Supplementary Materials

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 S1A)**. Yet, when disaggregating these trends **(Figure S1B)**, 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 S1C** 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.

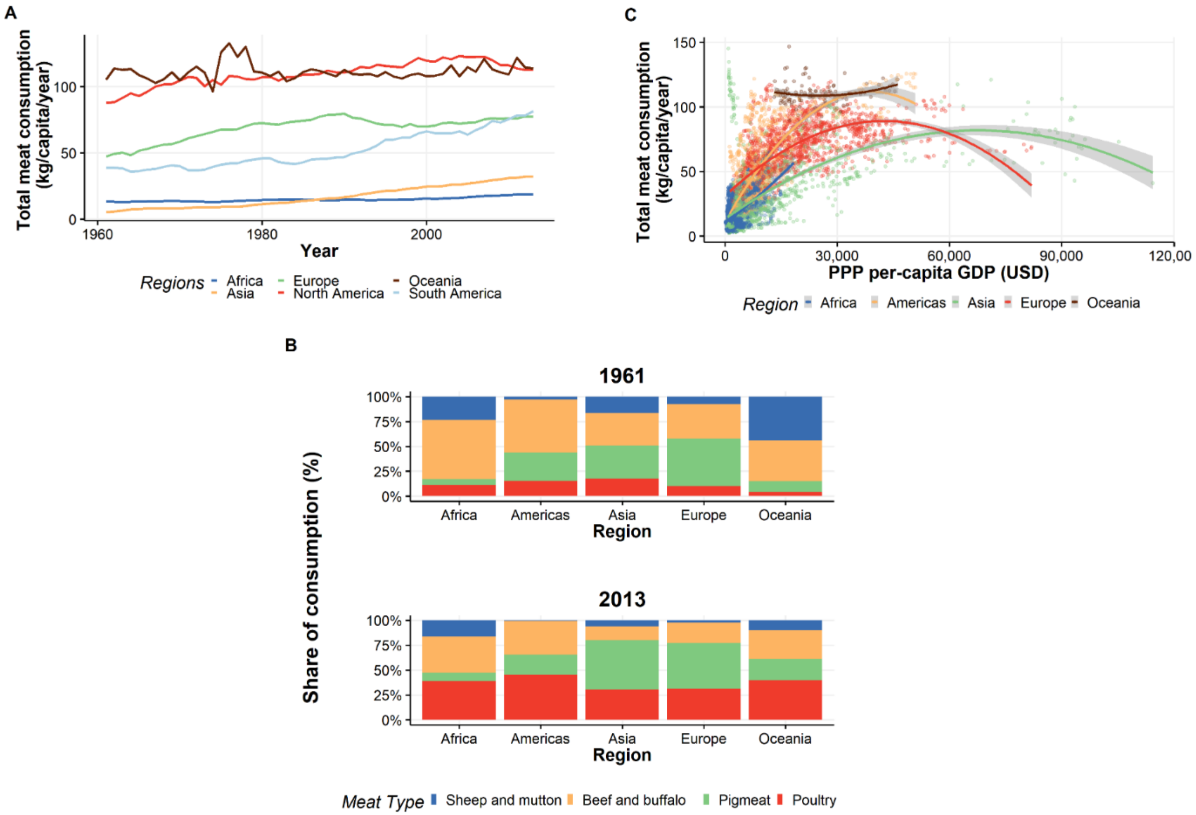


Figure S1. Historical meat consumption pathways in a global perspective. (A) Historical evolution of total per-capita meat consumption in selected regions; **(B)** Evolution of the shares of meat types between 1961 and 2013, by region. **(C)** Regional historical association between purchasing power 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 S1. RF model training results for each meat type.

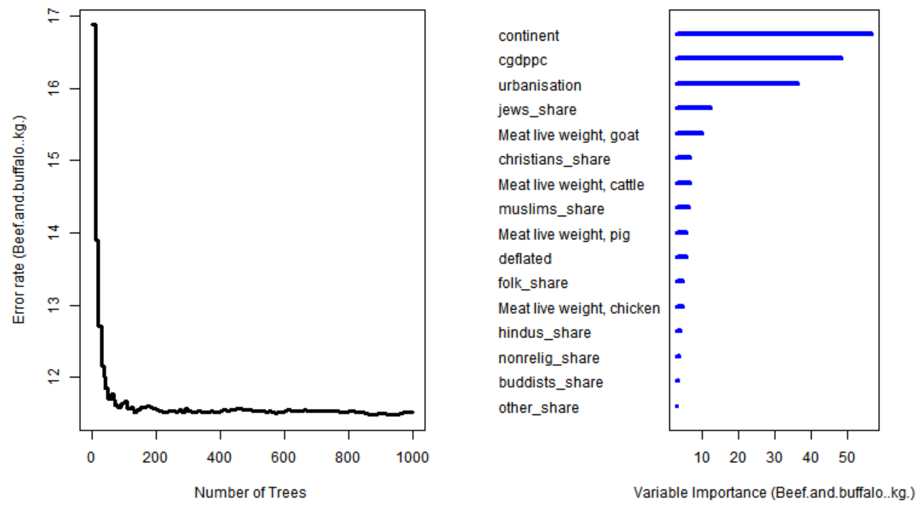
Sample size	4233
Number of trees	1000
Forest terminal node size	5
Average no. of terminal nodes	513.289
No. of variables tried at each split	6
Total no. of variables	16
Total no. of responses	4
User has requested response	Beef.and.buffalo..kg.
Resampling used to grow trees	swor
Resample size used to 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.

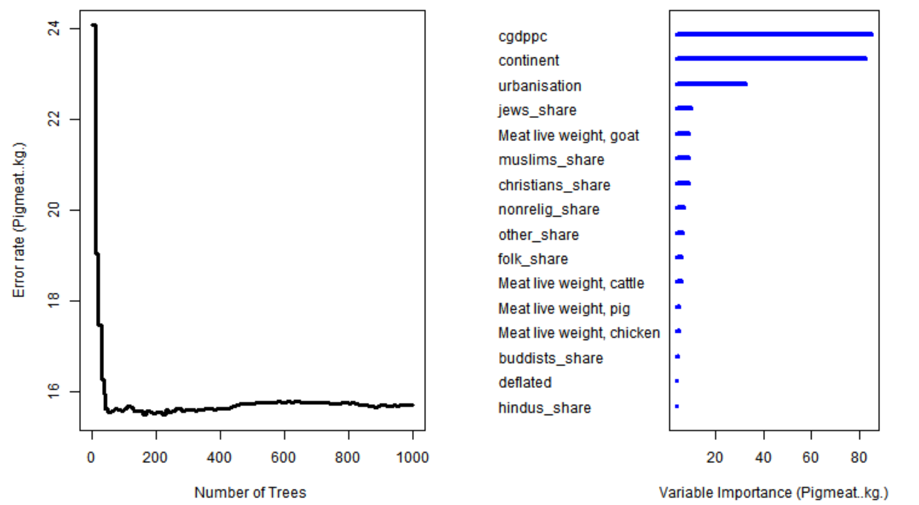
Resampling used to grow trees	swor
Resample size used to grow trees	2675
Analysis	mRF-R
Family	regr+
Splitting rule	mv.mse *random*
Number of random split points	10
% variance explained	92.12
Error rate	15.72

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

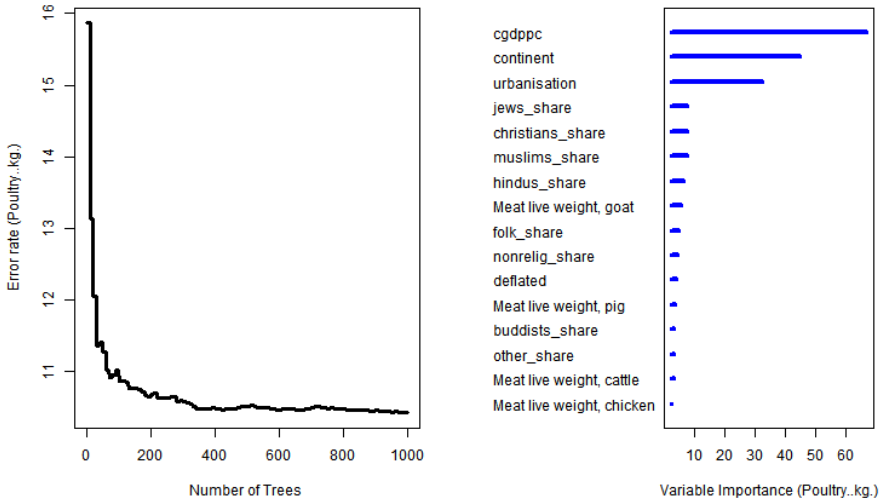
Sample size	4233
Number of trees	1000
Forest terminal node size	5
Average no. of terminal nodes	513.289
No. of variables tried at each split	6
Total no. of variables	16
Total no. of responses	4
User has requested response	Mutton...goat..kg.
Resampling used to grow trees	swor
Resample size used to grow 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


Error rate (Beef.and.buffalo..kg.)
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
Variable Importance (Beef.and.buffalo..kg.)

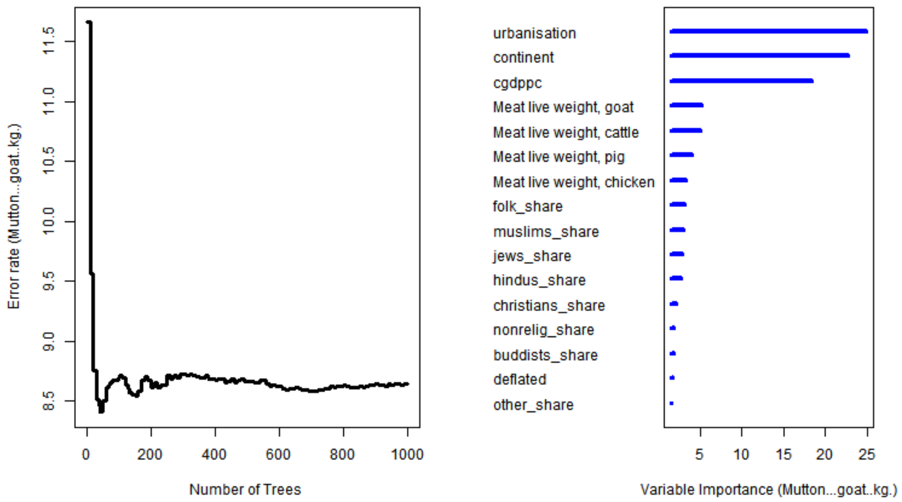
A


Error rate (Pigmeat..kg.)
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
Variable Importance (Pigmeat..kg.)

B



C



D

Figure S2. 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 S2. 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 S3. 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 S4. 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 S5. 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

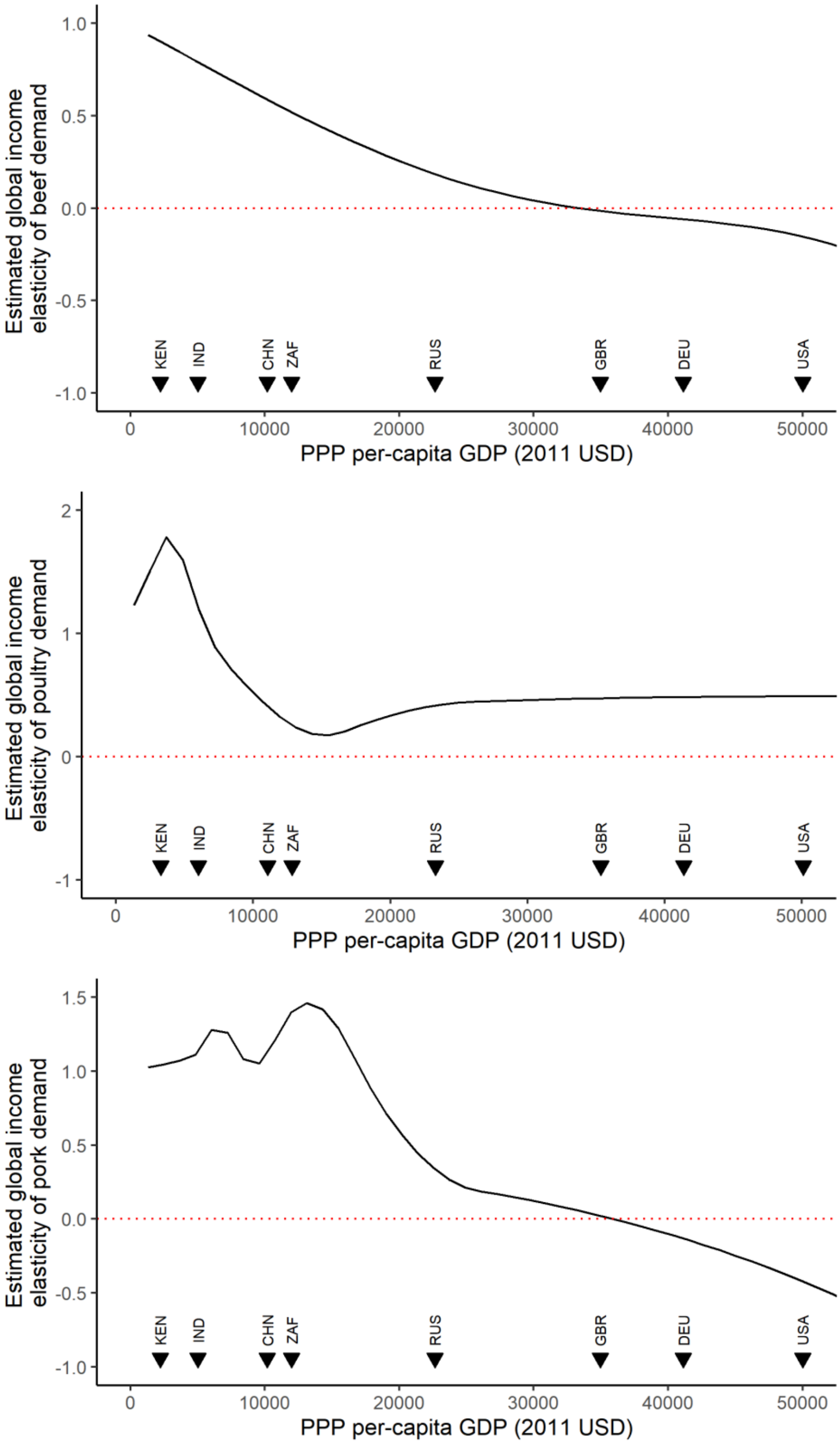


Figure S3. | Estimated income elasticity plots of meat demand (by meat type). The plots visualise the ceteris paribus % change in meat demand in response to a 1 % change of PPP per-capita GDP (2011 USD) for each meat type. A set of countries is reported as a reference at the corresponding PPP per-capita GDP income level.

FAO projections of meat consumption in sub-Saharan Africa

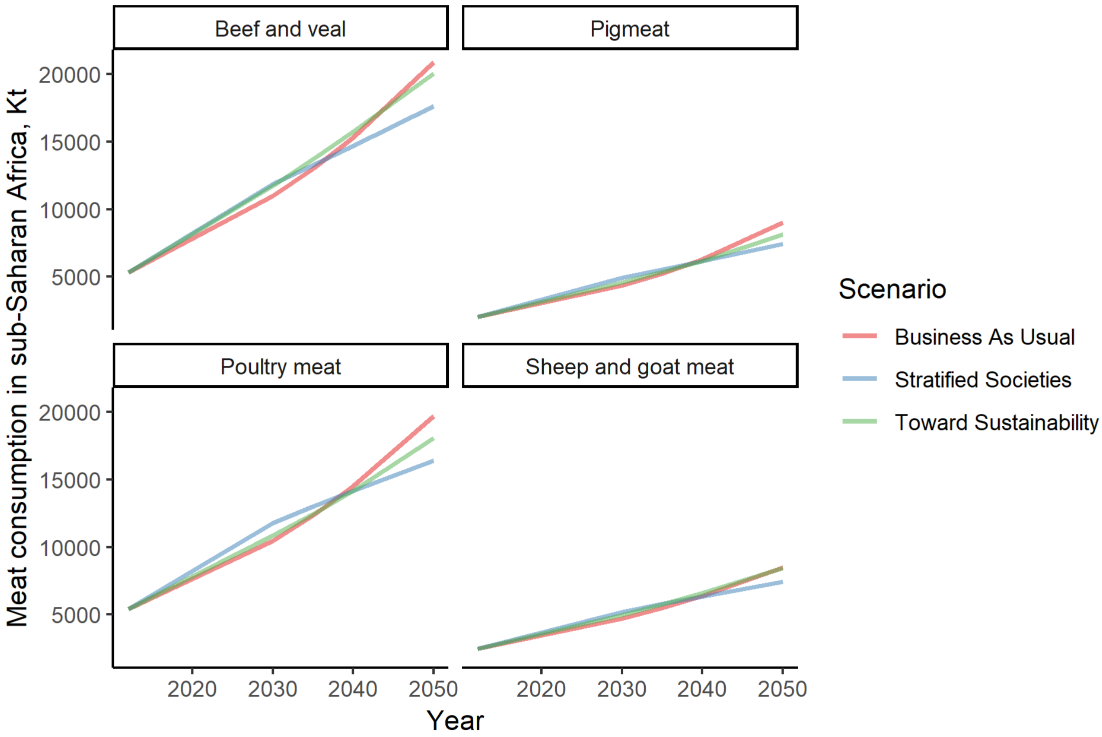


Figure S4. | Meat consumption in 2050 in sub-Saharan Africa according to three FAO scenarios, by meat type. Data source: FAO (2018).

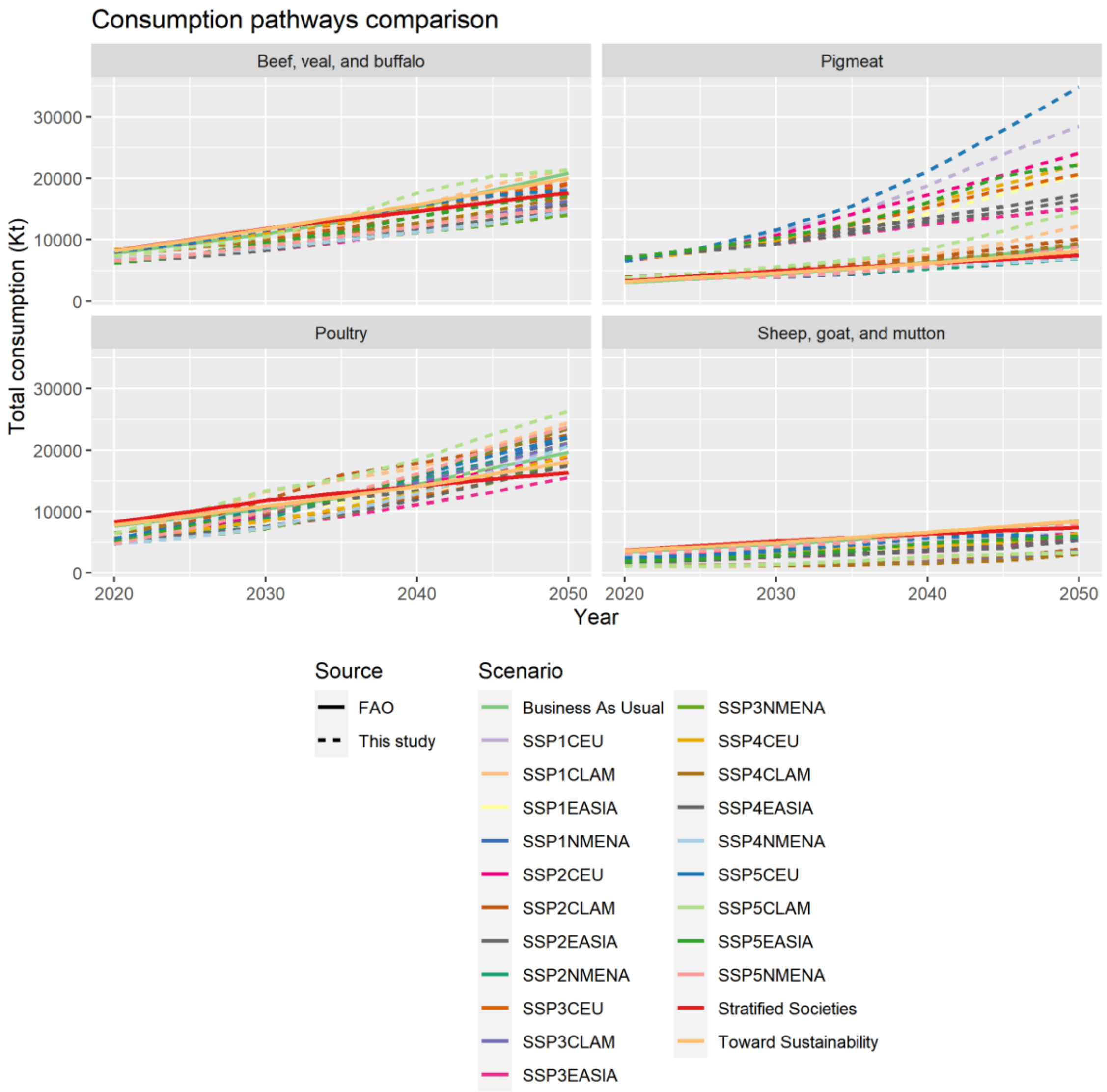


Figure S5. | Comparison of the meat consumption scenarios estimated in this paper with the FAO scenarios, by meat type. Data source: FAO (2018) .

Productive efficiency scenarios

Table S6. 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.

Figure S6. | Dynamic convergence process towards environmental impact coefficients of reference regions.

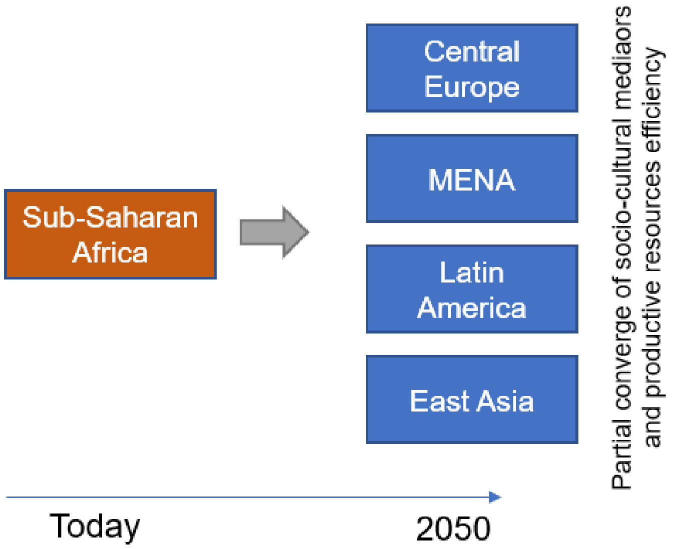
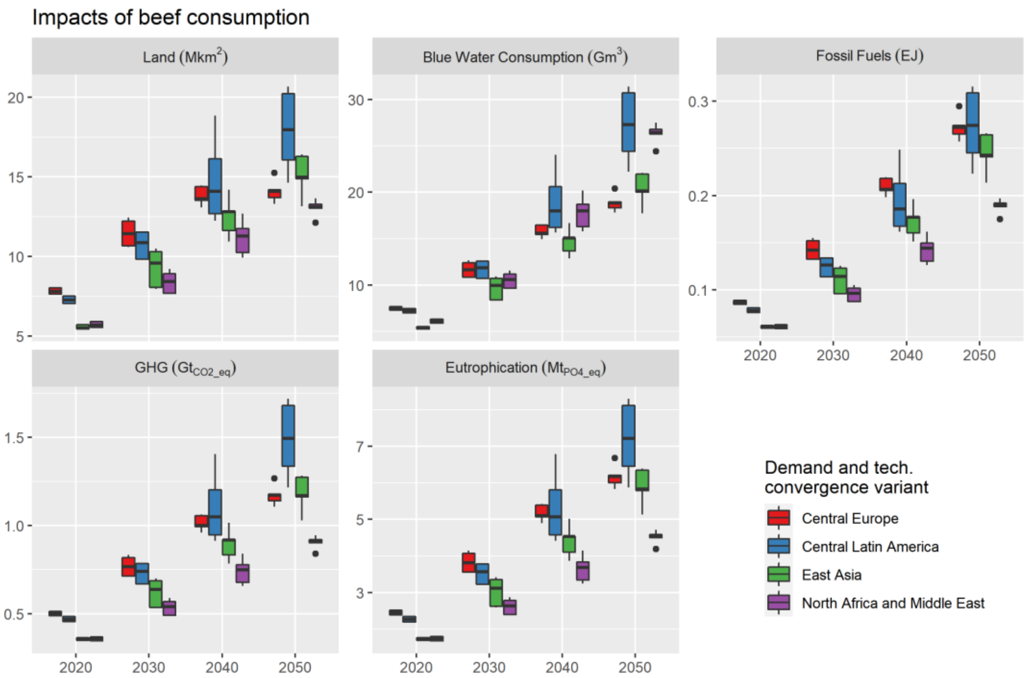


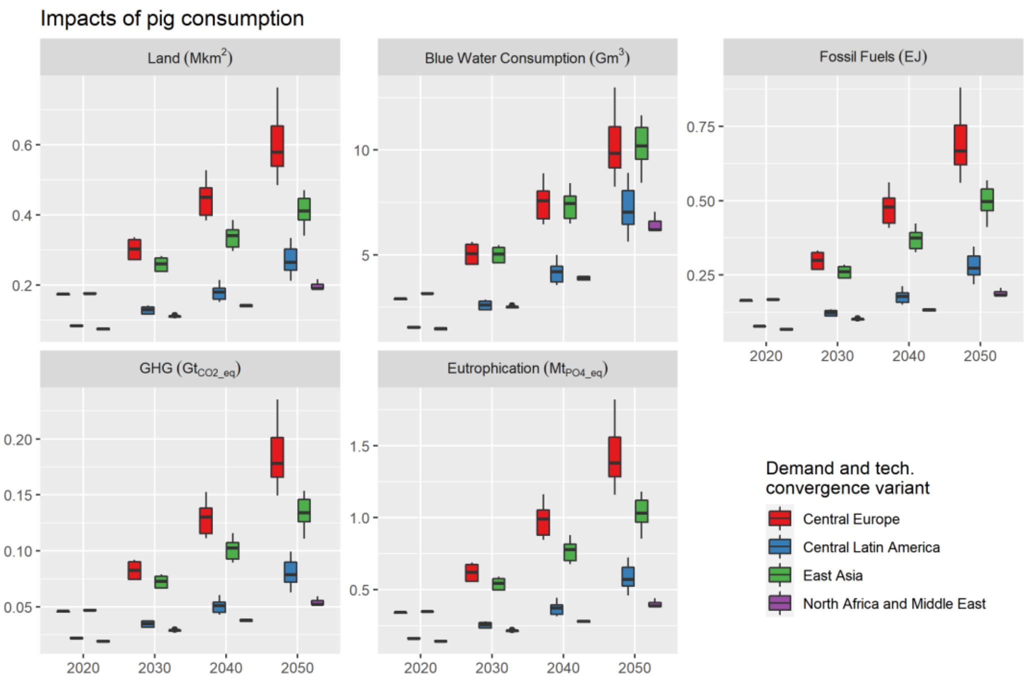
Figure S7. | Production and efficiency variants considered in the impact assessment analysis.

Meat-type specific environmental impact results

A



B



C

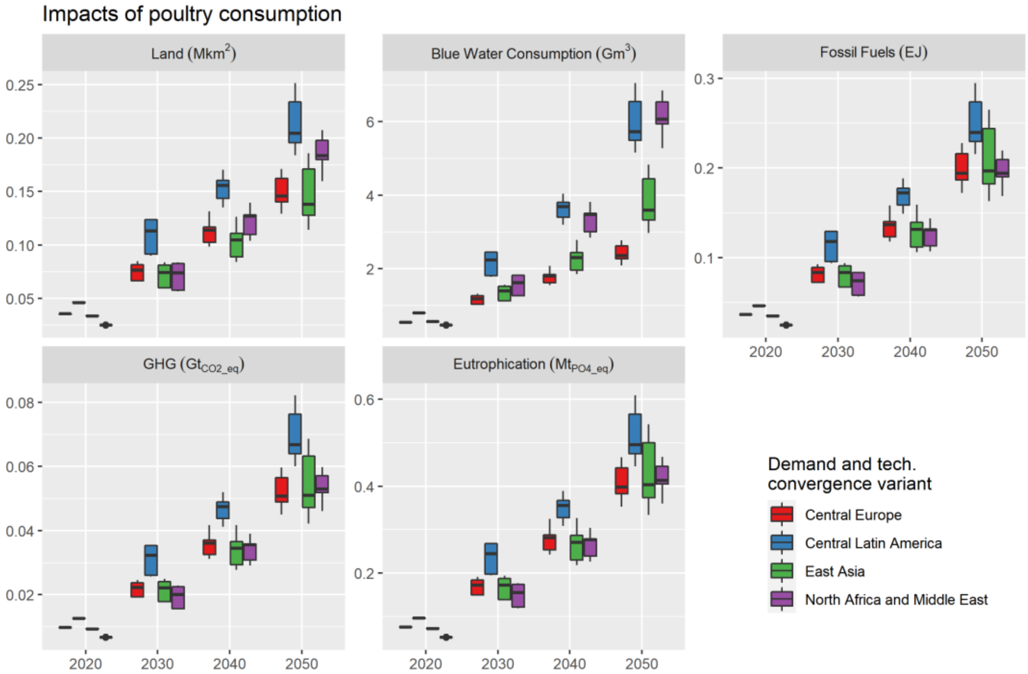


Figure S8. Meat specific environmental impacts. **(A)** Impacts related to beef consumption**; (B)** Impacts related to pig consumption; **(C)** Impacts related to poultry consumption.

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:

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

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).

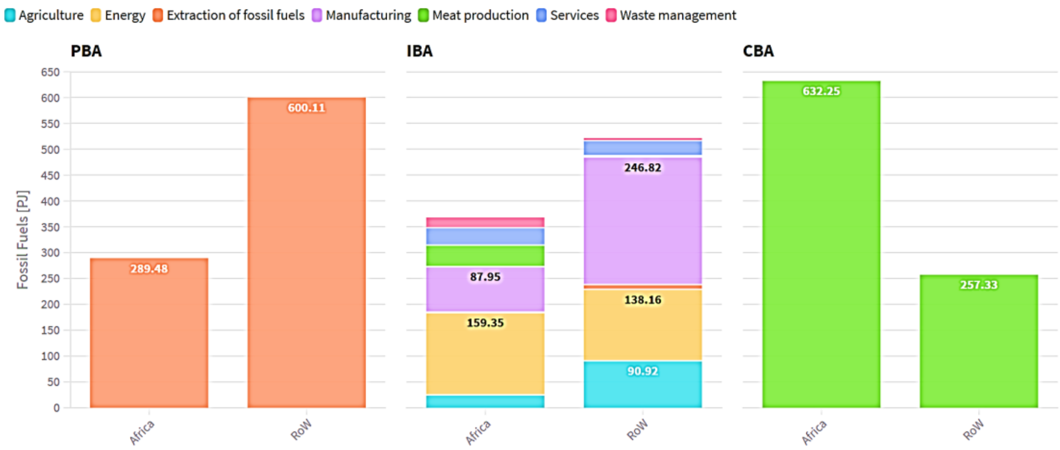


Figure S9. Allocation of Fossil Fuel resource use for fulfilling 2050 meat demand by local or import sector and allocation methodology. Values in PJ for median case among runned scenarios (SSP4—East Asia).

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 S9 visit the following link: Fossil fuels allocation | Flourish.

Meat substitutes LCA parameters

Table S7. Meat-based alternatives considered and their LCA environmental footprint.

Name	Substitute to	Type	LCA_kg_CO2eq_per_kg	LCA_l_blue-water_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 S8. 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]

Supplementary References

1. FAO. *Food Balance Sheet*; FAO: Rome, Italy, 2017.
2. Engel, E. Die productions-und consumtionsverhältnisse des königreichs sachsen. *Z State Bur K Sächs Minist Inn.* **1857**, *8*, 1–54.
3. Bennett, M.K. Wheat in national diets. *Wheat Stud.* **1941**, *18*, 37.
4. Sans, P.; Combris, P. World meat consumption patterns: An overview of the last fifty years (1961–2011). *Meat Sci.* **2015**, *109*, 106–111.
5. Cole, J.R.; McCoskey, S. Does global meat consumption follow an environmental Kuznets curve? *Sustain. Sci. Pract. Policy* **2013**, *9*, 26–36, doi:10.1080/15487733.2013.11908112.
6. Shafik N. Economic development and environmental quality: An econometric analysis. *Oxf. Econ. Pap.* **1994**, *1*, 757–773.
7. Clonan, A.; Roberts, K.E.; Holdsworth, M. Socioeconomic and demographic drivers of red and processed meat consumption: implications for health and environmental sustainability. *Proc. Nutr. Soc.* **2016**, *75*, 367–373.
8. Sequeira, T.N.; Viegas, R.; Ferreira-Lopes, A. Income and religion: a heterogeneous panel data analysis. *Rev. Soc. Econ.* **2017**, *75*, 139–158.
9. Bettendorf, L.; Dijkgraaf, E. The bicausal relation between religion and income. *Appl. Econ.* **2011**, *43*, 1351–1363.
10. Leahy, E.; Lyons, S.; Tol, R.S. Determinants of Vegetarianism and Meat Consumption Frequency in Ireland. *Econ. Soc. Rev.* **2011**, *42*, 406–436.
11. FAO. *The Future of Food and Agriculture: Alternative Pathways to 2050*; FAO: Rome, Italy, 2018.

12. Smetana, S.; Mathys, A.; Knoch, A.; Heinz, V. Meat alternatives: life cycle assessment of most known meat substitutes. *Int. J. Life Cycle Assess* **2015**, *20*, 1254–1267, doi:10.1007/s11367-015-0931-6.
13. Heller, M.C.; Keoleian, G.A. *Beyond Meat's Beyond Burger Life Cycle Assessment: A Detailed Comparison between a Plantbased and an Animal-Based Protein Source*. Center for Sustainable Systems: Ann Arbor, MI, USA, 2018.
14. 2019 Environmental Life Cycle Analysis (LCA) Update—Impossible Foods. Impos Foods n.d. Available online: https://impossiblefoods.com/mission/lca-update-2019 (accessed on 18 May 2020).
15. Mekonnen, M.M.; Hoekstra, A.Y. The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 1577–1560.
16. Putri, A.M.H.; Waluyo, J.; Setiawan, A.A.R. Carbon footprint analysis of modern and traditional tempeh production in Indonesia. In *AIP Conference Proceedings*; AIP Publishing LLC: College Park, MD, USA, 2018; Volume 2024, p. 020010, doi:10.1063/1.5064296.
17. Poore, J.; Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **2018**, *360*, 987–992.
18. US Department of Agriculture ARS. FoodData Central 2019. Available online: https://fdc.nal.usda.gov/ (accessed on 15 March 2021).
19. Valess—Vegetarisch, Vielseitig n.d. Available online: https://www.valess.de/ (accessed on 17 June 2020).
20. About the insect burger|Bugfoundation. Available online: https://www.bugfoundation.com/our-burger.html (accessed on 15 March 2021).
21. ETM Inc. Eat This Much, Your Personal Diet Assistant. Eat This Much n.d. Available online: https://www.eatthismuch.com/food/nutrition/soy-burger,179046/ (accessed on 17 June 2020).
22. Williamson, D.A.; Geiselman, P.J.; Lovejoy, J.; Greenway, F.; Volaufova, J.; Martin, C.K.; Arnett, C.; Ortego, L. Effects of consuming mycoprotein, tofu or chicken upon subsequent eating behaviour, hunger and safety. *Appetite* **2006**, *46*, 41–48, doi:10.1016/j.appet.2005.10.007.