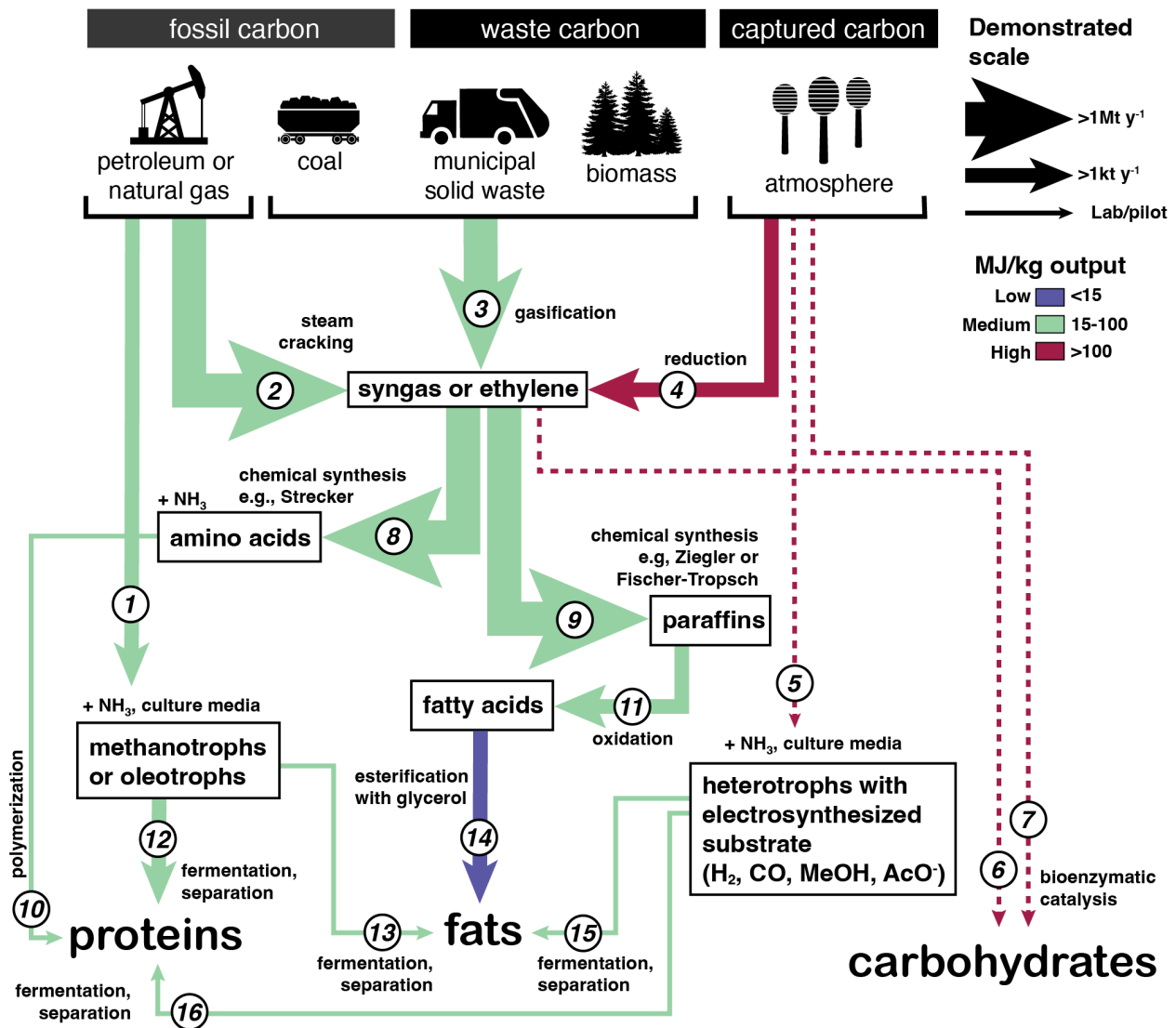

Food without agriculture

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Supplementary Information

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Supplementary Figure S1 | Reference key for potential food synthesis pathways. This figure mimics Figure 1 in the main text, but with numbered circles that refer to information and references shown in Table S1.

S1. Synthetic fat production

In the following analyses, we have used the conversion 1 kg edible fat = 9000 kcal.

S1.1 Emissions

Supplementary Table S1 gives values and references for the pathways and processes depicted in Figure 1 and Supplementary Figure 1. Information on well-known pathways (2, 3, 8, 9, 14) can be found in *Ullmann's Encyclopedia of Industrial Chemistry*, Wiley-VCH (2022). Note: that while reduction of CO₂ to syngas or ethylene is not currently practiced at scale, the line is drawn with a heavier weight because the reverse reaction (water-gas shift of CO₂ and H₂ to CO and H₂O) is currently practiced at large scale, generally in the process of steam methane reforming.

Table S1. Assumed values related to synthetic food pathways as numbered in Supplementary Figure S1.

Pathway	Ref 1	Ref 2	Ref 3
1: Fossil feedstock to heterotroph	Jones et al., Recent advances in single cell protein as a feed ingredient in aquaculture, Current Opinion in Biotechnology (2020)	Petersen, L. A. H. <i>Single cell protein production in U-loop bioreactors: Fundamentals, Modeling & Control</i> . Technical University of Denmark (2019).	Tawfik, Nizar I., Abd Al-Galil M. Khalil, and Abou-Zeid A. Abou-Zeid. "Utilization of Petroleum Fractions for the Production of Single-Cell Protein." Zentralblatt Für Bakteriologie, Parasitenkunde, Infektionskrankheiten Und Hygiene. Zweite Naturwissenschaftliche Abteilung: Mikrobiologie Der Landwirtschaft, Der Technologie Und Des Umweltschutzes 136, no. 5 (1981)
4: Reduction of CO₂ to syngas	Ullman's	Poon et al., <i>A review on recent advances in the electrochemical reduction of CO₂ to CO</i> , RCS Advances, 2022	
5: Heterotrophs grown on electrosynthesized substrate	Sillman et al., <i>Bacterial protein for food and feed generated via renewable energy and direct air capture of CO₂: Can it reduce land and water use?</i> , Global Food Security (2019)	Martinez et al., <i>Potential of microbial electrosynthesis for contributing to food production using CO₂ during global agriculture-inhibiting</i>	Hann et al., <i>A hybrid inorganic-biological artificial photosynthesis system for energy-efficient food production</i> , Nature Food (2022)

		disasters, Cleaner Engineering and Technology (2021)	
6 & 7: Carbohydrates via bioenzymatic catalysis	Cai et al., <i>Cell-free chemoenzymatic starch synthesis from carbon dioxide</i> , Science (2021)		
10: polymerization of amino acids to proteins	Dondapati et al., <i>Cell-Free Protein Synthesis: A Promising Option for Future Drug Development</i> , Biodrugs (2020)		
11: oxidation of paraffins to fatty acids	Stranges, A. N. <i>A History of the Fischer-Tropsch Synthesis in Germany 1926–45. Studies in Surface Science and Catalysis</i>	Imhausen, A. <i>Die Fettsäure-Synthese und ihre Bedeutung für die Sicherung der deutschen Fettversorgung. Kolloid-Zeitschrift</i> (1943)	
12: heterotrophic protein production.	Petersen, L. A. H. <i>Single cell protein production in U-loop bioreactors: Fundamentals, Modeling & Control</i> . Technical University of Denmark (2019).		
13, 15 & 16: separation of proteins and fats from single-celled organisms	Rasoul-Amini et al., <i>Single Cell Protein: Production and Process</i> , American Journal of Food Technology, (2011)		

S1.2 Emissions

Supplementary Table S2 summarizes all values used to calculate the three cases used to generate Figure 2b. Note that oxidation emissions assume complete oxidation to CO₂ of all input carbonaceous feedstocks. In practice, the thermochemical processes described here often produce heavy carbonaceous residues and chars, rather than CO₂; however, for completeness, we have assumed that all carbonaceous material extracted for synthetic fat production is fully oxidized and attribute those emissions to the production of synthetic fats.

Our emissions estimates for both agricultural and synthetic fats in Figure 2 neglect emissions related to the manufacture of capital infrastructure such as Haber-Bosch ammonia plants and facilities for the synthesis and/or processing of produced edible oils. Such capital-related emissions are similarly excluded from most life cycle analyses of biofuels, for example, given the small share of emissions entailed per unit of oil produced over the long lifetime of such facilities¹⁻⁵.

Supplementary Table S2. Assumed values related to synthetic fat production.

	Coal	Natural gas	Air-captured CO ₂
Extraction emissions <i>kg CO_{2-eq}/kg feedstock</i>	0.12 ⁶	0.41 ⁶	0
Oxidation emissions <i>kg CO_{2-eq}/kg feedstock</i>	3.14	2.75	0
$\eta_{feedstock}$ kg product/ kg feedstock	0.34	0.59	0.22
Carbon utilization efficiency: feedstock to paraffin conversion	0.4	0.78*	0.8
Carbon utilization efficiency: paraffin to fatty acid conversion	0.76**	0.76**	0.76**
Feedstock emissions <i>g CO₂/kcal_{product}</i>	1.1	0.60	0
Production energy <i>MJ/kg_{product}</i>	17 ⁷	17 ⁷	142 ^{7,8}
CO ₂ air capture <i>MJ/ kg CO_{2,captured}</i>	0	0	9
hydrogen generation (3H ₂ , CO ₂) <i>MJ/ kg_{product}</i>	0***	0	83
Plant electricity [Table 6.9 in ref. ⁷]	1.8		
Steam generation****	6.4		
Process heat energy [Table 6.9 in ref. ⁷]	9.0		

* assumes pressurized natural gas as input (natural gas extraction emissions include compression to 800 psig⁹)

** A 1968 review of synthetic fatty acid production reports values between 41.8–93.5 acids yield (wt % fatty acids)⁷, which includes C1–C20+ fatty acids and corresponds to 37–83% carbon utilization efficiency, assuming carbon content of the final product to be 75.9% by weight (approximated as the C16 fatty acid) and carbon content of the input feedstock to be 85.7% by weight (approximated as CH₂).

*** Makeup hydrogen needed for conversion of coal to paraffins is accounted for in the carbon utilization efficiency for coal to paraffin conversion

**** Using 2.9 kg steam/kg product from [Table 6.9 in ref. ⁷] and 2.2 MJ heat/kg steam¹⁰

The data in Supplementary Table S2 are then used to calculate three nominal cases of emissions intensity for synthetic fats production across different emissions intensities of process energy, as shown in Supplementary Table S3.

Supplementary Table S3. Assumed emissions related to energy inputs for synthetic fat production.

$g\ CO_{2-eq}$ $/kcal_{product}$	Emissions intensity of input energy: $CI_{energy}\ g\ CO_{2-eq}/MJ$										
	0	28	55	83	111	139	167	194	222	250	278
Coal	1.13	1.19	1.24	1.30	1.35	1.40	1.46	1.51	1.56	1.62	1.67
Natural gas	0.60	0.65	0.71	0.76	0.81	0.86	0.92	0.97	1.03	1.08	1.13
CO ₂	0.00	0.44	0.87	1.31	1.75	2.19	2.62	3.06	3.50	3.94	4.37

The values in Supplementary Table S4 were interpolated to generate the colormap and contours shown in Fig 2b. The parameters used to calculate the example cases shown in Fig 2b. are shown in Supplementary Table S4.

Supplementary Table S4. Assumed values for points in Figure 2b

Case	$CI_{energy}\ g\ CO_{2-eq}/MJ$	Feedstock emissions $g\ CO_{2-eq}$ $/kcal_{product}$	Product emissions $g\ CO_{2-eq}$ $/kcal_{product}$
Coal feedstock, coal power	278	1.13	1.67
Coal feedstock, current US energy	111	1.13	1.35
Natural gas feedstock, current US energy		0.60	0.81
Natural gas feedstock, non-fossil energy	0	0.60	0.60
CO ₂ feedstock, current US energy	111	0	1.75
CO ₂ feedstock, non-fossil energy	0	0	0

S1.3 Land use efficiency

Land-use for synthetic fat production is estimated according to equation Eq. S1:

$$\frac{kcal\ product}{ha \cdot year} = \left(\frac{MJ_{feedstock}}{ha_{extraction} \cdot year} \frac{kg_{feedstock}}{MJ_{feedstock}} \frac{kg_{product}}{kg_{feedstock}} + \frac{kg_{product}}{year \cdot ha_{processing}} \right) \frac{kcal_{product}}{kg_{product}}$$

The land-use intensity for synthetic fats produced with each: coal, natural gas, and CO₂ captured and reduced with solar energy are shown in Supplementary Table S5 (note that the feedstock efficiency for these processes, $\frac{kg_{product}}{kg_{feedstock}}$, is recorded in Supplementary Table S2).

Supplementary Table S5.

Feedstock	$\frac{GJ_{feedstock}}{ha \cdot year}$	$\frac{kg_{feedstock}}{MJ_{feedstock}}$	$\frac{kg_{product}}{year \cdot ha_{processing}}$	$\frac{million\ kcal_{product}}{ha \cdot year}$
Coal	90000*	0.034	$3 \cdot 10^6$ ***	7000
Natural gas	120000*	0.022	$3 \cdot 10^6$ ***	9270
CO ₂ + solar	120000*	0.037**	$3 \cdot 10^6$ ***	6540

* Values from ref.¹¹

** For CO₂ + solar, we use the energy to capture and reduce 1 kg of CO₂ to hydrocarbons as the input feedstock energy density: $MJ_{feedstock}$.

*** Ref.¹⁰ reports an average chemical plant is cited as being 4.2 ha for 50 kt output. We have used 4x this area to estimate the land required for physical plant. The factor of 4 was chosen to account for the multiple process areas shown in Fig 1: syngas production, paraffin synthesis, paraffin oxidation, and fatty acid esterification.

S1.4 Water use efficiency

Supplementary Table S6 gives values and references for global average water footprint for agricultural fats and oils from ref.¹², which range between 1000 – 5000 m³/ton. Water requirements for synthetic fat production are reported to be 6.2 m³/ton in ref.⁷. Synthetic fat production is thus expected to require approximately 100–800x less water than agricultural fat production.

Supplementary Table S6.

	Global Average Water Footprint (m³/ton)*			
	Green	Blue	Gray	Total
Oil crops	2023	220	121	2364
Soybean oil, refined	3980	137	73	4190
Oil palm	1057	0	40	1098
Palm oil, refined	4787	1	182	4971

* Values from ref.¹²

Supplementary Table S7.

Product Region or Country	Land-use emissions (2017)¹³, <i>gCO₂-eq/kcal</i>	Land required (2017)¹³, <i>m²/10³ kcal</i>	Energy-related emissions*, <i>gCO₂-eq/kcal</i>
Food from agriculture “Industrialized” “Developing”			0.04 ¹⁴ 0.10 ¹⁴
Oilcrops <i>East Asia</i> <i>Europe</i> <i>Latin America</i> <i>North America</i> <i>Southeast Asia</i> <i>South Asia</i> <i>sub-Saharan Africa</i> <i>Rest of World</i>	0.59 0.57 1.37 0.37 0.43 0.44 2.28 0.41	0.96 1.35 0.84 0.93 0.18 2.07 1.84 1.55	0.83 ^{15†}
Soybeans <i>Argentina</i> <i>Brazil</i> <i>China</i> <i>India</i> <i>Paraguay</i> <i>Ukraine (Europe)</i> <i>United States</i>	1.07 1.57 1.04 0.51 1.75 0.94 0.32	0.94 0.88 1.67 2.88 0.96 1.52 0.91	0.20 ¹⁶ 0.18 ¹⁷ 0.15 ¹⁸ 0.17 ¹⁹
Oil Palm <i>Indonesia</i> <i>Malaysia</i> <i>Thailand</i> <i>Colombia</i> <i>Brazil</i>	0.36 0.14 0.22 0.22 0.24	0.11 0.10 0.10 0.13 0.10	1.16 ²⁰ 0.07 ²¹ 0.65 ²² 1.16 ²²

* Where literature reports only energy/kcal, we assume an emissions intensity of energy equivalent to petroleum (218 gCO₂/MJ)

† Energy intensity of oil palm production in Cameroon.

Supplementary Table S8.

Feedstock	Extraction and delivery emissions <i>kg CO₂-eq/kg_{feedstock}</i>	Oxidation emissions <i>kg CO₂-eq/kg_{feedstock}</i>	$\eta_{feedstock}$ kg product/ kg feedstock	Production energy <i>MJ/kg_{product}</i>
Coal	0.12 ⁶	3.14	0.34	17 ⁷
Natural gas	0.41 ⁶	2.75	0.59	17 ⁷
CO ₂	0	0	0.22	142 ^{7,8}

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