Environmental Impacts of Cultured Meat Production

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Ⓢ *Supporting Information*

ABSTRACT: Cultured meat (i.e., meat produced in vitro using tissue engineering techniques) is being developed as a potentially healthier and more efficient alternative to conventional meat. Life cycle assessment (LCA) research method was used for assessing environmental impacts of large-scale cultured meat production. Cyanobacteria hydrolysate was assumed to be used as the nutrient and energy source for muscle cell growth. The results showed that production of 1000 kg cultured meat requires 26−33 GJ energy, 367−521 m^3 water, 190−230 m^2 land, and emits 1900−2240 kg CO_2-eq GHG emissions. In comparison to conventionally produced European meat, cultured meat involves approximately 7−45% lower energy use (only poultry has lower energy use), 78−96% lower GHG emissions, 99% lower land use, and 82−96% lower water use depending on the product compared. Despite high uncertainty, it is concluded that the overall environmental impacts of cultured meat production are substantially lower than those of conventionally produced meat.
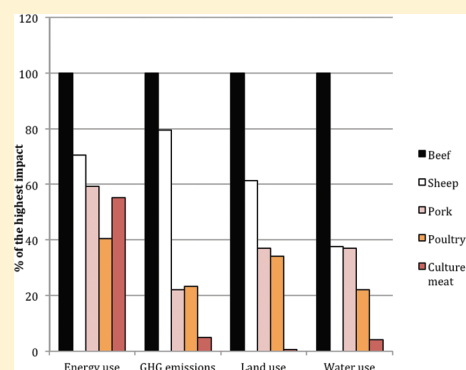
1. INTRODUCTION

Meat production is one of the major contributors to global environmental degradation. Currently, livestock raised for meat use 30% of global ice-free terrestrial land and 8% of global freshwater, while producing 18% of global greenhouse gas (GHG) emissions, which is more than the global transportation sector.[1] Livestock production is also one of the main drivers of deforestation and degradation of wildlife habitats, and it contributes to the eutrophication of water ways. Globally, 34% of the GHG emissions related to livestock production are due to deforestation, 25% are methane emissions from enteric fermentation of ruminants, and 31% of the emissions are related to manure management.[1] It has been found that generally beef has the highest environmental impacts, whereas poultry has the lowest impacts when different species are compared.[2] Because of increasing population size and per capita meat consumption in the developing world, global meat consumption is expected to double between 1999 and 2050.[1] Such an increase will also double meat's impacts on the environment unless more efficient meat production methods are adopted.

One proposed method for reducing the negative environmental impacts of meat production is to grow only animal muscle tissue in vitro, instead of growing whole animals.[3] This technology is called cultured meat (or in vitro meat) production, and it is currently in a research stage. The development of technologies for producing cultured meat for human consumption started in early 1950s.[4] Currently, small quantities of cultured meat are produced in laboratories, but large-scale production requires more research.

It is estimated that about $160 million investments in research are needed for commercializing the production.[5]

In addition to environmental impacts, cultured meat also has other potential benefits compared to conventionally produced meat. Cultured meat can prevent the spread of animal-borne diseases and epidemic zoonoses as a consequence of reduced human−animal contact.[6] Controlled conditions also enable the manipulation of nutritional, textural, and taste profiles. The quantity and quality of fat can be controlled, and, therefore, the nutrition-related diseases, such as cardiovascular diseases, can be reduced. The aim of this article is to estimate the potential environmental impacts of large-scale cultured meat production and compare them with conventionally produced meat products.

2. MATERIALS AND METHODS

2.1. Goal of the Study. The goal of this study is to estimate the energy use, greenhouse gas (GHG) emissions, land use, and water use for industrial scale production of cultured meat. Life Cycle Assessment (LCA) methodology based on ISO14000 guidelines is used.[7] Three different production locations are compared: Spain, California, and Thailand. These regions were

selected because of their different climatic conditions and availability of data related to cyanobacteria production in those regions.

2.2. Scope Definition. The functional unit (FU), toward which all the impacts are allocated, is 1000 kg of cultured meat with dry matter (DM) content of 30% and protein content of 19% of mass. The protein content is equal to conventional low fat meat. The species where the cells are taken do not impact on the outcome of this study as the species have only an impact on the type of growth factors used and that does not change the environmental impact. The cultured meat process described in this article produce minced-beef type of product as the production technologies for steak type of products are under development. Therefore, the textural characteristics of cultured meat are not equal to all conventionally produced meat products.

The system boundaries cover the major processes from input production up to the factory gate (Figure 1), including production of input materials and fuels, production of the feedstock, and growth of muscle cells. Land use category includes the land requirement for cyanobacteria cultivation. The indirect land use associated with land use change and the production of energy inputs are not included in the study because the reference studies of conventional meat production do not include those aspects. The decommissioning of the cultured meat plant has not been included in the analysis as most of materials would be possible to recycle for other purposes.

Cyanobacteria hydrolysate is used as the source of nutrients and energy for muscle cell production. Cyanobacteria are assumed to be cultivated in an open pond made of concrete. The protein content of cyanobacteria species varies generally between 50 and 70% of DM,[8] and in this study a protein content of 64% of DM was assumed. After harvesting, the cyanobacteria biomass is sterilized and hydrolyzed to break down the cells. The stem cells are taken from an animal embryo. Embryonic stem cells have almost infinite self-renewal capacity and theoretically one cell line would be sufficient to feed the world.[4] However, slow accumulation of genetic mutations over time limits the maximum proliferation period. As an embryonic stem cell can produce more than 1000 kg cultured meat, the impacts related to the production of the stem cells are not included in this study. Engineered *Escherichia coli* bacteria are used for the production of specific growth factors that induce the stem cells to differentiate into muscle cells. Those growth factors are proteins or hormones specific for the species used. The muscle cells are grown in a bioreactor on a medium composed of the cyanobacterial hydrolysate supplemented with the growth factors and vitamins.

The cyanobacteria biomass flows presented in the Figure 1 are based on experience from laboratory scale production at the University of Amsterdam. It is assumed that the hydrolysis yield is 50% of the original cyanobacteria biomass, 20% of the remaining cyanobacteria biomass is used as a raw material for anaerobic digestion, and 80% is utilized for other purposes (e.g., for processing of nutritional supplements). The cultured meat yield during muscle cell fermentation is assumed to be 50% of the cyanobacteria hydrolysate used, and 50% is lost as CO_2 and other losses. This is considered to be inevitable because the cyanobacteria hydrolysate serves as the energy source for the muscle cells, hence part of the hydrolysate is oxidized to CO_2 by respiration or fermented to end products like lactate. The production of growth factors and vitamins are not included in the study as the quantities needed are small (under 0.1% of the DM weight of the media), and therefore the environmental impacts are negligible.
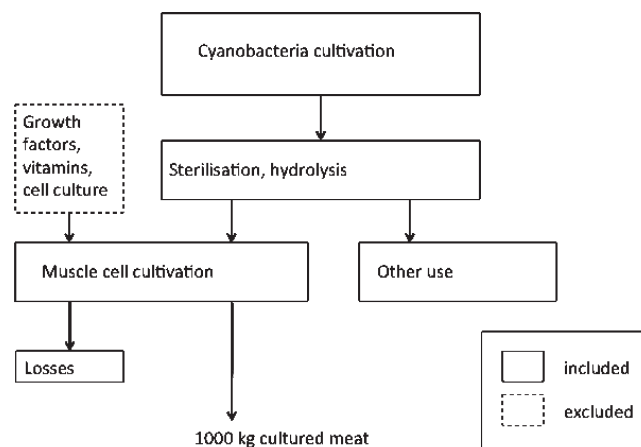

Figure 1. System diagram of cultured meat production and the cyanobacteria biomass flows.

Table 1. Temperature Range, Cyanobacteria Production Season, Rainfall, Evaporation and Cyanobacteria Yield in the Production Sites in Thailand, California, and Spain

site	temperature	season	rainfall	evaporation	yield
	°C	months	mm yr^{-1}	mm yr^{-1}	t ha^{-1} yr^{-1}
Thailand	25–29[a]	12[a]	1400[a]	1660[c]	38[f]
California	0–40[a]	7[a]	10[a]	1300[d]	32[f]
Spain	10–35[b]	10[b]	400[b]	1800[e]	31[b]

[a] Shimamatsu.[12] [b] Jimenez et al.[13] [c] Watanabe et al.[14] [d] Hidalgo et al.[15] [e] Alvarez et al.[16] [f] Belay.[17]

2.3. Methodology and Data. *2.3.1. Allocations.* All of the energy inputs for sterilization, hydrolysis, and fermentation are allocated to cultured meat. At hydrolysis of cyanobacteria, only about 50% of the biomass is suitable to raw material for muscle cell cultivation. The other 50% is used for other purposes. Here, it is assumed that 80% of that biomass is used for food supplements and 20% for raw material in anaerobic digester. Therefore, only the production of the biomass for anaerobic digester is allocated for cultured meat, as it would otherwise be wasted. The energy produced in the anaerobic digester is not allocated for cultured meat. The energy needed for cultivation of the cyanobacteria that is used for food supplements is not allocated to cultured meat. In the sensitivity analysis, other allocation options are compared.

2.3.2. Energy Inputs. The data sources for primary energy conversion factors and GHG emission factors for production of electricity and electricity mix profiles are presented in Tables S1 and S2 of the Supporting Information. Primary energy includes both renewable and nonrenewable energy sources. The carbon emissions from biogenic origin are regarded as zero because biomass fixed during the biomass growth is released back to the air when it is burned. The same applies to carbon fixed by cyanobacteria, as the carbon is emitted back to the air when the cultured meat is consumed. The GHG emissions are assessed as global warming potential (GWP) by using the 100 years time scale. The electricity and fuels used are converted to primary energy by using conversion factors that describe the amount of primary fuels (coal, natural gas, oil, and uranium) required for extraction and supply of fuels. In this study, it is assumed that diesel is used in the cultivation of cyanobacteria operations and

Table 2. Inventory Data[a]

cultivation of cyanobacteria		source
energy for cultivation $(MJ/m^2/d)$	0.0439	1
energy for harvesting $(MJ/m^2/d)$	0.0015	1
energy for construction and maintenance $(MJ/m^2/yr)$	4.02	1
Urea		
input (kg/kg cyanobacteria DM)	0.11	1
primary energy input in production (MJ/kg)	22.94	2
GHG emissions from production (kg CO_2-eq/kg)	1.35	2
Diammonium Phosphate		
input (per kg cyanobacteria DM)	0.11	1
primary energy input in production (MJ/kg)	11.68	2
GHG emissions from production (kg CO_2-eq/kg)	1.25	2
Total amount of cyanobacteria biomass allocated to		
cultured meat (kg/FU)	720	3
Sterilization		
Method: autoclaving		
volume 1500 L, power 140 kW, temperature		3
220 °C, time 20 min		
Muscle cell cultivation		3
Method: cylinder stirred-tank bioreactor		
volume 1000 L, height 1.72 m, diameter 0.86 m,		
weight 93 kg, 80% maximum filling capacity,		
cell density 1×10^{10} cells dm^{-3}, time per run		
60 days, temperature 37 °C, rotation 100 rpm,		
aeration 0.05 vvm		

[a] 1, Calculated based on data from Chisti.[10] 2, Calculated based on data from Williams et al.[18] 3, Own calculations based on experimental data.

transportation of the biomass, and electricity for sterilization and muscle cell cultivation. In the Spain model, the average European electricity generation portfolio was used, and in the California model the average U.S. electricity generation portfolio was used.

2.3.3. Cultivation of Cyanobacteria. The climatic conditions and cyanobacteria yields at the three production sites are presented in Table 1. It is assumed that cyanobacteria hydrosylate is used as an energy and nutrient source for the growth and proliferation of the muscle cells. Nitrogen-fixing cyanobacteria species, such as *Anabaena sp.* or *Nostoc sp.*,[9] can be used, but the most common commercially produced cyanobacteria species, *Arthrospira platensis* and *Arthrospira maxima* (*Spirulina*), do not fix atmospheric nitrogen gas. In the base scenario, synthetic nitrogen fertilizers are used, but the impacts of using nitrogen-fixing species are assessed in the sensitivity analysis. Synthetic fertilizers can also be replaced by using nutrient-rich wastewater or organic fertilizers.

Cyanobacteria biomass is assumed to be cultivated in an open pond (0.30 m deep) and harvested by using sedimentation and continuous vacuum belt filters. The energy requirements used for cultivation of cyanobacteria, harvesting, fertilizer production, and construction and maintenance of the facility are based on the data from Chisti[10] (Table 2). It is assumed that after harvesting the cyanobacteria biomass is transported without drying for 50 km, assuming energy need of 2.6 MJ t^{-1} km^{-1}.[11]

2.3.4. Cultured Meat Production. As large-scale cultured meat production does not currently exist, in this study the calculations are based on a hypothetical large-scale production system. The cyanobacteria biomass was assumed to be sterilized using autoclaving, and a cylinder stirred-tank bioreactor was assumed to be used for cultivation of the muscle cells. The details of the sterilization and autoclaving processes are presented in Table 2. The volume of the culture is assumed to be 30 m^3, by assuming maximum muscle cell density of 1×10^{10} cells dm^{-3} and weight of a cell 1×10^{-12} kg. Therefore, each reactor with a volume of 1 m^3 produces 10 kg DM of cultured meat during 60 days in 37 °C. As cells produce heat during the growth, additional energy inputs in heating of the reactor are not required.

The power input for agitation per cubic meter (P_a) was estimated to be 25 W m^{-3} by using the following formula: [19]

$$P_a = P_0 \rho N^3 D^5$$

where P_0 is the impeller power number, 2.14; ρ is the medium density, 1.03×10^3 kg m^{-3}; N is the impeller speed in revolutions s^{-1} (rps), 1.67 rps; and D is the impeller diameter, 0.30 (assumed to be 35% of the reactor diameter). The power requirement for aeration was estimated to be 16 W m^{-3} based on the data from Harding et al.[20]

It is assumed that the bioreactor is made from stainless steel. Production of 1 kg stainless steel requires 30.6 MJ primary energy and emits 3.38 kg CO_2-eq kg^{-1}.[21] As cells produce heat during the growth, additional energy inputs in heating the reactor are not required. The bioreactor is assumed to be used for 20 years.

2.3.5. Methodology and Data for Accounting of Water Use. The methodology for assessment of the water use was adopted from Mila i Canals et al.[22] Both direct and indirect water use is included. Direct water use refers to the direct water inputs used in the process, whereas indirect use refers to the water needed for production of energy sources used in the process. The water footprint included the use of blue (surface and groundwater) and green water (rainwater), but the gray water (water needed to assimilate pollution) was excluded to be consistent with the reference study that estimated the water footprint of conventionally produced meat.[23]

The data sources for the water inputs for production of electricity and electricity mix profiles are presented in Tables S1 and S2 of the Supporting Information. The direct water inputs are calculated as (the letter symbols refer to Figure 2):

Direct water input = Water Input1(WI1) + Water Input2(WI2) + Water Input3(WI3)

Where

$$WI1 = A - B + D$$

$$WI2 = E + F + H$$

$$WI3 = I + J$$

The water input for production of cyanobacteria consists of the water input that is needed for replacing the water lost as net evaporation (evaporation − rainfall) and with the cyanobacteria biomass. The water loss is calculated separately for each production region. It is assumed that the initial water input for the cyanobacteria system is seawater. This does not count toward the
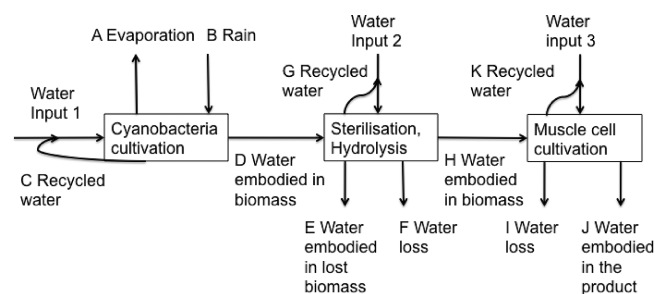
Figure 2. Water flows in the production chain of cultured meat.

water footprint as seawater resources are abundant.[24] To avoid excess salinity, fresh water is needed for replacing the evaporation loss. Therefore, the annual fresh water input for cyanobacteria production equals the amount of water lost as net evaporation (evaporation − rainfall) and the amount of water incorporated into the removed cyanobacteria biomass. The water embodied in the harvested biomass is calculated by assuming 30% DM content for the biomass.

During sterilization, 40% of the water embodied in the biomass is assumed to be lost. Water needed for muscle cell cultivation is 30 m^3, and the DM content of the end product (cultured meat) is 30%. It is assumed that 80% of the water used at the cell culturing process is recycled without any treatment.

2.4. Calculation Method, Uncertainty Analysis, and Sensitivity Analysis. The *Microsoft Excel 2011* spreadsheet program was used for the calculations. Monte Carlo analysis was used for the uncertainty analysis. The model was simulated using 50 000 replications with randomly generated input values. A uniform distribution was used for the random number generation within the estimated uncertainty ranges of the input values presented in Table S3 of the Supporting Information. As sufficient data about the uncertainty ranges were not available, the uncertainty ranges were based on authors' estimates and the ranges were rather over- than underestimated. Sensitivity analysis was used for examining the contribution of specific input values to the results. The sensitivity analysis was carried out by changing the base values in the primary data by the uncertainty range of some input factors and comparing the change to the base scenarios. In the sensitivity analysis higher uncertainty ranges were used than in the Monte Carlo analysis. The values were only changed to one direction as a change to the opposite direction would only change the sign. The explanation for the options chosen in the sensitivity analysis are presented in Table 3.

3. RESULTS

Total energy use, GHG emissions, and indirect water use of producing 1000 kg cultured meat are presented in Figure 3. The production of cyanobacteria accounts for approximately 23% of total energy use, 28% of GHG emissions, and 17% of indirect water use. The cultivation process of muscle cells has the greatest contribution to the results, accounting for 72% of total energy use, 71% of total GHG emissions, and 82% of indirect water use. The highest water input was needed for replacement of evaporation loss in cyanobacteria cultivation (blue water). Transportation of the cyanobacteria biomass to the cultured meat production facility was a minor contributor to the results. Thailand had the lowest primary energy use due to the low primary energy requirement for electricity production. California had the highest GHG emissions

Table 3. Parameters Included in the Sensitivity Analysis

parameter	explanation
cyanobacteria yield + 40%	Annual cyanobacteria yield was increased by 40%. The fertilizer inputs remained unchanged.
no fertilizers	Nitrogen fertilizers were not used in the cyanobacteria cultivation due to use of nitrogen fixing cyanobacteria species. This was not assumed to have an impact on the cyanobacteria yield.
transportation 100 km	Transportation distance of cyanobacteria was increased by 100 km.
sterilization + 50%	Energy input in sterilization increased by 50%.
steel production + 50%	Energy input in steel production increased by 50%.
aeration + 50%	Aeration energy input in muscle cell fermenter increased by 50%.
rotation + 50%	Rotation energy input in muscle cell fermenter increased by 50%.
100% allocation	100% of initial cyanobacteria production allocated to cultured meat.
50% allocation	50% of initial cyanobacteria production allocated to cultured meat and 50% to other side products.
fresh water used	Fresh water used for cyanobacteria production and the water is changed every year.

due to the high proportion of coal in the electricity mix. Water use was highest in Spain due to high rainfall and high proportion of hydropower in the European electricity mix.

The land requirements for producing feedstock for cultured meat production vary according to the location of the facility being 189, 225, and 232 m^2 FU^{-1} in Thailand, California, and Spain, respectively.

The results of the sensitivity analysis (Table 4) shows that the results of energy use and GHG emissions were most sensitive to the changes in energy requirements for muscle cell cultivation (aeration and rotation). Also, the change to 100% allocation had a substantial impact on the results. For the results of water use, the main parameters impacting the results were cyanobacteria yield, change to 100% allocation, and use of fresh water instead of seawater.

4. DISCUSSION

The results show that cultured meat production emits substantially less GHG emissions and requires only a fraction of land and water compared to conventionally produced meat in Europe (Figure 4). Energy requirements of cultured meat production are lower compared to beef, sheep, and pork, but higher compared to poultry. As a comparison with cultivated Atlantic salmon,[25] cultured meat has approximately 20% lower energy input and 40% lower GHG emissions.

In this study, the energy input calculations of cultured meat production are based on many assumptions and, therefore, have high uncertainty. Energy consumption for cultured meat production may be higher if additional processing is required for improving the texture of meat. However, the efficiency of both cultivation of cyanobacteria and muscle cell cultivation can be improved by technology development. For example, closed bioreactors for cyanobacteria and microalgae production could improve the efficiency of biomass production.[26]
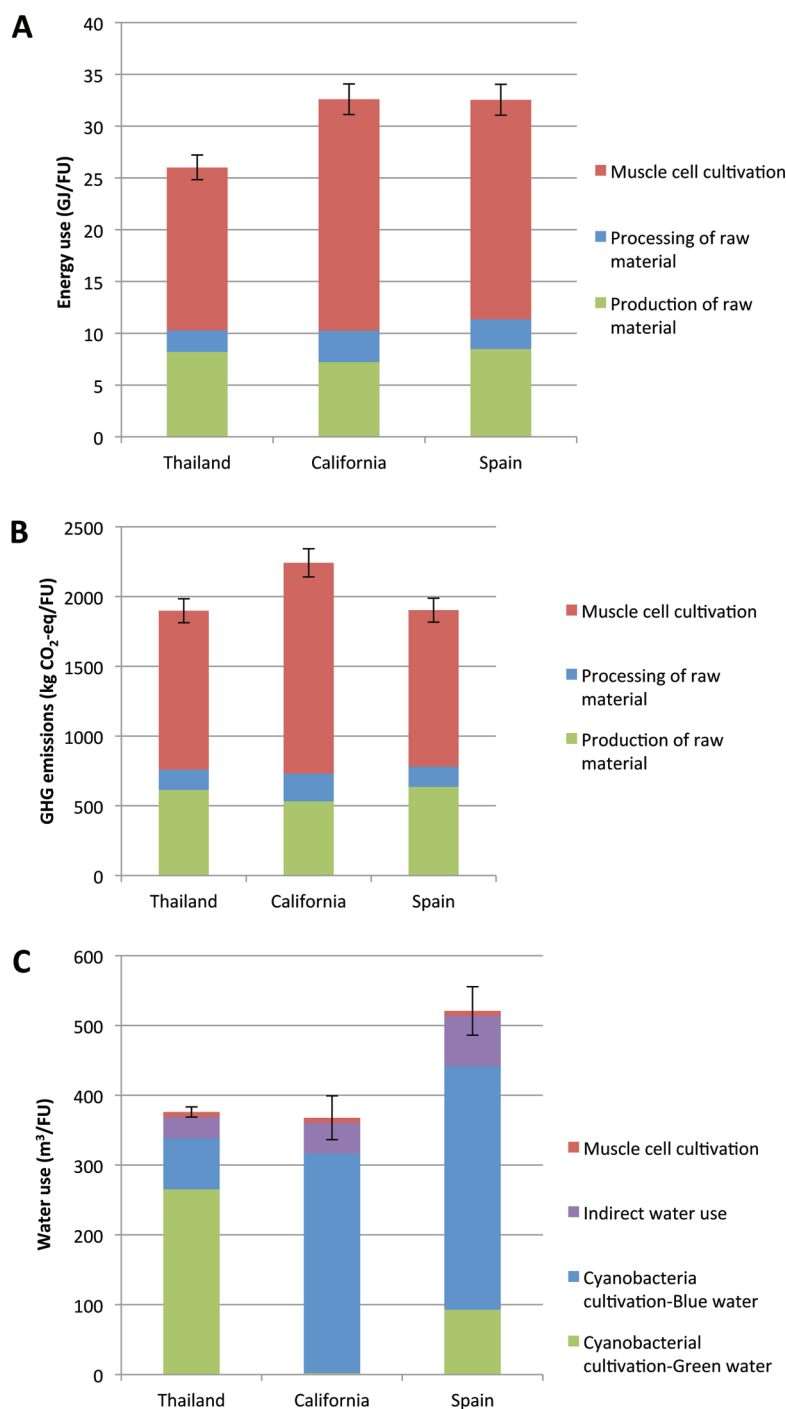
Figure 3. Primary energy use (A), greenhouse gas (GHG) emissions (B), and water use (C) of producing of functional unit (FU) of 1000 kg cultured meat in Thailand, California, and Spain. The error bars show the 25 and 75%iles based on the Monte Carlo analysis.

As shown in Figure 4, the energy input for cultured meat production is substantially lower compared to conventionally produced beef, sheep, and pork but requires more energy compared to conventionally produced poultry. However, energy input alone does not necessarily provide a sufficient indicator about the energy performance if the opportunity costs of land use are not taken into account.[27] Cultured meat production requires only a fraction of the land area that is used for producing the same mass of conventionally produced poultry meat. Therefore, more land could be used for bioenergy

production, and it can be argued that the overall energy efficiency of cultured meat would be more favorable.

As the majority of GHG emissions during the production of cultured meat are associated with the use of fuel and electricity, the emissions could be reduced by using renewable energy sources. In conventional meat production, the potential for reducing GHG emissions is more limited because most of the emissions are due to methane from manure and ruminants' enteric fermentation and nitrous oxide from soil. For example, about 57% of the GHG emissions of conventionally produced beef are methane emissions

Table 4. Results of the Sensitivity Analysis for Primary Energy Use, Greenhouse Gas Emissions, and Water Use

	Thailand		California		Spain	
energy use (GJ/FU)		%		%		%
base model	25.2		31.8		31.7	
yield + 40%	23.9	−5.2	30.7	−3.3	30.3	−4.4
no fertilizers	22.8	−9.5	29.4	−7.6	29.3	−7.6
transportation 100 km	25.5	1.5	32.1	1.2	32.1	1.2
sterilization + 50%	26.2	4.2	33.3	4.8	33.1	4.5
steel production + 50%	25.7	1.9	32.2	1.5	32.2	1.5
aeration + 50%	28.0	11.4	35.9	13.1	35.6	12.4
rotation + 50%	29.7	17.8	38.3	20.5	37.9	19.4
100% allocation	31.2	24.1	37.2	17.0	38.0	19.7
50% allocation	24.7	−1.9	31.4	−1.0	31.2	−1.6
Greenhouse gas emissions (kg CO_2-eq/FU)						
base model	1891		2235		1896	
yield + 40%	1782	−5.8	2149	−3.8	1780	−6.1
no fertilizers	1692	−10.5	2036	−8.9	1696	−10.5
transportation 100 km	1917	1.4	2261	1.2	1922	1.4
sterilization + 50%	1964	3.9	2335	4.4	1967	3.8
steel production + 50%	1945	2.9	2289	2.4	1950	2.8
aeration + 50%	2092	10.6	2509	12.2	2093	10.4
rotation + 50%	2205	16.6	2663	19.1	2205	16.3
100% allocation	2290	21.1	2579	15.4	2310	21.8
50% allocation	1800	−4.8	2157	−3.5	1801	−5.0
Water Use (m^3/FU)						
base model	376		368		521	
yield + 40%	360	−4.1	282	−23.4	334	−35.9
no fertilizers	373	−0.7	363	−1.2	426	−18.3
transportation 100 km	376	0.1	366	−0.4	428	−17.7
sterilization + 50%	377	0.4	368	0.1	432	−17.1
steel production + 50%	376	0.2	366	−0.3	429	−17.6
aeration + 50%	380	1.0	372	1.1	439	−15.8
rotation + 50%	382	1.5	375	2.1	444	−14.7
100% allocation	415	10.4	565	53.7	651	25.1
50% allocation	367	−2.3	317	−13.8	373	−28.3
fresh water used	433	15.1	435	18.4	590	13.4

Figure 4. Comparison of primary energy input, greenhouse gas (GHG) emissions, land use, and water use of cultured meat production with conventionally produced European beef, sheep, pork and poultry per 1000 kg edible meat as a percent of the impacts of the product with the highest impact in each impact category (Supporting Information for details of the data used).

meat production may have some negative impacts on rural biodiversity due to the reduction in need for grasslands and pastures. The overall value of the biodiversity impacts would depend on the indicators used. The conversion of grasslands into forest might benefit some species, whereas some others may suffer. Cultured meat production also has substantially lower nutrient losses to waterways compared to conventionally produced meat because wastewaters from cyanobacteria production can be more efficiently controlled compared to run-offs from agricultural fields.

The focus of the study was on the production chain, from input production up to the factory or farm gate and, therefore, it does not provide the full comparison of the impacts during the whole life cycle of the products. However, it can be estimated that the relative impacts of cultured meat maybe even lower if the whole product life cycles were compared. The transportation requirements for cultured meat are likely to be lower because whole animals are not transported and the production sites may locate closer to the consumers. Also, refrigeration needs may be reduced as cultured meat has lower mass because the excess bones, fat, and blood are not present. Further research is needed for estimating the total environmental impacts of cultured meat production during the whole life cycle from production to the consumer.

Alongside the research and development of large-scale production of cultured meat, efforts for improving the public acceptance of cultured meat are required. If the structure and taste can be developed to resemble conventionally produced meat, the main obstacle may be an intuitive aversion to unnatural foods. However, cultured meat consists of similar muscle tissue to conventionally produced meat, but only the production technique differs. It can also be argued that many current meat production systems are far from natural systems.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information. Primary energy and global warming potential conversion factors; water inputs in production

and 20% are nitrous oxide emissions when 100 years global warming potential is used.[18] The total GHG emissions of conventional meat production are actually higher than presented in Figure 4 because the referred studies do not take into account the emissions associated with the conversion of forests and other natural vegetation to agricultural land. The replacement of conventionally produced meat by cultured meat could potentially contribute toward mitigating GHG emissions because, instead of clearing more land for agriculture, large land areas could be reforested or used for other carbon sequestration purposes.

Cultured meat production could also have potential benefits for wildlife conservation for two main reasons: i) it reduces pressure for converting natural habitats to agricultural land, and ii) it provides an alternative way of producing meat from endangered and rare species that are currently overhunted or -fished for food. However, large-scale replacement of conventional meat production by cultured
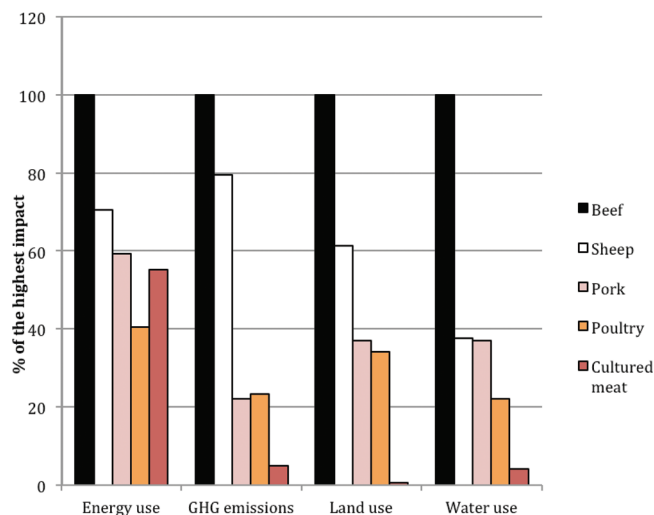
of energy sources; electricity generation profiles in EU, U.S., and Thailand; parameters included in Monte Carlo analysis; and data used for calculating the impacts of conventional meat production. This material is available free of charge via the Internet at http://pubs.acs.org.

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