Global Environmental Change 64 (2020) 102124

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Global inequalities in food consumption, cropland demand and land-use efficiency: A decomposition analysis

Juan Antonio Duro[a,*], Christian Lauk[b], Thomas Kastner[b,c], Karl-Heinz Erb[b], Helmut Haberl[b]

[a] Economics Department and ECO-SOS, Universitat Rovira i Virgili (URV), Avinguda Universotat 2, Reus, Spain
[b] Institute of Social Ecology, Department of Economics and Social Sciences (WiSo, University of Natural Resources and Life Science, Vienna, Schottenfeldgasse 29, 1070 Vienna, Austria
[c] Senckenberg Biodiversity and Climate Research Centre (SBiK-F), Senckenberganlage 25, 60325 Frankfurt am Main, Germany

ARTICLE INFO

Keywords:
Food supply
Cropland demand
Inequality
Land-use intensity
Land-use efficiency

ABSTRACT

The world population is expected to rise to 9.7 billion by 2050 and to ~11 billion by 2100, and securing its healthy nutrition is a key concern. As global fertile land is limited, the question arises whether growth in food consumption associated with increased affluence surmounts increases in land-use efficiency (measured as food supply per cropland area) associated with technological progress. Furthermore, substantial inequalities prevail in the global food system: While overly rich diets represent a serious health issue for many of the world's most affluent inhabitants and constitute a critical climate-change driver, undernourishment and hunger still threaten a considerable fraction of the world population, mostly in low-income countries. We here analyze trajectories in cropland demand and their main basic drivers food consumption (measured by a food index reflecting the share of animal products in diets) and land-use efficiency, for 123 countries (clustered in four income groups, covering 94% of the world population). We cover the period 1990–2013 and assess if these trajectories are associated with changes in inequality between countries. We find that while all groups of countries converged towards the high level of the per-capita food consumption of high-income countries, differences between income groups remained pronounced. Overall, cropland demand per capita declined over the entire period in all regions except low income countries, resulting in a tendency towards global convergence. However, the trend slowed in the last years. In contrast, land-use efficiency increased in all income groups with a similar trend, hence international inequalites in land-use efficiency remained almost unaltered. Because population and food requirements per capita are expected to grow in all income groups except the richest ones, failure to improve land efficiency sufficiently could lead to a less unequal but at the same time less ecologically sustainable world. Avoiding such outcomes may be possible by reducing the consumption of animal products in the richer countries and raising land-use efficiency in the poorer countries.

1. Introduction

The world population is expected to grow to ~9.7 billion by 2050 and ~10.9 billion by 2100 (UN, 2019). Adequately feeding this growing number of humans is high on the agenda: while the number of undernourished people steadily decreased for many years, it started to increase again in 2016 in absolute numbers, with an estimated number of undernourished persons of 812 million in 2017, i.e. 10.8% of the world population (FAO et al., 2019). Reducing malnutrition and hunger is high on the agenda (Sahn, 2015); e.g. it is one of the most important “Sustainable Development Goals” or SDGs (Griggs et al., 2013). At the same time, 640 million people representing 13% of all adults worldwide are obese (FAO et al., 2017). Both hunger and obesity are well-known threats to human health and wellbeing (Sahn, 2015; Swinburn et al., 2015).

Producing enough food for all is not a sufficient condition for food security, given prevailing inequalities, but it is still a necessary condition (Godfray et al., 2010). Increasing food production is a challenge because fertile land is limited, and land area represents an important planetary boundary (Rockströmet al., 2009; Haberl and Erb, 2017; Steffen et al., 2015). Although cropland covers only ~12% of the earth's lands area except Greenland and Antarctica (Erb et al., 2007), more than half of all biomass extracted and used globally by humans, including livestock feed, is harvested on croplands (Krausmann et al., 2008). Even considering the global potential to generate additional cropland through conversion of grassland, e.g. spared by increasing grazing intensities, many scenarios for 2050 are limited by cropland expansion if deforestation is to be avoided (Erb et al., 2016).

* Corresponding author.

https://doi.org/10.1016/j.gloenvcha.2020.102124
Received 12 February 2020; Received in revised form 31 May 2020; Accepted 20 June 2020
Available online 16 July 2020
0959-3780/ © 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Furthermore, the expansion of cropland is associated with many environmental pressures such as soil degradation, pesticide and nutrient leaching, biodiversity loss, carbon emissions, and many more (IAASTD, 2009). This calls for strategies that allow to increase cropland production without proportional increases in cropland area. Moreover, it means that tracking the land 'footprint' (Wackernagel et al., 1999) of supplying food is highly important. We do this by analysing data on the actual cropland demand (Erb, 2004), i.e. global cropland demand related to each country's food supply.

Inequalities of food provision are another key challenge. The fact that the volume of food produced globally is sufficient to feed everyone on the planet on the average, i.e. at a rate of 11.3–12.6 MJ/cap/day, i.e. > 2700 kcal/cap/day (D'Odorico et al., 2014), illustrates that food security is threatened by inequality at least as much as by insufficient production of food. Better understanding how inequality of food consumption between countries changes globally is hence an important research area, even though important additional questions remain with regard to within-country inequality of food access and distribution (d'Odorico et al., 2019) that are beyond the scope of this paper

Experiences from the past suggest that rising incomes are strongly related with higher demand for food energy in general, and higher demand for more resource-demanding food such as protein-rich animal products in particular (Tilman and Clark, 2014; Alexander et al., 2015). In the past, wealthier nations were able to increase productivities and efficiencies of the food system: higher yields and better feeding efficiencies counteracted the rising volume and quality of food consumed (Haberl et al., 2012; Krausmann et al., 2009). Beyond inequality, the question hence arises whether limited available cropland (Erb et al., 2016; Steffen et al., 2015) will allow producing enough food, which will require sufficient efficiency improvements to cope with expectedly richer future diets.

Concerns about global inequality are in the center of current sustainability debates (Motesharrei et al., 2016). It is widely held that not only global resource use should be reduced, but also the international inequalities of production and supply (Duro et al., 2018; United Nations, 2015). Given widespread hunger and malnutrition, global reductions in food consumption seem unacceptable and unoperative, but Contraction and Convergence strategies are being discussed as a means to reduce international inequalities (Meyer, 1999). Hence, it would make sense to incorporate international inequality instruments into the sustainabiliy debate and their analysis (Duro et al., 2018; Schaffartzik et al., 2019).

In this context, the main objective of this article is to analyze the international inequalities between all of the previous factors, that is, food supply, land-use efficiency and cropland demand, for the period 1990–2013 at the country level, using an integrated approach. We use the use the following terms in the text: food supply denotes the amount of food available in each country. Cropland-use efficiency denotes food provision per unit of global cropland area required to produce the food consumed in each country. Cropland demand denotes the extent of cropland area required within and outside a nations territory for the amount of food consumed domestically. We analyze these phenomena through a decomposition analysis that systematically links cropland demand per capita with two basic and consistent factors: per-capita food consumption, measured as a food index that reflects the share of animal products in diets, and land-use efficiency (measured as cropland demand per food index). For the international comparison, countries are grouped in four groups, based on the per capita income (World Bank, 2019).

2. Methods and data

We analyze the global relationship between food consumption, land-use efficiency and cropland demand using factorial decomposition instruments combined with an analysis by groups of countries (based on income) and international inequality through the Theil index (Duro and Padilla, 2006; Theil, 1967; Duro et al., 2018; Schaffartzik et al., 2019). The dataset underlying this study includes 123 countries, covering ~94% of the world population. The analysis covers the period 1990–2013. The section below describes indicators, how the individual data were assessed, what data sources were used and outlines the decomposition approaches.

2.1. Indicators and data sources

2.1.1. The food index

Adequate food supply depends not only on sufficient digestible food energy but also on the adequacy of macro- and micronutrients, vitamins, fibre and many other criteria. In this study, however, we focus on the relation between food availability and cropland demand. Therefore we choose a simplified approach: Given a country's level of food supply, the associated cropland demand (see below) is assumed to primarily depend on the amount of dry-matter respectively energy of primary crops related to this food, and on output per unit area (cropland yield) of the cropland where the crops are grown. We constructed a simple national food index that aims to indicate the resource costs of food production in terms of the trophic level of the consumed food. This implies that we give larger weight to food sourced from animals (meat, milk and eggs) compared to plant-based food. The construction of the index reflects that during the time period of our analysis, each unit of animal products required roughly the fivefold amount of crops from arable land in terms of energy (Bouwman et al., 2005; Krausmann et al., 2008; FAOSTAT, 2019). Accordingly, we differentiate total food supply into plant-based and animal-based products and weighted the latter by a factor of 5, resulting in the following formula:

$$F_{i,t} = (r_v + 5 * r_a) * kcal_{total}$$

with $kcal_{total}$ as average per capita food supply in each country in kcal/cap/day (from ref FAOSTAT), r_v the share of vegetal products and r_a the share of animal products in the overall supply ($r_v + r_a = 1$). Thus, the food index is aimed to express the amount of primary biomass required to provide the food consumed in a country and relates to energetic relationships; other dimensions, such as the supply of micronutrients, vitamins or fibres and their relationsships, are for the sake of simplicity neglected.

2.1.2. Cropland demand for food and feed

We estimate cropland demand for food and feed anywhere on the planet required to produce food consumed in each country, based on data that link countries of crop cultivation to countries where the related products are used. Total cropland demand therefore reflects differences in productivity in the crops and in countries that supply the cropland products demanded in a country. These data rely on national-level crop production data and bilateral trade data for crops and products processed from them (including livestock products, FAOSTAT, 2019). Matrix algebra is applied to the data to eliminate transit countries and to establish consistency between countries of cultivation and use (for details see, Kastner et al., 2011, 2014).

To exclude cropland not used for food or feed production, we multiply the obtained overall consumption data by the shares for food and feed use in overall crop use (i.e. food and feed use plus non-food/feed uses). These shares are derived from FAOSTAT's commodity balance accounts (http://www.fao.org/faostat/en/#data/BC). Data on country- and crop-specific yields are then used to translate the values into cropland area, which is expressed as the area of cropland harvested in a given year.

2.1.3. Population and country grouping

Population data were derived from the UN's population database (UN, 2019). The country groups are based on per capita income and come from World Bank (World Bank, 2019).

2.2. Decompositions and territorial differences

As analytical approach we use multiplicative factorial decompositions. Transforming the factors into logarithms allowed decomposing the trajectory of the global indicator into a sum of factors. In a first step, we decompose cropland demand of a country i in year t ($C_{i,t}$) into:

$$C_{i,t} = C_{i,t}/P_{i,t} * P_{i,t} = c_{i,t} * P_{i,t} \tag{1}$$

where $P_{i,t}$ is population in country i in year t. The first explanatory factor we analyze is per capita cropland demand, as an indicator of intensity, and the second, the country's population, as a basic indicator of scale. Calculating natural logarithms (abbreviated as ln, i.e. logarithms with the basis e) on both sides of (1) and differentiating two periods (t and t-1) yields:

$$ln\ C_{i,t} - ln\ C_{i,t-1} = (ln\ c_{i,t} - ln\ c_{i,t-1}) + (ln\ P_{i,t} - ln\ P_{it-1}) \tag{2}$$

Therefore, we can algebraically distinguish which part of the changes in C_{it} between two time points is attributable to changes in average per capita cropland demand (variable intensity) and to changes in population (variable scale). This simple decomposition allows an initial characterization of growth patterns in cropland use for food and feed.

In a second step, we decompose per-capita cropland demand ($c_{i,t}$) and aim to answer to what extent increased per-capita food consumption is counteracted by the efficiency of cropland use:

$$c_{i,t} = C_{i,t}/F_{i,t} * F_{i,t}/P_{i,t} = e_{i,t} * f_{i,t} \tag{3}$$

where $F_{i,t}$ is the food index explained in section 2.1 and all the other variables are as in Eq. (1). In this formulation, $e_{i,t}$ is cropland demand per unit of food which may be interpreted as the inverse of food production efficiency. $f_{i,t}$ is food supply (measured with the food supply index) per capita in the respective country and year. In logarithmic form, Eq. (3) can be written as

$$ln\ c_{i,t} - ln\ c_{i,t-1} = (ln\ e_{i,t} - ln\ e_{i,t-1}) + (ln\ f_{i,t} - ln\ f_{i,t-1}) \tag{4}$$

Beyond evaluating global patterns, this framework also allows to investigate international differences in a synthetic way using inequality indicators. We summarize inequality using a synthetic index for $c_{i,t}$ and decomposing it into the sum of the previous two factors. As Duro and Padilla (2006) have shown, this can be done using the Theil index (Theil, 1967) as a reference indicator for measuring inequalities in vector c. The Theil index T originates from the concept of entropy of information and coincides with a measure of average logarithmic deviation that has many desirable properties (Bourguignon, 1979). While there are other interesting inequality measures such as the Gini index, the Atkinson indicator family or the variation coefficient (Duro, 2012), the Theil index differs from those by being easily decomposable (Shorrocks and Wan, 2005), in particular when the factors are multiplicative, as in our case in (3). The algebraic expression of the Theil index for the analysis of cropland demand per capita by countries, is given as

$$T(c_i, t) = \sum_{i=1}^{n} p_{i,t} * \ln\frac{\mu(c_{i,t})}{c_{i,t}} \tag{5}$$

In this formula, $p_{i,t}$ is the population share of country i (that is, its population as a fraction of the population of all countries in the sample). $c_{i,t}$ is the cropland demand per capita in country i and year t. μ is the world average in the cropland demand per capita, and ln is the natural logarithm. Lower index values imply lower inequalities. The minimum value of the Theil index is zero and the maximum value is not generally defined[1].

It has been shown (Duro and Padilla, 2006) that the international inequality index T, in the context of the two-factor decomposition in (3), can be decomposed in an interesting way. On this regard, we would define two ficticious vectors of cropland demand per capita (c_i), where in each case only one factor is allowed to vary (and the other would be equalized to the world mean). Thus, we used the following hypothetical factors:

$$c_{e,i,t} = e_{i,t} * f_{,t} \tag{6}$$

$$c_{f,i,t} = e_{,t} * f_{i,t} \tag{7}$$

At this point, if we calculate the inequality in terms of these two ficticious vectors of cropland demand per capita (using the Theil index) and we compare their sum with the global Theil index (following the expression (5)) we get the following consistent decomposition:

$$T(c_i, t) = T(c_e) + T(c_f) + \log(1 + \frac{\sigma_{ei,t,fi,t}}{c_e}) \tag{8}$$

where c_e is the fictitious vector of cropland demand per capita that would emerge from the hypothetical assumption that $f_{i,t}$ were equal to the world average for all countries. Similarly, c_f is a second fictitious vector of cropland demand per capita where it is assumed that efficiency $e_{i,t}$ (cropland demand per food index) would hypothetically coincide with the world average. σ is the population-weighted covariance between the two factors $e_{i,t}$ and $f_{i,t}$.

In this formulation, therefore, the importance attributable to each factor can be interpreted as the amount of inequality that would exist if only the factor examined were allowed to vary between countries, while the other factor is assumed to equal the global average. The total cross-country inequality in cropland demand per capita can thereby be decomposed in a perfect way into two indices that reflect the partial contribution of each of the factors to the global inequality and a last factor of interaction that is represented by the interfactorial correlation[2].

Another useful possibility to decompose $T(c_i, t)$ is by groups (Shorrocks, 1984: Duro and Padilla, 2006). In this case, global inequality is divided into (1) a between-group inequality component (assuming zero inequality within groups) and (2) a within-group component (assuming no disparities between groups). In our case, the groups of countries by income levels have been used for the descriptive analysis, but there are other possibilities. In this regard, the Theil index has been shown to be the best candidate for this type of decomposition and its interpretation (Shorrocks and Wan, 2005). Thus, for example, the algebraic expression of this decomposition for factor our factor c would be given by the following formula:

$$T(c_i, t) = \sum_{k=1}^{m} p_{k,t} * \ln\frac{\mu(c_{i,t})}{c_{k,t}} + \sum_{k=1}^{m} p_{k,t} * T(c_{k,t}) \tag{9}$$

where k is the number of groups; $p_{k,t}$ is the relative population of each group; m_k the mean of each group; and $T(c_k)$ the Theil index applied to each group.

The first summatory in (9) would be the between-groups inequality component and the second one the within-group component. In fact, the role of the between-groups inequality component can be perceived as an indicator about the empirical rellevance of the groups as descriptive units.

[1] Many inequality indices do not have a fixed maximum value, as the maximum will depend on the respective sample (like is the case for the Atkinson family indices or the variation coefficient). Nevertheless, different illustrative

(*footnote continued*)
examples with our type of data (by countries) indicate that index values near to 1 indicate high values of inequality. Detailed results can be made available by the authors upon reasonable request.

[2] Note further that if $\frac{\sigma_{eit,fit}}{c_e}$ is sufficiently small, the decomposition could approach$T(c_i, t) = T(c_e) + T(c_f) + \frac{\sigma_{eit,fit}}{c_e}$And that if the covariance term is small, the expression is simplified to a sum of factorial Theils

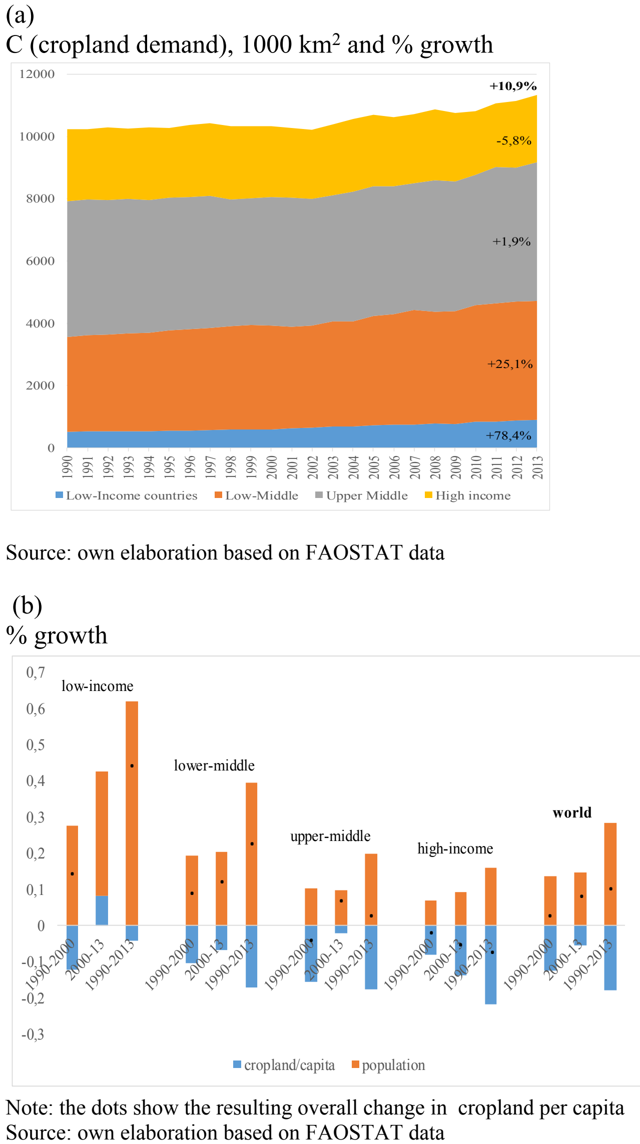

Fig. 1. Changes in cropland demand by income groups, 1990–2013. (a) Changes in total cropland demand, (b) decomposition of changes in cropland demand into population growth and cropland demand per capita according to Eq. (1). The unit in (a) is 1000 km^2 of cropland area harvested and % growth over the entire period 1990–2013, in (b) relative changes in % over each specified period. Note that global cropland is about 15.2 Mkm^2 in 2013, including food and feed provisiponing areas reflected here as well as the cropland used for the production of non-food goods and fallowed cropland areas. Note: the dots show the resulting overall change in cropland per capita Source: own elaboration based on FAOSTAT data.

3. Results

Global cropland demand for food production is shown in Fig. 1a, broken down into the four income groups. Total cropland demand grew unevenly over the period 1990–2013. It remained stable until 2002 and grew faster thereafter. After 2002, we note a significant plus of ~1 mio. km^2 of cropland for food (+9%). The trajectory of cropland demand is, however, heterogeneous across the income groups. The increases are small or negative in the two richer groups, while they amount to +25% in the low-middle and +78% in the low-income group.

The first decomposition according to eq. (1) is shown in Fig. 1b. The study period is broken down into two phases, 1990–2000 and 2000–2013, which are displayed separately for each of the income groups as well as for the global aggregate. The decomposition disaggregates total cropland demand into cropland demand per capita and population growth. Cropland demand per capita alone, a function of yields per unit area and food demand per capita (expression (3)), would have reduced cropland demand almost universally, with the exception of low-income countries in the second part of the period. Hence population growth emerges as the factor driving overall increases of cropland demand. Reductions in cropland per capita were a lot smaller in the second part of the period in the total as well as in three of the four regions (i.e., except the high-income group).

These results are further analysed in Fig. 2 (focusing on the per capita values). Fig. 2a reveals that cropland demand per capita follows a curvilinear pattern in two of the four world regions as well as the total of all countries. The total falls from ~2000 m^2/cap and seems to stabilize around 1700 m^2/cap towards the end of the study period. Upper-middle countries trajectory closely matches the global aggregate trajectory, lower-middle contries are below the average level and high income as well as low income groups are higher than the global average. The high-income trend shows a rather linear, decreasing trend. In contrast, low-income countries have the highest per-capita cropland demand which decreases only during the first part of the period and increases thereafter, without reaching the same level as in 1990.

Inequalities analysed in Fig. 2b refer to inequalities between countries, not only between groups. Here the Theil index (our referential inequality measure) refers to distances of cropland demand per capita in each country to the mean of all countries. Results reveal that these distances decline over the study period, suggesting a global convergence in per capita cropland demand. However, the convergence shows a decreasing rate after 2010, suggesting that in the last years of analysis international inequality remains almost constant.

Following the identity (3), the changes in the food index can play a role in driving up global cropland demand and, in particular, cropland per capita. Fig. 3a shows its evolution by income groups. The evidence suggests that the food index grows in all groups, except in high-income countries. While the food index remains largely constant around 7 Mcal/cap/day throughout the study period in the latter group, it rises rapidly in the higher-middle group and more slowly in the lower-middle and, mainly, in the low-income group. Consistently, the international distances in food indices (using all the countries and their differences regarding to the world mean), as represented by the Theil index, have decreased considerably, but most of this trend towards reduced inequality could be observed in the first few years, followed by a slight increase until 2004, and then further slow decreases until the end of the study period (Fig. 3b)[3]. Moreover, the income groups used are very rellevant in explaining global food inequalities, given that the between-groups inequality component, following formula (9), accounts for a 80% in 2013.

The second identity factor that can explain the trajectory of cropland demand per capita, and also the globals, in our context is the land-use efficiency in producing food (i.e. food index/cropland demand; Fig. 4). Specifically, the reduction of this factor would indicate greater efficiency in the production of food. If measured in this manner, land-use efficiency has improved over the period, which has consequently

[3] Previous literature on food inquality has used the Gini coefficient as a referential inequality mesure (Seekell et al, 2011; Carr et al, 2016). Both measures, the Gini coefficient and the Theil index are satisfactory relative indexes, given that they meet some basic well-known desirable properties. Although its evolution is often similar, we have selected the Theil index given its greatest advantages to be decomposed by factors, in particular in a multiplicative way as in identity (3). Additionally, the Theil index is better than the Gini index when we want to break down global inequality by groups, for example, in our case by countries'groups like in expression (9) (Shorrocks and Wan, 2005). In any case, the utilization of both indexes in our work (like in Fig. 3b) doesn't yield significant differences. Calculations are available from the authors upon reasonable request.

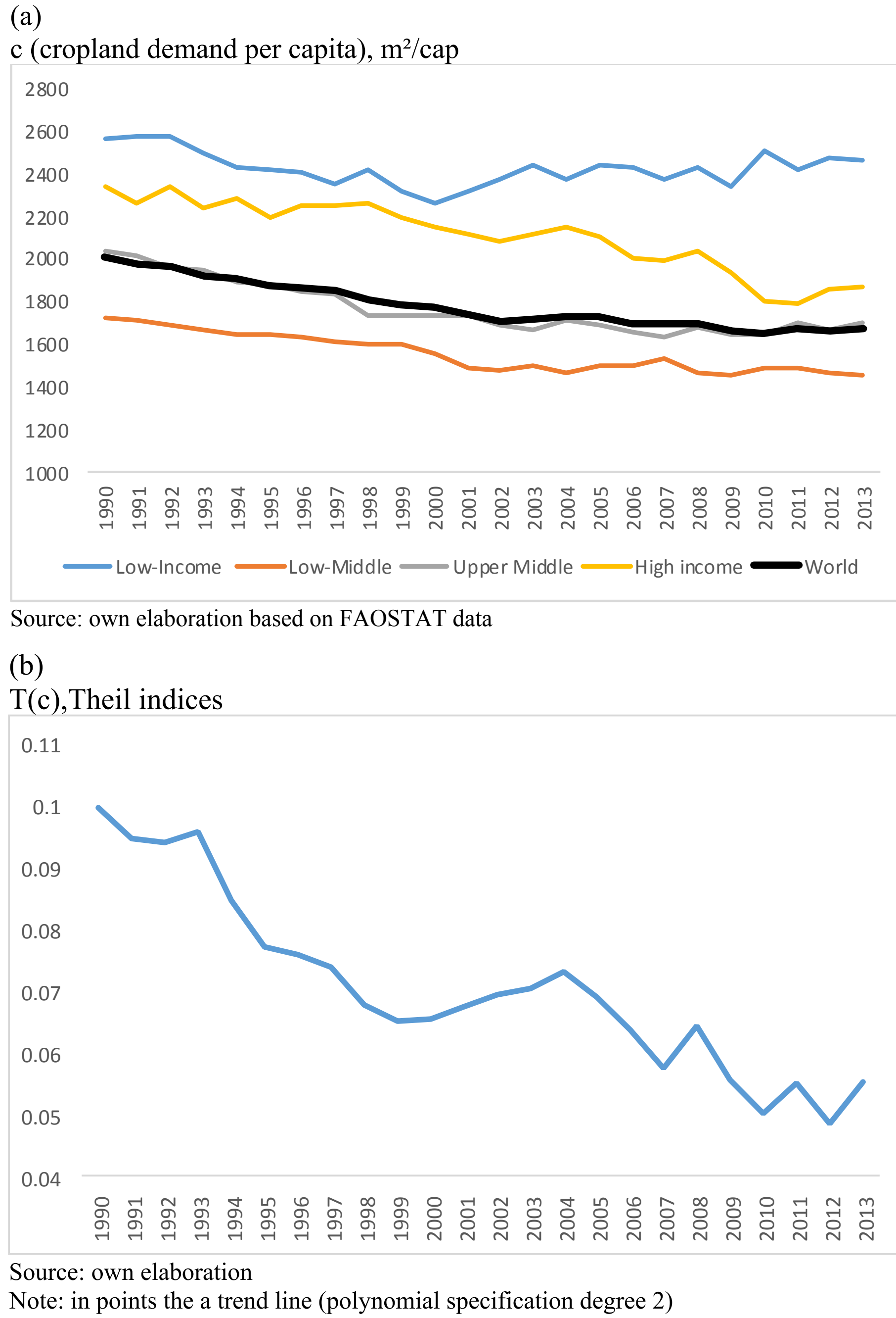

Fig. 2. Trajectories for 1990–2013 of (a) cropland demand per capita and (b) differences of cropland demand per capita between countries in the global average. Units: (a) m^2/capita (b) Theil index (dimensionless). Income groups shown in (a) explain 17% of the national-level inequalities analysed in (b). Source: own elaboration based on FAOSTAT data. Source: own elaboration. Note: in points the a trend line (polynomial specification degree 2).

tended to reduce cropland demand. However, the almost linear downward trend stops in 2010, in which year land-use efficiency stabilizes. The clearest increase in efficiency (i.e. reduction of cropland demand per food index) has occurred in the middle-income countries. In the case of the low-income group, the increase in efficiency stops in 2009 and in regard to high-income the increase in efficiency was not significant since 2000. Consequently, the saturation in efficiency improvements in recent years, together with the rise in food consumption (as measured by the food index), has contributed to the resurgence of growing cropland demand per capita since 2000, which, combined with the increase in population, has resulted in the final recent large increase in total cropland demand (Fig. 1a)[4].

In fact, putting together both factors (food index and area efficiency), and using the decomposition based on equation (3), Fig. 5a reveals which part of the changes of cropland demand per capita in each group results from changes in yields/area (cropland demand per food supply index) and which part from changes in food demand (diets), as assessed with the food index. At the level of all countries,

[4] Also in this case, the income groups are relevant in explaining global cross-country inequalities in terms of the area efficieny indicator. Specifically, the between-groups inequality component explains a 38% of total inequalities (see formula 9). More details are available upon request

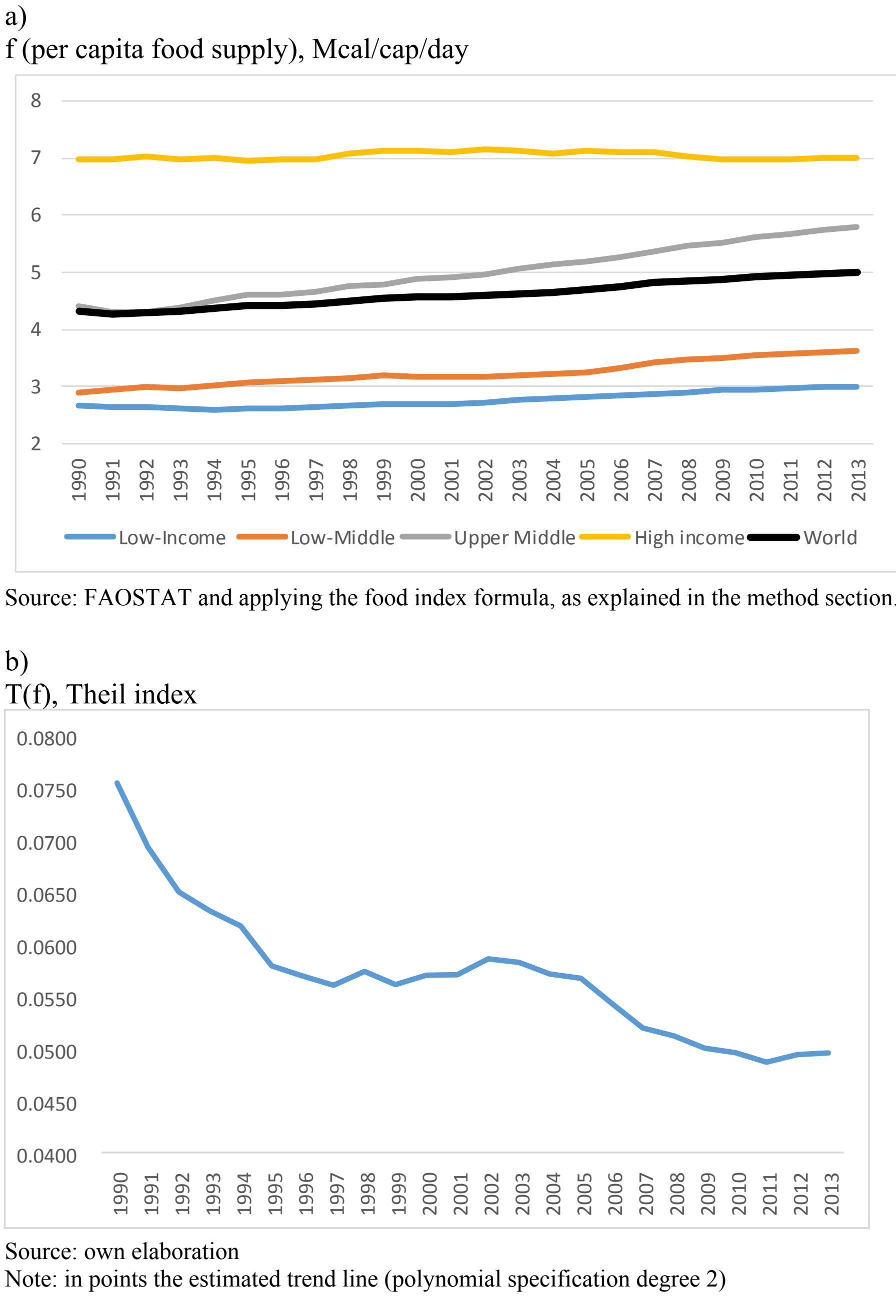

Fig. 3. Food supply per capita. (a) Trajectories of per-capita food supply, as represented by the food index, in the study period 1990–2013 for country groups and the total of all countries, (b) Theil indices of food consumption, given as food index per capita. Units: (a) food index [Mcal/cap/day], (b) dimensionless Theil index of inequality in per-capita food index. Source: own elaboration. Note: in points the estimated trend line (polynomial specification degree 2).

increased food supply alone would have resulted in stark increases in cropland demand, which was overcompensated by even stronger reductions in cropland demand per unit of food. It is noteworthy that the growth of land-use efficiency was stronger during the first part of the study period in the global aggregate and in all groups. Growth in food supply (as assessed by the food index) was strong throughout the entire period in both the lower-middle and the higher-middle group, whereas it was more or less absent in the high-income group, where small growth in the first period was compensated by a small reduction in the second half and food supply remained stable at ~7 Mcal/cap/day. Low-income countries show almost no increase in the food index in the first part of the study period, followed by some increase in the second part, while area-efficiency was practically stagnant in the second part of the period.

In addition to the analysis in levels, its seems interesting to extend this decomposition for the analysis of inequalities (using all countries data). On this regard, the decomposition on international cropland demand per capita inequalities (Fig. 2b) in terms of both factors (cropland demand per unit of food, and as food per capita) reveals two trends (Fig. 5b). First, the importance of the efficiency factor is currently larger than that of the food factor for explaining cross-country differences in cropland demand per capita around the world. Second, while the convergence in the food index per capita has reduced its role in explaining global international differences in cropland demand, the efficiencies have not been converging.

4. Discussion

We have analyzed the trajectories and the role of the intercountry inequalities of cropland demand, decomposed to the parameters per-

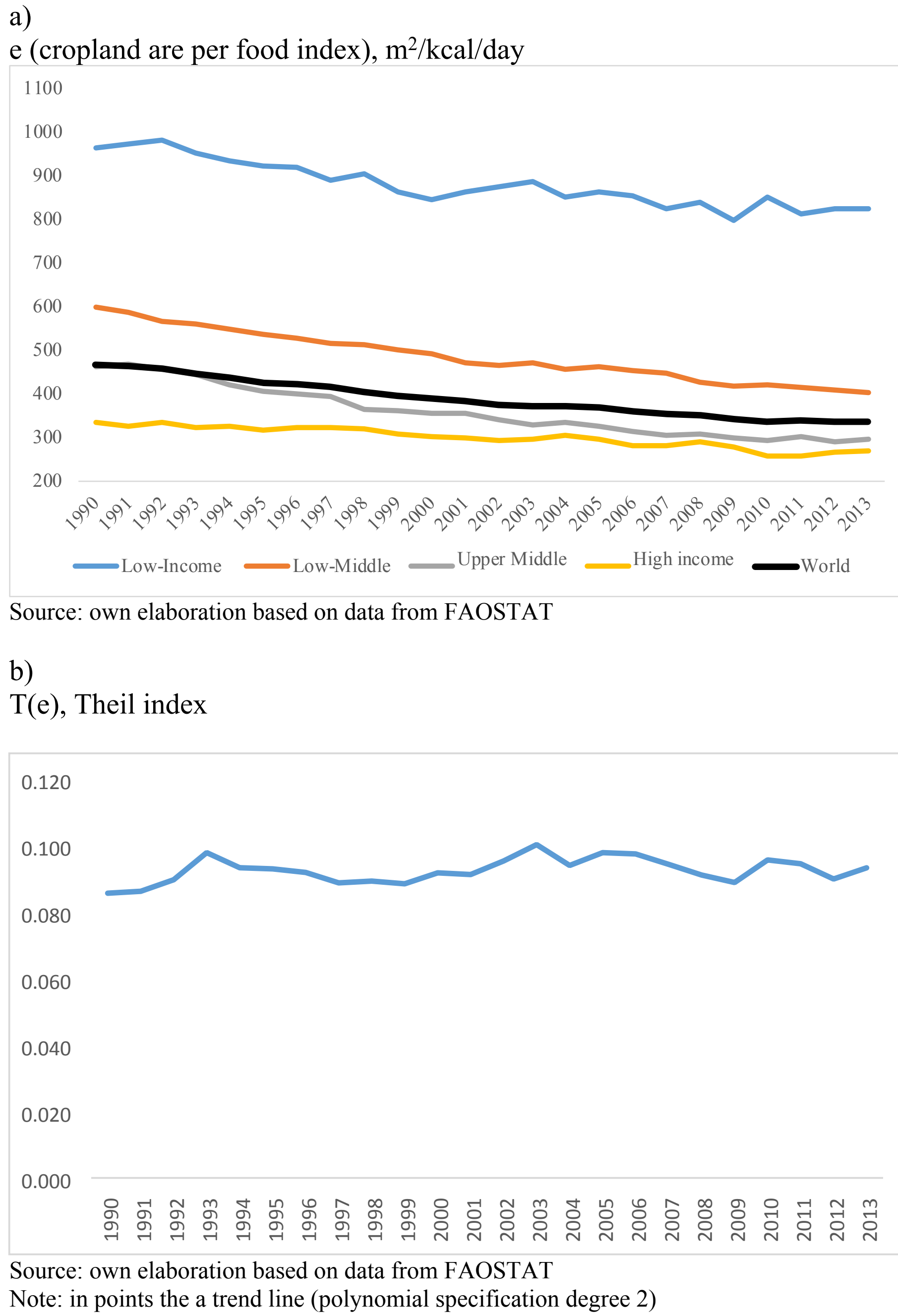

Fig. 4. Area efficiency (cropland area per food index) 1990–2013. (a) Trajectories of individual income group (b) Theil indices. Units: (a) cropland demand per food supply m^2/kcal/day; b) dimensionless Theil index of inequality in per-capita cropland demand. Source: own elaboration based on data from FAOSTAT. Note: in points the a trend line (polynomial specification degree 2).

capita food consumption (measured by the food index) and area efficiency of food production which we estimated as global cropland demand of each country per unit of food supplied (measured as food index). We first discuss the trends in inequality of the food index in various country groups and then possible future trajectories of global cropland demand.

The global state of food security, in which under- and overnutrition occur simultaneously, calls for a convergence towards healthy and adequate diets (Beal et al., 2017; Tilman and Clark, 2014; Kummu et al., 2017; Willett et al., 2019) in order to decrease environmental pressures. Such a convergence would require the quantitative and qualitative increase of food supply for many regions, mainly in the Global South, concomitant with a reduction in overconsumption in other world regions, mainly in the industrialized North. Indeed, we observe a marked increase of the food index in the lowest and both middle income groups of countries. The food index in the high-income country group is not falling, however. Here the food index remains remarkably stable over the entire period. Thus, while inequality related to the food index is improving over time, it does so only at moderate rates, and seems to converge towards the resource-intensive consumption pattern of the richest country group. A short period around the year 2000 even shows an increase in inequality, a trend that is reversed again afterwards (see Figs. 3a and 3b).

The most pronounced upward trend of the food index is found in the upper-middle country group, basically explained by trajectories in China (note that the analysis was performed a the national level, but

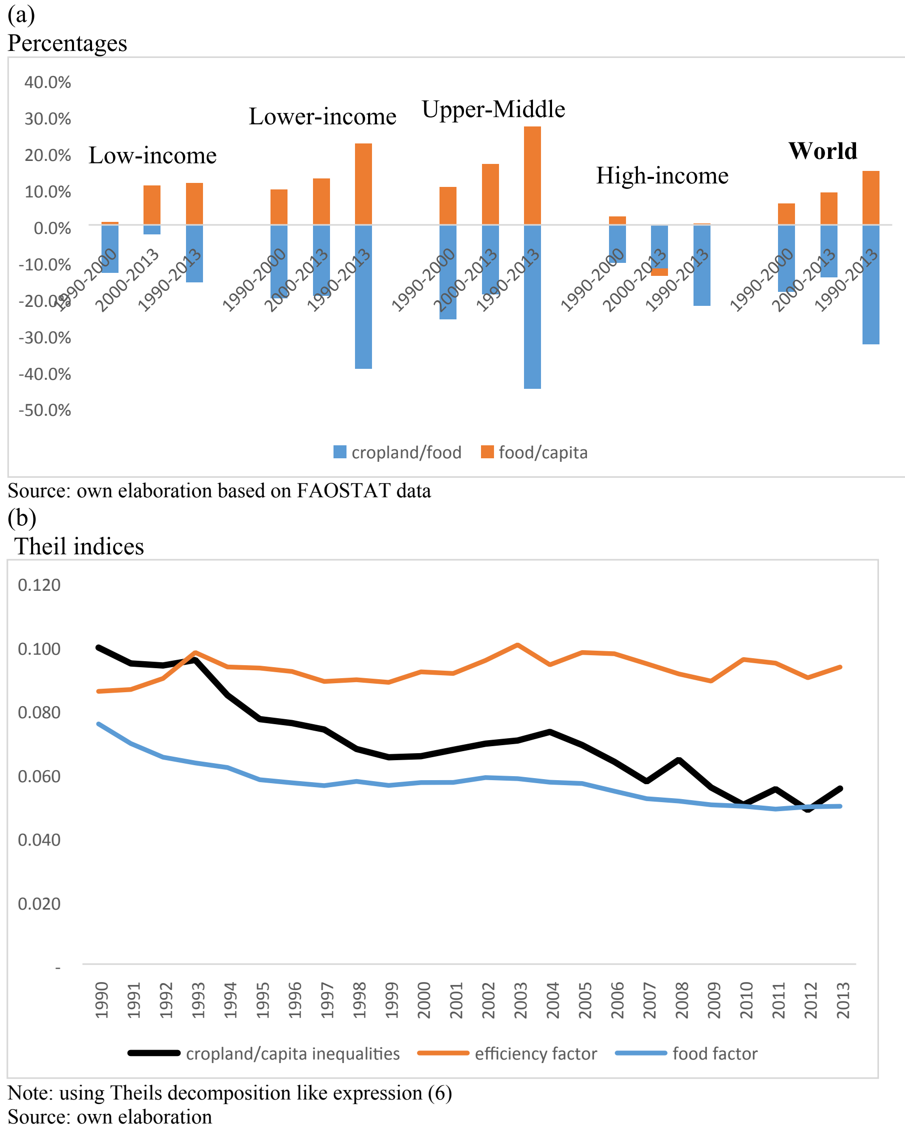

Fig. 5. Decomposition of changes in cropland demand per capita for the period 1990–2013. (a) Decomposition by income groups, (b) trajectory of the cross-country differences as Theil indices of efficiency (cropland demand per food index) and diets (food index per capita). Units are (a) percent changes for each specified period of cropland demand (m^2) per food index (weighted kcal/cap/day) and food index/capita and (b) inequality in cropland per capita, the efficiency and the food factor, dimensionless Theil indices. Note: using Theils decomposition like expression (6). Source: own elaboration.

only data at the country-group-level are displayed). For this group of countries, the food index increased almost linearly by 31% over the entire period, reaching levels of 83% of the high-income group; the food index of China even grows by 62%. If the current trends were to continue, the upper-middle income group would reach the food index of the highest income group in around 2030. The growth of the food index of the lower middle income group was 21% over the entire period, but their level is still only 52% of the high-income countries. In this case, the increase has affected most countries in the group, although large countries in this group have achieved higher increases, e.g. Vietnam (95%), Myanmar (110%) and Ghana (65%).

The smallest growth in the food index occurred in the low-income group of countries. Here, the food index grew on average by only 12%; at that rate, their catchup to the highest-income group would require 170 years. This slow convergence of the two lower income groups, in particular the low-income group, is a reason for concern: the poor remained poor, and are bound to continue to do so for a long time if current trajectories do not change. Significant growth of the per-capita cropland demand would result from a continuation of the trends observed in the three lower income groups towards the food index of the rich countries. Cropland area efficiency would have to grow by 40% over the level of 2013 until 2050 to compensate for a global convergences towards the food index currently observed in the high-income group of countries.

Food index trends in the observed period were only partly compensated by increases in cropland use efficiency (food index per m^2 of cropland) at the global scale. Overall, we found an increase of global cropland demand in the last two decades of +11%, which progressed most rapidly after 2002 (Fig. 1a). The decomposition shows that growing cropland area efficiency and the stabilization of the food index in the highest income group of countries was overwhelmed by population growth and a growing food index in the lower income groups of countries (Fig. 1b). In this context, efforts to close yield gaps without raising ecological pressures have been proposed to supply an increasing world population with sufficient food while requiring as little cropland as possible and avoidiong the manifold socio-ecological detriments related to mainstream intensification (Loos et al., 2014; Garnett et al., 2013). While crop yields seem to have reached a plateau in some countries with currently highest crop yields, large yield gaps prevail especially in many of the countries with currently low yields (Lobell et al., 2009). Our analysis reveals that the countries in the lowest income group have the largest cropland demand per capita, while their food index is lowest (Fig. 2a and 3a), implying very low land-use efficiency. High yield gaps that probably exist in many of these countries are the most likely explanation, and technology transfer may be a good strategy to address that situation (Tilman et al., 2011). Of course, decreasing the inequalities beween low and high income regions in terms of both diets and crop yields would also be highly beneficial in this context. However, given current conditions of widely prevailing ecologically unequal exchange (Jorgenson, 2010). It seems uncertain whether this will happen any time soon. An analysis of the extent to which these current patterns are result of unequal exchange was beyond the scope of our analysis.

Interestingly, our analysis reveals that the country-level inequality in area efficiency is not changing significantly over time. Rather, all regions show similar relative increases of yields (Fig. 4a and b). As crop yields seem to be stagnating in some countries with the highest yields (Ray et al., 2012), the question remains for how long this trend of globally rather uniform increases in cropland efficiency can continue in the next decades. Theoretical yield potentials are determined by climatic factors and the light-use efficiency of photosynthesis. Some agronomists argue that average yields in each country will not surpass 70% to 80% of maximum yields, beyond which costs of marginal yield increments exceed incremental economic gain (Lobell et al. 2009). It is therefore of paramount importance to preferentially raise the the low crop yields in the poorer regions. However, although this strategy additionally has been described as holding large potentials to increase global nitrogen-efficiency and thus decrease global environmental pressures (Niedertscheider et al., 2016; Mueller et al., 2012), it could not be observed in our analysis. This not only indirectly points to trends of decreased N-efficiency (Mueller et al., 2017), but also underlines that closing of yield gaps in poorer regions will not be achieved by a continuation of past policies or strategies (van Ittersum et al., 2016). This is so because when all regions show the same improvements, the yield-gap frontier for countries is growing as well (Niedertscheider et al., 2016; Erb et al., 2014).

In low-income countries, population increases drive total cropland demand despite improvements in per-capita cropland demand. In the lower-middle and upper middle countries, significant population growth has been partially offset by a reduction of per-capita cropland demand (Fig. 1b). If global trends do not change in terms of population growth in lower income countries concomitant with relatively low reductions in per-capita cropland demand, global cropland demand is bound to rise substantially in the next decades. For example, if we combine the population prospects for these country groups for 2050 and 2100 (UN, 2019) with per-capita levels of cropland demand in 2013 (i.e., assuming no improvements in per capita levels as the last years trend), the total cropland demand in 2050 would grow by 38% compared to 2013 levels, and by 58% until 2100. This is about the extent of the estimated upper limits of well-suited global land well suited for cropland (Ramankutty et al., 2002; Coelho et al., 2012), and would likely result in severe problems of making sufficient grazing land areas available without deforestation (Erb et al., 2016).

Our results show values on inequality, using the Theil index, near to 0.1 (Fig. 5b). These values are however much lower than e.g. inequalities for income and per capita CO_2 emissions, where Theil indices are 0.4 and 0.6, respectively (own calculations using IEA data for 2013). This can be linked to the central role that food provision and consumption holds for any society. Nevertheless, and in spite the previous argument, the inequality values are not irrelevant and they will need to be reduced. Thus, if we compute alternatively the Gini coefficient for measuring the food index international inequalities (which ranges from 0 to 1), the value for 2013 will indicate that these disparities would account a 20% of a maximum inequality scenario (Theil, 1967; Duro and Padilla, 2006; Duro, 2012).

As a caveat, we are of course aware that the simple food index we constructed by putting different weights to the share of plant an animal products expresses only one qualitative aspect of food provision, i.e. the primary biomass equivalent demand. Other aspects, such as the share of sugar or highly processed food commodities in diets, or nutritional values, are not grasped. It is difficult to judge if a food index that would also represent other qualitative differences would change the general insight of our study. The analysis by Tilman and Clark (2014) suggests that the share of animal products and of highly refined food are positively interrelated, which suggests that – while such an index would certainly be more informative – it would probably not drastically affect our overall conclusions. Another caveat is that our methods did not allow investigating within-country inequalities, which also need to be considered to get a more complete perspective on food security (d'Odorico et al., 2019).

5. Conclusion

To sum up, while the food index showed some moderate trends towards a more equal distribution among countries, mainly explained by the two middle income groups of countries, a similar trend could not be found for cropland area efficiency (food index per unit of cropland). For low-income countries, the trends of food demand and area efficiency are of similar magnitude and cancel each other, resulting in a stagnating per-capita cropland demand and hence rises in cropland demand roughly in accordance with population growth. In the other income groups, area efficiency gains overcompensated increases of the food index (middle groups) respectively helped to reduce per capita cropland demand at stagnating food index values. Thus, the relatively reduction in inequality of per-capita cropland demand is not a result of a global contract-and-converge trajectory, but strongly determined by the middle and high income groups. A massive sustainability challenge relates to low-income countries that face highly dynamic population trajectories paired with an apparent difficulty in increase agricultural yields in a situation of low purchasing power. Combating world hunger and reducing pressures on the land system from rising cropland areas will need to focus on that group if a more sustainable development of the global food system is to be achieved.

CRediT authorship contribution statement

Juan Antonio Duro: Conceptualization, Methodology, Formal analysis, Writing - review & editing. **Christian Lauk:** Conceptualization, Methodology, Writing - review & editing. **Thomas Kastner:** Conceptualization, Methodology, Writing - review & editing. **Karl-Heinz Erb:** . **Helmut Haberl:** Conceptualization, Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research was funded by the Austrian Science Fund (FWF), project GELUC, no. P29130-G27, ERA-NET SusAn project Animal-Futures (BMNT 101243/1) and Ministerio de Economía y Competitidad (Spain) ECO2016-79072-P (AEI/FEDER, UE).

Table A1
Factors and income-groups.

	1990			2000			2013		
	c	e	f	c	e	f	c	e	f
Low-Income	2568,4	963,2	2,7	2268,8	845,0	2,7	2461,9	823,4	3,0
Low-Middle	1733,4	599,9	2,9	1562,0	490,7	3,2	1459,3	404,0	3,6
Upper Middle	2039,5	461,8	4,4	1744,0	356,4	4,9	1706,1	294,9	5,8
High income	2339,0	335,3	7,0	2156,6	302,3	7,1	1877,4	268,4	7,0
World	**2011,6**	**466,3**	**4,3**	**1775,1**	**388,2**	**4,6**	**1680,5**	**336,3**	**5,0**

Note: c is cropland per capita (m^2/cap); e is cropland area per food index (m^2/kcal/day); f is food supply per capita (Mcal/cap/day).
Source: own elaboration based on data from FAOSTAT.

Appendix

A1. Groups

Low-Income: Benin, Burkina, Central African, Chad, Gambia, Guinea, Guinea-Bissau, Haiti, Liberia, Madagascar, Malawi, Mali, Mozambique, Nepal, Niger, Rwanda, Senegal, Sierra Leone, Togo, Uganda, Tanzania, Yemen and Zimbabwe.

Low-Middle: Angola, Bangla-D, Bolivia, Cape Verde, Cambodia, Cameroon, Congo, Cote d'Ivoire, Djibouti, Egypt, El Salvador, Ghana, Honduras, India, Indonesia, Kenya, Lao, Mauritania, MOngolia, Morocco, Myanmar, NIcaragua, Nigeria, Pakistan, Phillipines, Sri Lanka, Swazilandia, Tunisia, Vietnam and Zambia.

Upper-Middle: Albania, Algerie, Botswana, China, Colombia, Costa Rica, Dominican R., Ecuador, Fiji, Gabon, Grenade, Guatemala, Iran, IRak, Jamaica, Jordan, Lebanon, Malaysia, Maldives, Mauritania, MExico, Romania, Saint Lucia, South Africa, Surinam, Thailandia, Turkey, USSR, Venezuela and Yugoslavia.

Higher: Argentina, Australia, Austria, Barbados, Belgium-Lux, Brunei, Canada, Chile, Cyprus, Czecoslovakia, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Island, Italy, Japan, Kuwait, Malta, Netherlands, New Zealand, Norway, Panama, Poland, Portugal, Korea (Rep), Saudi Arabia, Spain, Switzerland, Trinidad, United Arab E., Uk and USA.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2020.102124.

References

Alexander, P., Rounsevell, M.D., Dislich, C., Dodson, J.R., Engström, K., Moran, D., 2015. Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy. Global Environ. Change 35, 138–147.

Beal, T., Massiot, E., Arsenault, J.E., Smith, M.R., Hijmans, R.J., 2017. Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. PLoS One San Franc. 12. https://doi.org/10.1371/journal.pone.0175554.

Bourguignon, F., 1979. Decomposable income inequality measures. Econometrica 47, 901–920.

Bouwman, A.F., Van der Hoek, K.W., Eickhout, B., Soenario, I., 2005. Exploring changes in world ruminant production systems. Agric. Syst. 84, 121–153.

Carr, J.A., D'Odorico, P., Suweis, S., Seekell, D.A., 2016. What commodities and countries impact inequality in the global food system? Environ. Res. Lett. 11.

Coelho, S., Agbenyega, O., Agostini, A., Erb, K.H., Haberl, H., Hoogwijk, M., Lal, R., Lucon, O., Masera, O., Moreira, J.R., 2012. Land and water: linkages to bioenergy. In: Johansson, T., Patwardhan, A., Nakicenonivc, N., Gomez-Echeverri (Eds.), Global Energy Assessment: Toward a Sustainable Future. International Institute of Applied Systems Analysis (IIASA), Cambridge University Press, Cambridge, UK, pp. 1459–1525.

D' D'Odorico, P., Carr, J.A., Davis, K.F., Dell'Angelo, J., Seekell, D.A., 2019. Food inequality, injustice, and rights. Bioscience 69, 180–190.

D'Odorico, P., Carr, J.A., Laio, F., Ridolfi, L., Vandoni, S., 2014. Feeding humanity through global food trade. Earth's Future 2, 458–469. https://doi.org/10.1002/2014EF000250.

Duro, J.A., Padilla, E., 2006. International inequalities in per capita CO2 emissions: a decomposition methodology by Kaya factors. Energy Econ. 28, 170–187. https://doi.org/10.1016/j.eneco.2005.12.004.

Duro, J.A., 2012. On the automatic application of inequality indexes in the analysis of the international distribution of environmental indicators. Ecol. Econ. 76, 1–7.

Duro, J.A., Schaffartzik, A., Krausmann, F., 2018. Metabolic inequality and its impact on efficient contraction and convergence of international material resource use. Ecol. Econ. 145, 430–440. https://doi.org/10.1016/j.ecolecon.2017.11.029.

Er Erb, K.-H., 2004. Actual land demand of Austria 1926–2000: a variation on Ecological Footprint assessments. Land Use Policy 21, 247–259. https://doi.org/10.1016/j.landusepol.2003.10.010.

Erb, K.-H., Gaube, V., Krausmann, F., Plutzar, C., Bondeau, A., Haberl, H., 2007. A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. J. Land Use Sci. 2, 191–224. https://doi.org/10.1080/17474230701622981.

Erb, K.-H., Niedertscheider, M., Dietrich, J.-P., Schmitz, C., Verburg, P.H., Jepsen, M.R., Haberl, H., 2014. Conceptual and Empirical Approaches to Mapping and Quantifying Land-Use Intensity. In: Fischer-Kowalski, M., Reenberg, A., Schaffartzik, A., Mayer, A. (Eds.), Ester Boserup's Legacy on Sustainability. Orientations for Contemporary Research, Springer, Dordrecht, pp. 61–86.

Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M.C., Haberl, H., 2016. Exploring the biophysical option space for feeding the world without deforestation. Nat. Commun. 7, 11382. https://doi.org/10.1038/ncomms11382.

FAO, IFAD, UNICEF, WFP, WHO, 2017. The State of Food Security and Nutrition in the World 2017. Building resilience for peace and food security. Food and Agriculture Organisation (FAO), Rome.

FAO, IFAD, UNICEF, WFP and WHO. 2019. The State of Food Security and Nutrition in the World 2019. Safeguarding against economic slowdowns anddownturns (FAO), Rome.

FAOSTAT, 2019. Statistical Database. Food and Agriculture Organization of the United Nations, Rome.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray, H.C.J., 2013. Sustainable intensification in agriculture: premises and policies. Science 341, 33–34.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818. https://doi.org/10.1126/science.1185383.

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M.C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N., Noble, I., 2013. Policy: sustainable development goals for people and planet. Nature 495, 305–307. https://doi.org/10.1038/495305a.

Haberl, H., Erb, K.H., 2017. Land as a planetary boundary – a socioecological perspective. In: Victor, P.A., Dolter, B. (Eds.), Handbook on Growth and Sustainability. Edward Elgar, Cheltenham, UK and Northampton, MA, USA.

Haberl, H., Steinberger, J.K., Plutzar, C., Erb, K.-H., Gaube, V., Gingrich, S., Krausmann, F., 2012. Natural and socioeconomic determinants of the embodied human appropriation of net primary production and its relation to other resource use indicators. Ecol. Ind. 23, 222–231. https://doi.org/10.1016/j.ecolind.2012.03.027.

IAASTD, 2009. Agriculture at a Crossroads. International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), Global Report. Island Press, Washington, D.C.

Ittersum, M.K. van, Bussel, L.G.J. van, Wolf, J., Grassini, P., Wart, J. van, Guilpart, N.,

Claessens, L., Groot, H. de, Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., Oort, P.A.J. van, Loon, M.P. van, Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J.H.J.R., Ouattara, K., Tesfaye, K., Cassman, K.G., 2016. Can sub-Saharan Africa feed itself? PNAS 113, 14964–14969.
Jorgenson, A.K., 2010. World-economic integration, supply depots, and environmental degradation: a study of ecologically unequal exchange, foreign investment dependence, and deforestation in less developed countries. Crit. Sociol. 36, 453–477. https://doi.org/10.1177/0896920510365204.
Kastner, Thomas, Erb, Karl-Heinz, Haberl, Helmut, 2014. Rapid growth in agricultural trade: effects on global area efficiency and the role of management. Environ. Res. Lett. 9 (3).
Kastner, Thomas, Kastner, Michael, Nonhebel, Sanderine, 2011. Tracing distant environmental impacts of agricultural products from a consumer perspective. Ecol. Econ. 70 (6), 1032–1040.
Krausmann, F., Erb, K.-H., Gingrich, S., Lauk, C., Haberl, H., 2008. Global patterns of socioeconomic biomass flows in the year 2000: a comprehensive assessment of supply, consumption and constraints. Ecol. Econ. 65, 471–487 https://doi.org/16/j.ecolecon.2007.07.012.
Krausmann, F., Haberl, H., Erb, K.-H., Wiesinger, M., Gaube, V., Gingrich, S., 2009. What determines geographical patterns of the global human appropriation of net primary production? J. Land Use Sci. 4, 15–33. https://doi.org/10.1080/17474230802645568.
Kummu, M., Fader, M., Gerten, D., Guillaume, J.H.A., Jalava, M., Jägermeyr, J., Pfister, S., Porkka, M., Siebert, S., Varis, O., 2017. Bringing it all together: Linking measures to secure nations' food supply. Curr. Opin. Environ. Sustain. 29, 98–117. https://doi.org/10.1016/j.cosust.2018.01.006.
Lobell, D.B., Cassman, K.G., Field, C.B., 2009. Crop yield gaps: their importance, magnitudes, and causes. Annu. Rev. Environ. Resour. 34, 179–204.
Loos, J., Abson, D.J., Chappell, M.J., Hanspach, J., Mikulcak, F., Tichit, M., Fischer, J., 2014. Putting meaning back into "sustainable intensification". Front. Ecol. Environ. 12, 356–361.
Meyer, A., 1999. The Kyoto protocol and the emergence of "Contraction and Convergence" as a framework for an international political solution to greenhouse gas emissions abatement. In: Hohmeyer, O., Rennings, K. (Eds.), Man-Made Climate Change, ZEW Economic Studies. Physica-Verlag HD, Heidelberg, pp. 291–345. https://doi.org/10.1007/978-3-642-47035-6_15.
Motesharrei, S., Rivas, J., Kalnay, E., Asrar, G.R., Busalacchi, A.J., Cahalan, R.F., Cane, M.A., Colwell, R.R., Feng, K., Franklin, R.S., Hubacek, K., Miralles-Wilhelm, F., Miyoshi, T., Ruth, M., Sagdeev, R., Shirmohammadi, A., Shukla, J., Srebric, J., Yakovenko, V.M., Zeng, N., 2016. Modeling sustainability: population, inequality, consumption, and bidirectional coupling of the Earth and Human Systems. Natl. Sci. Rev. 3, 470–494. https://doi.org/10.1093/nsr/nww081.
Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257.
Mueller, N.D., Lassaletta, L., Runck, B.C., Billen, G., Garnier, J., Gerber, J.S., 2017. Declining spatial efficiency of global cropland nitrogen allocation. Global Biogeochem. Cycles 31 2016GB005515.
Niedertscheider, M., Kastner, T., Fetzel, T., Haberl, H., Kroisleitner, C., Plutzar, Christoph, Erb, K.-H., 2016. Mapping and analysing cropland use intensity from a NPP perspective. Environ. Res. Lett. 11.
Ramankutty, N., Foley, J.A., Norman, J., McSweeney, K., 2002. The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. Glob. Ecol. Biogeogr. 11, 377–392.
Ray, D.K., Ramankutty, N., Mueller, N.D., West, P.C., Foley, J.A., 2012. Recent patterns of crop yield growth and stagnation. Nat. Commun. 3, 1293.
Rockström, J., Steffen, W., Noone, K., Persson, A.A., Chapin, F.S., Lambin, E.F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H.J., others, 2009. A safe operating space for humanity. Nature 461, 472–475.
Sahn, D.E., 2015. The Fight Against Hunger and Malnutrition, The Role of Food, Agriculture and Targeted Policies. Oxford University Press, Oxford.
Schaffartzik, A., Duro, J.A., Krausmann, F., 2019. Global appropriation of resources causes high international material inequality – growth is not the solution. Ecol. Econ. 163, 9–19. https://doi.org/10.1016/j.ecolecon.2019.05.008.
Seekell, D.A., D'Odorico, P., Pace, M.L., 2011. Virtual water transfers unlikely to redress inequality in global water use. Environ. Res. Lett. 6.
Shorrocks, A., 1984. Inequality decomposition by population subgroups. Econometrica 52, 1369–1385.
Shorrocks, A., Wan, G., 2005. Spatial decomposition of inequality. J. Econ. Geogr. 5, 59–81.
Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347, doi: 10.1126/science.1259855. https://doi.org/10.1126/science.1259855.
Swinburn, B., Kraak, V., Rutter, H., Vandevijvere, S., Lobstein, T., Sacks, G., Gomes, F., Marsh, T., Magnusson, R., 2015. Strengthening of accountability systems to create healthy food environments and reduce global obesity. Lancet 385, 2534–2545. https://doi.org/10.1016/S0140-6736(14)61747-5.
Theil, H., 1967. Economics and Information Theory. North-Holland.
Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. 108 (50), 20260–20264.
Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515, 518–522.
UN, 2019. World Population Prospects 2019 [WWW Document]. URL https://population.un.org/wpp/ (accessed 12.17.19).
United Nations, 2015. Transforming our world: the 2030 agenda for sustainable development. General Assembley 70 session.
Wackernagel, W., M., Onisto, L., Bello, P., Callejas Linares, A., Susana López Falfán, I., Méndez García, J., Isabel Suárez Guerrero, A., Guadalupe Suárez Guerrero, M., 1999. National natural capital accounting with the ecological footprint concept. Ecol. Econ. 29, 375–390.
Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet. https://doi.org/10.1016/S0140-6736(18)31788-4.
World Bank, 2019. World Bank Country and Lending Groups [WWW Document]. URL https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups (accessed 12.17.19).