumption (in tons of biomass) (**L**); calorie consumption per capita (**C**); ratio of animal-based products (in tons of biomass) to total calorie consumption (**R1**); and ratio of total calories production to animal-based production (in tons of biomass) (**R2**).

It is possible to note that there were positive effects related to technological advances in all countries. The higher calorie yield per hectare, expressed by the factor e, is the dominant driving force contributing to the reduction of land use impact. The intensification of pasture and animal husbandry, related to the factor R2, also contributes to minimising the impact, however, it has a relatively small influence on the result.

Nevertheless, the rebound effect caused by affluence and higher absolute consumption has nullified the gains and led to an increase in impact.

Greater production was required to meet the absolute higher demand for animal-based food. Despite technological advances, raising animals is still heavily land-intensive, dependent on large expanses of pasture and cropland. Hence, it proved to be the main driving force behind the land-use impact increase.

The increased demand for animal-based calories itself, as well as the shift toward affluent diets abundant in calories (higher calorie consumption per capita), are two other factors that have a significant impact on the negative impact. The relative importance of these factors for the impact varied but had more significant participation in the context of the USA, the wealthiest nation among those studied, whose population has greater purchasing power, greater access to animal-based products, and consumes large amounts of processed food (plentiful in calories).

In aggregate, from the point of view of domestic calorie consumption, the USA was the only one among the selected countries capable of dissociating the increase in calorie consumption from reliance on the land, likely because of its more efficient production system.

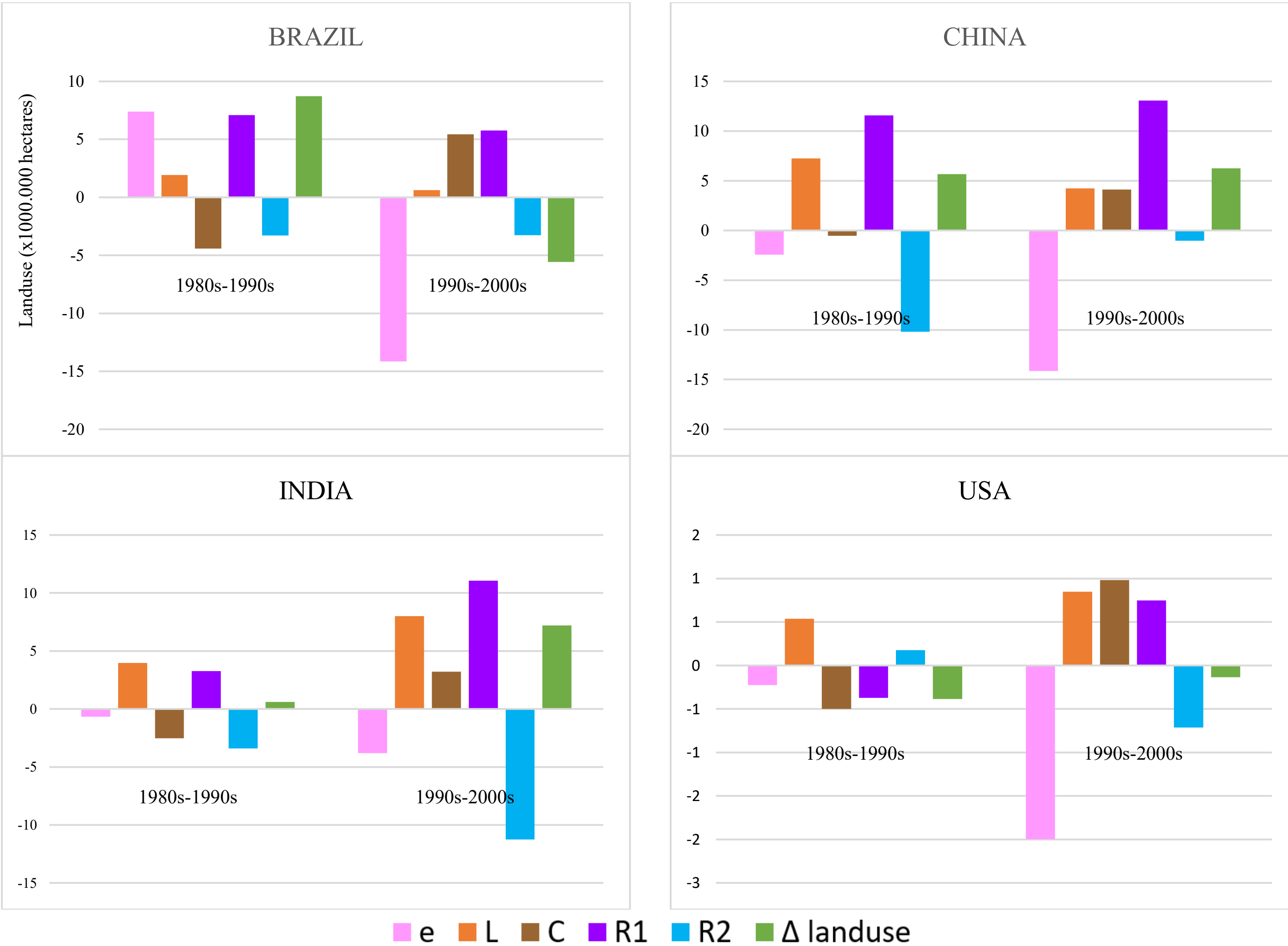


FIGURE 5.13: Decomposition of agriculture-related land-use impact from agri-food consumption in Brazil, China, USA, and India. **Note** that information is in x100.000 hectares, however, charts have different scales. **e** = Land use (hectare) per unit of calorie output. **L** = Consumption of animal-based products (ton)/ Total biomass consumption (ton). **C** = Calories consumption per capita (Gcal/capita). **R1** = Animal-based production (ton)/ Total calories consumption (Gcal). **R2** = Total calories production (Gcal)/Animal-based production(ton).

5.7. THE CALORIE FOOTPRINT OF NATIONS AND THE GLOBAL TRADE OF AGRI-FOOD COMMODITIES

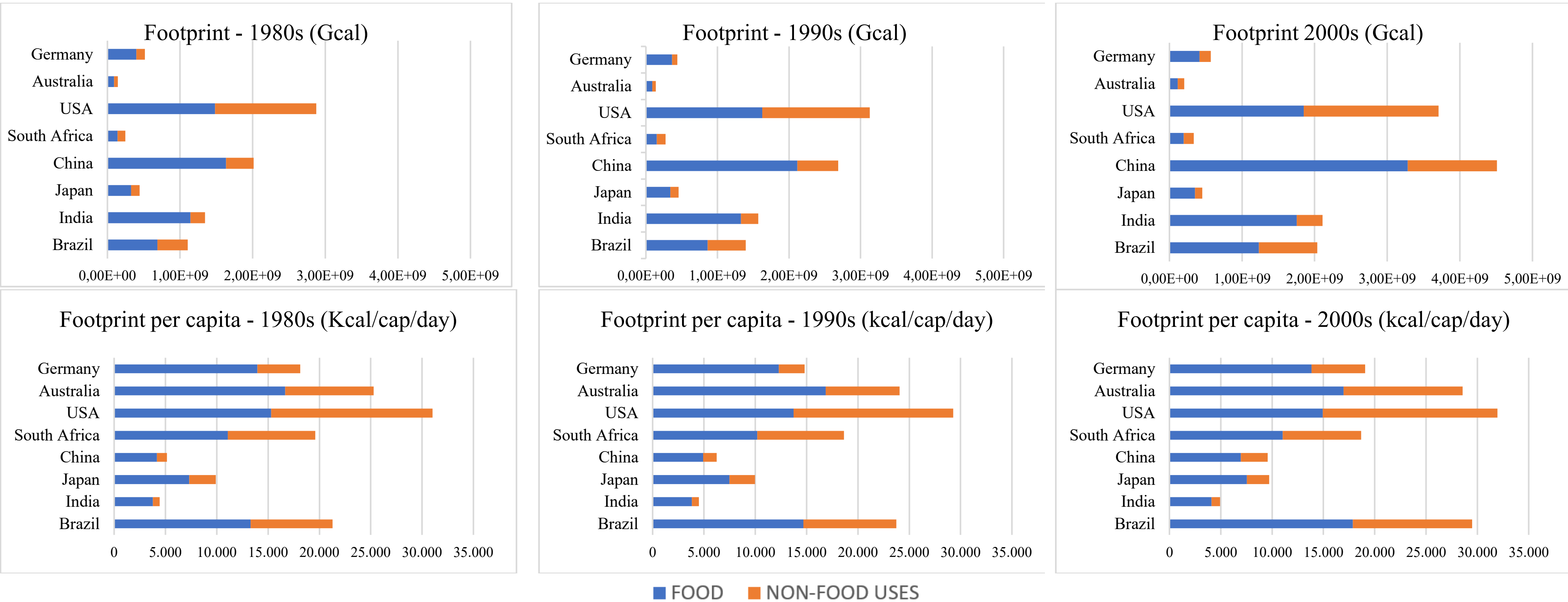
When all the calories (edible crops and fodder crops) consumed as food and non-food uses are added together, it was identified that the global production of calories appropriated by the human species grew by 59% over the period studied. In 2013, this amounted to 3.41E+10 Gcal. This number also represents the caloric footprint. Footprint is equal to production, however, differently from a production indicator, it reveals how the raw calorie yield was allocated to final demand, that is, who consumed the food products.

The analysis also illuminated the intensification of the global trade of food commodities. In 1986, international trade accounted for 16.75% of domestic output. In 2013, roughly one-quarter (23%) of total calorie production was displaced to meet demand in another region. In absolute numbers, this variation represented twofold as many calories being traded. This growth is in line with FAO data (2020) that indicate the escalation of exports of agri-food products over the last three decades. FAO (2015) highlights that even self-sufficient countries import some food products. Furthermore, according to D'Odorico et al. (2014), the growth of crop production has been driven mainly to meet international demand.

Focusing on the footprint related exclusively to food consumption. If calories from non-edible sources are accounted for, no country would have a food supply per capita below the ideal daily calorie intake (2500kccal/capita/day). However, when the percentage referring to non-edible calories (grazing and fodder crops) is excluded, it is found that in 1986 more than half of the countries had a calorie supply lower than the ideal. Over the years, there has been a general gain. More countries (77%) have enough calories to offer their population, and even those that still show suboptimal supply managed to improve their conditions. These countries are located mainly on the African and South Asian continents. In this regarding, Porkka et al. (2013) and Puma et al. (2015), point out that, although 85% of countries have either low or marginal food self-sufficiency, the share of the world population living in countries with sufficient food availability doubled between 1965 and 2005, reaching almost two-thirds of the population. In addition, the proportion of people living on less than 2000 kcal/day dropped from about 50% to only 3% in that same period.

To exemplify how the calorie footprint varies between different regions and different income patterns, 8 countries were selected. Brazil, China, India and USA, the largest agricultural producers in the world. South Africa, the Africa's third largest economy and a BRICS member State. Representative of the EU-27, Germany is the largest economic power and biofuel producer in the bloc. Australia has large herds of cattle and sheep and is also one of the countries with the highest consumption of meat per capita. Japan, USA, Germany, and Australia are in more advanced stages of economic development than other countries.

Again, decades average was chosen as the way to present the results (see figure 5.14).



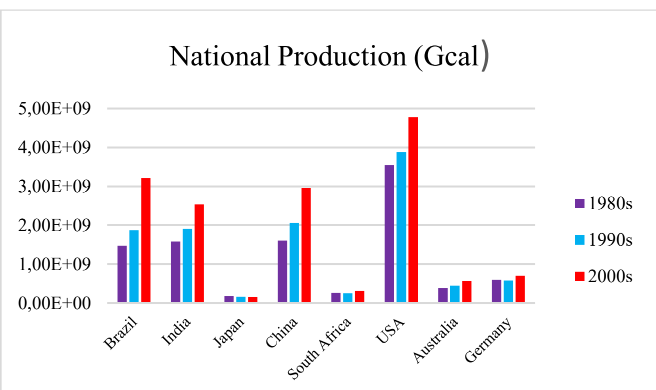


FIGURE 5.14: Calorie footprint, calorie footprint per capita and national production account of selected countries presented as decade average. PBA is related to food and non-food uses altogether.

The growth of the Chinese calorie footprint is remarkable. In the late 1990s, the country overtook the US to become the world leader in calorie footprint. In the 2000s, its footprint was almost 20% larger than the American one, mainly due to the food consumption footprint. Comparatively, China's footprint is almost twice as large as Brazil's and virtually 21 times larger than Australia's, the nation with the smallest footprint.

Even with comparable population sizes, the evolution of the Chinese food-related calorie footprint was much more pronounced than that of India. In the 2000s, the Chinese footprint was almost double that of India. This fact reflects the changes in dietary preferences among the Chinese population, which began to consume more animal-based products after the mid-1990s.

Overall, high-income countries have the biggest share of their food-related footprint made up of animal-based calories. However, the proportion of non-edible calories in the footprint composition was found to be higher in developing countries. This outcome may be attributed to the production model employed in each context as well as the type of product consumed. For example, the USA is a big beef consumer, its supply is practically internal since it is also a top producer, further, its production system is intensified, which results in 25% of non-edible calories in its food-related footprint. South American countries are also major meat producers and consumers, whereas their livestock system is still heavily reliant on pasture, in this way, non-edible calories accounted for more than 60% their food-related footprint. Yet, China and Germany have reduced share of non-edible calories in their food-footprint composition, 16% and 19%, respectively. This low ratio may be associated with the preference for pork and chicken in these countries.

The USA's non-food-related footprint is the largest in the world. It is 50% larger than the Chinese one and more than twofold as large as the Brazilian. Non-food uses make up roughly 50% of the US calorie footprint. This is due to the fact that the country is by far the top power in biofuel production (it produces 52% more ethanol than Brazil, the second largest producer) and has a large chemical and pharmaceutical hub, which also makes use of food products.

The comparison between footprint and national production (PBA) indicates that China, Japan, and South Africa are net dependent on imports to meet local demand. China is by far the nation that the most imports calories. Throughout the entire period, China was a net importer, and between 1986 and 2013, the amount of calories embedded in its imports increased by almost 700%. According to the China Power Team (2020), most of the large Chinese food production is consumed domestically, however, this does not afford self-sufficiency, and the country has become gradually more reliant on imports. Furthermore, due to changes in eating habits, China has seen a boost in beef imports, which contains an enormous amount of calories embodied upstream.

Overall, it was not possible to link the country's level of development to whether it is a net importer or exporter. Something similar was identified by Krausmann et al. (2008). African and Southeast Asian countries are the main dependents. However, European countries also rely on imports, not only to feed the population but also to produce biofuels and to feed livestock.

It is reasonable to relate the absolute caloric footprint to the size of the country's population. Although, the charts show that this is not ever true. The Chinese population has always been 3 to 4 times larger than the American one, however, it was only in the late 1990s when the Asian country took the lead in calorie consumption. The Indian population is, respectively, 6.4 and 4 times larger than the Brazilian and American populations. However, its food-related footprint is very close to the American one and is only 42% larger than the Brazilian one.

Based on the per capita footprint analysis, it was identified that countries in the most advanced stage of economic development have the largest per capita footprint. This fact results from the purchasing power that enables greater consumption of high-calorie diets and animal-based calories, the latter containing large amounts of calories embedded upstream. Australia, for instance, has the lowest absolute footprint, nevertheless, presents the highest food-related footprint per capita among developed countries. The country has one of the world's largest per capita meat supplies and stands out for raising sheep and cattle, ruminant animals that demand large amounts of resources. Among developing countries, the food-related footprints per capita of Brazil and South Africa are considerably high. However, these figures are not typical for countries at this stage of development, likely related to the abundant supply of animal-based food, primarily beef, produced by extensive methods. Different consumption patterns among developing and low-income countries (basically vegetarian diets) imply a reduced footprint, as in the Indian case.

It is outstanding the order of magnitude of the footprint per capita of these countries. In order to provide the final food supply, countries need up to five times as many calories embedded in products upstream in the supply chain. Brazil is the country with the highest proportion of calories incorporated in its final consumption. In the 2000s, 17878 kcal/capita/day were required to supply an average of 3200 kcal/capita/day. Hence, 14658 kcal/capita/day extras (or 4.58 times more). Slight lower picture is observed for USA, Australia, Germany, and South Africa. At the temporal analysis, China had the most significant increase in embedded calories over the decades, with its calorie footprint/calorie supplied ratio rising from 1.75 to 2.5. India is the country with the lowest ratio. In the 2000s, it was 1.8, reflecting the low consumption of animal-based products and practically no consumption of beef.

To the best of my knowledge, no other work has addressed the calorie footprint indicator. In this manner, comparing the results found here is not possible. However, as stated by Krausmann et al. (2008), biomass trade, including food and especially animal-based products, carries a large amount of upstream embedded resources. Thus, bearing in mind the efficiency of feed-food conversion and the growing consumption of meat, dairy and eggs, it is argued that the results presented are plausible.

Here it is noble to highlight the paramount importance of FABIO for this study. Until the release of FABIO, an IO model that provided the necessary information for this calculation was not available. In such a way that when it comes to calorie flow, the studies have considered the direct flow of products, that is, they estimate the final consumption, not taking into account the calories embedded. When dealing with agri-food footprints, studies have addressed related environmental impacts.

Complete information on all analysis regarding calorie footprint of nations can be found in supporting information SI 3.

5.7. EATING PATTERNS, FOOD SUPPLY AND LAND SPARE

Based on the most recent data from FABIO, after losses related to waste and non-food uses, the current food system delivers 1.05E+10 Gcal. The food supply (after animal losses) is equal to 7.31E+09 Gcal. Furthermore, to provide 2500 kcal/capita/day to the current population, 6.55E+09 Gcal is needed. By 2050, to offer the same amount of calories per capita, 9.13E+09 Gcal will be necessary. In other words, a 39% increase in the demand and an amount of calories that exceeds the current supply.

Hence, in order to investigate the influence of dietary choices on the capacity of the current food system, five dietary patterns were selected (see table 5.1). It was assumed that yields per hectare and feed-food conversion efficiency for 2013 would be maintained. The share of waste and non-food uses were also kept constant. Yet, with regard to the Quo pattern, which describes the present food consumption model, its current calorie supply (2791kal/capita/day) was set to the ideal daily intake (2500 kcal/capita/day), for then comparing all the patterns.

Observing table 5.1, which compares the current food supply to scenarios for the years 2013 and 2050, it is clear that only significant changes in food habits will allow the system to meet future demand.

In the present context (2013), all patterns proved to be viable options to increase the availability of calories, as well as reduce the strain on the use of cropland and grassland. Greater consumption of grains at the expense of animal-based products accounts for the lower reduction in edible crops delivered to the food supply in patterns other than Quo. However, lower total demand for edible calories is required in these diets. The VEG and Vegan diets are the patterns with the most expressive reduction, surpassing 40% in both.

In future scenarios, adopting the Quo2050 standard, it was found that the total demand for edible calories will grow 9% above the amount delivered by the current food system. This means that each inhabitant will have a deficit of 249 kcal/day in their supply. This number is close to that presented by Berners-Lee et al. (2018), who in their work claimed that such a system would deliver, in 2050, 2313kcal/capita/day.

The eating patterns EAT2050 and MED2050 also extrapolate the production capacity of the system. Willet et al. (2019), proponents of the EAT standard, are brilliant in linking dietary choices to improvements in health standards and safeguarding planetary boundaries. However, they suggest a relatively high consumption (12%) of animal-based calories, mainly dairy products, whose feed-food conversion is significantly low. It is argued that due to this fact, the adoption of the standard EAT2050 will require other joint changes, such as waste losses reduction, to provide the necessary energy supply.

Only the movement toward vegetarian and vegan diets has been shown to be able to feed the population in 2050 using current system yields. This is due to the supply surplus arising from the reallocation of calories used to feed livestock directly for human consumption. In the case of the Vegan2050 pattern, reallocation of crops would increase calorie availability by 1600 kcal/capita/day. As for the VEG2050 standard, for which the consumption of dairy products and eggs was assumed, the increase would be 1220 kcal/capita/day.

As a consequence, these were also the sole patterns that showed the potential to spare both croplands and grasslands, which implies extra gains for the environment. Yet, in the case of the EAT2050 pattern, following Willet et al. (2019), the necessary expansion in cropland area is likely because the spare of cropland dedicated to growing crops that feed animals is offset by the greater consumption of grain by humans and the expansion of vegetable and nut crops plantations – crops with low yield.

In a nutshell, the current food system will not be able to meet future demands without drastic reductions in animal-based food consumption. There will be a calorie shortage in the Quo2050, EAT2050, and MED2050 scenarios unless cultivable areas are expanded or yield per hectare increases.

TABLE 5.1: Eating patterns and their related variation on the amount of edible and non-edible calorie, cropland and grassland needed to meet the current and future demand. The variation is based on 2013' numbers of production and supply. Information about calories and land are in Gcal and hectare, respectively.

Eating patterns	Edible crops to food supply	Animal-based Products to food supply	Edible crops to feed livestock	Fodder Crops	Total raw edible demand	Cropland	Grassland
Base – year 2013	4,62E+9	1,20E+9	3,95E+9	5,27E+9	1,05E+10	9,60E+08	1,43E+09
ΔQuo	-10,4%	-10,4%	-24,9%	-23,2%	-16%	-7,0%	-0,9%
ΔEAT	-7,5%	-27,6%	-26,5%	-25,9%	-25%	-25,4%	-1,3%
ΔMED	-9,3%	-15,9%	-25,8%	-25,8%	-26%	-22,5%	-1,8%
ΔVEG	-7,2%	-42,7%	-78,2%	-80,4%	-43%	-16,9%	-77,0%
Δvegan	2,6%	-100,0%	-100,0%	-100,0%	-47%	-5,3%	-100,0%
ΔQuo2050	24,8%	24,8%	23,9%	10,2%	27%	16,4%	1,8%
ΔEAT2050	28,9%	-3,8%	3,5%	-20,3%	2%	1,4%	4,4%
ΔMED2050	25,6%	0,3%	4,6%	-19,5%	4%	2,2%	3,6%
ΔVEG2050	30,4%	-20,9%	-65,0%	-80,2%	-30%	-25,3%	-76,8%
ΔVegan2050	33,9%	-100,0%	-100,0%	-100,0%	-33%	-28,8%	-100,0%

6. SUSTAINABLE AGRI-FOOD SYSTEM

The core target of this study is to present strategies that could increase the technical efficiency of agriculture yield use. In other words, actions to make better use of existing material, boost the availability of food supply and ensure global food security. Attaining material technical efficiency use is evidently central to the sustainability of agri-food systems. However, it does not end the need for other actions to achieve socio-environmental objectives and strengthen the sector's sustainable development.

In this way, other measures that complement what has been discussed so far and could also contribute to achieving these objectives are presented below.

Reduction of food waste: The analyzes performed here show that 5%-6% of global calorie production is being wasted through pre- and post-harvest processes. Lack of knowledge to handle and store harvested crops is the main reason for these losses. Therefore, food waste could be reduced through better storage techniques and transport (UN WFP, 2020). UNEP (2016) highlights that rotten product should not leave the food system permanently, this could be employed as feed livestock and be converted into high-value products such as meat and dairy. The work also underlines that product that do not meet appearance standards are discarded, even being in perfect conditions to be consumed. Reincorporating these products into the system would also contribute to an increase in the food supply. In addition, studies indicate near 40% of food is wasted at the consumer level (UN TWF, 2020). Planning purchases and correct food stowage are fundamental.

Replace beef and lamb for chicken or pork. The complete adoption of vegetarian or vegan diets seems unrealistic and goes against all projections of increased meat consumption (OEDC-FAO, 2019). Therefore, adopting diets, such as the EAT or MED patterns, which give preference to pigmeat, poultry meat, and eggs (products with better performance in feed-food conversion), would represent lower animal-related calorie losses from the food system. Taking as an example the saves referring to the EAT standard indicated in table 5.1, adopting this diet could mean an increase in the availability of enough calories to feed approximately 160 million people, in addition to contributing to the land spare.

Alternative sources of protein: The production of cell- and fermentation-based proteins has been developed in recent years and emerges as an option to increase food availability. According to Sinke (2021) and Swartz (2021), when compared to beef production, alternative sources can have a feed-food efficacy conversion up to 16 times higher, a carbon footprint up to 92% lower, and a need for land reduced by up to 95% percent. According to Morach et al. (2022), these products have attracted the attention of investors and consumers so that by 2035, 11% of all protein consumption will be represented by alternative sources.

Regenerative agriculture practices: The traditional method of crop cultivation is characterized by large monocultures, whose productivity rely on expensive synthetic pesticides and fertilisers and costly tillage, which can lead to the pollution of the environment, high levels of greenhouse gas emissions, and soil degradation (Schipanski et al., 2016). LaCanne et al. (2018) and White (2020) argue that regenerative agriculture reduces the strain on the environment and could still be profitable. The authors indicate that the practices would involve, among others: the minimization of tillage and soil disturbance; using cover crops; crop rotation, including grazing; consortium and diversified cultivation of crops; integration of crops with planting native trees and flowers to increase the attraction of pollinators and natural pest controllers; and replace external fertilizers with organic matter. Restored, healthy, covered and stable soils increase crop productivity, potentially increase profitability (WWF-Brasil, 2020), help control the water regime, maximize the natural nutrient cycle and represent a carbon sink. Regenerative grazing in areas of low productivity of other crops (such as places with low rainfall) could be a sustainable alternative to animal husbandry, decreasing competition for edible crops.

Food design: According to the Ellen Macarthur Foundation (2021), food design involves the decision-making process that culminates in the formulation of food products and menus. That is, it is the process that defines the ingredients that will be consumed. In addition to nutritional value and taste, food designers should utilize ingredients that contribute to a healthier and more stable soil (such as beans, peas, and other leguminous that fix nitrogen and improve soil fertility). Incorporating a broader range of crops and wild plants into their product portfolios would benefit the business, as it would reduce the reliance on supply from conventional crops (maize, wheat, sugar cane), increasing food security. On the other hand, since local plants are more adapted to their natural environment, less pesticides and fertilizers would be needed. In the context of climate change and unpredictable impacts on food yield this factor becomes extremely relevant. Material upcycling should also be considered when thinking about food design. The inclusion in recipes of peels and seeds that would otherwise be discarded could reduce food waste. Together, such choices have power to influence what and how farmers grow the crops. Companies, restaurants, and consumers should give preference to ingredients grown trough regenerative agriculture practices.

7. CONCLUSION

While crop- and animal-based calorie yield gains have been consistent and substantial over the last few decades, a notable increase in food availability will be required to feed an estimated population of 10 billion people by 2050.

Paradoxically, the results presented here indicate that we are continually investing growing shares of crop production in competitive uses – feed livestock and non-food use. The analysis showed that the main countries sometimes employ more than 50% of their main crops (maize, sugar cane, soybeans) in animal feed or production of non-food products.

Despite still representing the smallest cause of calorie losses from the food system, the allocation of edible calories in non-food industries was the competitive use with the highest relative growth over the period studied. For example, the USA, the world's largest biofuel producer, allocates 27% of its maize production to ethanol production. Basil, second in the biofuel production ranking, reserves 40% of its sugarcane yields and 24% of its soybean production.

As animal husbandry intensified, the fraction of edible calories in the feed composition increased. This fact did not lead to an increase in the proportion of global edible calorie production delivered to animals. Nevertheless, we still allocate 34% to feed them. On the other hand, animal-based products provide to the food supply, on average, only 12% of all invested resources. In this manner, feed-food conversion corresponds to the largest source of calorie loss from the food system, whilst also demonstrates that employing edible calories to feed animals is not an efficient way to provide calories to humans.

Therefore, more than population growth, changes in eating patterns, with diets more abundant in calories and with greater consumption of animal-based products, turned out to be the main factor placing pressure on the global food supply.

While future crop yield increases are unattainable due to technological constraints, planetary boundaries and climate change, this study found that reallocating crops used for animal feed and non-food products to human consumption would result in a 75% increase in calorie availability, enough to feed 6.84 billion people.

Out of this total, 65% of this value would be achieved with the shift to vegan diets. In fact, vegan and vegetarian eating patterns were the two diets that presented themselves as viable options to feed the future population (10 billion people) with the current structure of the food system and with the potential to save cropland and grassland, which implies extra positive impacts on the environment. In other words, if there is no addition in productivity per hectare or expansion of cropland, only through profound changes in food preferences will it be possible to meet future demand.

However, this dietary shift doesn't seem realistic. The temporal analysis identified a 4% reduction in the fraction of calories from crops in the composition of the human diet. On the other hand, there was a tendency to increase animal-based calories making up the human diet. Over the period, this fraction increased by 11.20%. Furthermore, projections indicate sharp growth in the consumption of animal-based food in the coming decades. In this context, the substitution of meat from ruminant animals (beef and lamb) by other sources would be indicated. The study of the evolution of food-feed conversion showed that the improvement in average efficiency was mainly due to the optimization of milk and pigmeat production. Egg and poultry meat are also more efficient than average. Therefore, replacing beef and lamb with these products would bring gains. Still, to meet the demand, complementary actions would be necessary, including reducing waste losses, higher system productivity or incorporating other protein sources, such as cell-based meat.

But it is also worth mentioning here the importance of ruminants for the food system. They can convert the non-edible calories from pasture and fodder crops into refined food for humans. Based on this, an intriguing question is whether we should eliminate ruminant-based meat from our menus. In fact, the reduction of consumption is imperative to achieve the sustainability of the system. But the investment in a regenerative pasture in areas not suitable to grow crops and limiting the breeding of animals in these areas presents the potential to provide high-quality feed without rivalling the use of edible calories between animal husbandry and human consumption and still deliver high-quality food to humans.

Performing the analysis of calorie footprint of nations, it was highlighted that, over time, a larger number of countries became net importers, that is, they would not be able to satisfy domestic demand only with the amount of calories produced domestically. At the same time, more countries can offer their population the ideal per capita daily calorie intake. This picture reveals the intensification of international food trade and the tendency for production concentration in a few countries. In 2013, nearly 24% of global calorie production was used to enable exports to other nations. Also noteworthy are (i) the sharp growth of the Chinese footprint after the 1990s due to the greater consumption of animal-based products and (ii) the non-food-related footprint of the USA, which represents 50% of its total footprint.

Through the per capita footprint indicator, it was also possible to identify the influence of dietary preferences on the total amount of calories needed to meet the final demand. Countries with affluent diets and high consumption of animal-based food, mainly ruminant-source, have an amount of calories embedded in their products that is up to 5 times higher than their final consumption. At the other extreme, countries such as India, where the population's diet is mostly vegetarian, have a calorie footprint/final calorie supply ratio of 1.8.

In nutshell, calorie footprints helped clarify the magnitude of calories needed to satisfy the final demand of wealthier nations with higher consumption of animal-based food. The imbalance in the distribution of global production, combined with the inefficiency of the food system, results in millions of people worldwide going undernourished. The pursuit of hunger eradication must be continuous and tireless. To achieve sustainability in the food sector and enable minimum access to food for all human beings now and in the future, attaining the technical efficiency use of agriculture yields is fundamental, and necessarily involves reducing animal-based food consumption, lower allocation of edible calories to non-food uses, replanning the food production (given preference to regenerative methods) and food re-designing

Finally, it is necessary to mention the limitations of this study. Although FABIO contains a higher number of countries and agri-food products when compared to other MRIO models, there is still a certain degree of aggregation and assumptions that, in a way, can influence the accuracy of the results (Majeau-Bettez et al. 2016). For example, FABIO data assumes that any corn produced anywhere has the same nutritional characteristics. All cattle breeds are aggregated into a single category, and it is assumed that in any region the group can produce the same amount of calories. Disaggregation is time and effort demanding, and for some categories, carrying out it may not make sense. However, it is vital to clarify here these aspects involved in the data and their influence on the accuracy of the results.

Calorie allocation was based on FABIO data. As it is an IO model, its numbers may be slightly different from those recorded in food balance sheets. Despite this, the results presented here are generally consistent with those found in the literature, leading to the conclusion that the influence on the results is minimal.

The redistribution of calories between food products in each of the scenarios did not take into account cultural matters or food taste preferences. It was assumed that any edible product is appropriate human food and can be consumed by any individual anywhere on the planet.

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