Could cultured meat reduce environmental impact of agriculture in Europe?

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ABSTRACT

This paper assesses the potential of cultured meat to reduce environmental impacts of livestock production in Europe. Cultured meat (i.e. in vitro meat or lab-grown meat) is produced by cultivating livestock muscle cells in a growth media. The environmental impacts of hypothetical large-scale production of cultured meat were compared to the impacts of livestock production in the EU-27. The results showed that if all meat produced in the EU-27 was replaced by cultured meat, the GHG emissions, land use and water use would be reduced by two orders of magnitude compared to current meat production practices. When the opportunity costs of land use were included, the environmental benefits were even higher. More research and development is required before the product can be commercialised. Further effort is needed to gain public acceptance for this technology.

Keywords: in vitro meat, greenhouse gas emissions, land use, life cycle assessment, water footprint

1. Introduction

Livestock production is one of the major contributors to global environmental degradation. The contribution of livestock production to greenhouse gas (GHG) emissions in the European Union (EU) has been estimated to account for 9.1% of total EU emissions or 12.8% when land use and land use change emissions are taken into account (Weiss and Leip, 2012). Furthermore, livestock production accounts for a large share of land and water use and is the main contributor to the eutrophication of water ways and loss of biodiversity. The main strategies to reduce the negative environmental impact of livestock production include changes in feedstock, improvements of manure management and breeding animals with higher feed-to-food conversion ratios. To achieve more substantial improvements, new approaches to meat production will be required, unless vast majority of people adopt purely vegetarian diets. However, the current trends show that the global meat consumption will increase rather than decrease by 2050 (FAO, 2006).

A novel alternative to conventionally produced meat is to cultivate animal muscle cells *in vitro* without growing the whole animals. Currently, production of *in vitro* meat, also known as cultured meat, is in the research stage, but it has been estimated that the commercial production could start within a decade. It has been shown that the potential environmental impacts of cultured meat are substantially lower than those of meat produced in Europe (Tuomisto and Teixeira de Mattos, 2011). When cyanobacteria hydrolysate is used as the main nutrient and energy source for muscle cell growth, life-cycle-assessment-based GHG emissions, land use, and water use are 78-96%, 99%, and 82-96% lower, respectively, per tonne of meat compared to those of conventionally produced European meat. Energy use for cultured meat production was 38% higher than that of poultry, but lower than those of beef, sheep or pork.

This paper extends previous research by demonstrating the total potential GHG emission reductions and changes in land, water and energy use requirements in the EU-27 when conventional meat production is replaced by cultured meat. The environmental benefits resulting from alternative use of land released from agriculture are also considered. Furthermore, the impacts of cultured meat are compared with plant-based and livestock-based protein sources. Finally, the uncertainties related to the potential of cultured-meat-mediated reductions in environmental impacts of meat production in the EU are discussed.

2. Methods

2.1 Cultured meat production

The data for the environmental impacts of cultured meat production came from Tuomisto and Teixeira de Mattos (2011) (Table 1). The cultured meat production process used in the study is briefly described here. This process produces minced-beef type of product as the production technologies for steak type of products are still under development. 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. After harvesting, the cyanobacteria biomass is sterilised and hydrolysed to break down the cells. The stem cells are taken from an animal embryo. Embryonic stem cells have almost infinite self-renewal capacity and theoreti-

cally a small number of these cells would be sufficient to feed the world. However, the differentiated product of these stem cells, such as muscle cells, has a limited proliferation period. Embryonic stem cells can produce more than 1000 kg of cultured meat, and therefore, 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. The muscle cells are grown in a bioreactor on a medium composed of the cyanobacteria hydrolysate supplemented with growth factors and vitamins. The system boundaries cover the major processes from input production up to the factory gate, including production of input materials and fuels, production of the feedstock, and growth of muscle cells. 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. The impacts of the waste management are not allocated to cultured meat as it is assumed that the waste will be used for other commercial processes.

Table 1. Environmental impacts of cultured meat production per 1000 kg of cultured meat (Tuomisto and Teixeira de Mattos, 2011) (in italics the breakdown of the impacts of the main category)

Production stage	Primary energy GJ	GHG kg CO_2-eq	Indirect water use m^3	Direct water use m^3	Land use m^2
CYANOB. CULTIVATION	8.1	611.0	8.6	441.9	232.0
Fertiliser production	*3.2*	*205.9*	*3.4*		
Cultivation of cyanobacteria	*3.7*	*303.2*	*3.9*	*441.9*	*232.0*
Harvesting of cyanobacteria	*0.1*	*10.4*	*0.1*		
Construction and maintenance of the cyanobacteria production plant	*1.1*	*91.4*	*1.2*		
BIOMASS TRANSPORTATION	0.4	25.9	0.4		
STERILISATION	2.9	143.8	7.6	7.2	
MUSCLE CELL CULTIVATION	21.2	1121.8	56.1		
Steel production	*1.0*	*107.9*	*2.6*		
Aeration	*7.9*	*395.6*	*20.9*		
Rotation	*12.3*	*618.2*	*32.6*		
GRAND TOTAL	**32.5**	**1902.4**	**72.6**	**449.1**	**232.0**

2.2 Environmental impacts of livestock production in the European Union

Data about meat production quantities and GHG emissions in the EU-27 were based on Weiss and Leip (2012) (Table 2). GHG emissions were considered both with and without land use and land use change (LULUC) emissions. Weiss and Leip (2012) included three scenarios for estimating the LULUC emissions, and in this study the Scenario II was used, which represents the most likely mix of land use change probabilities. As the production quantities are reported in tonnes of carcass deadweight, the amount of cultured meat needed to replace the conventionally produced meat was calculated by using conversion factors that convert the carcass deadweight to edible meat (Table 3).

The water footprint data of conventionally produced meat was based on datasets of the Water Footprint Network. The total water footprint of meat production in the EU-27 was calculated based on the data about water footprint of each meat type (m^3/t) produced in each EU-27 country (Mekonnen and Hoekstra, 2012) and that was multiplied by the meat production quantities in each country reported by Weiss and Leip (2012).

Table 2. Production quantities and greenhouse gas (GHG) emissions (with and without land use and land use change (LULUC)) of conventionally produced meat in the EU-27 (Weiss and Leip 2012)

Impact	**Beef**	**Sheep**	**Pork**	**Poultry**	**Total**
Production (1000 t)	8146	1014	22384	11091	42635
GHG emissions (1000 t CO_2-eq)					
Without LULUC	156814	19920	97431	27405	301570
With LULUC	191000	24425	164780	54360	

Table 3. Conversion factors used for estimating edible meat production quantities.

	% of carcass dead weight			
	Beef[a]	**Sheep**[a]	**Pork**[a]	**Poultry**[b]
Edible meat	38.56	45.55	44.55	51.47

[a] (Garnett, 2007)
[b] (Igri and Ausaji, 2006)

2.3 Opportunity costs of land use

Opportunity costs of land use were estimated by assuming that the land area released from meat production was used for bioenergy production or forestry. It was assumed that grassland was used for forest and arable land for bioenergy crops. As the aim was not to estimate the bioenergy production potential in the EU, but only to demonstrate opportunity costs of land use, generic data for the entire EU was used. Energy production and GHG-emission savings by forest and bioenergy crops were from Tuomisto et al. (2012a), who estimated the yearly net energy production of woodland as 92.6 GJ/ha and its GHG mitigation as 10.2 t CO_2-eq/ha, and the yearly net energy production of a bioenergy crop, *Miscanthus*, as 159.2 GJ/ha and its net GHG mitigation as 15.4 t CO_2-eq/ha.

The calculations of the energy yield and GHG emission mitigation from woodland were based on the following assumptions. It was assumed that 15 m^3/ha/yr wood was harvested and 0.57 t wood chips (75% DM), 2.3 t composite board (90% DM) and 0.39 t sawn timber was produced from the harvested wood. For the wood chips, a heating value of 17.8 MJ/kg was used and the boiler was assumed to operate at 90% efficiency. Life cycle energy use (345 ± 36 MJ/t) and GHG emissions (21 ± 2 kg CO_2-eq/t) were associated with the harvesting of wood (75% DM). It was assumed that the wood chips replaced oil used for heating, and the composite board and timber replaced steel. Production of 1 kg stainless steel requires 30.6 MJ primary energy and emits 3.38 kg CO_2-eq. It was assumed that soil carbon stocks increase during the first 100 years after planting by an average of 0.1 t C/ha/yr (equals 0.37 t CO_2-eq/ha/yr). To avoid double-counting, carbon mitigation by aboveground vegetation was not included, as the wood was harvested and burned or used as materials which will ultimately decompose.

It was assumed that *Miscanthus* bioenergy crop was planted on arable land. An average yield of 10.4 t DM/ha through the whole growing cycle was used in the base calculations. The energy yield of *Miscanthus* was calculated by using the lower heating value of 17.6 MJ/kg DM and a 90%-efficient boiler. The energy inputs required for production of *Miscanthus* through the whole growing cycle was 9.26 GJ/ha/yr.

2.4 Data used for product comparisons

Data for energy use, land use and GWP of crops, livestock products and quorn (meat substitute that is produced from filamentous fungus Fusarium venenatum and egg albumin) was based on Tuomisto (2010). Data for energy use, land use and GWP of tofu and salmon was from Blonk (2008). Data for water use of crops and livestock products came from Mekonnen and Hoekstra (2011) and Mekonnen and Hoekstra (2012).

3. Results

The results showed that if all meat produced in the EU-27 was replaced by cultured meat, the GHG emissions would be reduced by 98.8%, land use 99.7% and water use 94% compared to current meat production practices (Table 4). When the opportunity costs of land use are taken into account the cultured meat system produced 21.1 EJ net energy, which is about 30% of the gross inland primary energy consumption in EU-27 in 2009. The GHG emission mitigation achieved by using the cultured meat system corresponds to 43% of the annual GHG emissions in the EU-27. Also in the EU-27, total water use would be reduced by 21%, and 38% of the total land area would be released from livestock production.

When the environmental impacts of cultured meat were compared with meat products, crops, tofu and quorn per unit of product, protein and energy (Table 5), it was found that cultured meat had lower land use requirements than any other product, regardless of functional unit, except spirulina. The energy use and GHG emissions of cultured meat were higher than those of crops. Cultured meat had also higher energy use

than most livestock-based products. GHG emissions of cultured meat were almost always lower than those of livestock-based products and meat substitutes.

Table 4. Estimated impacts for the entire EU-27 of current meat production practices and reduction achieved by using cultured meat technology with and without taking into account land use and land use change (LULUC) emissions (the former includes opportunity costs of land use).

Impact	**Unit**	**Current meat**	**Cultured meat**	**Reduction quantity**	**%**
GHG without LULUC	1000 t CO_2-eq	301570	3669	297900	99
GHG with LULUC	1000 t CO_2-eq	434565	-2183663	2618200	603
Water use	1000 m^3	164250	10060	154200	94
Land use	km^2	1650000	4474	1645500	100

Table 5. Land use, energy use, greenhouse gas emissions (GHG), and water use of plant, livestock and meat substitute products per functional unit of mass, protein, or energy in the product.

	per edible (t)				**per protein (t)**				**per energy unit (TJ)**			
Product	**Land ha**	**Energy TJ**	**GHG t CO_2-eq**	**Water 1000m^3**	**Land ha**	**Energy TJ**	**GHG t CO_2-eq**	**Water 1000m^3**	**Land ha**	**Energy TJ**	**GHG t CO_2-eq**	**Water 1000m^3**
wheat	0.14	2.5	0.8	3.6	1.1	19	6	28.2	11	0.2	62	27.6
soybean	0.42	3.0	1.3	2.2	1.2	8	4	6.1	27	0.2	84	140.9
maize	0.14	2.4	0.7	1.4	1.1	19	5	10.8	10	0.2	44	92.8
field bean	0.30	2.0	1.0	3.0	1.4	9	5	13.6	22	0.1	74	219.5
spirulina	0.02	10.1	0.8	0.5	0.0	16	1	0.7	2	0.7	54	29.3
beef	4.34	52.5	29.8	11.8	19.3	233	132	99.2	679	8.2	4665	3491.6
pork	0.99	22.3	8.5	4.9	4.5	102	39	29.8	108	2.4	928	711.1
sheep	2.91	48.7	36.9	8.3	14.5	243	184	87.9	297	5.0	3766	1796.3
poultry	0.94	17.6	6.7	3.8	4.2	79	30	25.2	103	1.9	733	612.5
salmon	-	25.4	1.8	-	-	151	11	-	-	3.7	260	-
eggs	0.55	11.8	4.6	3.4	4.4	94	37	30.1	105	2.2	878	716.4
milk	0.12	2.5	1.1	1.1	3.7	79	33	33.6	45	1.0	400	406.0
cheese	0.72	20.0	8.8	5.2	2.8	78	34	20.2	42	1.2	510	299.0
quorn	0.17	38.0	2.3	-	1.0	233	14	-	38	8.5	514	-
tofu	0.30	15.6	2.0	-	3.8	200	26	-	86	4.5	575	-
cultured meat	0.02	31.7	1.9	0.5	0.1	166	10	2.7	5	7.1	423	116.5

4. Discussion

Many technological and social issues have to be resolved before cultured meat can contribute to the reduction of environmental impacts of food production in the EU. Currently, only small quantities of cultured meat have been produced in research laboratories, and more research is required before the production can be scaled up to commercial levels. The main challenges for scaling up the production include development of growth media, optimising the production conditions and making the whole process financially feasible.

As the technology for producing cultured meat in large-scale production plants is currently not well defined, there are many uncertainties about the data of the environmental impacts of cultured meat production presented in this paper. An uncertainty analysis of the environmental impacts of cultured meat production is presented in Tuomisto et al. (2011). More information about the commercial scale cultured meat production system will assist with generating more accurate environmental impact estimates. This study did not take into account the production of scaffolds on which the cells are cultivated. These scaffolds could be made of edible materials or alternatively the cells could be harvested on the surface of the scaffolds. Furthermore, this study did not consider the production of fat cells, and the mechanical and/or electric stretching that would be required for exercising the muscle cells.

Nonetheless, cultured meat would provide substantial environmental benefits, as its land use, GHG emission and water use impacts are only a fraction of those of conventionally produced meat. In particular, when opportunity costs of land use are taken into account, cultured meat could help reduce most environmental impacts of livestock production if the land released from livestock production were used for providing envi-

ronmental services. However, it has to be noted that the analysis presented in this paper did not take into account the fact that if majority of meat was produced by using cultured meat technology, the co-products of meat production, such as leather and wool, should be produced by alternative ways.

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 over-hunted or –fished for food. However, large-scale replacement of conventional meat production by cultured meat production may have some negative impacts on rural biodiversity due to the reduction in need for grasslands and pastures. In some hilly areas, livestock also has an important role in maintaining the open landscapes that are preferred over forested hills. The overall value of the biodiversity impacts would depend on the indicators used. The conversion of grasslands into forest and arable-lands to *Miscanthus* or other bioenergy crops might benefit some species whilst some others may suffer. *Miscanthus* and wood land were used in this study to demonstrate the opportunity costs of land use, but those options would not be the optimal for each location.

Even though eutrophication impacts were not considered in this study, it can be hypothesised that cultured meat production has substantially lower nutrient losses to waterways compared to conventionally produced meat; since wastewaters from cyanobacteria production can be more efficiently controlled compared to run-offs from agricultural fields.

Large-scale production of cultured meat also requires sufficient demand for the product. This would require consumers to accept cultured meat as a substitute to conventionally produced meat. Therefore, taste and texture should be close to conventionally produced meat, and affordability should be taken into account. Taste of meat is influenced by many factors, such as the source of muscle cell, fat content, texture, colour, and shape. Controlled production conditions may ease the addition, removal or modification of any feature in the final product based on consumer preferences. Fat can be added later, and the content and quality of fatty acids can be controlled. The first cultured meat products will most likely be processed products, such as sausages and/or hamburgers. The development of a steak structure will require more research. The costs of cultured meat production based on the current approach have not yet been quantified.

In this study, it was assumed that 100% of the meat production in the EU would be replaced by cultured meat. However, this choice was made mainly to demonstrate the potential of cultured meat. Like other technologies on the market, cultured meat production and adoption will likely follow the 'Technology S-curve' (Sood, 2010). This entails that initially current methods of meat production will outcompete cultured meat on both aspect but within a very short time based on the efficiency categorised in this paper cultured meat will outcompete other methods of production. We also envision that consumer adoption of cultured meat will probably increase as it becomes more available and marketable.

5. Conclusion

Regardless of the uncertainty of the study, the potential environmental benefits of replacing livestock production with cultured meat are substantial. However, more research and development are needed before cultured meat products can be commercialised. Once more knowledge about the processes of the commercial-scale cultured meat production becomes available more detailed estimates about the environmental impacts of cultured meat production can be provided. In order to gain the environmental benefits that cultured meat can offer, the wider acceptance of cultured meat among consumers is required. This could be achieved by improving the public understanding of science.

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