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Summary

In sub-Saharan Africa (SSA) diets are largely based on cereal or root staple crops. Together with socio-cultural change, economic and demographic growth could boost the demand for meat, with significant environmental repercussions. We model meat consumption pathways to 2050 for SSA based on several scenarios calibrated on historical demand drivers. To assess the consequent environmental impact, we adopt an environmentally-extended input-output (EEIO) framework and apply it on the EXIOBASE 3.3 hybrid tables. We find that, depending on the interplay of resources efficiency and demand growth, by 2050 global greenhouse gases emissions could grow by 1.4 [0.9-1.9] Gt CO_2e/yr (~175% of current regional agriculture-related emissions), cropping and grazing-related land may cover additional 15 [12.5-21] $\cdot 10^6$ km^2 (one quarter of today's global agricultural land), blue water consumption could rise by 36 [29-47] Gm3 /yr (nearly doubling the current regional agricultural consumption), the eutrophication potential could grow by 7.6 [4.9-9.5] t PO_4e/yr and additional 0.9 [0.5-1.4] EJ/yr of fossil fuels and 49 [32-73] TWh/yr of electricity may be consumed. These results suggest that – in the absence of drastic resource efficiency or technological improvements – meat demand in SSA is bound to become a major sustainability challenge. We show that a partial substitution of the protein intake with plant-based alternatives carries significant potential for mitigating these impacts. The policies affecting farming practices and dietary choices will thus have a significant impact on regional and global environmental flows.

Keywords: Meat Consumption, Economic Development, Environmental Impact Assessment, Environmentally Extended Input-output Analysis, Sub-Saharan Africa

JEL Classification: O13, Q01, Q21, Q56

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Abstract

In sub-Saharan Africa (SSA) diets are largely based on cereal or root staple crops. Together with socio-cultural change, economic and demographic growth could boost the demand for meat, with significant environmental repercussions. We model meat consumption pathways to 2050 for SSA based on several scenarios calibrated on historical demand drivers. To assess the consequent environmental impact, we adopt an environmentally-extended input-output (EEIO) framework and apply it on the EXIOBASE 3.3 hybrid tables. We find that, depending on the interplay of resources efficiency and demand growth, by 2050 global greenhouse gases emissions could grow by 1.4 *[0.9-1.9]* Gt CO_2e/yr (~175% of current regional agriculture-related emissions), cropping and grazing-related land may cover additional 15 *[12.5-21]* $\cdot 10^6$ km^2 (one quarter of today's global agricultural land), blue water consumption could rise by 36 *[29-47]* Gm^3 /yr (nearly doubling the current regional agricultural consumption), the eutrophication potential could grow by 7.6 *[4.9-9.5]* t PO_4e/yr and additional 0.9 *[0.5-1.4]* EJ/yr of fossil fuels and 49 *[32-73]* TWh/yr of electricity may be consumed. These results suggest that – in the absence of drastic resource efficiency or technological improvements – meat demand in SSA is bound to become a major sustainability challenge. We show that a partial substitution of the protein intake with plant-based alternatives carries significant potential for mitigating these impacts. The policies affecting farming practices and dietary choices will thus have a significant impact on regional and global environmental flows.

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1. Introduction

Food, diets, and nutrition – together with a steeply growing human population – are determining the escalation of several grand environmental challenges (Springmann *et al* 2018, Willett *et al* 2019, Gerten *et al* 2020). In response to these growing issues, numerous global assessments of the future of food systems and the sectoral environmental footprint have been carried out (Springer and Duchin 2014, Pastor *et al* 2019), including initiatives such as the EAT-Lancet Commission (Willett *et al* 2019). Among all agri-food segments, the meat and dairy industry have the highest resource and energy intensities (Poore and Nemecek 2018, Martinez *et al* 2019). The livestock supply chain occupies 83% of total farmland and it results in 60% of global greenhouse gases (GHGs) emissions from the agricultural sector (Poore and Nemecek 2018) – i.e. 14.5% of the total GHGs emissions (Dong *et al* 2006).

The agri-food sector is also responsible for other major environmental impacts (de Vries and de Boer 2010, Raphaely 2015, Westhoek *et al* 2014), including land use change and degradation (Röös *et al* 2017), biodiversity loss (WWF 2017), and water consumption and contamination (Gerbens-Leenes *et al* 2013). In addition, farming and grazing-related activities require a significant input of energy throughout their supply-chains (Ramirez et al., 2006, p. 200). The projected increase in the global food demand (Valin, 2019) coupled with a growing share of animal-based products (Bodirsky et al., 2015) might put the global ecosystem equilibrium under pressure, and its related impact must be carefully accounted. Indeed, it poses a significant challenge to the achievement of several Sustainable Development Goals (and primarily SDGs 2, 3, 6, 7, 13, 14, and 15).

While trends have been heterogeneous across regions, in most countries meat consumption has grown steadily together with economic development (see **Appendix** for an account of historical trends in a global perspective). During the twentieth century, the global demand for all meat types has in fact grown from 28.5 kg/capita/year in 1961 to 51 kg/capita/year in 2013, the latest year available in FAOSTAT statistics[1] (FAO Food Balance Sheet, 2017).

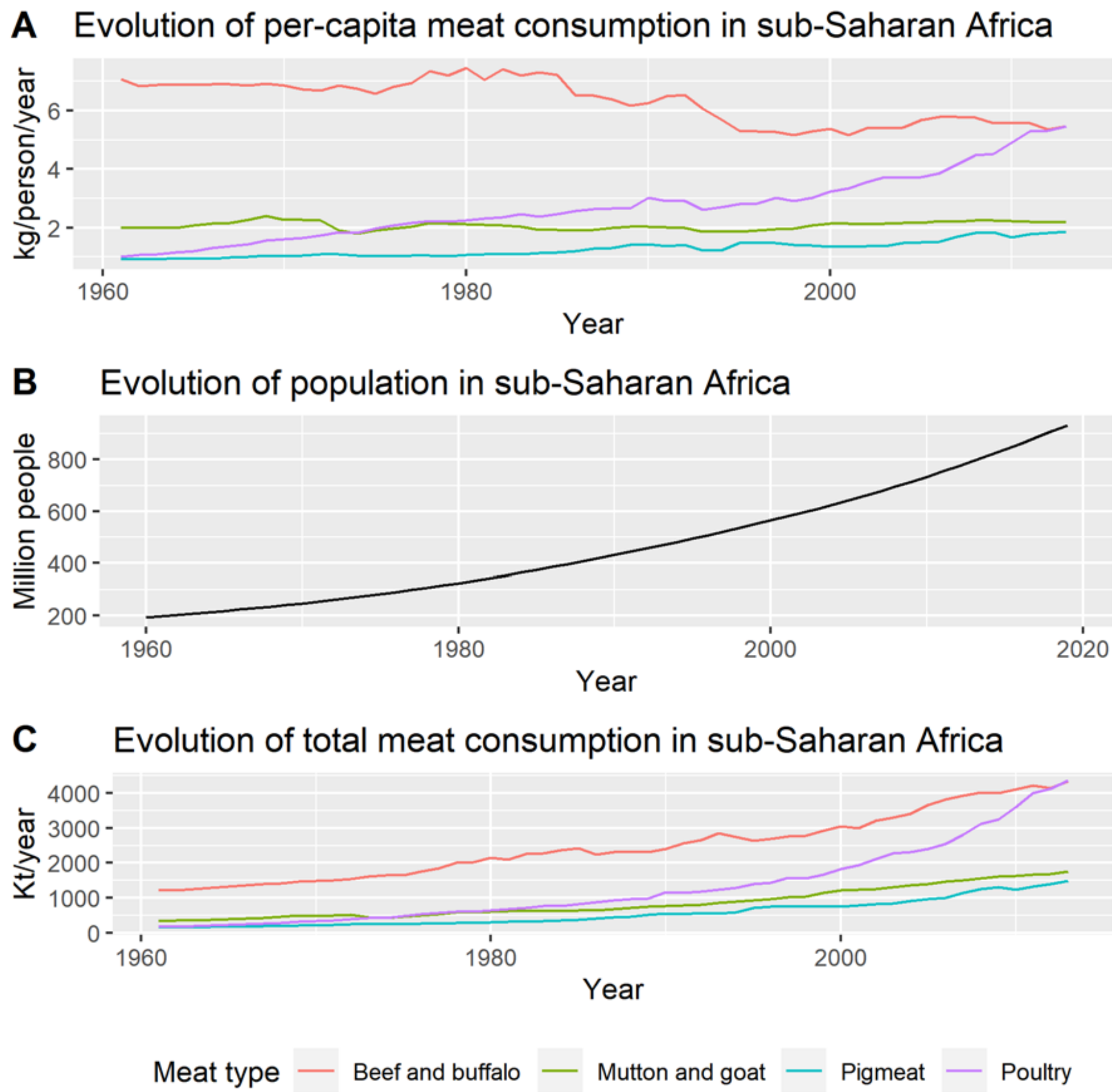

Fig. 1 | Historical evolution of meat consumption in sub-Saharan Africa. (A) Per-capita meat-consumption, by meat type; **(B)** Population; **(C)** Total meat consumption, by meat type.

[1] http://www.fao.org/faostat/en/#data/CL

Yet, when restricting the analysis for sub-Saharan Africa (excluding the Republic of South Africa; from now on SSA throughout the paper), it can be observed (**Figure 1**) that consumption of all meat types in the region stood at an average of 11.5 kg/capita in 2013 (FAO Food Balance Sheet, 2017) with little change from the 9.5 kg/capita in 1960. A stronger growth rate has characterized the region in the first decade of the twenty-first century, mostly driven by demand for poultry. Irrespective of low meat consumption levels, SSA is the first region in the world by grazeland and cropland areas (Klein Goldewijk et al., 2017), with 24% and 16% of the global total, respectively. This is both the result of large and growing populations, of robust agricultural exports, and of low efficiency of mostly extensive farming and grazing activities. On top of current agricultural land, it is estimated that in the region there are still two million squared kilometres of arable land (Byamugisha, 2013), about half of the world's total.

Previous studies have evaluated the historical relationship between the demand for meat and socio-economic and cultural factors at both a global scale (Clonan et al., 2016; Eker et al., 2019; Revell, 2015; Schroeder et al., 2013) and in developing countries (Cornelsen et al., 2016; Taljaard et al., 2006). Researchers estimated long-run income elasticities of demand for meat (Marques et al., 2018; Sans and Combris, 2015; Simo-Kengne et al., 2015) and showed that, historically, economic development has been largely associated with an increased demand for meat, albeit with meat-type and regional heterogeneity. The current and projected sustained economic and demographic growth in SSA could therefore significantly boost the demand for meat (Mathijs, 2015; Reuters, 2017).

Yet, few systematic meat demand projection studies for SSA have been carried out, e.g. Desiere et al. (2018) and the regionally-disaggregated global assessment by FAO (2018). Moreover, a rigorous, meat-focused analysis of the future of meat in SSA and an assessment of the related environmental impacts is missing in the existing literature. This is irrespective of MRIO EEIO (Multi-Regional Environmentally-Extended Input-Output Analysis) having been used extensively in large-scales assessments of the environmental footprint of food, diets, and nutrition (e.g. see Wood *et al* 2015, Springer and Duchin 2014, Schepelmann *et al* 2020, Hamilton *et al* 2018, Ivanova *et al* 2016).

Other relevant aspects that we could not find in published studies include an explicit modelling of future demand under different scenarios encompassing economic, demographic, and socio-cultural dimensions and an evaluation of the potential role of meat substitutes. Such comprehensive picture is however crucial for understanding the role that transformations in SSA could affect global environmental flows.

In the remainder of the paper we estimate the expected magnitude of the growth in the regional demand for different meat types by 2050. This allows us to quantity both the related impacts on the regional environment and energy system, and the implications for global environmental change. Our analysis is supplemented by an assessment of different scenarios over the adoption of several meat substitutes and the relative change in the total environmental impact. We conclude discussing the role of policy and technology in defining both demand and supply-related environmental impacts.

2. Materials and methods

2.1. Scope of the analysis

The aim of this paper is to evaluate pathways of meat consumption in SSA to 2050 to appraise the potential environmental implications in the region and globally. Being a long-term scenario analysis, the purpose of the study is to provide the reader with a range of results that could materialise depending on the interaction of demographic, economic, technological and cultural factors change in the next three decades. The scenarios shed light on the role of these different factors in determining the meat demand and the relevant environmental pressure. The demand modelling evaluates how socio-economic and cultural factors can be crucial determinants of the meat demand pathway followed by SSA. The EEIO analysis exploits a table of technical coefficients and environmental extensions with schematic assumptions over the future changes in productive efficiency to evaluate the ranges of potential environmental impact from the increased meat consumption. The main purpose of the analysis is therefore to support the framing of policies targeting food security and sustainable environmental resources management. It must be remarked that the demand modelling and EEIO analysis carried out are however not meant to deterministically predict future trends, as the uncertainty in the transformation that will occur remains broad. The results of the analysis should therefore be interpreted with explicit reference to the limitations stated in Section 4.2.

2.2. Input data and processing

Figure 2 provides a schematic framework of the workflow followed in this study and detailed below. The input data sources of each methodological step are described in Table 1. A panel dataset (country by year) of the processed input data for each variable, including projections for the future, is available as Supplementary Information.

For the statistical modelling of demand drivers, the OECD-FAO Agricultural Outlook database (OECD-FAO *et al* 2017) is used to draw historical consumption and price data (country-level between 1961 and 2013) for four types of meat: (i) beef and buffalo; (ii) pigmeat; (iii) poultry; and (iv) goat and mutton. A composite price index of cereals is also added as a control variable. These data are combined with the Maddison Project database of historical per-capita GDP (Bolt and Van Zanden, 2014) for the same period. To project the scenarios, we refer to the Shared Socio-Economic Pathways (SSPs) database

(Riahi et al., 2017), containing five scenarios over the potential evolution of the global (and country-level) population and GDP until 2100. The SSPs are based on narratives of global development (including inequality) and anthropogenic warming. Since the GDP numbers of the Maddison Project database are reported in constant 2005 USD while those of the SSPs database are in 2010 constant USD, we harmonised the former to the latter using the World Bank *PA.NUS.ATLS* local currency unit (LCU) to International Dollars adjustment factor.

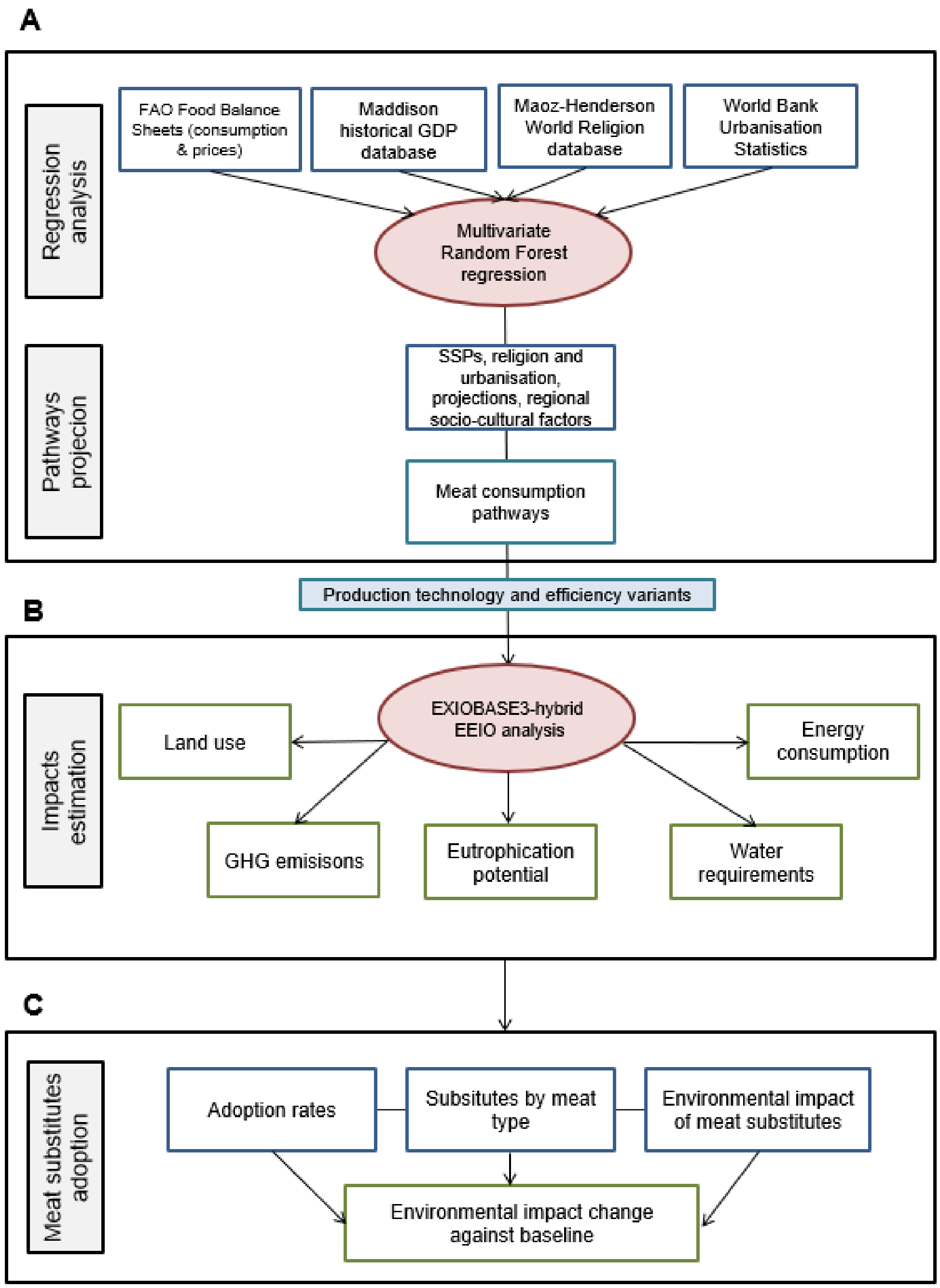

Fig. 2 | Schematic framework of the analysis carried out to estimate environmental impacts on meat consumption to 2050 in sub-Saharan Africa. (A) Main data inputs to the statistical modelling of meat demand and projection of pathways for SSA to 2050. **(B)** Environmentally Extended Input Output Analysis (EEIO) carried out in hybrid units for the reported impact categories. **(C)** Simulation of meat substitutes adoption and relative environmental impact change. Dark blue blocks identify input data; red blocks refer to model-based analysis; green blocks define final environmental impacts results.

Additional predictors considered in the statistical modelling and future pathways projection are derived from the *World Religion Dataset, 1945–2010* (Maoz and Henderson, 2013) and the *Future of World Religions* (Center, 2015) report. Future prices of meat and cereals (to predict future meat demand) are drawn from OECD-FAO *et al* (2017) and FAO (2018). Future For the environmental impacts estimation, we exploit the EXIOBASE 3 hybrid units database (Stadler et al., 2018). EXIOBASE 3 is characterised by a high sectorial detail matched with multiple social and environmental satellite accounts. The database is constructed using rectangular Supply and Use tables in a 164 industry by 200 products classification exploiting national and international accounts and inventories to represent the global economy in year 2011.

Table 1: Main input data table

Dataset	Variable(s)	Source	Temporal resolution	Spatial resolution	Time scope
OECD-FAO Agricultural Outlook database	Per-capita consumption, by meat type (kg/capita)	(OECD-FAO *et al* 2017)	1 year	Country-level, global: 239 regions	1961 – 2050
OECD-FAO Agricultural Outlook database	Meat (by meat type) and fundamental crops producer prices (LCU/tonne)	(OECD-FAO *et al* 2017)	1 year	Country-level, global: 200 regions	1961 – 2015
The future of food and agriculture – Alternative pathways to 2050	Meat (by meat type) and fundamental crops producer prices (LCU/tonne)	(FAO 2018)	5 years	Country-level, global: 178 regions	2012 – 2050
World Bank Data	›PP conversion factor	(World Bank 2019)	1 year	Country-level, global: 213 regions	1990 – 2019
Project Maddison Database	Historical population and PPP per-capita GDP	(Bolt and Van Zanden 2014)	1 year	Country-level, global: 169 regions	1000 – 2016

SSPs database	Projected population and PPP per-capita GDP	(Riahi *et al* 2017)	5 years	Country-level, global: 198 regions	2010 – 2100
Historical religion adherence	Share of the population	(Maoz and Henderson 2013)	5 years	Country-level, global: 200 regions	1945 – 2010
Forecasted religion adherence	Share of the population	(Pew Research Center 2015)	10 years	Country-level, global: 198 regions	2010 – 2050
Historical and forecasted urbanisation levels	Share of the population	(UN DESA 2018)	5 years	Country-level, global: 273 regions	1950-2050
EXIOBASE3 products database	Technical, economic, and impact coefficients	(Stadler *et al* 2018)	1 year	Global coverage: 48 regions	1995 – 2011

2.3. Demand drivers modelling

To estimate the demand for the four different types of meat considered we resort to literature contribution analysing the key drivers of meat consumption (Milford *et al* 2019) and, based on this literature, we appraise the available data and projections that can be used to train a statistical model and make predictions for the future. The meat consumption drivers we consider include income (Vranken *et al* 2014), prices of each meat type (Gallet 2010a) as well as of a composite index of cereal crops (Milford *et al* 2019), urbanisation levels (Milford *et al* 2019), religions adherence (a strong driver of dietary choices; Heiman *et al* 2004), and a set of residual regional socio-cultural mediators (reflecting historical and cultural mediators for the impact of economic growth on the demand for meat). The modelling analysis is carried out in per-capita consumption units because in developing countries per-capita demand growth will likely be a more important driver of food demand than population growth between now and 2050 (as discussed in Fukase and Martin 2020).

To model the statistical relationships, we rely on multivariate regression analysis **(Figure 2A)**. The model choice is justified by the presence of four outcome variables of interest (the demand for each meat type) which are correlated among each other. In general, a multivariate regression is a statistical model where two or more correlated outcome variables are simultaneously predicted with the same set of predictor variables. A multivariate system aims at describing how elements in a vector of variables respond simultaneously to changes in a set of mutual predictors. The objective of a multivariate approach is to cope with the outcome variables and thus the stochastic error terms ε_{nt} being simultaneously correlated across the regression equations for each meat type (in our case, as a result of the dynamics of substitution and complementation across meat types due to changing tastes) by simultaneously modelling the relationships. Equation 1 reports the general multivariate model:

$$Y_{nt\times m} = f(X_{nt\times(k)}) + \varepsilon_{nt} \qquad \text{(Eq. 1)}$$

where:

- Y is a set of *m* outcome variables (in our study four, one for each meat type);
- *n* and *t* are the number of entities and time-steps measured, respectively (and thus their product is the size of the panel dataset);
- *f* is a function that associates the outcome variables with the regressors (*X);*
- *k* is the number of independent regressors *X*;
- ε is the regression residual or error.

To empirically estimate the regression model, we adopt a learning-based approach, whereby the data is split into a training and a test set with shares of

70% and 30% of the data, respectively. To account for time auto-correlation in data splitting, i.e. ensure statistical independence between the groups, we follow Griffin (2020): the splitting is performed such that every observation in each country has an equal chance of being in the training and test sets, respectively. Namely, the random sampling is stratified by country. The model is then cross-validated over tuning parameters.

This approach allows for a non-parametric assessment that is able to capture non-linearities and mediated effects of the regressors. It is worth remarking that the purpose of this statistical analysis is modelling historical patterns based on the complex historical socio-economic and cultural interlinkages to predict plausible future pathways, and not investigating causal relationships. Namely, the key goal of our regression model is to replicate the outcome variables (meat consumption levels) as accurately as possible based on the inputs (the meat demand drivers considered in our analysis). Furthermore, the predictive nature of the analysis prevents us to include additional drivers for which no reliable long-term projections can be formulated and cannot therefore be included in the assessment (the main meat drivers identified in Milford *et al*, 2019, are however included in our analysis). For the same reason, year fixed-effects cannot be added to the regression (unless a time-trend of region-invariant factors is assumed for future years with respect to the past, which is at odds with the non-linear inquiry carried out).

Specifically, we estimate the following model:

$$Demand_{ict} = f(PCGDP_{ct}\ , price_{rct}, cerealsprice_{ct}\ religionshares_{ct}\ , urbrate_{ct}, region_{r}) + \varepsilon_{ct} \qquad \text{(Eq. 2)}$$

where:

- *i,c,r,* and *t* refer to each of the four meat types, countries, regions (see below), and years in the dataset, respectively;
- *Demand* is the per-capita amount of meat consumed (in kg);
- *PCGDP* is the purchase-power-parity per-capita GDP in constant 2011 US Dollars;
- $price_{irt}$ is the average real price of each meat type *i* in each region *r* in each year *t;*
- $cerealsprice_{ct}$ is a composite index of average cereals real price in each region *r* in each year *t;*
- $urbrate_{ct}$ are country-level urbanisation levels, i.e. the fraction of the national population living in urban settlements;
- $religionshare$ represents a set of 7 fractional variables expressing (for each year in each country) the share of the country's population adhering to each of the major global religions (plus an additional variable for the fraction of non-religious people);
- $region$ is a mediating categorical variable which links each country *c* to the corresponding region among the 20 country groups considered[2]. These variables control for mediating regional socio-cultural factors that affect the link between the regressors and the demand driver variables;
- $\varepsilon_{ct}$is a vector of stochastic error terms.

The data is randomly split into a training and a test set. The multivariate random forest (MRF) regression is implemented through the *randomForestSRC* package (Ishwaran and Kogalur, 2020) in the R scientific computing environment v3.6. The model – with 1,000 trees – is trained on the training subsets – producing training accuracies in the 82.9% - 92.2% range – and then validated on the test set, with resulting accuracies in the 87% - 93% range depending on the meat type inquired. The **Appendix** contained figures of OOB

[2] "North Africa and Middle East", "Central Sub-Saharan Africa", "Central Europe", "Southern Latin America", "Central Asia", "Australasia", "Western Europe", "Western Sub-Saharan Africa" "South Asia", "Eastern Europe", "Andean Latin America", "Tropical Latin America" "Caribbean", "Southern Sub-Saharan Africa" "High-income North America", "East Asia", "Central Latin America", "Eastern Sub-Saharan Africa" "Southeast Asia", "High-income Asia Pacific"

error rates and variable importance plots for each outcome variable, which altogether provide a comprehensive benchmark for the random forest modelling carried out. Moreover, income elasticity plots for each meat type calculated out-of-bag are plotted in **Figure SI3** in the Appendix. These show the evolution of the marginal (i.e. *ceteris paribus*) response of meat consumption over the range of income levels in the training data (the % change in Y_i variables in response to a 1% change in X, at different levels of each X, net of the effect of all other variables).

2.4. Future consumption pathways projection

Based on the trained model, we generate pathways of meat consumption for SSA to 2050. These are determined by a set of published projections of (i) PPP per-capita GDP growth; (ii) population growth; (iii) the forecasted share of people adhering to each religious belief; (iv) the forecasted urbanisation level; and (v) the mediating region, i.e. the region among the 20 considered which accounts for the mediating the relationship between the regressors (e.g. income and urbanisation) and the consumption of each meat type. This region variable thus embeds the unmeasured regional socio-cultural factors which define the magnitude and functional form of the relationship between the regressors and the consumption of the different meat type in each region. Thus, each of our projections for future meat consumption in SSA assumes an anchoring towards a given SSP (numerical pathways for the growth of GDP/capita and population in the SSA region until 2050) scenario and – simultaneously – a certain mediating region. For our projections we consider Central Europe, Eastern Asia, Central Latin America, and North Africa & Middle East. Namely, we evaluate the impact of SSA's residual socio-cultural factors evolution towards those of these four regions.

Finally, to validate our estimates, the resulting pathways are appraised against estimates of meat demand in SSA obtained from FAO's *Future of Food and Agriculture: Alternative Pathways to 2050* (FAO 2018) global modelling study. A visual comparison is found in the **Appendix**, showing general consistency of future trends, although our scenarios cover a wider range of variability.

2.5. MRIO EEIO analysis and resource efficiency evolution

Multiregional input-output analysis methodologies have been recently employed in literature for evaluating consequential impacts associated with different diets (Springer and Duchin 2014, Behrens *et al* 2017, Rehkamp and Canning 2018, Hitaj *et al* 2019). Here, in order to evaluate the environmental impact **(Figure 2B)** associated with future meat demand pathways in SSA, we adopt a Leontief impact model (Eq. 4) exploiting the hybrid version of EXIOBASE (Stadler *et al* 2018), a multi-regional environmentally extended input-output table (version 3.3.18 hsut 2011). The database offers a physical – when possible – and monetary representation of the economy, describing the interactions among 164 sectors of 48 regions and the environment. SSA is here modelled on the African “Rest of the World” region. We run the analysis using an in-house under-development Python module which expands the capabilities offered by *pymrio* (Stadler, 2015). Beef, poultry, and pork demand in physical dry units are allocated to the *Products of meat cattle*, *Products of meat poultry*, and *Products of meat pigs* sectors, respectively (mutton and goat are not considered due to absence of an explicit corresponding sector in the adopted database). Impacts are estimated throughout the entire supply-chain (all sectors) and globally (including import/export flows). The analysis is run at four time steps: 2020, 2030, 2040, and 2050.

$$Impact = E_s[(I - A)^{-1} y_s] - E_s[(I - A)^{-1} y_0] \qquad \text{(Eq. 4)}$$

Where:

- *E* identifies the matrix of environmental extensions coefficients (i.e. matrix of resource efficiencies) in scenario *s*;

- y is the vector of final demand (subscript s refers to the specific scenario while 0 refers to the baseline);
- I the identity matrix with the same dimension of A which is the matrix of intermediate transaction coefficients (i.e. matrix of technology coefficients).

Every scenario is identified by each combination of pathways and time steps which results in impacts which are strongly related to the production technology and yield. Indeed, in evaluating the environmental impacts of future demand of meat products, changes in economic-wide efficiencies plays a role. Here no explicit change in sectoral interactions, nor change in international trade patterns, are assumed (i.e. the same matrix of intermediate transaction coefficient is adopted in every scenario – see Eq. 4). Nevertheless, several resources efficiency variants, representing a set of potential pathways of use of environmental resources change over time in the livestock supply chain of SSA, are introduced. These pathways of production techniques changes assume dynamic resource efficiency gains, whereby regional efficiency gradually converges towards the efficiency of different countries worldwide as expressed by the current impact coefficients of the EXIOBASE 3 hybrid tables. The dynamic transition is operated at a ten-year time-steps, from 2020 to 2050 (**Figure SI6**).

As detailed in **Table SI6**, resource efficiency scenarios mirror a gradual convergence (**Figure SI7**) towards the median efficiency in the reference regions selected when generating the meat consumption scenarios: Central Europe, East Asia, Central Latin American, and MENA. For each scenario, in the 2020s the resource efficiency is assumed to reflect 90% of today's SSA's efficiency an 10% of the reference region median efficiency; in the 2030s the ratio shifts to 80% and 20%, respectively; in the 2040s to 65% and 35% each; and in year 2050s it reaches levels of 50% for both today's SSA coefficients and the reference regions coefficients.

2.6. Environmental impact assessment

In every year environmental impacts are assessed starting from the technological description of national and international interlinkages described in the global input-output table adopted, by means of final demand, intermediate transactions (i.e. technology) and environmental extensions (i.e. environmental resource efficiency) coefficients. In every time step, a demand shock is performed updating the level of final meat demand accordingly to the future consumption pathways projection together with a change of SSA's environmental extensions coefficients in both baseline and specific scenario's matrices. In this way, the impact is evaluated computing the difference between two scenarios which differ only in terms of meat consumption levels.

In each time step *t*, environmental extensions coefficients are used to evaluate midpoint life cycle impact assessments indicators. Greenhouse gases emissions are expressed in CO_2^{equiv} units as the weighted sum of CO_2, CH_4, N_2O (i) by their emission factors (EF):

$$CO_2^{equiv}{}_t = \sum GHG_{it} \times EF_i$$

(Eq. 5)

We define emission factor in kg of CO_2^{equiv} based on Pachauri et al. (2014) at 1 for CO_2, 28 for CH_4, and 265 for N_2O.

The eutrophication potential is estimated using the seminal methodology by Heijungs et al. (1992) and adopted in recent seminal studies (Behrens *et al* 2017):

$$EP_i = \frac{v_i/M_i}{v_{ref}/\ M\_ref}$$

(Eq. 6)

Where v_i and v_{ref} are the potential contributions to eutrophication of one mole of substance *i* and *ref* (i.e. $PO_4^{3-} equivalents$), respectively, M_i and M_{ref} ($kg\ mol^{-1}$) are the mass of *i* and *ref*. To calculate eutrophication potential, we consider PO_4^{3-} equivalence factors in land, air, and water reported in Huijbregts (1999).

We consider blue water consumption as the key indicator for the water footprint of meat products. Blue water refers to water sourced from surface or groundwater resources and is either evaporated or incorporated into a product. The concept of blue water footprint thus refers to the physical resource depletion as opposed to green water footprint, which describes direct use of water recharge, i.e. water from precipitation. Moreover, we refer to water consumption (i.e. the amount of water removed for use and not returned to its source) as opposed to water withdrawal (total water removed from a water source such as a lake or river, a portion of which is returned to the source and is available to be used again).

To estimate the land footprint of the meat supply-chain, we consider the total land requirements for agriculture, pastures, forestry and woodfuel by summing them up.

EXIOBASE 3 hybrid tables report energy consumption as resource use (i.e. fossil fuels such as coal, oil, and natural gas) or as an economic sector (i.e. electricity production). To translate these units into a comprehensive figure of primary energy demand, we transform physical units of fossil fuels (FF*i*) into primary energy by multiplying them to average energy contents (*EC*) as reported in the International Energy Agency unit converter tool:

$$PED_t^{FF} = \sum FF_{it} \times EC_i$$

(Eq. 7)

This estimated energy requirements are only in part directly driven by the energy-economic sector such as the electricity production one. A significant share of these requirements reflects embodied energy into machinery and services consumed throughout the supply-chain. For further information on resource allocation procedures see SI.

2.7. Comparison with current environmental stocks and flows

To put the estimated environmental impacts into perspective, it is useful to compare them with current environmental stocks and flows along the examined impact dimensions. We refer to the current suitable non-cultivated land and the current crop and grazing land in the region from FAO (2011). Greenhouse gases emissions from the agricultural sector are retrieved from Tongwane and Moeletsi (2018). The sectoral primary energy demand is obtained from Ouedraogo (2017). Last, both the current blue water consumption and the eutrophication potential from the agricultural sector in SSA are derived directly from the 2011 physical-unit EXIOBASE 3 tables (Stadler et al., 2018).

2.8. Meat substitutes adoption and relative environmental impact

Plant-based, protein-rich meat alternatives such as tempeh and soy-based products are already cheaper than animal meat and widespread in many developing countries. On the other hand, high-tech meat substitutes such as lactose-based products and in-vitro beef are generally more expensive. Yet, production costs are rapidly declining (Northfield, 2019) and social perceptions are also shifting (Gómez-Luciano et al., 2019), and might make such products highly competitive over the next decades. With regards to the plausibility of adoption of meat substitutes in SSA, growing interest has been recently reported by international and local companies in the sector, e.g. refer to

Mulumba (2020) and CleanTechnica (2020). In addition, as reported by van Huis (2003), in sub-Saharan Africa more than 60 grasshopper and locust species are already widely eaten, alleviating psychological barriers to e.g. insect-based burgers.

For each of the meat types considered, scenarios of different degrees of meat substitutes adoption are designed **(Figure 2C)**. We refer to peer-reviewed state-of-the-art LCA assessment of environmental impact (refer to **Table SI7**) of popular meat alternatives, including vegetal alternatives, dairy-based products and in-vitro meat. Each alternative is identified as a substitute to a specific meat type depending on texture, characteristics, and consumer perception. The LCA estimates collection aims at capturing the same dimensions of environmental impact examined in this study for animal meat.

We implement the meat substitution dynamics on the median meat demand scenario for each resources efficiency variant, simulating 10%, 25% and 50% of animal product consumption substitution by 2050. In our assessment, we assume that each meat type is evenly substituted by those shares. Where multiple substitutes are identified for one single meat type, we simulate an equal mix of those substitutes (gluten, leguminous, insect, and lab-based products for beef; dairy-based products for poultry; soy-based products for pork; World Economic Forum, 2019), hence adopting the mean value of each environmental impact category.

In particular, we simulate substitution such that the absolute quantity of meat substitutes per kg of meat substituted in each adoption scenario provides the same amount of proteins which would be provided by one kg of each meat type. **Table SI8** summarises the assumed protein content (g/kg of product) of each meat type and of each meat substitute considered.

3. Results

3.1. Demand drivers and regional consumption pathways to 2050

Figure 3 illustrates the projected per-capita (panel A) and aggregate (panel B) regional demand for each of the four types of meat in the five SSP scenarios. Each line therefore describes the reference-region mean outcome across each of SSP scenario. The results and model benchmarks of the underlying statistical modelling are reported in **Tables SI1-SI5 and Figure SI2**. The projections are also compared to FAO regional projections (FAO, 2018) in **Figures SI4-5**, showing a general consistency. Yet, our projections follow non-linear growth trends and encompass a larger range of variability compared to the FAO projections, for which all three scenarios predict a very narrow outcome range for 2050. This is the result of the broad underlying drivers, with interactions different scenarios of demographic and economic growth, the latter mediated by the prevalent socio-cultural dynamics.

According to the estimated pathways, beef and buffalo meat consumption in 2050 is projected in the 7-15 kg/capita/year range, with a mean value of 10 kg/capita/year, implying a scenario-median aggregate demand of 17.5 Mt in 2050. Poultry meat consumption is estimated to reach a value in the 8-18 kg/capita/year range, with a median of 12 kg/capita/year, and thus a scenario average aggregate demand of 21 Mt in 2050. Pork consumption is projected in the 3.5-23 kg/capita/year range, with a median value of 9.5 kg/capita/year, implying a scenario-average aggregate demand of 16 Mt in 2050. Finally, goat and mutton meat consumption will lie in the 1.5-5 kg/capita/year range, with a mean value of 3.4 kg/capita/year and a scenario-average aggregate demand of 5.9 Mt in 2050.

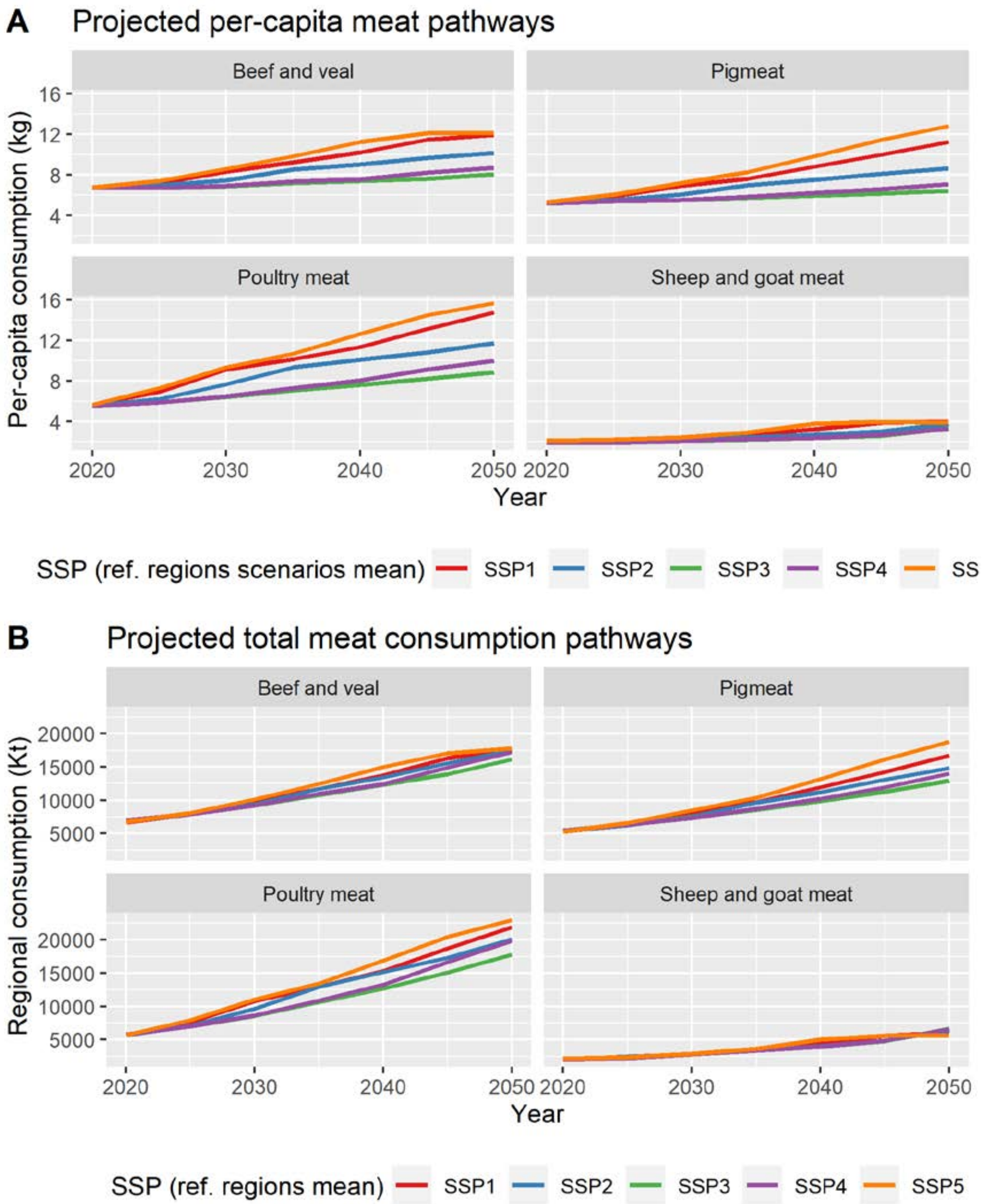

Fig. 3 | Estimated consumption pathways. Resulting pathways of meat consumption until 2050 in SSA, by meat type. Panel A: per-capita consumption (kg/capita/year); Panel B: total consumption (Kt/year), inclusive of population growth. The scenarios from FAO's *Future of Food and Agriculture: Alternative Pathways to 2050* report are visualised for comparison in Figures SI4-5.

3.2. Related environmental impacts assessment

Figure 4A summarises the results of the environmental impact assessment, carried out according to the LCA approach, hence accounting for the resources consumption and emissions throughout the entire supply chain of production of the final meat products. In the same figure, colours identify the socio-cultural and resource efficiency convergence regions and within each category they differ by the assumed SSP scenario. The black lines express the median values across all scenarios for each impact category, to which we attach the greatest significance in the interpretation of the numbers. It must remark that the figures describe the additional impacts, i.e. on top of today's regional environmental impact due to meat consumption.

We find that by 2050 – depending on the interplay of resources efficiency and demand growth – globally greenhouse gases emissions could grow by 1.4 *[0.9-1.9]* Gt CO_2e/yr (~175% of today's regional agriculture-related emissions), cropping and grazing-related land may cover additional 15 *[12.5-21]* $\cdot 10^6$ km^2 (one quarter of today's global agricultural land), blue water consumption would rise by 36 *[29-47]* Gm^3/yr (nearly doubling the current regional agricultural consumption), the eutrophication potential would grow by 7.6 *[4.9-9.5]* t PO_4e/yr, and additional 0.9 *[0.5-1.4]* EJ/yr of fossil fuels and 49 *[32-73]* TWh/yr of electricity would be consumed. These results are inclusive of the different meat type considered in our analysis; meat type specific results are reported in **Figure SI8** and suggest that in relative terms beef meat is responsible for greater environmental impact than the other meat types, and mainly when it comes to its land, GHG, and eutrophication potential footprints, which are all at least ten times larger than those of pork and poultry. Blue water consumption is more evenly spread among meat types, but pork is the main consumer. Finally, energy consumption shows similar values across the meat types.

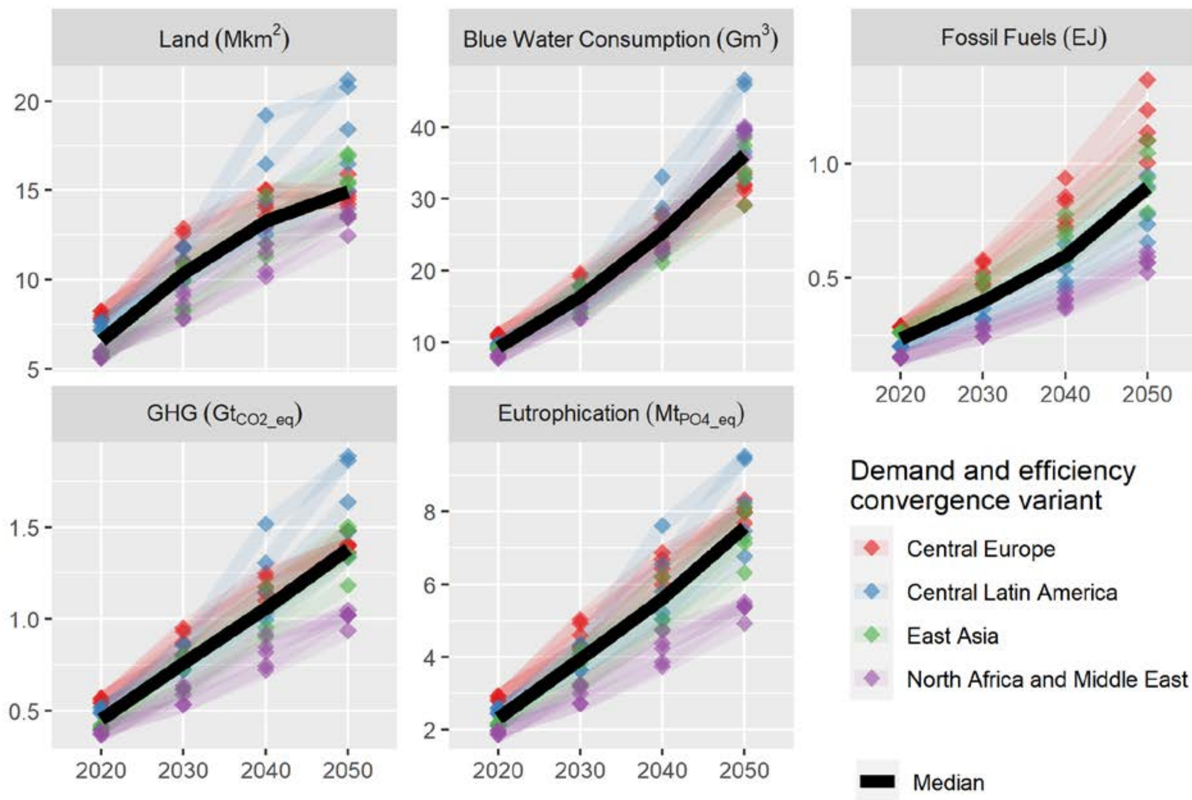

Fig. 4 | Distribution of the estimated additional local environmental impacts across scenarios 2050. Distribution of additional (i.e. on top of today's levels) impacts across the five categories analysed for 2020, 2030, 2040, and 2050 by consumption and resources efficiency scenarios

As previously detailed, the environmental impacts relative to each consumption pathway are estimated with hybrid-units EEIO tables. Environmental impacts of the supply-chain of meat depends on the production of the total quantities required, the resource efficiency of the adopted production processes (i.e. natural resource and emissions intensities). To represent the role of resources efficiency of the economic system with respect to environmental dimensions, five resource efficiency variants – responsible for linking production with environmental impacts – are designed (see Section 2.5). These pathways of resource efficiency change assume dynamic efficiency gains, whereby regional resource intensities gradually converge towards resources efficiencies of different reference economies worldwide, as expressed by the coefficients of the EXIOBASE 3 dataset. Each coefficient represents the marginal sectoral impact or resource consumption per additional physical unit produced in each region. The dynamic transition is operated at a ten-year time-steps, from 2020 to 2050 (**Figure SI6**).

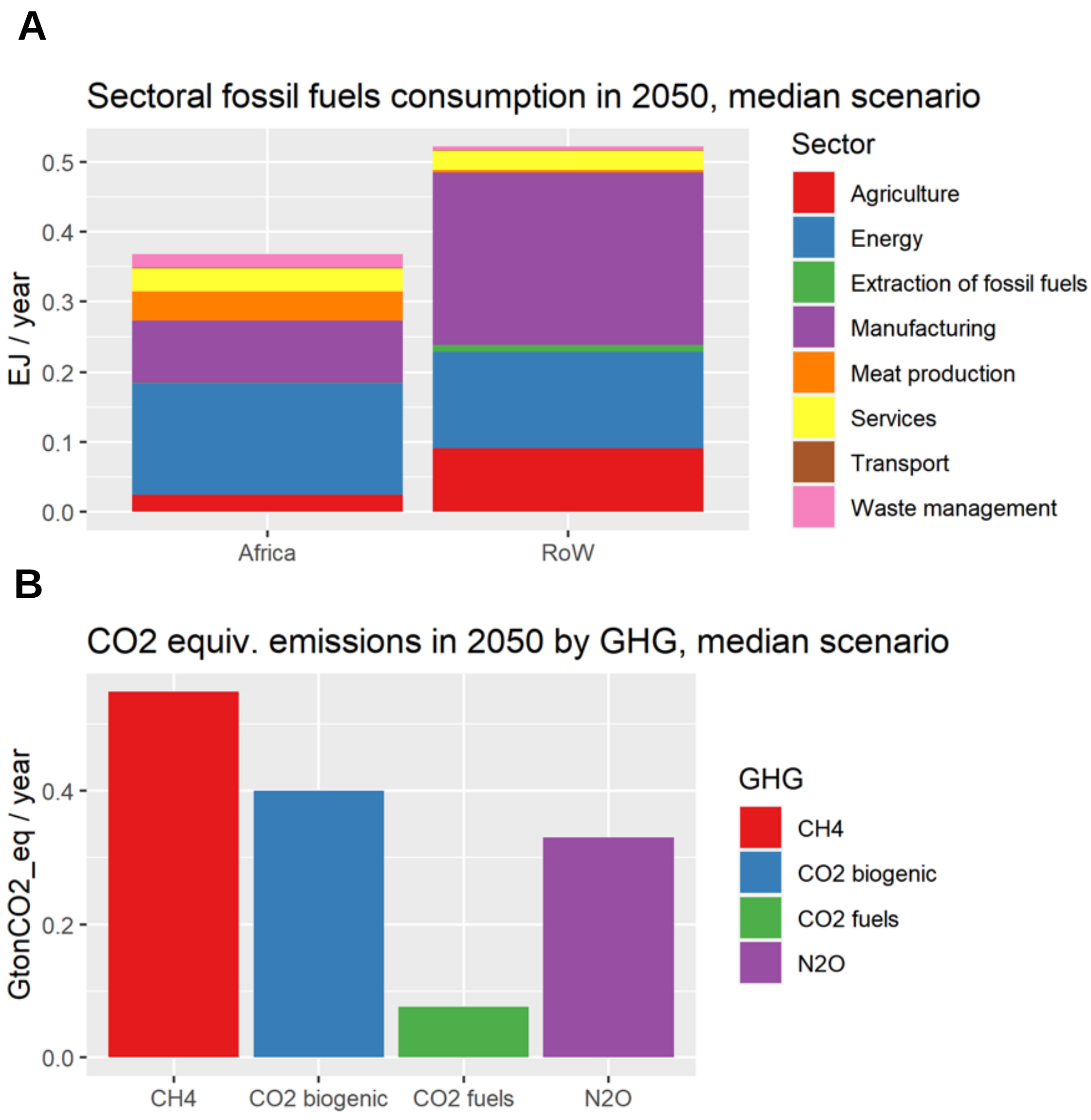

Figure 5: (A) Distribution of fossil fuels consumption across world regions for a set of aggregated final use sectors. **(B)** Distribution of LCA greenhouse gases emissions for the four GHGs considered: CO_2 (biogenic and fossil fuels), N_2O, and CH_4.

As schematically represented in **Figure SI7,** those scenarios (described in **Table SI6**) mirror a convergence towards the median resource efficiency in the reference regions selected when generating the meat consumption scenarios: Central Europe, East Asia, Central Latin American, and MENA. Moreover, in our study the evolution in resource efficiency over time is associated with socio-cultural convergence: meat demand scenarios where the impact of economic development is mediated by a given regional preference are later evaluated in the EEIO environmental impact analysis assuming resource efficiency convergence towards the same region.

Overall, our results show that while the demand-side has a prominent role in defining the expected environmental outcome, there is also very large room for resource efficiency and technology to mediate these impacts. The mechanisation and industrialisation of the agricultural sector and of breeding sites are prone to long-lived lock-ins, and thus the paradigm followed has a big long-run impact. In general, it seems that reference regions which imply higher consumption pathways (such as the Central European and the Central Latin American paradigms) are at the margin also more resource-efficient, and yet the final environmental impact of each scenario is a trade-off between the two.

When looking at the sectoral final consumption of fossil fuels (see Section 2.6 for a description of the sectoral allocation approach), the results for the median scenario in 2050 **(Figure 5A)** show about 60% of the total consumption occurs outside of SSA (about 0.52 EJ/year of the total 0.89 EJ/year). The sectoral repartition shows that manufacturing and the services sectors dominate the final consumption of fossil fuels, while a marginal role is played by the primary (agricultural) and meat production sectors. This result is justified by the LCA nature of the analysis, which includes embodied energy into machinery and services provision, emerging as the dominant consumption drivers. Disaggregation of the different greenhouse gases **(Figure 5B)** for the median scenario shows that the largest sectoral source of warming potential comes from increases in CH_4 emissions, responsible for about 40% of the total 1.35 Gt CO_2equiv. The residual 60% is divided into 49% of biogenic CO_2 emissions from biomass combustion or decomposition, 41% of N_2O (mainly from fertilisation), and only 9% CO_2 emissions from the combustion of fossil fuels. Note that here emissions from land use change are not accounted for.

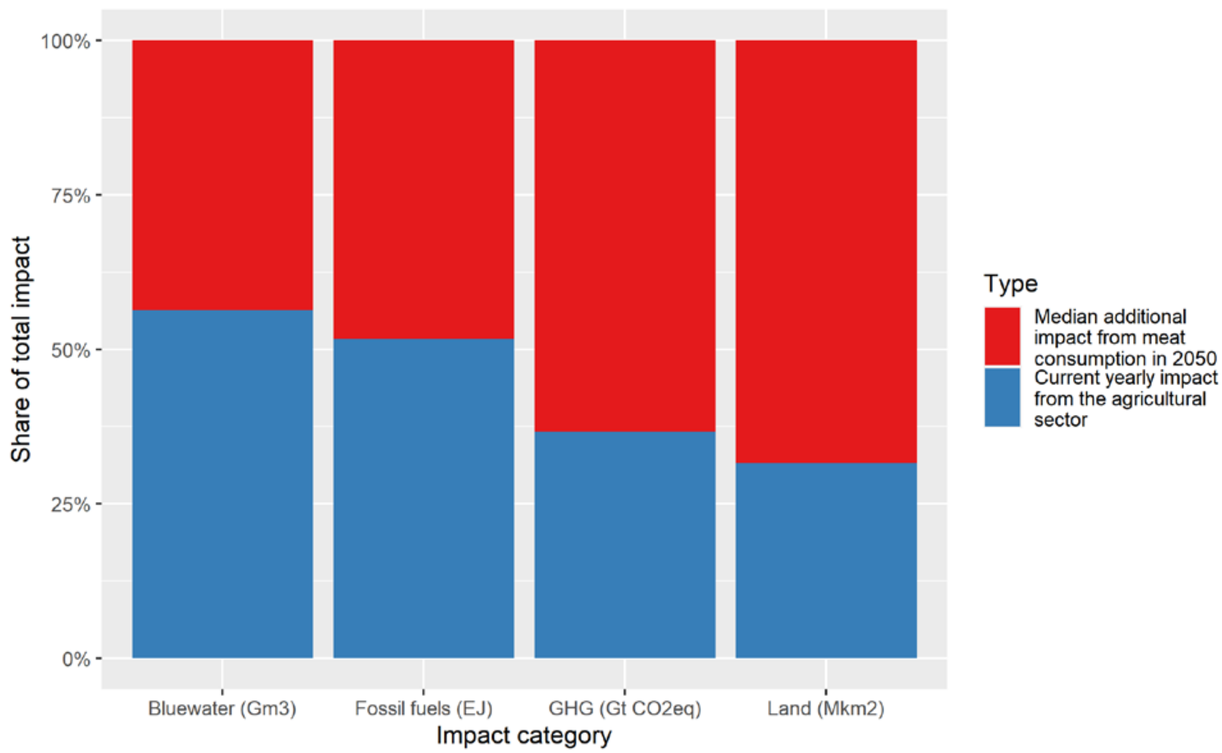

Fig. 6 | Comparison of estimated impacts by 2050 with current environmental flows in sub-Saharan Africa. The boxplot compares the magnitude of the current regional environmental flows analysed in this study (sources: Stadler *et al* 2018; FAO 2011; Tongwane and Moeletsi 2018; Ouedraogo 2017) with the range of impacts estimated for year 2050 under all the demand and resources efficiency scenarios.

To put the absolute magnitude of the results into perspective, **Figure 6** provides the comparison of the relative significance of the estimated median impacts in 2050 with reference environmental flows at the present time. The median blue water consumption in 2050 in SSA would nearly double the current regional agricultural consumption (Stadler et al., 2018), significantly increasing the pressure on groundwater aquifers and freshwater surfaces. However, it must be remarked that today SSA more than 90% of total cropland is rainfed only (Xiong et al., 2017), and therefore substantial volumes of irrigation water for intensification purposes will be required to produce feedstock. Moreover, in the agricultural sectoral of SSA the fossil fuels consumption will also nearly double, while greenhouse gases emissions will grow almost threefold (Ouedraogo, 2017). Yet, the most pervasive impact will perhaps be in the land use. Crop and grazing land will together require a more than threefold increase in the currently 6.9 million km^2 occupied by the sector in SSA (FAO 2011), unless very strong intensification of production takes place. More strikingly, the additional 15 million km^2 of median requirement would account for over one quarter of today's global agricultural land (FAOSTAT, 2017).

3.3. Environmental benefits of meat substitutes adoption

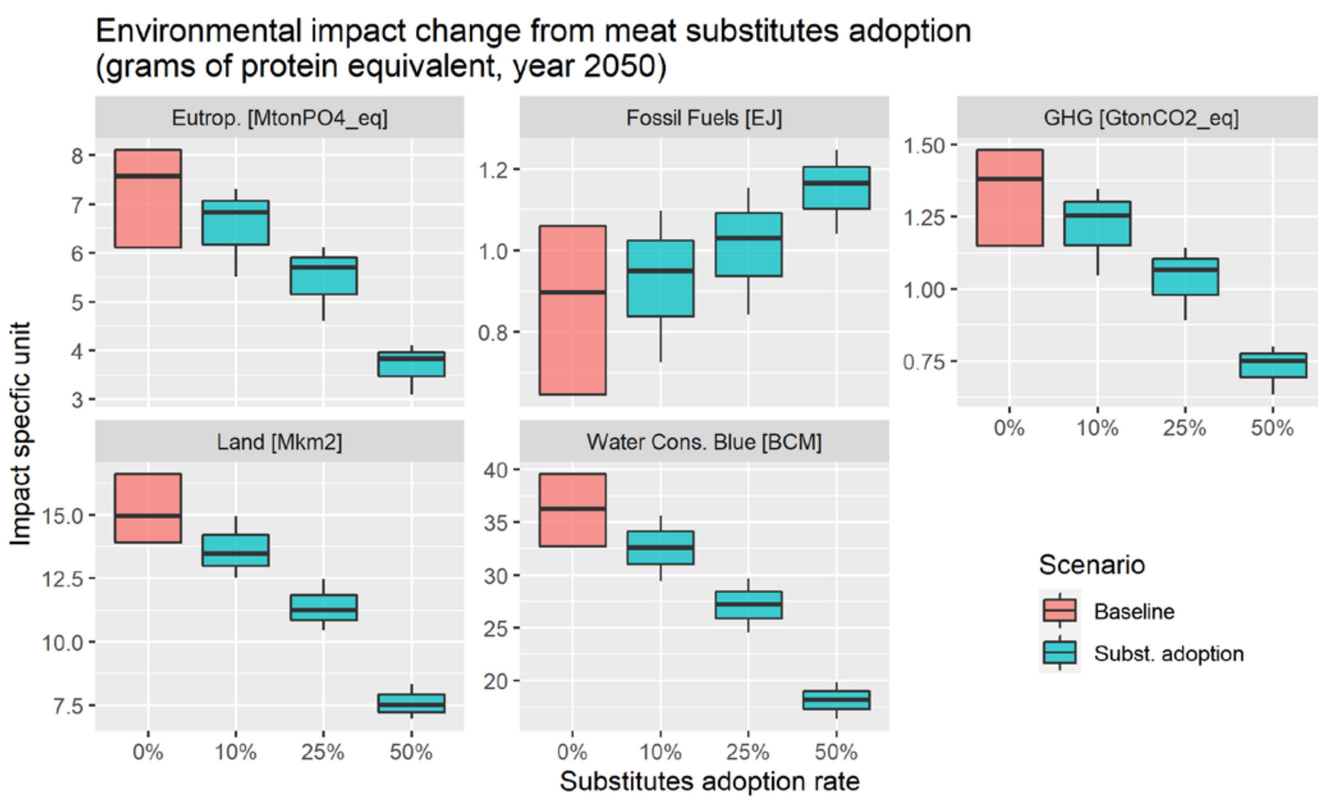

Fig. 7 | Change in the environmental impact of different levels of penetration of plant-based meat alternatives relative to baseline meat consumption scenarios. Facets distinguish the impact categories; fill colours identify the baseline vs. the substitutes adoption scenarios.

To evaluate the role that different levels of adoption of meat substitutes could play in reducing the regional environmental footprint of diets, we simulate future substitution dynamics. For each of the meat types considered, we simulate scenarios of gradual adoption of most diffused meat alternatives (where 10%, 25% and 50% of animal product consumption by 2050 is substituted). In particular, the absolute quantity of meat substitutes per kg of meat substituted in each adoption scenario is such that it provides the same amount (grams) of proteins which would be provided by one kg of each meat type (see **Table SI8**). We then consider the distribution of demand/resource-efficiency scenarios and compare it with counterfactuals of substitutes adoption. We refer to peer-reviewed, state-of-the-art LCA assessments to evaluate the footprint of these products (**Table SI7**).

Figure 7 shows the change in environmental impact for each impact category relative to the baseline of 25th, 50th and 75th percentiles of consumption and resources efficiency scenarios. The analysis shows that across all environmental impact categories but fossil fuels consumption, adoption of meat substitutes implies significant reductions in the 2050 environmental impact. In response to a 25% substitution, most (median) impacts show nearly linear reductions, with -24.9% for land and Blue water, -22.8% for greenhouse gases emissions, and -24.7% for eutrophication at the 50th percentile of the impact distribution. Conversely, fossil energy consumption grows by 15% as – according to the compiled LCA database – the production of some of the substitutes is more energy-intensive than animal meat.

As previously highlighted by **Figure 5A**, CO_2 emissions from fossil fuels combustion play a marginal role in the final GHG impact of meat. Therefore, irrespective of a larger fossil fuels consumption observed in the meat substitution scenarios presented in **Figure 7**, little impact from the combustion of those additional fossil fuels is observed on the final sectoral GHG emissions.

Conversely, the final GHG emissions are strongly reduced because of the substantial decrease in the emission of other greenhouse gases in the meat supply chain (and chiefly CH_4), which more than offset the larger fossil energy consumption. A decarbonisation of the regional energy systems could also reduce the environmental impact of energy consumption for production of meat substitutes.

4. Discussion and conclusions

4.1. Policy implications

We have estimated the potential environmental and energy-related implications of a shift towards more meat-intensive diets in countries of SSA. To achieve this, we have evaluated the historical associations between economic growth and meat consumption in a set of countries that over the last decades have experienced a robust economic growth. We found that for beef, pork, poultry, and sheep meat, the levels of total consumption would reach a scenario-median of 19, 15, 21, and 8 kg/capita/year by 2050, respectively. Considering a representative average weight of 225 grams per beef steak, 19 kg/capita/year are equivalent to slightly more than one beef steak per week. Not a very high intake, compared to most western diets. We then calculated that – depending on the resources efficiency variants considered – global greenhouse gases emissions could about 175% of today's regional agriculture-related emissions), cropping and grazing-related land may require about one quarter of today's global agricultural land), blue water consumption would nearly double the current regional agricultural consumption. Moreover, the eutrophication potential would grow by 7.6 t PO_4e/yr, and additional 0.9 EJ/yr of fossil fuels and 49 TWh/yr of electricity would be consumed. These results suggest that – in the absence of drastic resource efficiency or technological improvements – meat demand in SSA is bound to become a major reason for concern if environmental flows are to be preserved at a sustainable level.

But what trends have been observed so far in SSA? Worku et al. (2017) have highlighted that as a result of the steep economic growth of Ethiopia (at 6.8% in 2018), the share of food in the total consumption basket of households is declining, and yet total food quantities and calorie intakes have considerably increased between 1996 and 2011. The Authors found that growing household income is the driving force behind these trends, also highlighting that a shift towards animal products is actually occurring: this implies that households are complementing and expanding their diets, rather than substituting vegetal products. Cockx et al. (2017) focused on the impact of the urbanisation process on diets in Tanzania, finding that urban migration is associated with a shift away from traditional staples towards more processed and ready-to-eat foods, and with increased consumption of both vegetables and animal-source foods. These studies hint at a “westernisation” of diets in two rapidly growing economies of the region, consistently with the pathways introduced in this paper.

It is still too early to evaluate what pathways are being followed at a regional level: these are indeed due to a mix of several factors, including economic aspects (e.g. prices and availability) (Gallet 2010b), behavioural factors (e.g. social norms and peer effects) and self-efficacy (self-control induced by external factors, e.g. information) (Eker et al., 2019), but also habits and ease-of-access (Rees et al., 2018), public policy implemented through non-coercive actions such as nudges – which can include changing physical microenvironments that affect meat purchase and consumption decisions (Rose, 2018) –, taxation (Caro *et al* 2017, Allen and Hof 2019), or structured information campaigns aligning environmental and health messages (Stubbs et al., 2018).

Another significant role will be played by the quality and pace of global growth of plant-based meat substitutes (which generally have a significantly lower environmental impact than meat (Smetana et al., 2015)) or in-vitro cultured meat breakthroughs (Bhat et al., 2017). Our analysis on the adoption of these alternatives shows that at high levels of substitutes adoption there is nearly a linear reduction between the substitutes adoption rate and the reduction in environmental impact of most impact categories (and chiefly land use, blue water consumption, and eutrophication potential). Conversely, the substitution implies a significant growth in fossil fuels energy consumption, but such increase remains very marginal in terms of its GHG emission potential when compared to the reductions due to lower CH_4, and N_2O emissions.

Another relevant dimension to consider relates to the household energy requirements for cooking and the role of changing diets on those needs. Currently, about 900 million people in SSA rely on traditional biomass for cooking (wood, charcoal, dung, or agricultural residues) (IEA, 2019), with significant health (390,000 premature deaths per year due to ambient pollution according to Collaborators, 2018) and environmental implications (498 million tons of fuelwood have been consumed in SSA in 2016, with a significant contribution to deforestation and land degradation trends). This energy use is also very inefficient. Thus, the cooking energy pathways and the dietary choices will thus play a major role in determining the cooking energy and environmental requirements, which are outside the scope of the analysis presented in this paper. For instance, it has been estimated that if households halt using biomass, greenhouse gases emissions from cooking will cut by at least half (Dagnachew et al., 2019). At the same time, if households that in 2030 will cook with electricity switch to pre-cooked food or low energy intensive diets, their final energy demand would become 50% lower.

4.2. Limitations and future research prospects

As all other scenario-based forecasting assessments, the analysis carried out in this paper is characterised by multiple sources of uncertainty that can be mitigated but not completely eliminated. The first concerns the “inherited” uncertainty from modelled data on drivers for the future meat demand projection: while certain drivers are well understood, such as population growth dynamics, other are susceptible to exogenous shocks, and chiefly real GDP growth rates or food prices. In addition, our analysis can neither factor in drastic, unpredictable cultural changes that simply cannot be predicted when training a model on historical data.

A second layer of uncertainty concerns the data quality of the Exiobase hybrid tables and the relative environmental impact coefficients, grounded on intensive data dependency. This data is sometimes limited by data shortages, usually overcome by the adoption strong of assumptions necessary to balance the global-scale input-output table Merciai and Schmidt 2018). This issue is further exacerbated by the lack of consolidated data for African countries, which are lumped together in one unique averaged regional aggregation.

Relatedly, resource efficiency trends have a tremendous impact on environmental impact and the possibility that new technologies can disrupt existing paradigms and boost efficiency cannot be ruled out. In response to this source of uncertainty, our analysis includes different “target” efficiency levels to evaluate a broad range of efficiency outcomes.

Finally, also the meat substitutes assessment is affected by technological uncertainty: research and development in innovative and low-impact food solutions is growing robustly, and ground-breaking technologies such as lab-cultured meat could become pervasive if costs fall sufficiently. Similarly, cultural attitudes and perception of these alternatives could also shift rapidly from the current situation.

Overall, we encourage future research in the field to address the key sources of uncertainty detailed above by endogenously modelling technological and cultural changes.

Data availability

The R and Python code for replicating the analysis will be hosted at the following public repository: https://github.com/giacfalk/MEAT_SSA. A data repository hosting input data, comma separated value files with the estimated pathways, and the resulting input-output impact matrixes will be made accessible on Zenodo.

CRediT author statement:

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- **Nicolò Golinucci:** Methodology, Resources, Data curation, Formal analysis, Software, Writing - original draft, Writing - review & editing.
- **Michel Noussan:** Methodology, Visualization, Writing - review & editing.
- **Matteo Vincenzo Rocco:** Methodology, Writing - review & editing.

Conflict of interest

The authors declare no conflict of interest.

Supplementary Information

Supplementary Information materials are available for this article.

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Environmental and energy implications of meat consumption pathways in sub-Saharan Africa

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Supplementary Information Appendix

List of supplementary figures

List of supplementary tables

Historical trends in a global perspective

Global historical (1960-2013) statistics on meat consumption [1] show that while in aggregate terms consumption has been increasing robustly due to both population growth and per-capita demand growth, in some regions the numbers have been declining over the last decades **(Figure SI1-A)**. Yet, when disaggregating these trends **(Figure SI1-B)**, it is evident that the consumption of each meat type has evolved heterogeneously, also because of substitution dynamics. In fact, while Engel's Law [2] states that as income rises, the proportion of income spent on food falls (i.e. the income elasticity of demand of food is between 0 and 1), Bennett's law [3] postulates an increasing dietary diversity as income rises. Dietary models worldwide have gradually converged with respect to the proportion of meat consumption and the share of animal protein intake [4].

Previous studies [5] have empirically verified the hypothesis that per capita meat consumption follows an Environmental Kuznets-style inverted U-curve, following the original hypothesis that environmental quality and economic development are related through an inverted U-shaped functional form [6]. Yet, the functional inflection point is only reached at levels of per-capita GDP that have been reached in a small number of countries. Moreover, in high-income countries there is evidence of a social gradient, with lower socioeconomic groups consuming more and more often meat [7].

To visualise the relationship between per-capita GDP (a proxy of income) and total meat consumption, **Figure SI1-C** reports a scatterplot with quadratic fit curves by world regions based on data from the FAO Food Balance Sheet (2017). The analysis reveals evidence of quadratic relationships in all global regions but Africa, where a hitherto moderate yet steep growth trend has begun to be observed.

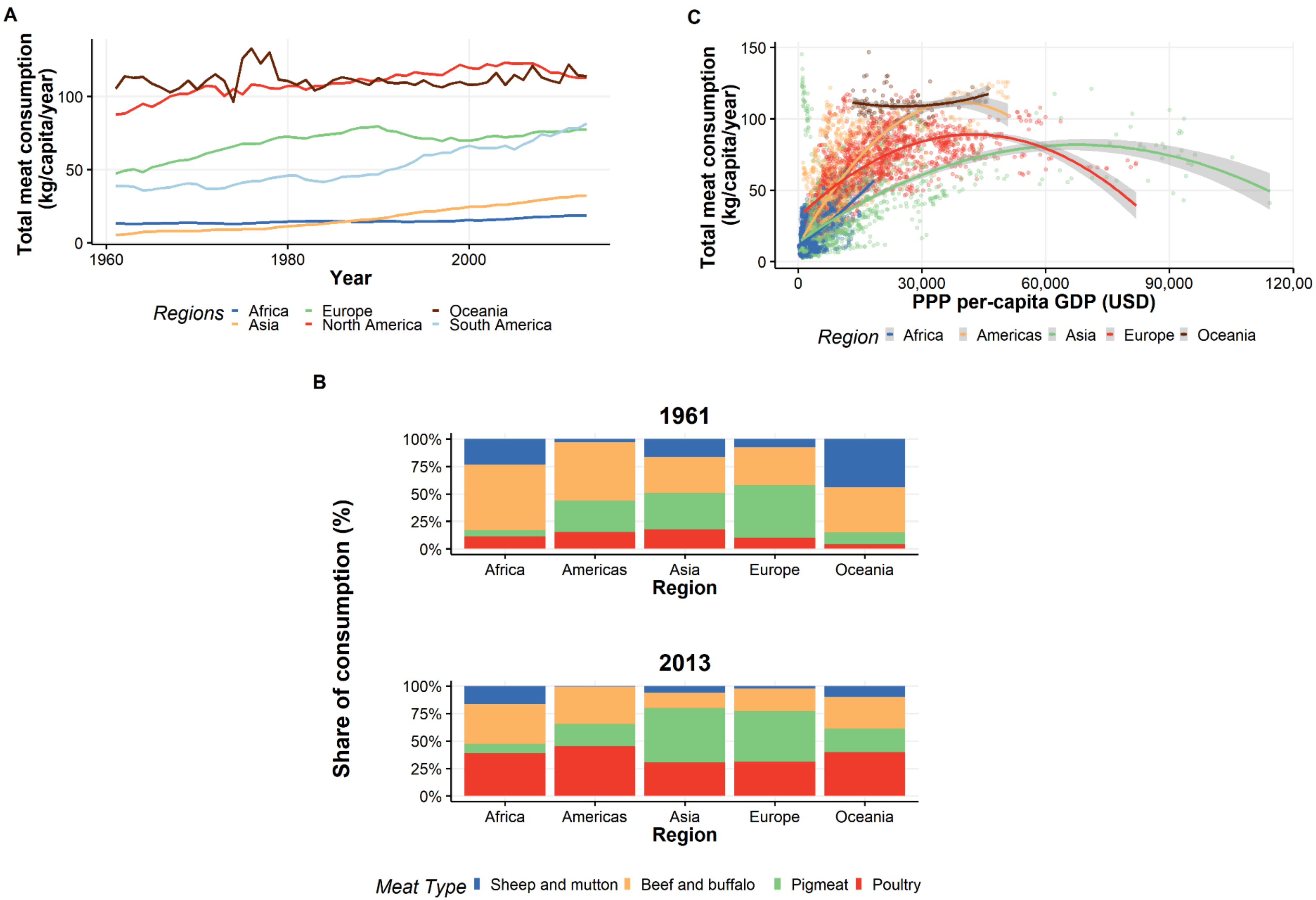


Fig. SI1 | Historical meat consumption pathways in a global perspective. (A) Historical evolution of total per-capita meat consumption in selected regions; **(B)** Evolution of the shares of meat types between 1961 and 2013, by region. **(C)**

Regional historical association between purchasing power parity per-capita GDP and meat consumption, by global region.

Drivers of meat consumption

Meat consumption is limited or forbidden in several religions and cultures globally. However, econometric evidence shows that both across [8] within-country [9], religion has no statistical relationship with income.

Environmental consciousness, including becoming vegetarian, has been found to be positively associated with income in high-income countries [10]. Therefore, this is a potential omitted effect which affects the estimated coefficients for the effect of per-capita GDP on meat consumption. However, to our purposes capturing this effect within the GDP linear and quadratic coefficients is not problematic, but rather offers room for explaining differences in the magnitude of coefficients across the different reference countries analysed, and offers more heterogeneity in the projection of scenarios, in particular as higher levels of development are attained close to the end of the century (given that our analysis is restricted to low and middle-income countries, where generally environmental awareness and its impact on dietary choices is lower).

Finally, concerns of reverse causality, i.e. the hypothesis that meat production (where its correlation with meat consumption is sufficiently strong) could contribute to per-capita GDP through increased agricultural and grazing activity. Here we assume that the role of the meat industry is not strong enough to have a significant effect on the overall economic development level.

Demand driver regressions results

Table SI1: RF model training results for each meat type

Sample size	4233
Number of trees	1000
Forest terminal node size	5
Average no. of terminal nodes	513.289
No. of variables tried at each split	6
Total no. of variables	16
Total no. of responses	4
User has requested response	Beef.and.buffalo..kg.
Resampling used to grow trees	swor
Resample size used to grow trees	2675
Analysis	mRF-R
Family	regr+
Splitting rule	mv.mse *random*
Number of random split points	10
% variance explained	91.48
Error rate	11.53

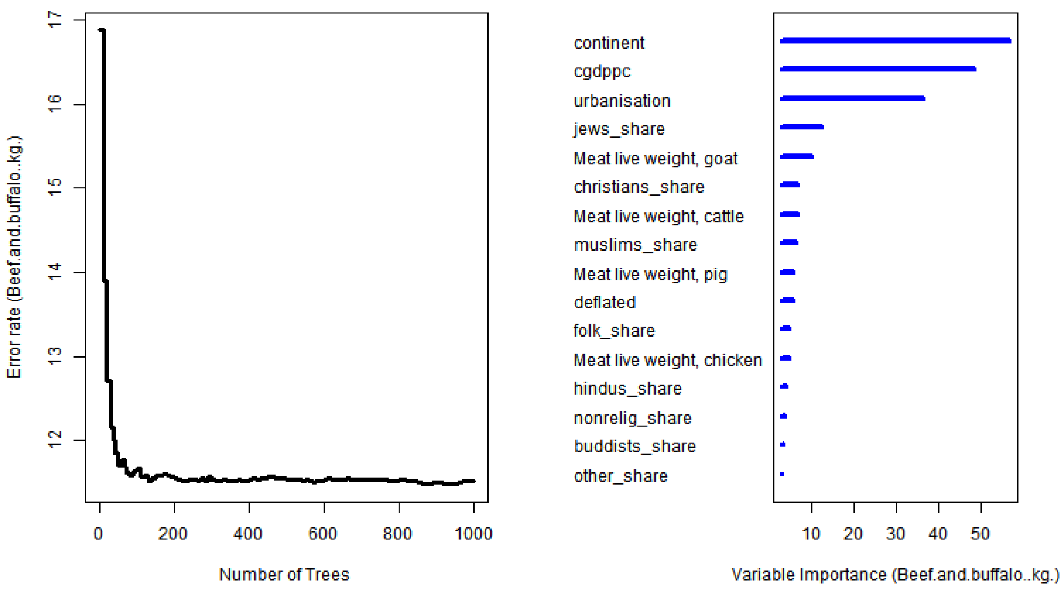
Sample size	4233
Number of trees	1000
Forest terminal node size	5
Average no. of terminal nodes	513.289
No. of variables tried at each split	6
Total no. of variables	16
Total no. of responses	4
User has requested response	Pigmeat..kg.
Resampling used to grow trees	swor
Resample size used to grow trees	2675
Analysis	mRF-R
Family	regr+
Splitting rule	mv.mse *random*
Number of random split points	10
% variance explained	92.12
Error rate	15.72

Sample size	4233

Number of trees	1000
Forest terminal node size	5
Average no. of terminal nodes	513.289
No. of variables tried at each split	6
Total no. of variables	16
Total no. of responses	4
User has requested response	Poultry..kg.
Resampling used to grow trees	swor
Resample size used to grow trees	2675
Analysis	mRF-R
Family	regr+
Splitting rule	mv.mse *random*
Number of random split points	10
% variance explained	91.4
Error rate	10.42

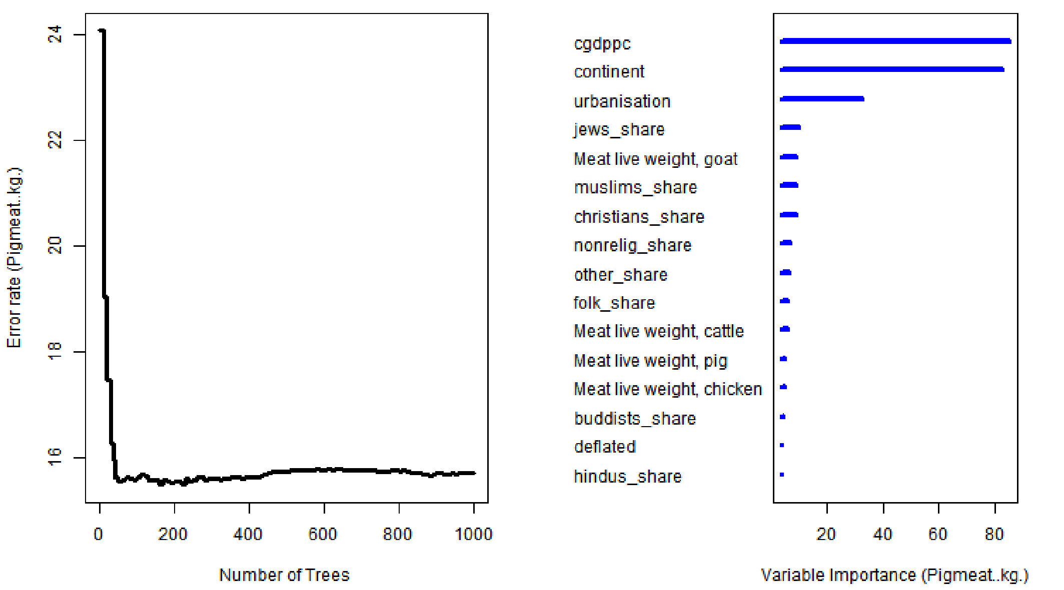
Sample size	4233
Number of trees	1000
Forest terminal node size	5
Average no. of terminal nodes	513.289
No. of variables tried at each split	6
Total no. of variables	16
Total no. of responses	4
User has requested response	Mutton...goat..kg.
Resampling used to grow trees	swor
Resample size used to grow trees	2675
Analysis	mRF-R
Family	regr+
Splitting rule	mv.mse *random*
Number of random split points	10
% variance explained	83.45
Error rate	8.65

A



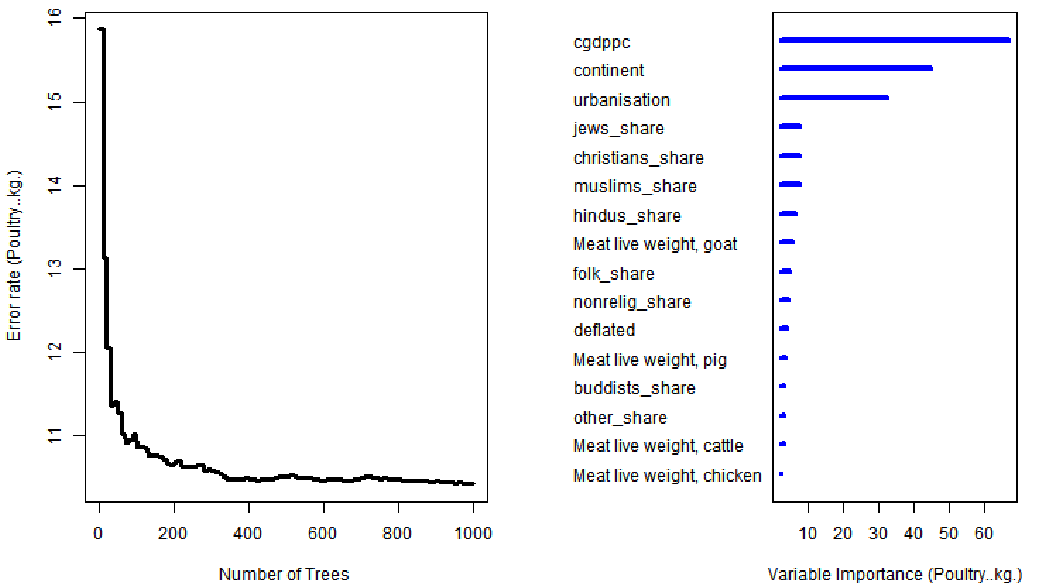
17
16
15
14
13
12
Error rate (Beef.and.buffalo..kg.)
0
200
400
600
800
1000
Number of Trees
continent
cgdppc
urbanisation
jews_share
Meat live weight, goat
christians_share
Meat live weight, cattle
muslims_share
Meat live weight, pig
deflated
folk_share
Meat live weight, chicken
hindus_share
nonrelig_share
buddists_share
other_share
10
20
30
40
50
Variable Importance (Beef.and.buffalo..kg.)

B



24
22
20
18
16
Error rate (Pigmeat..kg.)
0
200
400
600
800
1000
Number of Trees
cgdppc
continent
urbanisation
jews_share
Meat live weight, goat
muslims_share
christians_share
nonrelig_share
other_share
folk_share
Meat live weight, cattle
Meat live weight, pig
Meat live weight, chicken
buddists_share
deflated
hindus_share
20
40
60
80
Variable Importance (Pigmeat..kg.)

C



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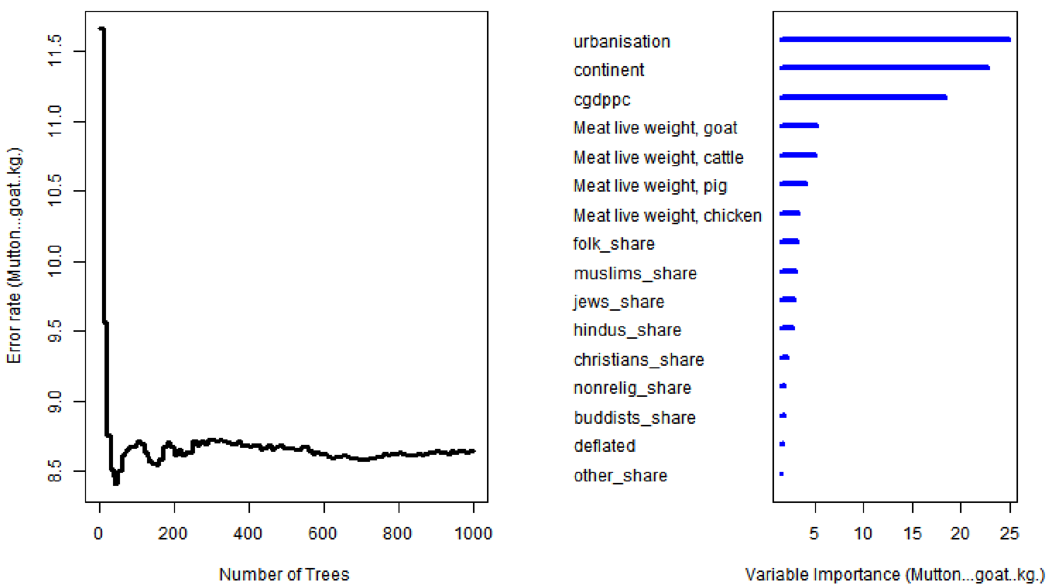


Fig. SI2 | Plots of out-of-bag (OOB) error rates and variable importance (VIMP) for the multivariate random forest model. (A) Beef; (B); Pigmeat; (C) Poultry; (D) Mutton.

Table SI2: RF model validation results – beef and buffalo

.variable	.stat	Model 1
(Intercept)	Estimate	-1.09
	t Value	-9.25
	p Value	0
Beef.and.buffalo..kg._forecasted	Estimate	1.075
	t Value	146.89
	p Value	0
	N	1779
	R2	0.924
	adj R2	0.924
	AIC	9273.587

Table SI3: RF model validation results - pigmeat

.variable	.stat	Model 1
(Intercept)	Estimate	-0.77
	t Value	-5.907
	p Value	0
Pigmeat..kg._forecasted	Estimate	1.077
	t Value	139.754
	p Value	0
	N	1779
	R2	0.917
	adj R2	0.917
	AIC	10180.16

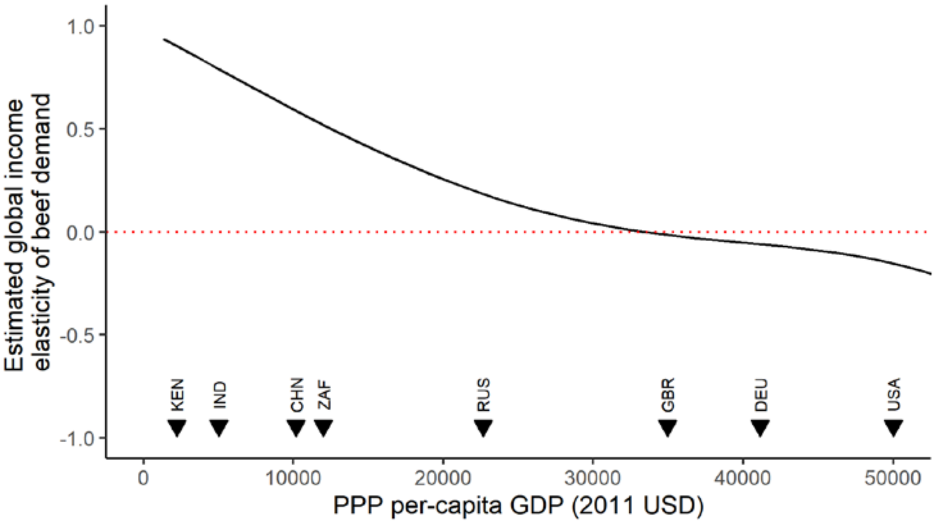
Table SI4: RF model validation results - poultry

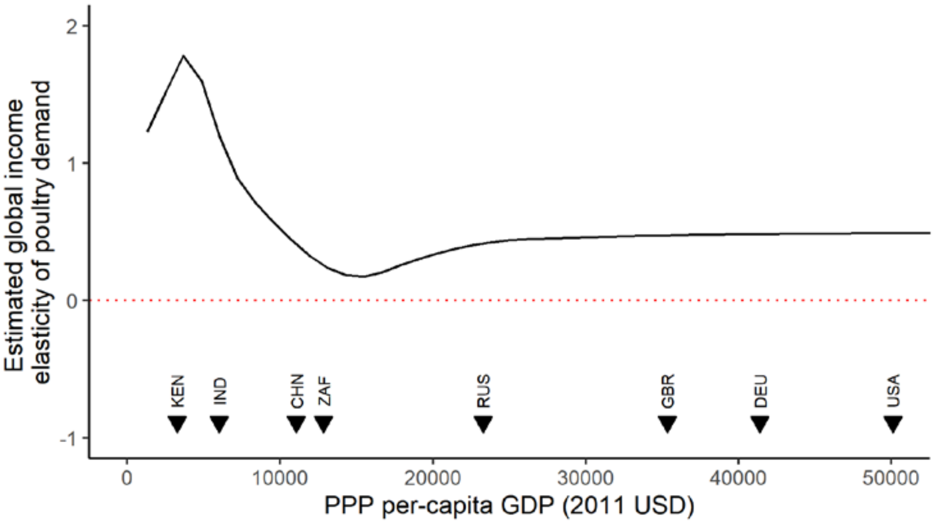
.variable	.stat	Model 1
(Intercept)	Estimate	-1.225
	t Value	-11.154
	p Value	0
Poultry..kg._forecasted	Estimate	1.114
	t Value	142.205
	p Value	0
	N	1779
	R2	0.919
	adj R2	0.919
	AIC	9256.582

Table SI5: RF model validation results – mutton and goat

.variable	.stat	Model 1
(Intercept)	Estimate	-0.687
	t Value	-8.091
	p Value	0
Mutton...goat..kg._forecasted	Estimate	1.136
	t Value	92.374
	p Value	0
	N	1779
	R2	0.828
	adj R2	0.828
	AIC	8896.089

Estimated income elasticites





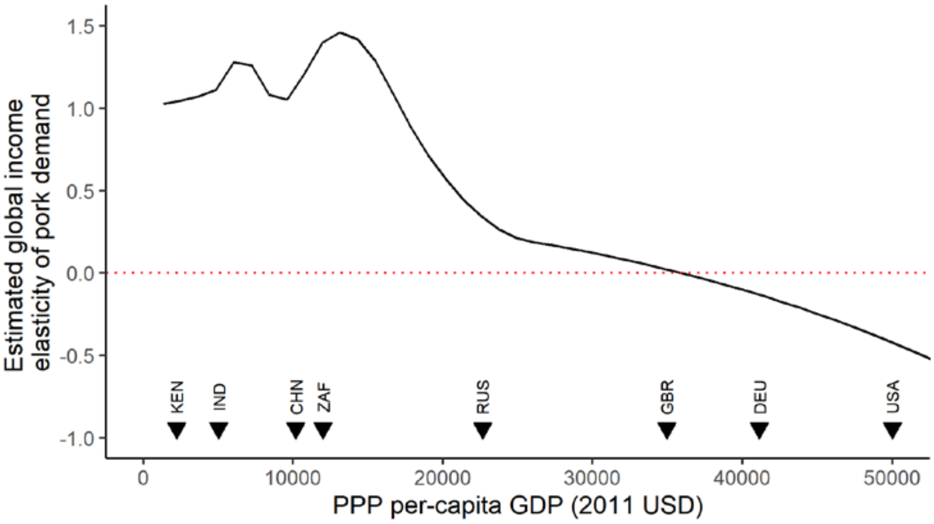


Fig. SI3 | Estimated income elasticity plots of meat demand (by meat type). The plots visualise the ceteris paribus % change in meat demand in response to a 1 % change of PPP per-capita GDP (2011 USD) for each meat type. A set of countries is reported as a reference at the corresponding PPP per-capita GDP income level.

FAO projections of meat consumption in sub-Saharan Africa

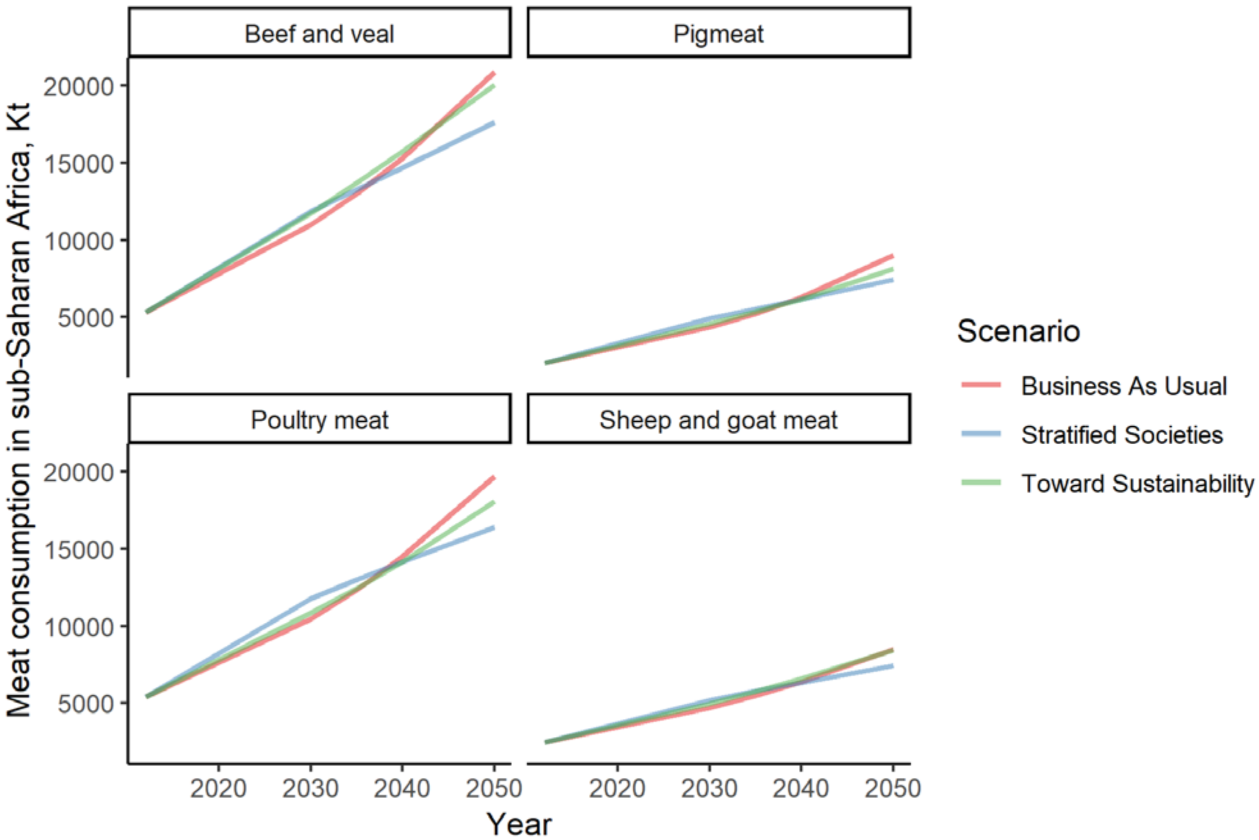


Fig. SI4 | Meat consumption in 2050 in sub-Saharan Africa according to three FAO scenarios, by meat type. Data source: FAO (2018)

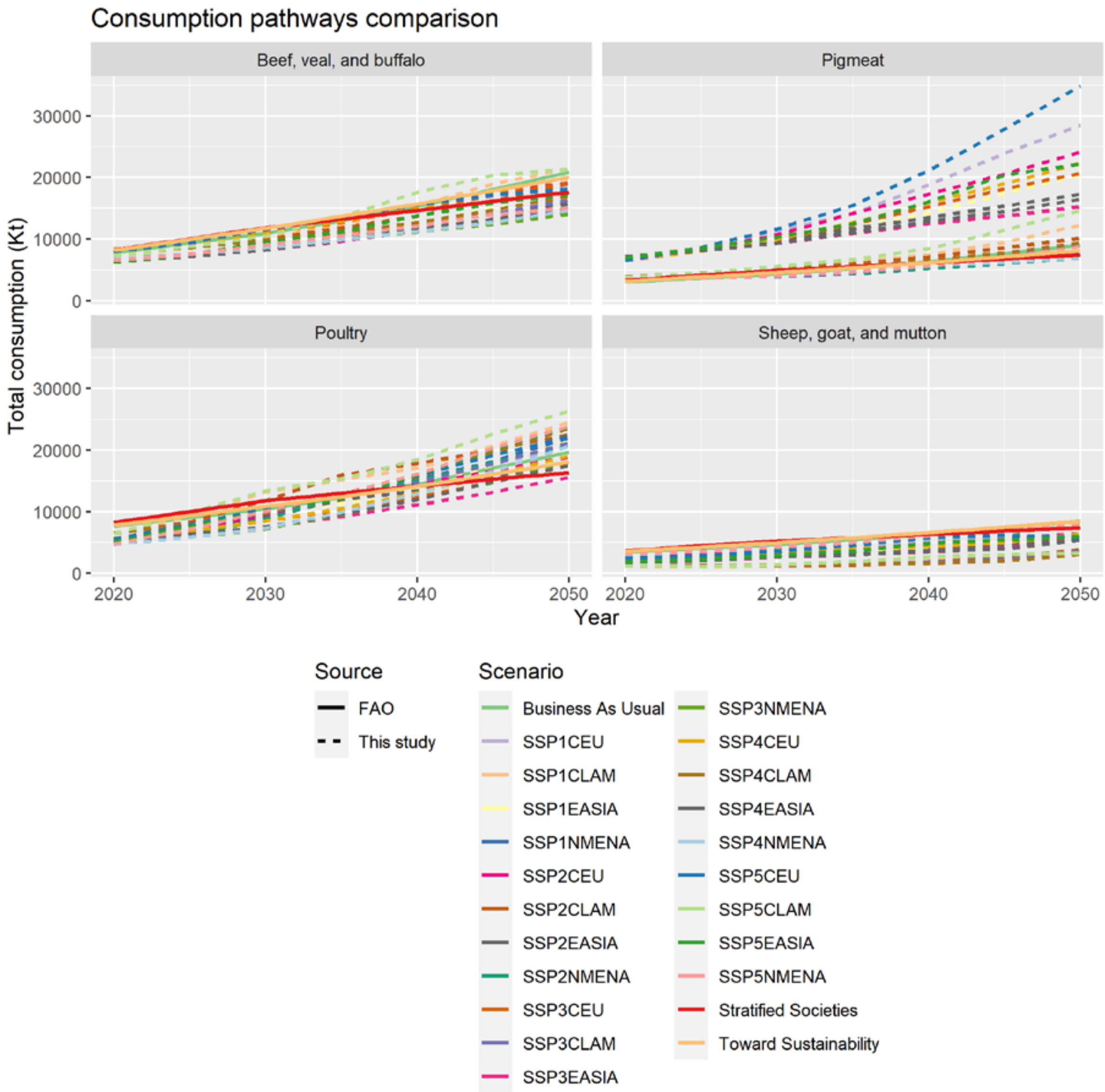


Fig. SI5 | Comparison of the meat consumption scenarios estimated in this paper with the FAO scenarios, by meat type. Data source: FAO (2018)

Productive efficiency scenarios

Table SI6: Technological efficiency variants

Scenario	Reference region	Exiobase region
LAM	Central Latin America	RoW Africa – Median(RoW America, Mexico)
ASIA	East Asia	RoW Africa – Median(China, RoW Asia and Pacific)
EU	Central Europe	RoW Africa – Median(Centro-european countries*)
MENA	Middle East and North Africa	RoW Africa – Median(RoW Middle East, RoW Africa, Turkey)

* RoW Europe, Bulgaria, Croatia, Hungary, Poland, Romania, Slovakia, Slovenia.

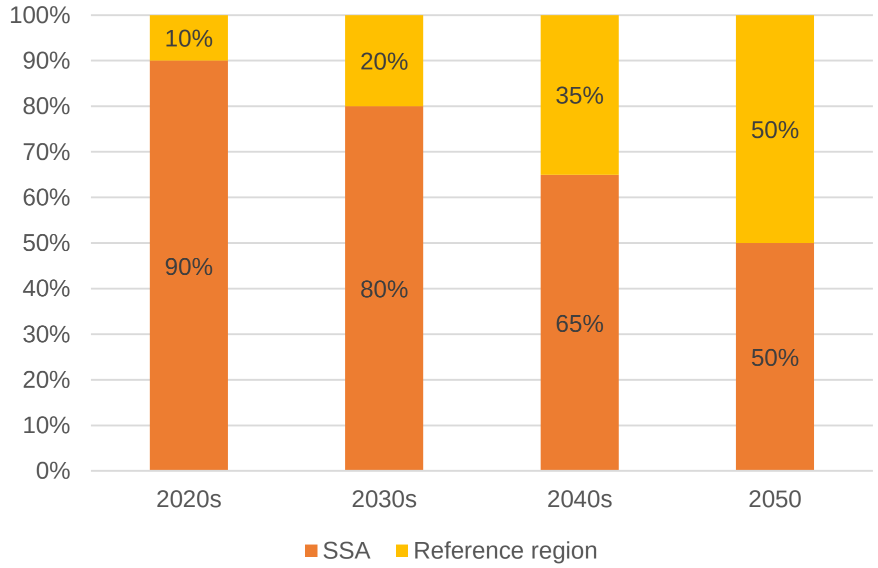


Fig. SI6 | Dynamic convergence process towards environmental impact coefficients of reference regions.

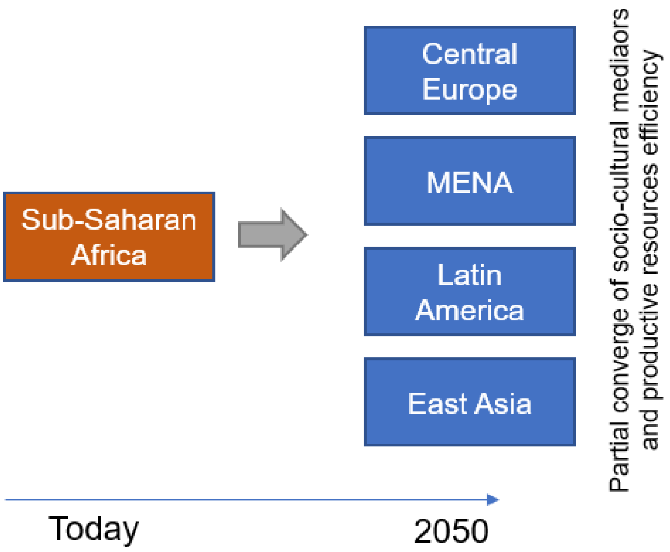
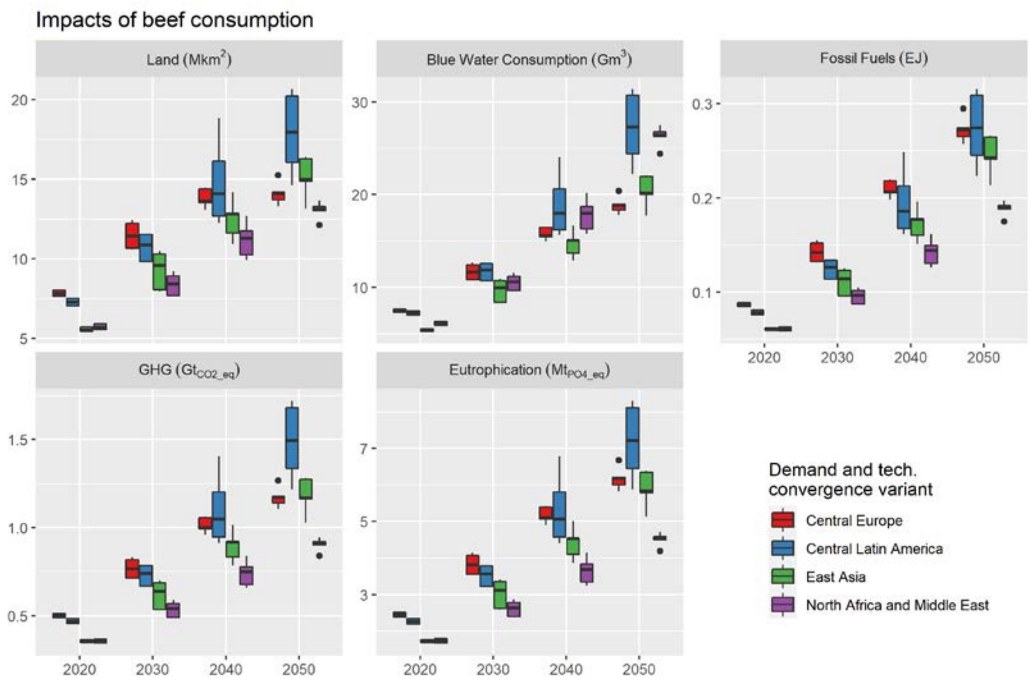


Fig. SI7 | Production and efficiency variants considered in the impact assessment analysis.

Meat-type specific environmental impact results

A



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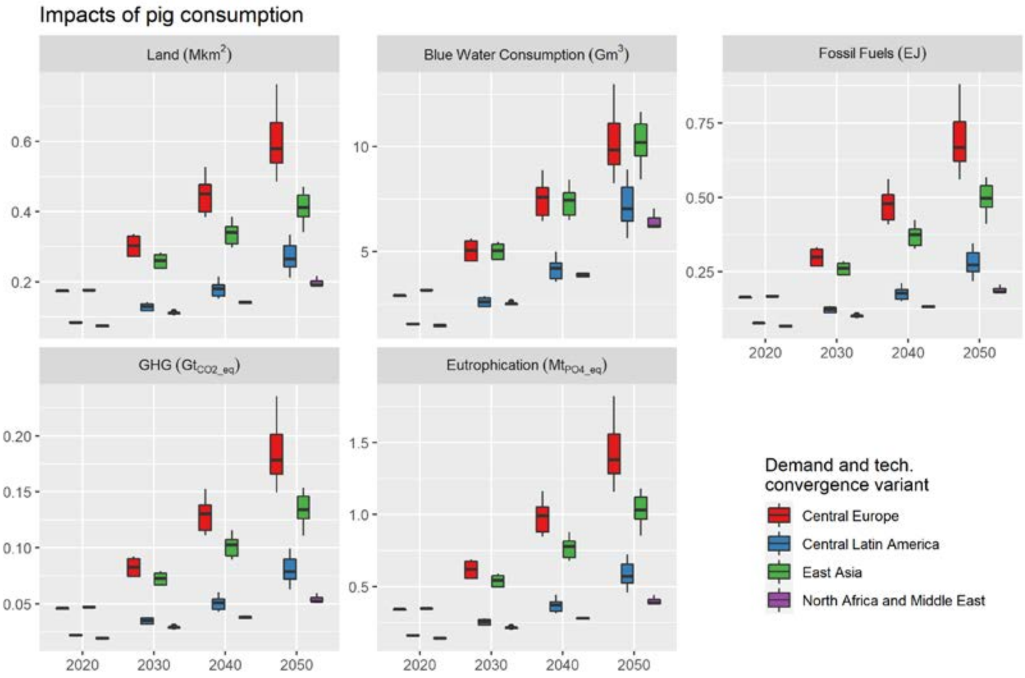

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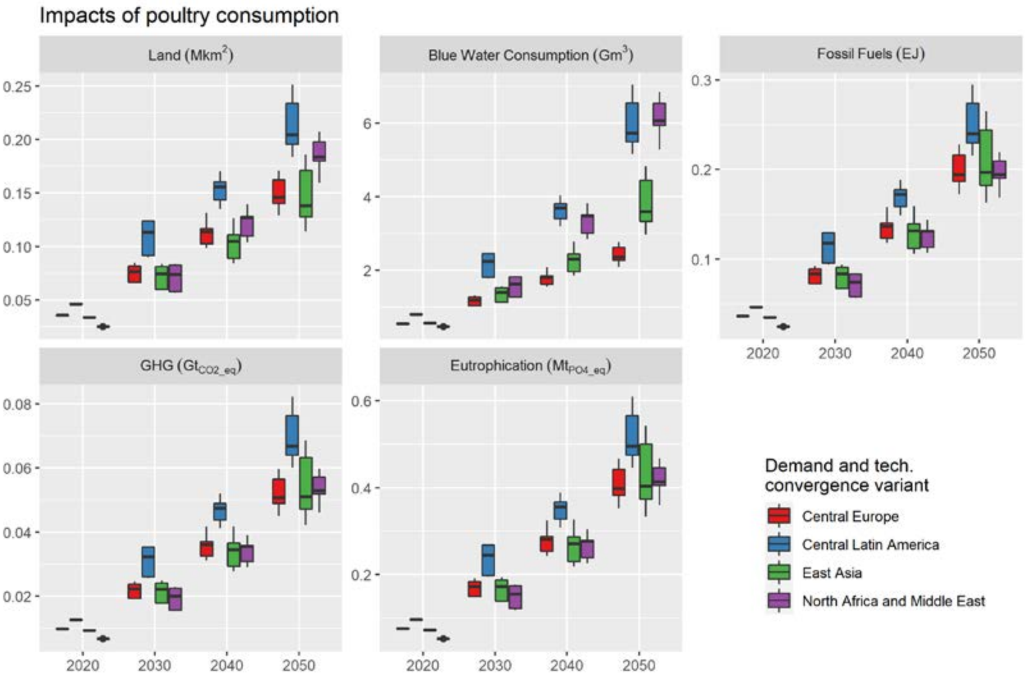

Fig. SI8 | Meat specific environmental impacts. (A) Impacts related to beef consumption**; (B)** Impacts related to pig consumption; **(C)** Impacts related to poultry consumption.

Allocating use of fossil fuel among sectors

Different accountability methodologies can be adopted to partition the burden of environmental resources use across sectors. In a production-based approach (PBA), environmental accounts are attributed to the sectors of the economies that have primarily extracted the resources. For the case here presented, this approach would lead to trivially assigning the responsibility for the additional primary energy requirements to the *extraction of fossil fuels.* On the other hand, in a consumption-based approach (CBA), environmental extensions are assigned to the sectors that have triggered the increase in production in all the sectors directly and indirectly involved. In this case, a trivial result would be presented since the only sectors that are driving all the changes are the meat production ones.

Therefore, here a third allocation methodology is adopted to enable an understanding of the intermediate sectors responsible for the additional energy requirements. This approach assigns the environmental accounts redistributing them on the basis of the input of sectors which primarily extract the analysed resource (e.g. extraction of fossil fuels sector for primary energy resource). In this way it is possible to assess the energy consumption needs sustained by each sector to respond to the assumed increase in demand. The methodology has been here named input-based approach (IBA). Algebraically, the three approaches can be summarised as:

$$PBA = E\Delta x$$
$$CBA = E(I - A)^{-1}\Delta y$$
$$IBA = \widehat{\Delta x}^{-1}\Delta Z\ PBA$$

(Eq. 1)

where:

- *E* identifies the matrix of exogenous transaction coefficients;
- Δx represents the vector of net output production;
- Δy is the vector of net final demand;
- ΔZ is the matrix of net intermediate transactions;
- PBA represents the amount of resource requirements;
- *I* refers to the identity matrix with the same dimension of A, which is the matrix of endogenous transaction coefficients (i.e. matrix of technology coefficients).

Note that for the case of use of fossil fuel here presented, in the IBA approach, all the amount of resource requirements are allocated to intermediate sector (i.e. no additional final demand of fossil fuels is assumed).

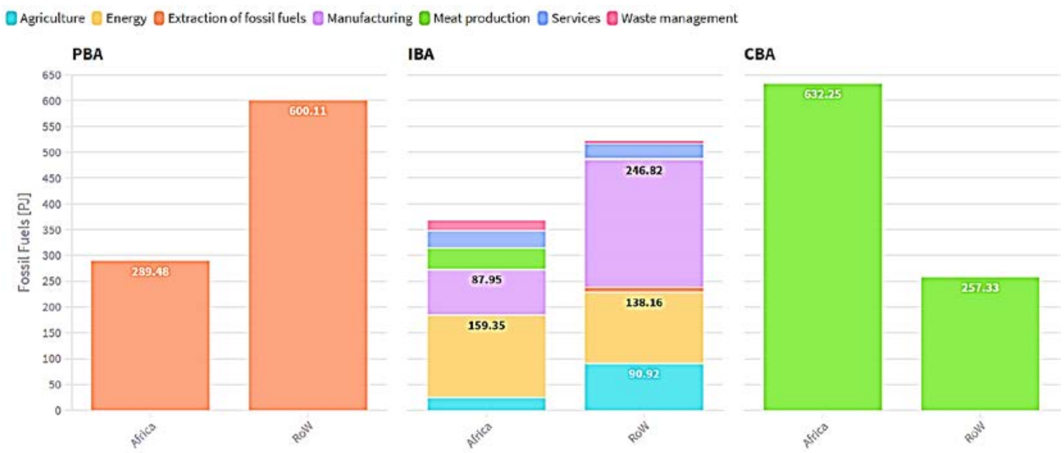

Fig. SI9 | Allocation of Fossil Fuel resource use for fulfilling 2050 meat demand by local or import sector and allocation methodology. Values in PJ for median case among runned scenarios (SSP4 - East Asia).

PBA and CBA provide trivial results: all the fossil fuel is extracted by the “Extraction of fossil fuels” sector while it is driven by the additional demand of “Meat production” from African and non-African (i.e. Rest of the World – RoW) regions. In fact, from the one hand most of the PBA fossil fuel is allocated to the RoW regions (600 PJ), where most of the physical extraction takes place. From the other hand, all the requested additional fossil fuel extraction is induced by the increased final demand of local (632 PJ) and imported (257 PJ) meat products.

Observing the IBA results, a relevant amount of direct use of inputs from the sector which extracts fossil fuels is present at both local and imported level. The energy and manufacturing sector show the highest amount of requested input, both at local (247 PJ) and non-local (385 PJ) level. Furthermore, the agricultural sector from outside the African continent (mostly relying on Brazil and USA for complementing its local production), is demanding a considerable quantity of fossil fuels (91 PJ).

For exploring the interactive version of Figure SI9 visit the following link: Fossil fuels allocation | Flourish.

Meat substitutes LCA parameters

Table SI7: Meat-based alternatives considered and their LCA environmental footprint

Name	Substitute to	Type	LCA_kg_CO2eq_per_kg	LCA_l_bluewater_per_kg	LCA_g_PO4equiv_per_kg	LCA_MJ_ton_per_kg	LCA_m2_y_per_kg	Reference
Dairy based	Chicken	Animal-based	4.4	4.2	3.2	48.8	3.3	[12]
Impossible burger / Beyond meat	Beef	Plant-based	3.5	106.8	1.3	53.8	2.5	[13,14]
Lab grown	Beef	In-Vitro	23.9	420.0	5.0	291.0	0.4	[12]
Insect based	Beef	Animal-based	2.8	1.3	2.0	32.0	1.5	[12]
Gluten based	Beef	Plant-based	3.6	1.0	4.3	39.7	5.5	[12]
Soy meal based	Pork	Plant-based	2.7	0.7	5.6	27.8	1.1	[12,15]
Mycoprotein based	Beef	Plant-based	5.6	40.0	4.0	60.1	0.8	[12]
Falafel	Beef	Plant-based	1.3	247.0	7.5	12.2	4.4	[16,17]

Table SI8: Assumed protein values per kg of product

Name	Protein content (g/kg final product)	Source
Meat types		
Beef	200	[18]
Pork	150	[18]
Poultry	280	[18]
Mutton/goat	270	[18]
Meat substitutes		
Dairy based	140	[19]
Impossible burger / Beyond meat	175	[13]
Lab grown	200	-
Insect based	200	[20]
Gluten based	175	[13]
Soy meal based	180	[21]
Mycoprotein based	140	[22]
Falafel	130	[18]

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