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METHODS FOR ESTIMATING GREENHOUSE GAS EMISSIONS FROM FOOD SYSTEMS
PART V: HOUSEHOLD FOOD CONSUMPTION

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PART V: HOUSEHOLD FOOD CONSUMPTION

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Abstract

This paper is part of a series detailing new methodologies for estimating key components of agrifood systems emissions, with a view to disseminate the information in FAOSTAT. It describes methods for estimating greenhouse gas (GHG) emissions in households, which include fossil fuel-based energy use and non-renewable (i.e. beyond sustainable wood harvesting levels) woodfuel use. This update would be reflected in the database of the annual carbon footprint of energy use in pre- and post-production agrifood system processes, on a country basis and with global coverage, for the period 1990–2020. Methods for estimating GHG emissions from other agrifood system processes and complementing this work are discussed elsewhere, specifically in relation to estimating emissions from fertilizer manufacturing, food processing, packaging and retail (Tubiello *et al.*, 2021), food transport (Karl, 2021), waste disposal (Karl and Tubiello, 2021), woodfuel used in the household (Flammini *et al.,* 2022a), on-farm energy use (Flammini *et al.*, 2022b), and pesticides manufacturing (Karl *et al.*, 2022). We find that in 2019, annual household food system emissions were about 1 655 million tonnes of carbon dioxide equivalent (Mt CO_2eq). The largest source of these emissions is from non-renewable woodfuel consumption at about 744 Mt CO_2eq, followed by electricity use at 562 Mt CO_2eq. However, over the period 1990–2019, the largest emission increases were from electricity use (+217 percent), natural gas (+190 percent) and petroleum products (+179 percent). Conversely, while woodfuel recorded the biggest share of emissions throughout the period, it recorded modest emissions increases compared to other fuel sources (+6 percent).

Our efforts help to better characterize agrifood systems and the role they can play in achieving the Sustainable Development Goals (SDGs). In particular, they align well with SDG 12 to ensure "sustainable consumption and production patterns'', specifically Target 12.2, "achieve the sustainable management and efficient use of natural resources" and Indicator 12.2.1, which monitors the "material footprint, material footprint per capita, and material footprint per GDP" of different products. This work also aligns well with Goal 7 to "ensure access to affordable, reliable, sustainable and modern energy for all", and in particular Target 7.1, which is to "ensure universal access to modern energy".

Contents

Acknowledgements

This paper has been drafted by Alessandro Flammini, Kevin Karl, Hanif Adzmir and Francesco N. Tubiello of the Statistics Division of the Food and Agriculture Organization of the United Nations (FAO).

Many principles of this methodology build on previous collaborative FAO work on the use of energy in agrifood systems, led by Olivier Dubois. We are thankful to Cynthia Rosenzweig, Philippe Benoit, David Sandalow, Erik Mencos Contreras, Matthew Hayek and the Food Climate Partnership for their useful inputs and comments, which helped to improve the quality of this work. We are also thankful to Leonardo Sousa at the United Nations Statistics Division (UNSD) for his support with data provision.

1 Introduction

Agrifood systems generate about one-third of GHG emissions from human activity and, therefore, are a key component of any effective climate change mitigation strategy. More recently, and building on the FAO pioneering work, Crippa *et al.* (2021a) and Tubiello *et al.* (2021) have significantly moved forward the methodological basis for full quantification of agrifood systems emissions. In particular, Crippa *et al.* (2021a) built EDGAR-FOOD, the first country-level database of agrifood systems emissions, covering the period 1990–2015. The work in Tubiello *et al.* (2021) lays the foundations for the development of an independent database in FAOSTAT, with a view to disseminate country-level statistics on GHG emissions from agrifood systems, with annual updates and global coverage.

Through quantification efforts, FAO has identified and classified agrifood systems emissions into three main categories: farm gate, land-use change, and pre- and post-production (Tubiello *et al.*, 2021). While the GHG emissions attributable to the first two categories have been widely established (Garnett, 2011; Smith *et al.*, 2014; Tubiello, 2019), the emissions estimation for the third has historically been uncertain due to lack of sufficient studies (Mbow *et al.*, 2019). Therefore, subsequent FAO works have developed methods to estimate emissions from energy use in pre- and post-production processes, such as from fertilizer manufacturing, food processing, packaging and retail (Tubiello *et al.*, 2021), food transport (Karl, 2021), waste disposal (Karl and Tubiello, 2021), woodfuel used in the household (Flammini *et al.,* 2022a), on-farm energy use (Flammini *et al.*, 2022b), and pesticide manufacturing (Karl *et al.*, 2022). An upcoming separate paper plans to extend this work where methodologies for the quantification of the F-gas emissions across the agrifood system is described.

Food-related activities within households (cooking and kitchen appliance use) are one of several critical pre- and post-production processes of agrifood systems and contribute a significant amount of carbon emissions. This paper aims to quantify the emissions attributable to these food-related activities. The first section describes the role of household food system activities overall and its implications on climate change. The second section describes the updated methodology for the quantification of emissions from household food systems through two different components: stratified fuel shares and household non-renewable woodfuel consumption. The third section validates the results obtained against published data from other sources. Finally, the last section discusses the limitations associated with this methodology and the way forward needed for methodological refinements and future applications.

Our efforts help to better characterize agrifood systems and the role they can play in achieving the SDGs. They align well with SDG 12 to ensure "sustainable consumption and production patterns'', specifically Target 12.2, "achieve the sustainable management and efficient use of natural resources" and Indicator 12.2.1, which monitors the "material footprint, material footprint per capita, and material footprint per GDP" of different products. Additionally, the work presented contributes to linking statistics on agrifood systems – typically reported by countries to FAO – to those reported under the United Nations Framework Convention on Climate Change (UNFCCC). We do so by explicitly linking relevant FAO classifications to those of the Intergovernmental Panel on Climate Change (IPCC) – used by countries to report to the UNFCCC (Rosenzweig *et al.*, 2020; Tubiello *et al.*, 2021).

2 Household consumption in context

2.1 Household agrifood systems, human health and environmental sustainability

Cooking is a primary household activity regardless of household income level or socioeconomic background (Sovacool, 2011). Cooking and kitchen appliance use (refrigerators, dishwashers, etc.) serve important functions that ensure basic nutritional needs within the household are met. Storing and preparing food with such technologies contributes to GHG emissions via combustion of energy sources. Therefore, providing sufficient access to meet such needs is one of the most important agendas in achieving three of the Sustainable Development Goals, which are: SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-Being) and SDG 7 (Affordable and Clean Energy).

About 780 million people in sub-Saharan Africa, almost four-fifths of the population, rely on solid biomass for cooking. This number has grown by nearly 50 percent since 2000, as population growth has outpaced the number of people gaining access to clean cooking (IEA, 2017). Globally, around 3.2 million premature deaths are caused due to the inhalation of polluted air in households, sourced mainly from the traditional use of biomass for heating and cooking. The pollution comes in the form of small particles that are absorbed into the lungs and enter the bloodstream. Air is considered polluted when the mean concentration of particulate matter (PM10 and PM2.5) and other combustion derived indoor pollutants such as carbon monoxide are beyond the World Health Organization (WHO) air quality guideline values (WHO, 2014). Another study pointed at an estimation of 3 million deaths per year from indoor air pollution by open fires and smoky stoves (IEA, 2021; WHO, 2021). However, very few studies have examined the climate impact of woodfuel consumption for residential use, except in the context of carbon offsets for carbon financing (e.g. using improved cookstoves). For example, one report estimated that the global potential for GHG emission reductions for improved cookstoves (ICS) is estimated at 1 Gt CO_2 per year (Lee *et al.*, 2013). Therefore, the climate impacts of household food system consumption processes are also significant, and must be addressed, in part because climate change poses a serious threat to global food security in turn (Rosenzweig *et al.*, 2020).

This paper strives to quantify the GHG emissions attributable to energy use across all household food-system activities. Crippa *et al.* (2021) found that global GHG emissions from food systems were approximately 18 billion tonnes of CO_2 equivalent (Gt CO_2eq) in 2015, or 34 percent of the global total, and that household food consumption contributed 0.46 Gt of GHG emissions in 2015, for roughly 3 percent of food system emissions. An analysis examining the GHG emissions estimates of the different stages of the food chain in the year 2007 had similar findings, estimating that catering and domestic food management accounts for approximately 1 to 2 percent of all food system emissions (excluding refrigeration use) from a total of between 9.8 and 16.9 Gt CO_2eq from the entirety of food systems (Vermeulen *et al.*, 2012).

2.2 Mapping agrifood system components

The data work in this paper complements existing information on the new methods introduced on computing emissions from fertilizers manufacturing, food processing, retail, household consumption, transport and waste disposal and pesticides manufacturing that were already disseminated in companion papers. Previously, only food-related emissions falling under the Energy category of the IPCC were covered. However, in this new update, CO_2 emissions from woodfuel burned in households associated with unsustainable harvesting – traditionally accounted under the land use, land-use change and forestry (LULUCF) category – are analysed and estimated. More details on how the IPCC traditionally accounts for biomass consumption can be found in Flammini *et al.* (2022a).

Table 1. Mapping IPCC to FAO emissions categories

IPCC		Agrifood systems activity	GHG CH_4	GHG N_2O	GHG CO_2	FAO			Blue highlight
AFOLU	LULUCF	Net forest conversion	x	x	x	LAND-USE CHANGE	AGRICULTURAL LAND	AGRIFOOD SYSTEMS	
		Tropical forest fires	x	x	x				
		Household consumption (woodfuels)	x	x	x				yes
		Peat fires	x		x				
		Drained organic soils	x		x				
	AGRICULTURE	Burning – Crop residues	x	x		FARM GATE			
		Burning – Savanna	x	x					
		Crop residues		x					
		Drained organic soils		x					
		Enteric fermentation	x						
		Manure management	x	x					
		Manure applied to soils		x					
		Manure left on pasture		x					
		Rice cultivation	x						
		Synthetic fertilizers		x					
ENERGY		On-farm energy use	x	x	x				
		Fertilizer manufacturing	x	x	x	PRE- AND POST-PRODUCTION			
		Processing	x	x	x				
		Packaging	x	x	x				
		Transport	x	x	x				
		Household consumption	x	x	x				yes
		Retail – Energy use	x	x	x				
INDUSTRY		Retail – Refrigeration	x	x	x				
WASTE		Solid food waste	x						
		Incineration			x				
		Industrial wastewater	x	x					
		Domestic wastewater	x	x					

Note: Blue highlights represent pre- and post-components of agrifood systems covered in this work.
Source: Adapted from Tubiello, F.N., Flammini, A., Karl, K., Qiu, S., Heiðarsdóttir, H., Pan, X. & Conchedda, G. 2021. *Methods for estimating greenhouse gas emissions from food systems – Part III: energy use in fertilizer manufacturing, food processing, packaging, retail and household consumption.* FAO Statistics Working Paper Series, No. 29. Rome, FAO. https://doi.org/10.4060/cb7473en

3 Household consumption methodology overview

3.1 Overview

The methodology presented in this paper presents two stepwise approaches for the estimation of household agrifood system emissions. The total emissions for household consumption are the additions of the emissions obtained from two components: fuel-specific food share or stratified fuel shares, to be applied to household GHG emissions; and household non-renewable woodfuel consumption. The terms 'household' here refers to the activities that are covered by national statistics on household energy consumption, which usually include also small businesses and restaurants. Household energy consumption includes electricity as well as fossil and non-fossil fuels.

3.2 Component 1: stratified fuel shares

GHG emissions from stratified fuel shares refer to the CO_2, methane (CH_4) and nitrous dioxide (N_2O) generated by the consumption of the four main energy carriers (hereafter called "fuels") used for cooking, kitchen appliances and refrigeration as outlined by WHO. These energy carriers are natural gas, oil and petroleum products (liquefied petroleum gas [LPG] and kerosene), electricity and coal (Stoner *et al.*, 2021). F-gases emitted by refrigeration systems in households will be estimated in an upcoming separate paper that aims to quantify the amount of F-gas produced throughout the entire food systems chain. The energy consumption of each fuel, and thus emissions, can vary significantly depending on the country, region and industrialization level.

Component 1 applies the following formula for the estimation of emissions based on stratified fuel shares.

$E1_{i,y} = AD_{i,y} * f_{i,y} * EF$ (formula 1)

where

$E1_{i,y}$ = emissions in select country or region i, for select inventory year y, in CO_2 equivalent (kt CO_2eq)

AD = activity data for each fuel, in terajoules (TJ), based on IPCC (2006) default calorific values, in country or region i, for year y,

f = food share, shares of fuel use attributable to food systems in households in country or region i, for year y,

EF = emission factor, by fuel type based on IPCC (2006) default values.

Activity data were taken from UNSD energy statistics, Flow 1231: consumption by households (UN, 2022). UNSD data represented official country data from 238 countries and territories. All data were then converted to energy units by applying the IPCC (2006) default heating values.

Subsequently, the food-related shares (i.e. the share of energy that is directly associated with food consumption) of each fuel activity data for a selected country and a selected year were determined. The food share can be considered as the sum of the shares of cooking (all fuel types), refrigeration (electricity) and appliances (electricity). Food shares were collected from a variety of sources, mainly the International Energy Agency (IEA) Energy efficiency indicators annual reports, academic journals and reports from government publications. For years where food share data for certain countries and territories were not available, we calculated regional averages according to FAOSTAT definitions and applied the regional food shares to those countries.

Additional gap-filling was also performed by FAO by interpolating between available years using linear regression and extrapolating using the "last-observation-carried-forward" method. The method used to apply food shares in this update is distinct from our previous estimations as we are now able to provide year-specific food share values (i.e. with information of what share of each fuel or electricity consumed in the household is associated with food consumption in a given year) compared to previous estimations where a constant food share value is applied. Table 1 provides the old food share values and the updated food share ranges available for countries and regions over the period 1990–2019.

Table 2. Food share ranges for household food system's energy consumption by country and region

Country/ region	Old food shares		Updated food share ranges (based on a review of a variety of sources, mainly the IEA Energy Efficiency Indicators, academic journals, and government reports)			
	Cooking	Refrigeration	Coal	Electricity	Natural gas	Oil and petroleum products
Albania	0.272	-	0	0.144–0.205	0	0.505–0.555
Argentina	0.17	-	0	0	0.082–0.100	0.403–0.653
Australia	0.06	0.07	0	0.199–0.237	0.043–0.046	0.286–0.360
Austria	-	0.03	0–0.005	0.247–0.300	0.006–0.020	0.0002–0.0008
Belarus	-	-	0	0.0378–0.0382	0.195–0.210	1
Belgium	-	-	0	0.046–0.059	0.011–0.015	0.002–0.0039
Bosnia and Herzegovina	0.05	-	0.004–0.007	0.093–0.094	0.097–0.103	0.067–0.224
Brazil	0.55	-	0	0.320–0.371	0.600–0.601	0.900
Bulgaria	-	-	0.013–0.038	0.132–0.150	0.053–0.064	0.86–0.94
Canada	0.04	0.03	0	0.146–0.218	0.0054–0.011	0
Chile	-	-	0	0.270–0.377	0.067–0.182	0.110–0.248
China	0.40	0.02	0.0715	0.420	0.515	0.749
Colombia	-	-	0	0.369	0.660	1
Croatia	-	-	0	0.102–0.105	0.074–0.088	0.266–0.387
Cyprus	-	-	0	0.058–0.071	0	0.156–0.163
Czechia	-	0.03	0.001–0.012	0.275–0.405	0.078–0.121	0.196–0.866
Denmark	-	0.02	0	0.233–0.321	0.003–0.005	0.005–0.025
Egypt	-	-	0	0.173	0.698	0.797
Estonia	-	-	0–0.04	0.119	0.136–0.141	0.371–0.795
Finland	-	0.02	0	0.027–0.185	0.024–0.267	0
France	-	0.04	0	0.215–0.261	0.052–0.071	0.065–0.104
Georgia	-	-	0–0.2	0.092–0.102	0.229–0.237	0.977–1
Germany	-	0.03	0	0.371–0.429	0.002–0.008	0.0003–0.0042
Greece	-	0.09	0	0–0.394	0–0.007	0–0.059
Hungary	-	-	0	0.029–0.053	0.050–0.083	0.719–1
India	0.63	-	0	0.116	0	0.6953
Ireland	-	0.02	0	0.058–0.071	0.015–0.025	0.0005–0.0011
Italy	-	0.03	0	0.251–0.294	0.067–0.091	0.042–0.112

Country/ region	Old food shares		**Updated food share ranges** (based on a review of a variety of sources, mainly the IEA Energy Efficiency Indicators, academic journals, and government reports)			
	Cooking	**Refrigeration**	**Coal**	**Electricity**	**Natural gas**	**Oil and petroleum products**
Japan	0.08	-	0	0.034–0.051	0.158–0.176	0.097–0.114
Kenya	-	-	0	0	0	0.1792
Kosovo	-	-	0	0.210	0	0
Latvia	-	-	0	0.087–0.089	0.289–0.291	0.235–0.369
Lithuania	-	-	0–0.011	0.058–0.088	0.229–0.314	0.588–0.981
Luxembourg	-	-	1	0.045–0.091	0.021–0.031	0
Malaysia	-	-	0	0.548	0	1
Malta	-	-	0	0.025–0.037	0	0.677–0.780
Mexico	-	-	0	0.301	0.632	0.633
Morocco	-	-	0	0.519	0	0.817
Netherlands	-	-	0	0.212–0.290	0.017–0.023	0
New Zealand	0.06	0.03	0–0.010	0.107–0.125	0.144–0.154	0
Nigeria	0.43	-	0	0.0634	0	1
North Macedonia	-	-	0	0.133–0.144	0	0.297–0.902
Norway	0.02	-	0	0.019–0.022	0	0
Philippines	-	-	0	0.223	0	1
Poland	-	-	0.012–0.015	0.107–0.125	0.181–0.228	0.355–0.848
Portugal	-	0.02	0	0.266–0.514	0.302–0.422	0.350–0.439
Republic of Korea	-	0.03	0	0.145–0.370	0.129–0.176	0.034–0.197
Republic of Moldova	0.13	-	0	0.129–0.130	0.328	0.736–0.742
Romania	-	-	0.080–0.085	0.0004–0.0005	0.1871	0.790–0.791
Saudi Arabia	-	-	0	0.079	0	1
Serbia	0.07	-	0.013	0.108	0.02475	0.174–0.373
Slovakia	-	0.04	0.014–0.019	0.180–0.235	0.177–0.186	0.731–0.881
Slovenia	-	-	0	0.196–0.283	0.040–0.061	0.047–0.106
Spain	-	-	0	0.026–0.093	0.105–0.213	0.062–0.152
Sweden	-	0.01	0	0.026–0.135	0.047–0.105	0–0.001
Switzerland	-	0.03	0	0.229–0.272	0.006–0.017	0
Türkiye	0.08	-	0–0.020	0.041–0.092	0.051–0.136	0.194–0.979
Ukraine	0.16	-	0.004–0.005	0.070–0.086	0.287–0.300	0.787–0.878
United Kingdom of Great Britain and Northern Ireland	0.03	0.03	0–0.006	0.184–0.278	0.018–0.025	0–0.002
United States of America	0.02	0.03	0	0.087–0.132	0.019–0.027	0.012–0.020
Uruguay	-	-	0	0.021–0.037	0.105–0.204	0.586–0.719
Eastern Africa	-	-	0	0	0	0.180
Northern Africa	-	-	0	0.346	0.349	0.807
Western Africa	-	-	0	0.063	0	1

<table>
<tr><th rowspan="2">Country/ region</th><th colspan="2">Old food shares</th><th colspan="4">Updated food share ranges (based on a review of a variety of sources, mainly the IEA Energy Efficiency Indicators, academic journals, and government reports)</th></tr>
<tr><th>Cooking</th><th>Refrigeration</th><th>Coal</th><th>Electricity</th><th>Natural gas</th><th>Oil and petroleum products</th></tr>
<tr><td>Northern America</td><td>0.03</td><td>0.03</td><td>0</td><td>0.117–0.175</td><td>0.013–0.017</td><td>0.006–0.100</td></tr>
<tr><td>Central America</td><td>-</td><td>-</td><td>0</td><td>0.301</td><td>0.632</td><td>0.633</td></tr>
<tr><td>South America</td><td>0.44</td><td>-</td><td>0</td><td>0.205–0.231</td><td>0.309–0349</td><td>0.634–0.694</td></tr>
<tr><td>Eastern Asia</td><td>-</td><td>-</td><td>0.024</td><td>0.203–0.275</td><td>0.271–0.285</td><td>0.298–0.348</td></tr>
<tr><td>Southern Asia</td><td>-</td><td>-</td><td>0</td><td>0.116</td><td>0</td><td>0.695</td></tr>
<tr><td>South-eastern Asia</td><td>-</td><td>-</td><td>0</td><td>0.385</td><td>0</td><td>1</td></tr>
<tr><td>Western Asia</td><td>-</td><td>-</td><td>0–0.05</td><td>0.073–0.080</td><td>0.071–0.093</td><td>0.589–0.778</td></tr>
<tr><td>Eastern Europe</td><td>-</td><td>-</td><td>0.014–0.019</td><td>0.112–0.126</td><td>0.177–0.186</td><td>0.731–0.881</td></tr>
<tr><td>Northern Europe</td><td>-</td><td>-</td><td>0.001–0.006</td><td>0.093–0.144</td><td>0.096–0.120</td><td>0.167–0.202</td></tr>
<tr><td>Southern Europe</td><td>-</td><td>-</td><td>0.001–0.002</td><td>0.149–0.178</td><td>0.062–0.075</td><td>0.250–0.352</td></tr>
<tr><td>Western Europe</td><td>-</td><td>-</td><td>0.143–0.144</td><td>0.210–0.232</td><td>0.017–0.024</td><td>0.010–0.015</td></tr>
<tr><td>Australia and New Zealand</td><td>-</td><td>-</td><td>0–0.005</td><td>0.156–0.174</td><td>0.094–0.099</td><td>0.143–0.180</td></tr>
<tr><td>Africa</td><td>0.31</td><td>-</td><td>0</td><td>0.189–0.189</td><td>0.175</td><td>0.698</td></tr>
<tr><td>Americas</td><td>-</td><td>-</td><td>0</td><td>0.195–0.226</td><td>0.276–0.301</td><td>0.477–0.515</td></tr>
<tr><td>Asia</td><td>0.30</td><td>0.23</td><td>0.007–0.027</td><td>0.181–0.201</td><td>0.11–0.122</td><td>0.603–0.672</td></tr>
<tr><td>European Union</td><td>0.06</td><td rowspan="2">0.03</td><td rowspan="2">0.032–0.034</td><td rowspan="2">0.139–0.164</td><td rowspan="2">0.090–0.098</td><td rowspan="2">0.317–0.355</td></tr>
<tr><td>Europe (excluding European Union)</td><td>0.10</td></tr>
<tr><td>Oceania</td><td>0.06</td><td>0.05</td><td>0–0.005</td><td>0.156–0.174</td><td>0.090–0.099</td><td>0.143–0.180</td></tr>
</table>

Source: Authors' own elaboration.

Finally, the generic IPCC method for estimating GHG emissions at Tier 1 (formula 1), using inputs of activity data and emission factors, is applied. The emission factors used were the IPCC (2006) default values for stationary combustion in the residential category.

3.3 Component 2: household non-renewable woodfuel consumption

GHG emissions from household non-renewable woodfuel consumption refer to the GHG emissions generated by household cooking using non-renewable woodfuel (i.e. beyond sustainable wood harvesting levels). Hence, the GHG emissions refer only to the amount of woodfuel harvested beyond the annual increment. The consumption of non-renewable woodfuel for cooking, and thus emissions, varies significantly depending on the country, region and industrialization level.

Component 2 follows the following stepwise approach for the estimation of agrifood systems emissions, by applying the following formula.

$E2_{w,i,y} = A_{i,y} * f_{w,i,y} * nRBf_i * EF$ (formula 2)

where

$E2_{w,i,y}$ = emissions in select country or region i, for select inventory year y, kilotonnes of CO_2 equivalent (kt CO_2eq)

$A_{i,y}$ = woodfuel consumed in the household (activity data) for country or territory i, for inventory year y, expressed in energy content,

$f_{w,i,y}$ = share of woodfuel used for cooking for country i, for inventory year y,

$nRBf_i$ = non-renewable biomass fraction for country i,

EF = emission factor of woodfuel.

The amount of woodfuel consumed in the household is extracted from UNSD energy statistics, Flow 1231: Consumption by households (UN, 2022), Code: FW (cubic metres, thousand), and converted to joules (J) by applying a calorific value of 11.203 J/m^3. This calorific value is calculated by multiplying the average heating value of air-dried wood fuel and completely dry wood and its average density. This heating value is estimated from the heating value of woods typically used as woodfuel, as reported in the IEA Energy Statistics (IEA, 2004) (Table 3). The average density of the wood fuels is estimated by taking the density of woods typically available in tropical countries as reported in FAO (2007). More details are provided in Flammini *et al.* (2022a).

Table 3. Typical heating values of woods used as fuelwood

Wood type	Heating value
Air-dried wood (10–20 percent moisture content)	16 MJ/kg
Completely dry wood (oven-dried)	18 MJ/kg
Average	17 MJ/kg

Source: IEA (2004).

The share of non-renewable woodfuel consumption in households that is used for cooking is then calculated. The share of woodfuel used for cooking is set to unity for all tropical countries concerned, while countries with little to no tropical coverage would have their share set as 0.847. This is considering that the rest of the portion would be used for heating. These values assume that most of the unsustainable wood harvest takes place in pan-tropical countries (Daioglou *et al.*, 2012; Morgan, 2011).

Subsequently, the non-renewable biomass fraction (nRBf) for the woodfuel used for each country is determined. The nRBf is collected using the Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM), a spatial model developed by FAO in the early 2000s (Drigo *et al.*, 2002) and gradually improved over time. Bailis *et al.* (2015), in their paper published in Nature, present the non-renewable biomass fraction of various countries across Asia, Africa and Latin America. For countries and territories where data are not available, we calculated regional averages according to FAOSTAT definitions, and applied the resulting NRB fractions to those countries.

Table 4. Non-renewable biomass fractions

Country/region	NRB fraction
Angola	0.350
Argentina	0.283
Bangladesh	0.510
Belize	0.993

Country/region	NRB fraction
Benin	0.217
Bhutan	0.559
Bolivia (Plurinational State of)	0.325
Botswana	0.895
Brazil	0.238
Brunei Darussalam	0.872
Burkina Faso	0.476
Burundi	0.570
Cambodia	0.384
Cameroon	0.758
Central African Republic	0.264
Chad	0.237
Chile	0.138
China	0.16
Colombia	0.344
Congo	0.099
Costa Rica	0.18
Côte d'Ivoire	0.163
Democratic Republic of the Congo	0.24
Dominican Republic	0.33
Ecuador	0.99
El Salvador	0.372
Equatorial Guinea	0.94
Eritrea	0.679
Ethiopia	0.613
French Guyana	0.165
Gambia	0.412
Ghana	0.286
Guatemala	0.334
Guinea	0.297
Guinea-Bissau	0.279
Guyana	0.039
Haiti	0.666
Honduras	0.637
India	0.231
Indonesia	0.434
Jamaica	0.185
Kenya	0.635
Lao People's Democratic Republic	0.273
Lesotho	0.525
Liberia	0.283
Libya	0.327

Country/region	**NRB fraction**
Malawi	0.371
Malaysia	0.465
Mali	0.291
Mauritania	0.348
Mexico	0.268
Mozambique	0.397
Myanmar	0.085
Namibia	0.476
Nepal	0.524
Nicaragua	0.579
Niger	0.235
Nigeria	0.511
Pakistan	0.836
Panama	0.496
Papua New Guinea	0.403
Paraguay	0.384
Peru	0.309
Philippines	0.214
Rwanda	0.585
Senegal	0.361
Sierra Leone	0.219
Singapore	0.755
Solomon Islands	1
Somalia	0.524
South Africa	0.238
Sri Lanka	0.244
Sudan	0.411
Suriname	0.181
Thailand	0.03
Timor-Leste	1
Togo	0.44
Trinidad and Tobago	0.554
Uganda	0.613
United Republic of Tanzania	0.235
Venezuela (Bolivarian Republic of)	0.527
Viet Nam	0.115
Zambia	0.340
Zimbabwe	0.377
Eastern Asia	0.16
Latin America and the Caribbean	0.396
Melanesia	0.702
Northern Africa	0.369

Country/region	NRB fraction
South-eastern Asia	0.421
Southern Asia	0.484
Sub-Saharan Africa	0.415

Source: Authors' own elaboration.

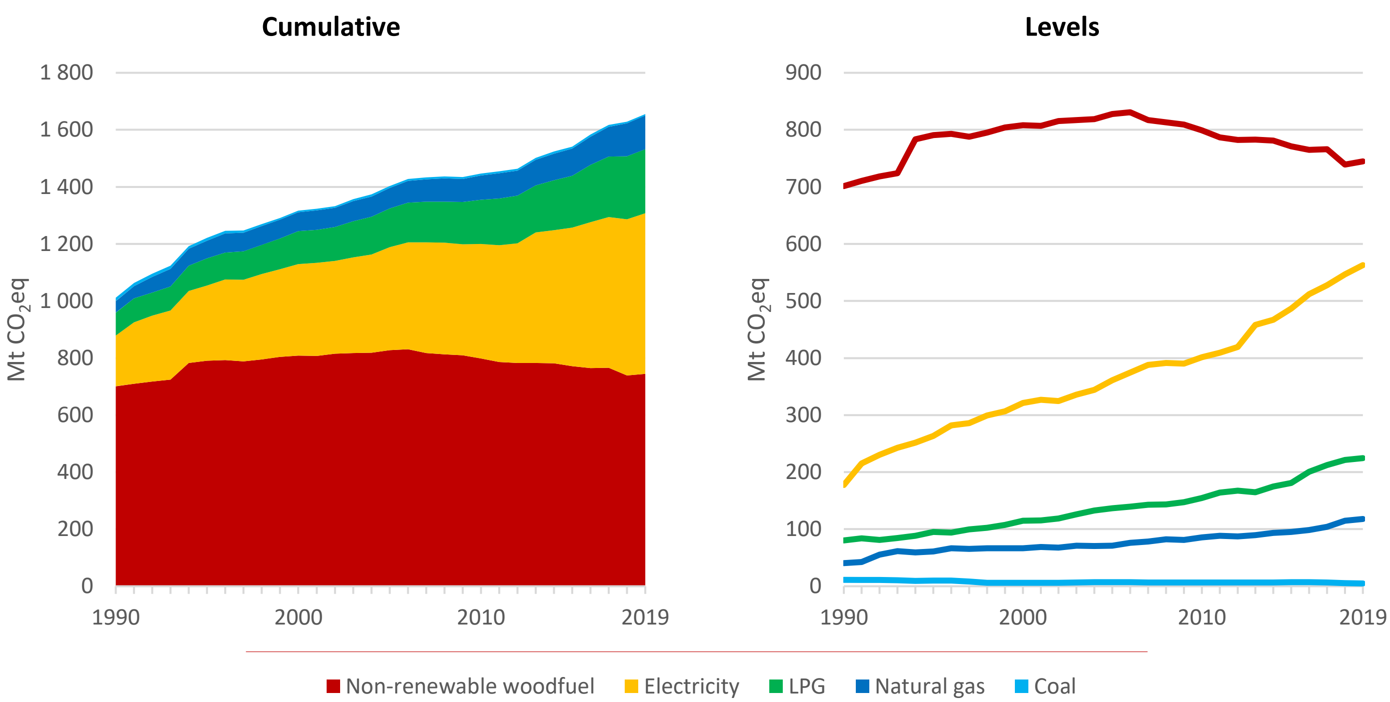
Finally, the generic IPCC method for estimating GHG emissions using inputs of activity data, emission factors and share of non-renewable woodfuel consumption from the first two steps, is applied. The emission factors used were the IPCC (2006) default values for stationary woodfuel combustion in the residential category.

4 Validation of results

4.1 Validation of results: comparison with previous estimates and EDGAR-FOOD

Our new estimates indicate that the global GHG emissions from household food systems including non-renewable woodfuel consumption amounted to 1 655 Mt CO_2eq in 2019, 63 percent higher than in 1990. The average annual increase was 2 percent over the period 1990–2019 and was consistent with the overall global population growth (1.09–1.51 percent annual increase) (UNdata, 2022). The breakdown by fuel shows that 45 percent of these emissions (744 Mt CO_2eq) are associated with non-renewable woodfuel consumption, followed by electricity (562 Mt CO_2eq, or 34 percent) and petroleum products (224 Mt CO_2eq, or 14 percent) while natural gas and coal contributed a mere 7 percent (117 Mt CO_2eq) and 0.2 percent (5 Mt CO_2eq) respectively. Emissions from electricity grew rapidly over the study period (with mean annual growth rates of more than 7 percent) while the growth rates for natural gas and petroleum products follow closely behind (around 6 percent on average for both). This, together with a modest increase in non-renewable woodfuel emissions (the mean annual growth rate is 0.2 percent), suggests a global transition towards cleaner forms of energy being used in households, such as grid electricity, liquefied petroleum gas and natural gas. These three sources of energy are typically considered to be clean as combustions of such fuels produce concentrations of fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) that are within acceptable ranges according to WHO guidelines (Bisaga and Campbell, 2022).

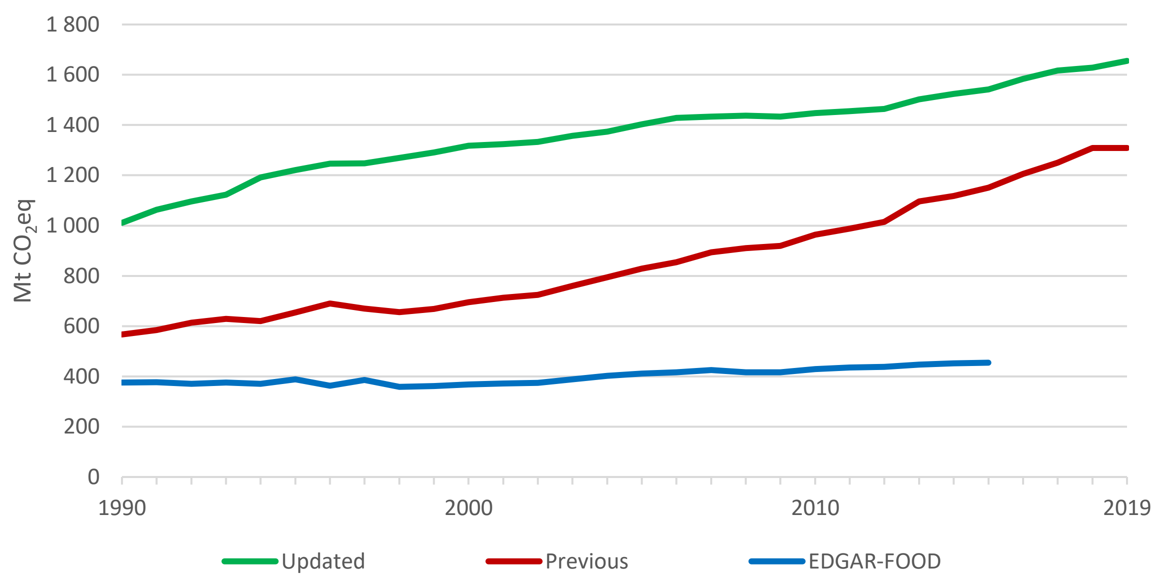
Figure 1. Household food-system emissions by energy source



Source: Author's own elaboration.

Our updated total estimations (a combination of emissions from food-related household consumption from fossil fuels, plus emissions from non-renewable woodfuel consumption) exceed both our previous estimates and EDGAR-FOOD estimates. For the year 2015, the food-related household emissions were 1.6 Gt CO_2eq, 25 percent higher than our previous estimate (Tubiello *et al.*, 2021 and 2022) and almost four times the estimate provided by Crippa *et al.* (2021). By including GHG emissions from non-renewable woodfuel consumption in households, our estimate better reflects the impact of fuel use in countries where there is a higher dependence on woodfuel overall, such as those in sub-Saharan Africa (World Bank, 2011). Other estimates do not include woodfuel emissions because CO_2 emissions from woodfuel use are typically accounted for under deforestation of the land use, land-use change and forestry (LULUCF) section of the IPCC. FAO (2011) estimates of this agrifood systems component in the early 2000s, of about 1.2 Gt CO_2eq (based on the existing literature at that time), are very close to our new country-level estimates of about 1.3–1.4 Gt CO_2eq for the same period (whereas EDGAR-FOOD estimates are only about half of that).

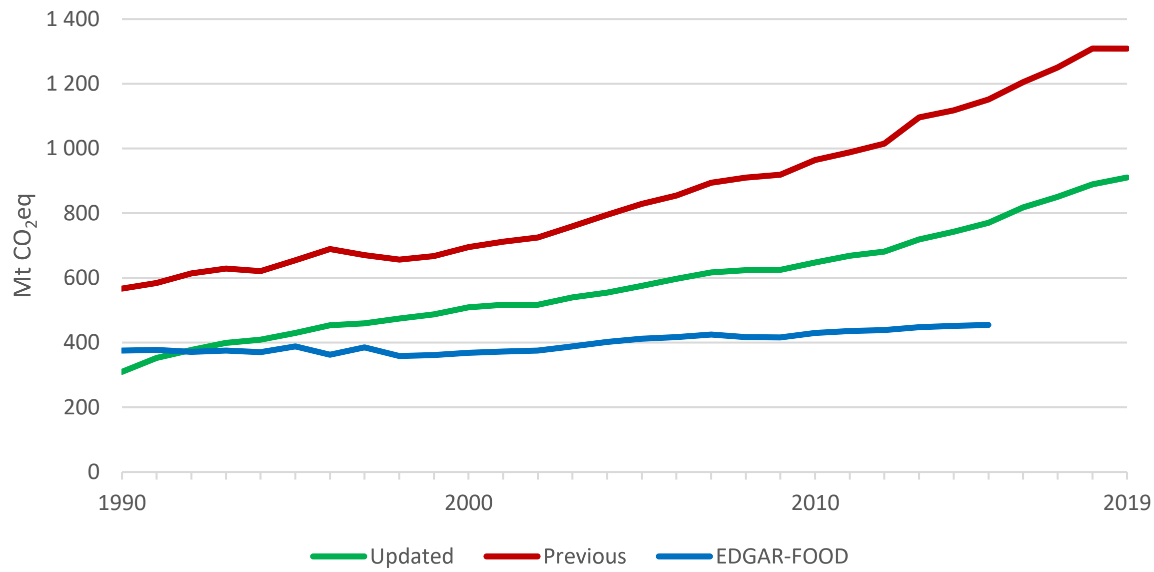
Figure 2. Comparison of updated FAO estimates with previous FAO and EDGAR-FOOD estimates of global emissions from household food consumption



Source: Authors' own elaboration.

However, if estimates of only fossil fuels and electricity used in the household were to be compared, our new estimates of GHG emissions for household consumption are lower than previous FAO estimates but higher than EDGAR-FOOD. The new country food shares, stratified by fuel, lead to estimated emissions in 2015 of roughly 0.77 Gt CO_2eq, 37 percent lower than our previous values, or 75 percent higher than the EDGAR-FOOD values. This is due to the improved 'food shares' that have been applied.

Figure 3. Comparison of updated FAO estimates with previous FAO and EDGAR-FOOD estimates of global emissions from household food consumption excluding woodfuel

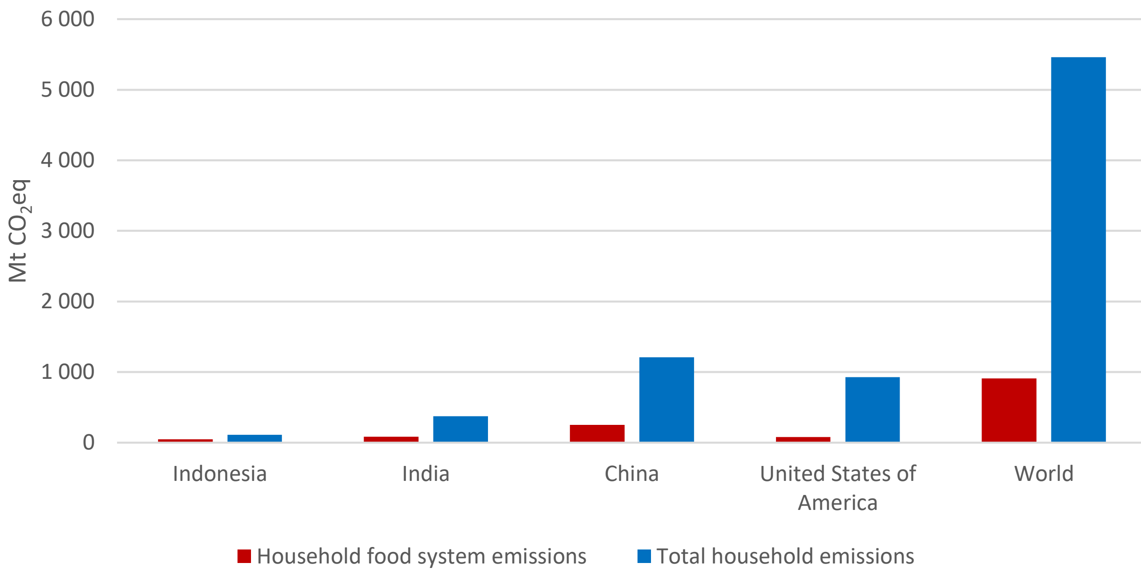


Source: Authors' own elaboration.

4.2 Validation based on emissions from total household energy consumption

Based on our calculations, the contribution of food-related fossil fuel and electricity use to total household emissions from energy use in 2019 is 16.7 percent. This is in line with existing literature that estimates that 13 percent of total energy-related household emissions come from food-related activities (Ivanova *et al.*, 2016). For the year 2019, three of four analysed countries (China, India and the United States of America) have a similar share of food-related emissions out of total household emissions, within ±6 percent of this range. For Indonesia, the household CO_2 emissions from fuel, light and food combined are estimated at 43 percent of the total household CO_2 emissions, according to Irfany *et al.* (2015). This value is close to our calculated value for 2019 of 45 percent. The higher percentage in Indonesia is in line with the general finding that cooking constitutes a greater percentage of total household energy use in low-income households and countries than in high-income ones (Sovacool, 2011). One country-level analysis of food systems in households for the United States of America shows that food-related fossil fuel and electricity percentage is typically 10–30 percent of total household emissions (Jones and Kammen, 2011), while another study estimated the cooking and refrigeration and freezing percentages for in-home use at 10.2 percent (Gardner and Stern, 2008), compared to our estimates of 8.7 percent for this value. Other studies have found that food system contributions to total household emissions in China decreased in recent decades, from 40 percent in 1992 to 20 percent in 2007 (Feng *et al.*, 2020). Our values for China show a value of about 21 percent in 2019, which is in line with the range provided in the study mentioned. For India, the sectoral contribution of food, beverage and tobacco products to private consumption is 14 percent (Zhu *et al.*, 2018), not far from our estimated share of 22 percent.

Figure 4. Comparison between household food consumption emissions and total household emissions for selected countries and the world, 2019



Source: Authors' own elaboration.

Household food systems include cooking and the use of refrigerators, freezers and dishwashers. Heller and Keoleian (2000) estimate that 40 percent of household food-related energy consumption is used in operating refrigerators and about 20 percent for cooking at home. Another study pointed that in 2020, global commercial and household refrigeration contributes nearly 1 000 Mt CO_2eq, with household refrigeration approximately half (Dong *et al.*, 2021). These values are aligned with our findings for 2019 when household food refrigeration contributed about 465 Mt CO_2eq (around 51.1 percent of total household emissions)

In global terms, the results are also in line with previous FAO estimates, where food preparation, cooking and retail were responsible for around 14 percent of global emissions in the early 2000s (FAO, 2011), as well as with other literature on the subject (Sims and Flammini, 2014).

5 Limitations and areas for advancement

5.1 Boundaries of this analysis

The household consumption activities described herein are not meant to be an exhaustive list of GHG emissions from all activities and processes within households attributable to agrifood systems. In particular, the scope of this work does not include, by design, upstream GHG emissions in the fuel chain such as petroleum refining, methane leaks during extraction processes and piping. F-gas emissions from household refrigeration were not included, but they have been estimated separately in an upcoming focused paper that aims to quantify the F-gases across the whole agrifood system.

5.2 Uncertainty

Significant errors may be introduced using subregional and regional coefficients, given the diversity in agrifood system typology and their dependence on physical geography and national socioeconomic drivers. These limitations nonetheless reflect the paucity of activity data available to describe agrifood systems components and their trends, globally and regionally. While knowledge and data exist for regions and countries such as China, the European Union, India, and the United States of America, much remains to be done in terms of regional and country-specific coverage. Uncertainties also exist in estimating GHG emission factors. These are typically related to difficulties in deriving generic coefficients in the face of natural spatial and temporal variability characterizing the underlying biophysical processes. More detailed information on uncertainties associated with emission factors and activity data can be found in the IPCC guidelines of 2006 or in Flammini *et al.* (2022a).

5.3 Areas of advancement

Work towards estimating agrifood systems emissions at the country level can be advanced in several ways. The present approach could be expanded by including other country- and region-specific studies that estimate trends in energy consumption across a range of similar activities as proxies – whether they are distinctly related to food. Additional indicators should be considered for a fuller characterization of agrifood systems and their future trajectory, for example by linking GHG emissions to economic productivity, calorie intake and output flows across food sector activities, food types, or to per capita indicators. This is inherently linked to assessing the impact that achieving SDG 7 goals on access to clean energy for all would have on GHG emissions, including for food production and consumption.

This work could be expanded by focusing on specific food commodities that are purchased in the household – requiring an additional focus on embedded emissions that are attributable to different types of food commodities from factors such as international trade and supply and demand patterns. Such an analysis would enable household consumers to further understand their full carbon impacts of the consumption of certain types of food commodities across the whole global supply chain.

Finally, relevant indicators can enhance our characterization of agrifood systems and their future trajectory, such as linking GHG emissions to overall economic productivity and output flows across food sectors activities, or to per capita indicators.

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