An Emerging Technology Assessment of Factory-Grown Food

by

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A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved December 2013 by the
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May 2014

ABSTRACT

In vitro, or cultured, meat refers to edible skeletal muscle and fat tissue grown from animal stem cells in a laboratory or factory. It is essentially meat that does not require an animal to be killed. Although it is still in the research phase of development, claims of its potential benefits range from reducing the environmental impacts of food production to improving human health. However, technologies powerful enough to address such significant challenges often come with unintended consequences and a host of costs and benefits that seldom accrue to the same actors. In extreme cases, they can even be destabilizing to social, institutional, economic, and cultural systems. This investigation explores the sustainability implications of cultured meat before commercial facilities are established, unintended consequences are realized, and undesirable effects become reified and locked in. The study utilizes expert focus groups to explore the social implications, life cycle analysis to project the environmental implications, and economic input-output assessment to explore tradeoffs between conventionally-produced meat and factory-grown food products. The results suggest that, should cultured meat be widely adopted by consumers, food is likely to be increasingly a product of human design, perhaps becoming integrated into existing human institutions such as health care delivery and education. Environmentally, cultured meat could require smaller quantities of agricultural inputs and land than livestock. However, those avoided costs could come at the expense of more intensive energy use as biological processes are replaced with industrial systems. Finally, the research found that, since livestock production is a driver of significant economic activity, shifting away from traditional meat production in favor of cultured meat production could result in a net economic contraction.

DEDICATION

For my family: generations past, present, and future

ACKNOWLEDGMENTS

To paraphrase a fellow student at Arizona State University, I always knew I wanted a PhD, but I didn’t fully understand what that meant. My time at ASU has been both intellectually and personally challenging and transformative. It is not an experience I would trade for anything, but it took time and attention away from the most important person in my life, Zachary Hughes. So I would like to thank him for his patience, understanding, support, and extraordinary willingness to read draft manuscripts. He is the best man I know.

I would also like to express deep gratitude to my advisor and committee chair, Braden Allenby, without whom this research and degree would not have been possible. Words cannot express the positive influence he has had on me and other students. It has been an honor and privilege to watch every semester as he shows students a larger and more interesting world. The world is without a doubt a far better place for his presence in it. He is a better mentor, teacher, and role model I could have hoped for. I will continue to aspire to his example.

Amy Landis and Jameson Wetmore (listed in alphabetical order) completed the ideal committee for this dissertation project. Amy always asked just the right question at the right time and pointed me toward significant insights. She also expressed confidence in the work when I needed it most. Jamey not only contributed significant time, skill, talent, and commitment to the project, but was consistently optimistic as well. He repeatedly inspired me to keep going when I least wanted to. Thank you both for saying yes.

A number of other people contributed to the success of the project in other ways. In particular, Nicholas Genovese provided key information for the life cycle analysis, patiently answered endless questions via Skype, and provided invaluable feedback on articles meant for publication. Sincere thanks also go to the multi-talented Lori Hidinger who generously introduced me to a few ranchers who turned out to be some of the smartest and most interesting people I've ever met. And to those smart, interesting people, thank you for taking the time to share your wisdom and knowledge of ranching. Thank you also to the 23 brilliant scholars who generously donated their valuable time, knowledge, and creativity to the factory meat workshops. You know who you are.

Finally, special gratitude goes to the people and organizations that funded this endeavor. They include the School of Sustainable Engineering and the Built Environment in general, but specifically for its support of CEE 181 and its teaching assistants. Once again, Brad deserves credit for his brilliant construction of this course that allowed me to undertake a PhD in the first place. The social assessment portion of the research was funded by the generous support of the Lincoln Center for Applied Ethics. It was an honor to be named Lincoln Graduate Fellow in Emerging Technologies. The spirit of excellence and service demonstrated by everyone there was inspirational, but I want to specifically acknowledge Kelly O'Brien for being so enthusiastic and supportive of this project. Last but not least, heartfelt thanks go to the Graduate College at Arizona State University. Their dissertation fellowship allowed me the time and space to not only finish this research, but to learn how to be an academic. I am sure they could quantify the total cost of the fellowship, but believe when I say it was priceless.

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GLOSSARY

Term	Definition
Basal medium	A predefined mixture containing a number of inputs including water, glucose, amino acids, lipids, vitamins, salts, and other compounds meant to facilitate cell growth.
Bioreactor	An apparatus in which a biological reaction or process is carried out, especially on an industrial scale.
Carnery	Facility where meat is produced on a large scale.
Culture medium	A solution of nutrients and growth factors that facilitate cell proliferation. Culture medium typically contains basal medium with added animal serum and/or other animal-free compounds.
Cultured meat	Also called *in vitro* meat, this is edible muscle and fat tissue grown from animal stem cells in a laboratory or factory. This is meat that does not require an animal to be killed.

Term	Definition
Hydrolysate	Enzymatic or acid digests of biological materials such as animal tissues, milk products, microorganisms, grains, and vegetables. They contain “undefined mixtures of low-molecular weight components, including amino acids, peptides, vitamins and trace elements, are frequently utilized as SFM additives to provide nutrients in cell culture” (Sung, Lim, Chung, & Lee, 2004, p. 527).
Lysis	The disintegration of a cell by rupture of the cell wall or membrane.
Myoblast	A type of satellite cell, myoblasts are stem cells derived from adult tissue and are responsible for muscle regeneration (Post, 2012). Myoblasts are muscle cells with a finite proliferative capacity.
Myosatellite cell	Myosatellite cells are adult stem cells that, once activated, become myoblasts (precursors to muscle fibers).
Stirred-tank reactor	A simple type of bioreactor consisting primarily of a tank outfitted with a mixing device such as an impeller.

ABBREVIATIONS

Term	Definition
ALA	Alanine
AMM	Ammonia
EIOA	Economic input-output assessment
FBS	Fetal bovine serum
GHG	Greenhouse gas
GLC	Glucose
GLN	Glutamine
IMDM	Iscove’s Modified Dulbecco’s Medium
IVM	*In vitro* meat
LCA	Life cycle analysis
O_2	Oxygen
OXY	Oxygen
RO	Reverse osmosis
SFM	Serum-free media
SH	Soy hydrolysate
STR	Stirred-tank reactor
YH	Yeast hydrolysate

Chapter 1

The Unintended Anthropocene

The earth and its ecosystems have become so significantly influenced by engineered processes that some scientists have suggested the Holocene, or "entirely recent," epoch has given way to the Anthropocene, the "age of the human." Yet this anthropogenic world has been constructed largely unintentionally as individual investment and purchase decisions have cumulatively caused unexpected changes in earth-scale processes. Thus, this anthropogenic planet, though the direct result of human technology, is the product of unintentional – not conscious or conscientious – design. Similar dynamics exist in socioeconomic systems where seemingly benign strategies can lead to surprising outcomes as they ripple through very complex global linkages. Given that the anthropogenic perturbations in global systems are not caused by any one individual, institution, or nation, it follows that no party is responsible for managing them. Yet engineers and technologists are increasingly being called upon to understand the broader social, economic, and environmental dimensions of their work, with an implication that they bear some culpability for its ramifications. In order to anticipate the impacts of emerging technologies, however, there must be methodologies capable of projecting a range of possible futures before they become realities. Thus the goals of this investigation are two-fold. First, the investigation will propose a forward-looking assessment framework for emerging technologies, aimed at identifying their environmental, economic, and social implications before products become widely adopted by consumers. Second, the approach will be applied to the specific emerging technology of cultured meat. As such, the research will utilize lifecycle impact analysis, economic input-output analysis, and a panel of experts, to project a range of possible consequences that could emerge in seemingly disparate systems under various cultured meat diffusion scenarios.

Context and Motivation

The next generation of food products may not be grown on farms or in fields; in fact, the technology exists to produce *cultured meat* in laboratories, and ongoing research could soon enable the growth of meat in a factory without the need to maintain a large animal population (Jones, 2010). At first glance, the sustainability of such an endeavor might seem obvious: By moving away from concentrated animal feeding operations (CAFOs) to factories that can engineer protein, fat, and other nutrient sources, the world would experience an increase in food quality concurrent with a reduction in methane emissions and water quality degradation. However, the transition to commercial cultured meat technologies may not be without significant sustainability challenges ranging from impacts to farming culture and jobs to increased demand for feedstocks and nutrients to support tissue growth. Thus, the aim of this project is to help guide the emerging technology of cultured meat down a sustainable path by applying an interdisciplinary mix of research methods to assess its implications for the environment, the economy, and society.

Meat cultivated in factories, or *carneries* (McLeod, 2011), is not yet commercially available, but a significant technological transition away from agricultural meat production may be on the horizon as several researchers have suggested that large-scale production of cultured, or *in vitro*, meat is possible (Edelman, McFarland, Mironov, & Matheny, 2005; Langelaan et al., 2010; Post, 2012). While the industrial shift may at first appear to be decades away, innovation is progressing at a rapid rate: Two US patents for commercial production have already been issued (van Eelen, 2007; Vein, 2004); at least three American startup firms have expressed an interest in cultured meat development (Jones, 2010; McDermott, 2012); and, perhaps most saliently, a prototype sample of cultured meat was consumed at a well-publicized event in London on August 5, 2013 (“Cultured beef: The event,” n.d.).

Many believe that cultured meat is a benign technology. By some accounts it will reduce the environmental impact of meat production (Siegelbaum, 2008), address global hunger issues (Tuomisto & Roy, 2012), promote human health by eliminating harmful contents such as saturated fats and pathogens (Siegelbaum, 2008), and alleviate the ethical concerns associated with industrial livestock operations (Bartholet, 2011). While some of these claims may prove correct, supporting scientific evidence is tenuous. Thus far, peer-reviewed studies of the implications of this technology have been limited to a preliminary life cycle analysis (Tuomisto & Teixeira de Mattos, 2011); a projection of future consumer cost (eXmoor Pharma Concepts, 2008); and, though not yet complete, an assessment of factors that will influence adoption, with the stated goal of preempting prohibitive regulation and public scorn in Europe (Wageningen UR, 2011).

Meanwhile, technologies powerful enough to address significant global challenges often come with unintended consequences and a host of costs and benefits that seldom accrue to the same actors. In extreme cases, they can even be destabilizing to social, institutional, economic, and cultural systems (Allenby, 2009). Cultured meat may, in fact, be such a technology: It has been suggested that a shift away from agricultural meat production in favor of factory processes could “have large climatic impacts” and constitute a substantial, though unacknowledged, geoengineering strategy (Olson, 2011, p. 3). Yet, to date, no analyses have considered the impact of cultured meat on the global nitrogen or phosphorus cycles, economic sector output and employment, human health, global development, and factors such as cultural identity. Given that cultured meat may appear on store shelves in the coming years, a more comprehensive anticipatory sustainability assessment of cultured meat is currently warranted.

Vision

This research aims to assess the sustainability of emerging cultured meat technologies by identifying a range of environmental, economic, and social implications that could result from a shift away from agricultural meat production in favor of factory-grown substitutes in the United States. Such a transition will have significant and unintended impacts within tightly-coupled physical, economic, and social systems; therefore, to the extent possible, this investigation is meant to anticipate these impacts in order to promote prudent decision making and adaptive management of cultured meat development and commercialization.

To this end, the research described herein (1) defines three diverse “agriculture-to-factory” transition scenarios (no production of cultured meat, moderate production, and complete replacement of conventionally-produced meat with factory-grown products); (2) identifies possible environmental, economic, and social ramifications associated with the scenarios; (3) assesses the future states associated with each scenario as compared to the present; and (4) develops a set of quantitative metrics that can be monitored and utilized by other researchers and institutions as part of adaptive technology management programs.

Chapter 2

Cultured Meat

The field of biological tissue engineering is relatively young, but since the 1980s, it has made significant strides toward developing tissue for three principal applications: grafts that can be implanted in the human body to repair or replace defective tissue, models of disease for research purposes, and "*in vitro* platforms for drug development" (Kosztin, Vunjak-Novakovic, & Forgacs, 2012, p. 1792). However, on August 5, 2013, a prototype sample of meat grown using tissue engineering techniques was tasted at a well-publicized event in London ("Cultured beef: The event," n.d.). This hamburger, consisting almost entirely of skeletal muscle cells, was not grown in an animal, but rather from bovine stem cells in Dr. Mark Post's laboratory at Maastricht University in the Netherlands. The event may foreshadow a day when traditional livestock production has given way to large-scale growth of meat in factories, or *carneries*. While Dr. Post has suggested that commercialization of cultured meat could be ten to twenty years away ("Cultured beef: The event," n.d.), innovation is progressing rapidly and could soon transform the way food is produced in the United States along with its agricultural landscapes.

Literature Review

While this number is difficult to verify, it has been reported that approximately thirty cultured meat research programs currently exist around the world (Flynn, 2012) including initiatives at the American startup firms Mokshagundam Biotechnologies and Pure Bioengineering in California (Jones, 2010), and Modern Meadow in Missouri (McDermott, 2012). As a result, a number of cultivation methods have been proposed, but perhaps the most promising (Bhat & Bhat, 2011) begins by isolating adult stem cells from a donor animal explant (the animal remains otherwise unharmed). These stem cells are then submerged in a culture medium containing nutrients, oxygen, and a cocktail of hormones and growth factors (Datar & Betti, 2010), where the cells proliferate and the culture increases in mass.

Even though Dr. Post believes that the process could be scaled up for commercial meat production in perhaps 10-20 years ("Cultured beef: Frequently asked questions," n.d.), he has also stated that challenges still exist in terms of ensuring quality and safety of the final products (Post, 2012). One of these is the need to develop and optimize synthetic (animal-free) nutrient growth media. Another is the need to design production facilities that ensure all cells receive sufficient nutrients and oxygen: cells will die if they are more than 0.5 mm from a nutrient supply for a significant period of time (Bhat & Bhat, 2011). Carneries must also promote cell exercise in order to impart a familiar and acceptable texture. Absent exercise, meat grown *in vitro* could be perceived by consumers as "weak and textureless" (Jones, 2010). For the purposes of this investigation, it was assumed that all of the aforementioned challenges will be overcome and that cultured meat will all but replace traditional, agricultural meat by 2050.

Social implications. In February, 2011, Wageningen University announced that it was receiving a round of funding from the Dutch Ministry of Economic Affairs, Agriculture and Innovation (Wageningen UR, 2011). This grant will support cultured meat development research by Henk Haagsman at the University of Utrecht, as well as an investigation into the social, ethical, and moral aspects of cultured meat. The social research will be headed up by Cor van der Weele of Wageningen University and will include an examination of attitudes and factors impacting adoption. The stated overarching goal of this research is to avoid any negative perceptions that people may develop toward cultured meat, as occurred with genetically modified foods (Wageningen UR, 2011). Hence Dutch research is not only limited in scope, but it is meant to influence public opinion.

Environmental Implications. In July, 2011, a partial life cycle analysis (LCA) was published comparing cultured meat to conventionally-produced meat. The study was funded by New Harvest, a non-profit aimed at supporting the development of meat substitutes. The findings indicated that a transition to cultured meat could reduce greenhouse gas (GHG) emissions by 78-96%, land use by 99%, and water use by 82-96% as compared to the equivalent meats produced by conventional methods (Tuomisto & Teixeira de Mattos, 2011). In addition, it showed lower energy consumption for cultured meat than for beef, mutton, and pork. In short, the LCA characterized cultured meat as being significantly less environmentally detrimental than agricultural meat. However, this study did not consider the relevant categories of eutrophication potential, acidification potential, ozone depletion potential, or human health impacts.

Economic Implications. To date, the only known economic analysis of cultured meat is a forward-looking European study aimed at determining whether cultured meat is likely to become competitive with conventionally-produced meat in terms of factory gate prices (eXmoor Pharma Concepts, 2008). This is a reasonable question when one considers that the first cultured hamburger cost about $350,000 (“Cultured beef: The event,” n.d.), largely due to the high price of the growth medium (one of the primary inputs to cultured meat production). At €7000 – 8000 or about $10,000 per tonne of cultured meat (eXmoor Pharma Concepts, 2008), it currently makes up about 90% of the production cost (Jones, 2010).

Using a net present value financial model, the investigators projected that, if economies of scale bring the cost of growth medium to about one tenth of its current price, cultured meat could become comparable in price to conventional beef but remain more expensive than poultry (eXmoor Pharma Concepts, 2008). While this is important information, the study failed to explore the farther-reaching economic consequences of the findings. If, as they say, cultured meat becomes as affordable as conventional beef, and is widely adopted on a regional or global basis, questions remain regarding what industries would grow and what industries would contract.

Needs Analysis: Implications of Cultured Meat

While cultured meat is beginning to draw more attention from researchers interested in its environmental, economic, and social implications, significant questions remain. Above all, a more complete life cycle analysis is needed. Such an LCA should evaluate the assumptions made by the prior study and take into account flows of nutrients such as nitrogen and phosphorus. Economically, there is a need to better understand what, if any, regional and global impacts might be felt as a result of widespread adoption of cultured meat. Socially, intelligence as to what issues could arise under a high-adoption scenario is generally lacking. Whereas these specific knowledge gaps seemingly point to the need for discrete analyses, in reality, environmental, economic, and social factors are interdependent and coevolve with the technology itself.

Chapter 3

Methods

The research described herein employs an interdisciplinary set of methods to assess the implications of cultured meat for all three pillars of sustainability: environment, economy, and society. This section provides background information on the tools used for the sustainability assessment. While none of the frameworks described below provides a comprehensive “cookbook” approach to assessing emerging technologies, each is forward-looking and can lend some value to an anticipatory evaluation. Using these tools, an approach will be constructed that can provide intelligence to decision makers considering the management or regulation of new products, though not the decisions themselves.

Life Cycle Analysis

The field of industrial ecology focuses on environmental design and technological impacts, but largely excludes social and economic considerations. Nonetheless, industrial ecology encompasses a number of analytical tools, life cycle analysis (LCA) in particular, that lend themselves well to a technology assessment. LCA enables an investigator to quantify and understand the environmental effects of a product or technology over its entire life cycle: from material sourcing to manufacture to use and, finally, disposal (Graedel & Allenby, 2010). Process life cycle analysis, as described by the ISO 14040 series (International Organization for Standardization, 2006), will be employed in the assessment of cultured meat.

Economic Input-Output Assessment

Economic input-output analysis (EIOA), sometimes known as inter-industry analysis, was developed by Wassily Leontief in the late 1930s and later earned him the 1973 Nobel Prize in Economic Science (Miller & Blair, 1985). Economic input-output (EIO) tables aggregate the links between industries in order to quantify interdependencies within the economy as a whole. Once constructed, these economic input-output models facilitate the exploration of "what if" scenarios whereby a hypothetical condition is allowed to propagate through the economy at large. It lends itself to a variety of applications including policy analysis and technology assessment. A more detailed explanation can be found in APPENDIX C.

For the purposes of the proposed research, EIOA will be used to address the economic pillar of sustainability. An EIO model will be constructed to demonstrate the far-reaching and potentially obscure economic implications of simultaneously reducing agricultural meat production and scaling-up factory generation. This method will also address the coupled nature of environmental and economic systems, allowing the complex nature of emerging technologies to be understood at a level that would be impossible via an environmental analysis alone.

Technology Assessment

Technology assessment (TA) was first proposed in the late 1960s as a means to help the U.S. Congress "perceive, appraise, and initiate actions required to secure the greatest values from technology" (National Academy of Engineering, 1969, p. 3). While TA could extend to environmental and economic analyses, the focus is foremost on social implications of technology. In practice, TA has historically consisted primarily of panels of experts constructing in-depth analyses meant to aid Congress in making decisions concerning technology policy and “gain political control over the potential negative effects of technological development by means of early warnings” (Carlsen et al., 2010). This research will draw from the TA literature to develop the conceptual framework for the overall investigation as well as its expert panel approach to address the social pillar of sustainability.

Scenarios

Scenarios are not predictions of the future, but rather they are simply descriptions of possible sets of future conditions that can help to assess and select different strategies in order to manage risk (Becker, 1983). A number of scenario development methods exist for a variety of purposes including corporate planning, public policy, and military tactics (Becker, 1983; List, 2007). Given that scenario development can be an integral component of TA (Porter, Rossini, Carpenter, & Roper, 1980), EIOA (Leontief, 1986), and industrial ecology analyses (Graedel & Allenby, 2010), then it should prove to be a useful tool for assessment of emerging technologies as well.

Earth Systems Engineering and Management

Earth systems engineering and management (ESEM) “may be thought of as sustainable engineering at the planetary scale” (Allenby, 2012, p. 348). At its core are a set of guiding principles for technologists that do not provide a framework for analysis, but do serve as important considerations for those developing and managing emerging technologies. Perhaps most relevantly for cultured meat, ESEM principles indicate that “major shifts in technologies and technological systems should be evaluated before, rather than after, implementation” (Allenby, 2012). From that perspective, the investigation proposed herein is directly in line with ESEM guidelines. Moreover, ESEM principles recommend that a set of metrics be developed that can be used to assess and guide development of a technology on an ongoing basis.

Goals and Objectives

On its surface, this research is aimed at identifying a broad range of possible environmental, economic, and social impacts that could result from large-scale replacement of agricultural products with factory-grown food in the United States. However, given the inherent unpredictability of complex coupled human, natural, and technological systems that increasingly characterize the modern world, sustainability arises from the ability to perceive, and then respond with agility and rapidity to, unintended perturbations in the system. This work will employ case studies to evaluate the emergence of cultured meat as a new technology within a complex system. As such, it will illuminate obscure interdependencies that could contribute to unintended consequences in seemingly disparate systems and develop a set of metrics to monitor progression toward specific outcomes. Hence the research is expected to produce objective intelligence for the adaptive management of cultured meat development and commercialization.

To that end, the sustainability of cultured meat emerging technologies via the following tasks:

1. Identification of environmental, economic, and social impacts associated with diverse cultured meat transition scenarios (shown in Figure 2 on page 16) via the following methods:
   a. Expert focus groups (society);

    b. Life cycle analysis (environment);
    c. Economic input-output analysis (economy).
2. Assessment of the sustainability implications of each scenario and identification of the most significant deviations from the present state.
3. Development of a set of sustainability metrics for ongoing monitoring and adaptive management of cultured meat production.

The goal of this investigation is *not* to determine whether the technology should or should not be commercialized, nor to try to predict the degree to which it will be adopted and by what groups. Instead, the goal is to project a range of possible consequences that could emerge in seemingly disparate systems under various diffusion scenarios. In this way, it is meant to provide unbiased intelligence for effective leadership and governance. Gaining an understanding of some possible future scenarios can serve to minimize overall risk and facilitate a smoother, more tempered technological transition.

Research Methods

The conceptual framework for this investigation was modeled on the technology assessment practices discussed by Porter et al. (1980) and shown in Figure 1. As such, it consists of an environmental, economic, and social assessment of technology commercialization and diffusion within a consistent framework of technology transition, or cultured meat production, scenarios. Per Table 1, the specific analyses will be as follows: the environmental analysis will consist of an LCA, the economic analysis will be an EIOA, and social consequences of each scenario will be assessed via expert panel discussions. While each analysis will be performed relatively independently, the research will include an impact evaluation step in which synergies between the analyses and their findings will be identified and reported. Each component of the overall approach is discussed below.

Table 1

Overview of Sustainability Assessment Methods

Method	Conceptual framework	Environmental assessment	Economic assessment	Social assessment
Industrial ecology	N/A	LCA for environmental impacts	N/A	N/A
Economic input-output analysis	N/A	EIO-LCA for environmental impacts	EIOA for impacts on related economic sectors	N/A
Technology assessment	TA for research approach and steps	N/A	N/A	Expert panels for social projections
Scenarios	N/A		Projections of possible future conditions	
ESEM	N/A		Metrics for ongoing dialog and management of the system.	

Cultured meat transition scenarios. Diverse technology transition scenarios associated with cultured meat were developed for the purposes of comparing the sustainability implications of alternative futures. The first scenario is a baseline or "business as usual" case that assumes no cultured meat production. Two additional cases represent both moderate adoption and complete replacement of conventionally-produced meat with factory-grown products in the United States by 2050. These cases, shown in

Figure 2, do not reflect predictions or normative judgments regarding the desirability of the technology. Instead, they are constructed to provide insight into the possible effects of the technology under diverse future conditions.

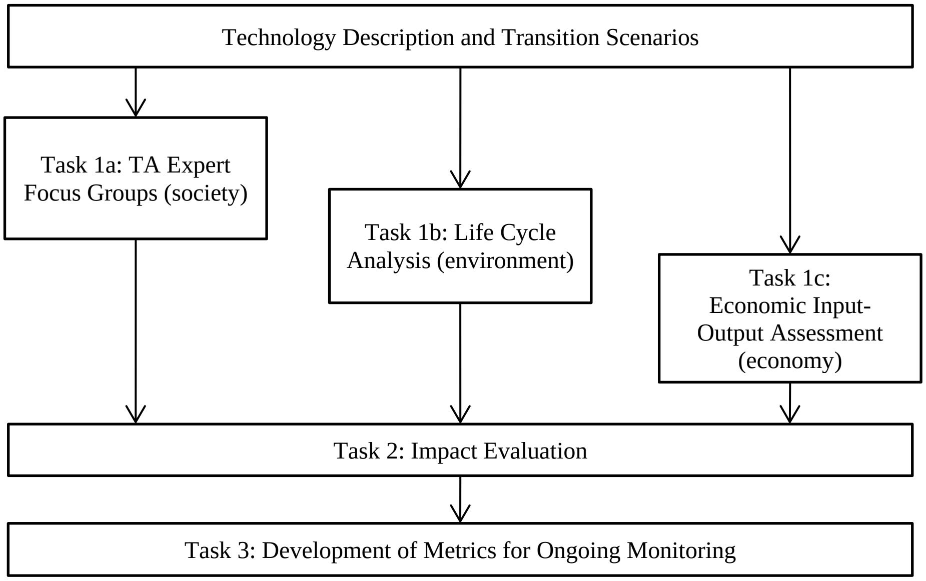


Figure 1. Conceptual framework for analysis. Based on Porter et al. (1980).

Because meat consumption occurs on a global basis, the analyses would ideally encompass all nations in aggregate. However, despite the fact that meat of various kinds is generally a commodity product, production methods and consumption patterns vary from nation to nation, as do available economic data sets. For these reasons, this particular study will be simplified by focusing exclusively on the United States. As an additional simplifying assumption, all factors that would be expected to contribute to cultured meat adoption, including prices, regulations, and personal preferences, are assumed to precede, and be inherent within, the adoption scenarios. Therefore, by presenting three very different technology futures, the specific factors that would bring about those futures can be ignored.

The cultured meat adoption scenarios to be used in this study are illustrated in Figure 2. Meat production (as opposed to consumption) will serve as the independent variable since production can be linked to both domestic environmental and economic impacts via models developed as part of this research. Production will also serve as an approximate indicator of domestic consumption as needed for the social assessment.

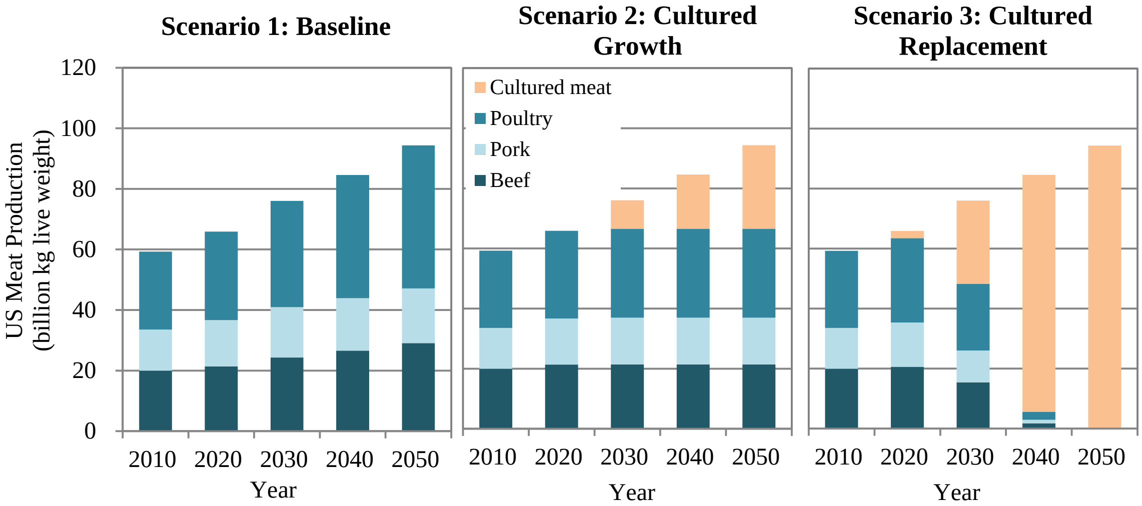


Figure 2. Production associated with cultured meat transition scenarios. Projections are based on the long-term agricultural projections through 2021 published by the United States Department of Agriculture (USDA, 2012). Beyond 2021, US production is assumed to grow at the annual world rate estimated by the Organisation for Economic Cooperation and Development (OECD) and the Food and Agricultural Organization of the United Nations (FAO) (FAO, 2006; OECD-FAO, n.d.). Values are converted from dressed carcass weight (excluding byproducts) to live weight by dividing by 0.6 for beef and 0.75 for pork and poultry.

Task 1a: Social framework: TA expert panels. The proposed expert TA process will be a modified version of the standard approach discussed by Porter et al. (1980) and will be designed to accommodate the same forecasts considered by the environmental and economic analyses. In this task, three groups of 6-10 scholars with expertise in a number of areas including law, journalism, agriculture, environmental engineering, tissue engineering, technology and society, and emerging technologies will be assembled. Because this portion of the research will require human subjects, IRB review was sought, and approval #1301008706 was granted on January 17, 2013.

In order to obtain the best possible input from participants, this investigation will take a hybrid approach that combines the creative interaction of focus groups with the individual communication enabled by surveys. After an initial briefing, participants will be asked to develop and discuss narratives associated with cultured meat adoption as a group, where creativity will be encouraged and plausibility will not be requested. Notes will be taken during the focus groups, but at the end of the two-hour discussions, participants will be asked to write down the details of their own vision of a society that includes large-scale cultured meat production. In this way, unique views will be contributed by all participants, but only after they have been influenced by a discussion meant to stimulate “out-of-the-box” thinking.

In order to frame the panel discussions, participants will be asked to consider how cultured meat will impact the social categories of education, employment, human health, family, general population dynamics, religion and culture, and global development (based on Bennett, 1999; Organisation for Economic Cooperation and Development [OECD], 2011; World Bank, n.d.). Should the conversation stagnate, the expert panels will be presented with example metrics from each of these categories, but to a large extent, participant will be encouraged to identify the social factors that they feel are the most important.

At the end of this task, the investigator will transcribe, code, and analyze the narratives reported, using thematic analysis (Liamputtong, 2011, pp. 173-174) to aggregate trends described by the experts. Similar to tasks 1a and 1b, the output of this task will be a list of deviations, albeit qualitative, from the present state, organized by indicator of interest. Together, these variables and their projected outcomes will form the input to the impact evaluation phase of the study (task 2).

Task 1b: Environmental framework: LCA. The LCA for cultured meat will follow accepted procedures as described by the ISO 14040 series standards (ISO, 2006). A process-sum approach will be taken to compile the life cycle inventory and expert input from cultured meat researchers will be sought to ensure accuracy of the system process flow diagram (shown in Figure 3) and inventory data. One of the most common challenges facing LCAs of emerging technologies is data availability for the life cycle inventory. In this case, a model for cellular growth is available from a peer-reviewed source (see Table 2). Impact categories of focus will include land use, water use, energy use, greenhouse gas emissions, and eutrophication (a proxy for nitrogen and phosphorus flows). The functional unit will be 1 kg of cultured meat and will be compared to the impacts of livestock on a live weight basis. As such, life cycle impacts associated with livestock production will be obtained from peer-reviewed sources as shown in Table 2.

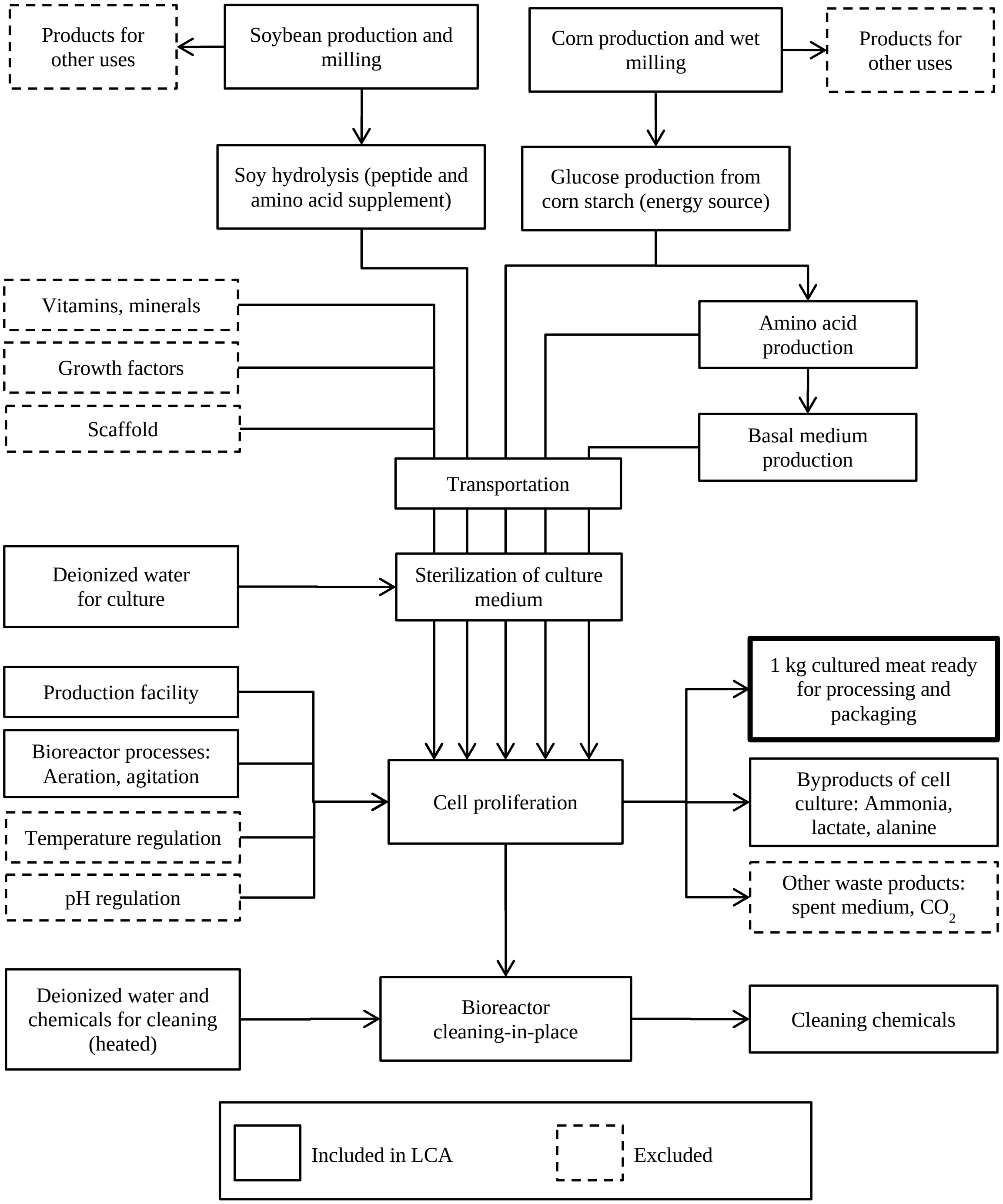


Figure 3. System diagram for hypothetical cultured meat production system. Separation (possibly via centrifugation) as well as cultured meat processing and packaging are not included in this study.

Table 2

Data sources for the Life Cycle Inventories

Product	Life cycle inventory data source
Cultured meat	Flickinger (2013); Hu (2012); Sung, Lim, Chung, and Lee (2004)
Beef	Pelletier, Pirog, & Rasmussen (2010)
Pork	Pelletier, Lammers, Stender, & Pirog (2010)
Poultry	Pelletier (2008)

Task 1c: Economic framework: EIOA. This task will require the construction of a very simple economic input-output model that will highlight significant changes in sector output associated with cultured meat production. Using Microsoft Excel® software, an EIO model will be developed from the 2002 detailed (benchmark) national input-output tables published by the United States Bureau of Economic Analysis (BEA). These tables provide economic flows for approximately 439 US industries. Due to the certainty of economic adaptation to changing food production paradigms and the static nature of input-output models, projections associated with the three production scenarios outlined above will not be constructed. As with all input-output analyses, this model will rely on historical data, and therefore will not allow for technological advancement that would yield a more realistic analysis (because complex systems react and evolve under changing conditions). Hence, while EIOA appears to be the best extant method to provide a relatively rigorous and structured analysis of the economic shifts that might result from a transition to cultured meat, projections associated with such shifts would be incorrect and therefore essentially meaningless.

Task 2: Impact evaluation. As depicted in Figure 4, the impact evaluation task will encompass the compilation of results of the environmental, economic, and social assessments. Trends that constitute unintended and detrimental impacts in any part of the system will be highlighted.

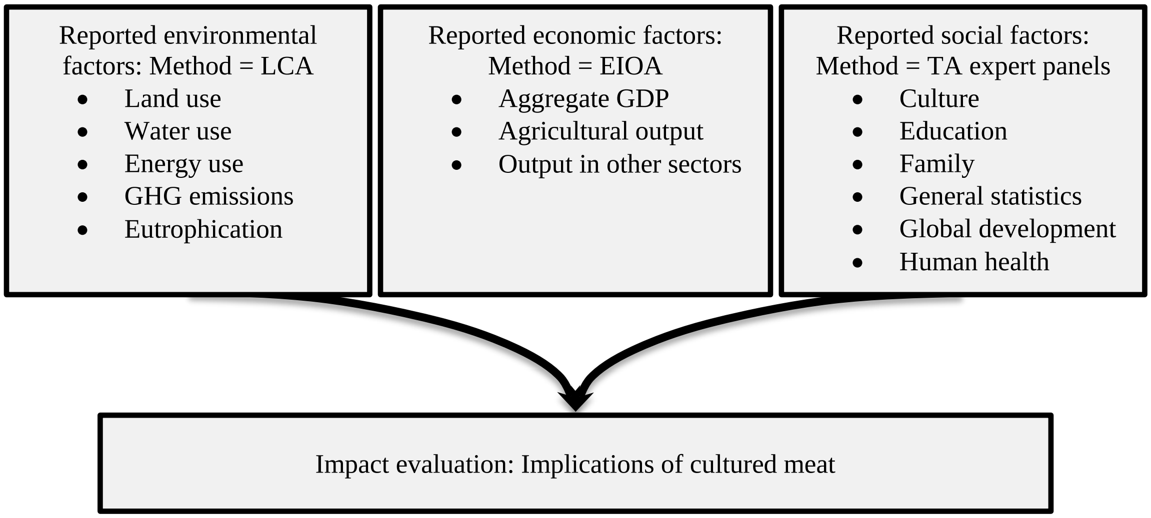


Figure 4. Impact evaluation phase of the research. In order to address the 3 pillars of sustainability, Task 2 will constitute the results compilation and methodology review phase of the research.

Task 3: Development of metrics for ongoing monitoring. The complexity of global interdependent systems all but precludes the ability to control them. Yet the ability to manage – or at least influence – coupled human, natural, and technological systems can be developed and maintained through a measured dialog. That is, by establishing and continuously monitoring a set of metrics indicative of important system benchmarks, managers have the capacity to identify undesirable trends before significant problems arise (Allenby, 2005). Based on the output from task 3, the most significant changes from the present state will be identified, along with metrics that would serve as early warning indicators for undesirable states.

Validation, Verification, and Uncertainty

Due to the anticipatory nature of this investigation, validation of many aspects of the approach will be very difficult to accomplish. Realistically, the quality of the model output can only be assessed in retrospect as events unfold in the real world, implying that refinements in the overall framework must be made based on real-world comparisons over time. Moreover, this approach includes a great deal of inherent uncertainty. As summarized in Table 3, however, sensitivity to specific factors can be assessed in the LCA model, but not the social narratives. Sensitivity analysis methods for economic input-output models exist (Mattila, Koskela, Seppälä, & Mäenpää, 2013), but will not be pursued as part of this project.

Verification and validation of the component LCA and EIOA can be accomplished via expert and peer review. To this end, a tissue engineer working to develop meat production techniques has been engaged to provide advice and feedback as the work progresses. Further, verification of the EIO model can be accomplished by comparing single-variable cases with results generated by the EIO-LCA database maintained by Carnegie Mellon University (Carnegie Mellon University Green Design Institute, 2008).

Table 3

Methods of Validation, Verification, and Sensitivity Analysis for All Stages of This Investigation

Research component	Validation (does the model accurately represent the system?)	Verification (was the model built according to specifications?)	Sensitivity analysis
Overall framework	Refinement over time	Peer review	N/A
Transition scenarios	Assessment over time	Peer review	N/A
Task 1a: Social narratives	Assessment over time	N/A	N/A
Task 1b: LCA	Review by cultured meat researchers	Peer review	Monte Carlo analysis
Task 1c: EIOA	Peer review	Comparison to EIO-LCA database [a]	N/A
Task 2: Impact evaluation	Assessment over time	Peer review	N/A
Task 3: Metrics for ongoing monitoring	Assessment over time	Peer review	N/A

[a] Source: Carnegie Mellon University Green Design Institute (2008).

Intellectual Merit

In order to realize the benefits of cultured meat while avoiding its unintended consequences, society needs to understand the wide spectrum of impacts associated with large-scale deployment of this emerging technology before production methods and consumer preferences are established. By applying mature analytical methods within an anticipatory framework, this project will provide unique insight into what the emerging technology of cultured meat might mean for the environment, the economy, and society. As such, this interdisciplinary study is meant to provide objective intelligence that can aid decision-making by scientists, engineers, regulators, policymakers, and business leaders involved in developing and deploying these technologies. The results of this interdisciplinary research will provide novel insight into the implications, and perhaps unintended consequences, of an emerging technology. Moreover, they will, for the first time, facilitate the adaptive management of a technological transition on a large scale.

More broadly, the proposed research is designed to produce a widely-applicable framework for anticipatory evaluations of emerging technologies. Due to the increasing impact of anthropogenic processes on earth-scale systems, a growing chorus of voices is calling for greater understanding and responsible management of new products (Allen et al., 2008). Unfortunately a suitable assessment methodology is currently lacking. The proposed investigation seeks to fill the void by introducing a novel approach to anticipating the sustainability implications of new products, thereby facilitating early detection of undesirable outcomes and expediting dynamic and effective corrective action. Through article submissions to sustainability journals, the research is potentially transformative as it could impart engineers and scientists with evolving and widely-applicable technology assessment tools, allowing them to balance knowledge acquisition with prudent and reversible application.

Chapter 4

Social Assessment

Meat grown from stem cells in a factory and not in an animal, often referred to as "cultured meat," may reach store shelves and restaurants in 10 to 20 years. This paper summarizes expert focus group discussions aimed at providing insight into the possible social implications of a shift away from agricultural meat in favor of cultured meat. The investigation explores relevant dynamics and diverse implications for a number of directly- and indirectly-related systems including human health, family dynamics, education, culture, ethics, global development, and food system security.

Introduction

On August 5, 2013, a prototype sample of cultured, or in vitro, meat was tasted at a well-publicized event in London ("Cultured beef: The event," n.d.). This hamburger was not grown in an animal, but rather from bovine stem cells in Dr. Mark Post's laboratory at Maastricht University. The event may foreshadow a day when traditional livestock production has given way to large-scale growth of meat in factories, or carneries. Dr. Post has suggested that commercialization of cultured meat could be ten to twenty years away ("Cultured beef: The event," n.d.), and the implications are profound. By some accounts the technology could reduce the environmental impact of meat production (Siegelbaum, 2008), promote human health by eliminating harmful contents such as saturated fats and pathogens (Siegelbaum, 2008), address global hunger issues (Tuomisto & Roy, 2012), and alleviate the ethical concerns associated with industrial livestock operations (Bartholet, 2011). However, technologies powerful enough to address such significant challenges often come with unintended consequences and a host of costs and benefits that seldom accrue to the same actors. In extreme cases, they can even be destabilizing to social, institutional, economic, and cultural systems (Allenby, 2009).

This investigation seeks to complement ongoing technical research efforts in two ways. First, a more balanced consideration of the impacts of in vitro meat (IVM) will be sought in the areas where potential benefits are already well-publicized. This will include unintended and potentially negative consequences for human health, the environment, global hunger, and ethics. Second, the implications for seemingly remote, but still coupled, systems will be explored. That is, as shown in Figure 5, the complexity inherent in the world ensures that changes in food production technologies could have repercussions far beyond the selection of foods sold in the grocery store. They will modify norms in environmental, economic, and social domains in ways that have not yet been considered by prevailing scientific analyses or public discussions. A better understanding of the potential implications of cultured meat could serve to facilitate effective decision-making as the technology becomes commercialized.

To address these goals, distinct environmental, economic, and social analyses are being performed. This article is a report of the findings from the social assessment which consisted of three expert focus groups, or workshops, held on the campus of Arizona State University in the spring of 2013. These workshops each brought together 6-8 scholars with expertise in a number of areas including law, journalism, agriculture, environmental engineering, tissue engineering, technology and society, and emerging technologies. These diverse groups were asked to qualitatively explore the possible social ramifications of IVM at all scales, from personal to systemic.

Cultured Meat

Meat consists primarily of skeletal muscle and fat cells in varying proportions. Emerging engineering techniques have enabled the growth of these cells *in vitro*, as opposed to the traditional *in vivo* process which requires the raising and slaughtering of a whole animal. A number of *in vitro* cultivation methods have been proposed, but perhaps the most promising (Bhat & Bhat, 2011) begins by extracting adult stem cells from a donor animal tissue sample (the animal remains otherwise unharmed). These stem cells are then submerged in a nutrient broth that enables the cells to grow, divide, and increase in mass.

Even though Dr. Post believes that the process could be scaled up for commercial meat production in perhaps 10-20 years (“Cultured beef: Frequently asked questions,” n.d.), he has also stated that challenges still exist in terms of ensuring quality and safety of the final products (Post, 2012). One of these is the need to develop and optimize synthetic (animal-free) nutrient growth media. Another is the need to design production facilities that ensure all cells receive sufficient nutrients and oxygen (cells will die if they are more than 0.5 mm from a nutrient supply for a significant period of time [Bhat & Bhat, 2011]). In order to impart a familiar and acceptable texture, carneries must also promote cell exercise. Absent exercise, meat grown *in vitro* could be “weak and textureless” (Jones, 2010). Additional challenges associated with IVM commercialization include the high cost of production (eXmoor Pharma Concepts, 2008) and the “yuck” response elicited by some individuals (van der Weele & Driessen, 2013). While these factors are certainly not trivial, the goal of this investigation was to assess the possible social consequences of this technology; therefore, it was assumed that all of the aforementioned challenges had been overcome and that cultured meat had all but replaced traditional, agricultural meat by 2050.

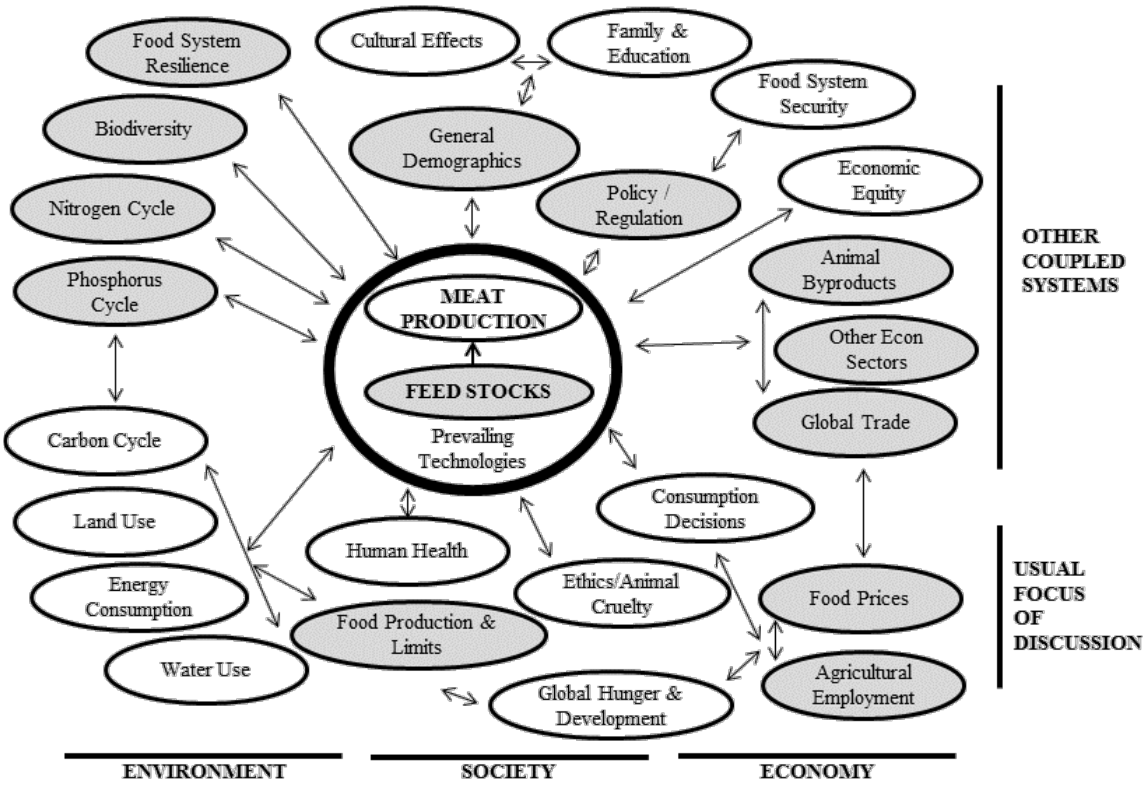


Figure 5. Systemic representation of meat production. Note that environmental, social, and economic systems are highly interdependent and neither the factors included here nor the arrows representing causal links should be considered exhaustive. White ovals represent factors addressed in this paper. Based on (Allenby, 2012).

Social Assessment Workshops

The series of workshops was designed to create a space for discussing the broader aspects of cultured meat and encourage a creative interplay of ideas from diverse perspectives. Prospective workshop participants were identified based on their research expertise and its relevance to the goals of this investigation. The workshop invitations included an article that provided an overview of the technology in question (Jones, 2010), but most participants had little to no prior knowledge of cultured meat. The workshops themselves lasted approximately 3 hours and began with a high-level briefing that described the research goals as well as cultured meat and the underlying technology. For the purposes of the workshops, participants were asked to imagine that a shift toward ubiquitous factory meat production would be largely complete by 2050. The briefing was followed by participant introductions, a moderated group discussion to encourage creative synergy, and a role-play session where participants were invited chose a character (i.e. doctor, lawyer, high school student, etc.) and describe the world of 2050 from that person's perspective. This was followed by time allotted for participants to complete a written questionnaire aimed at capturing information that may not have been verbalized during the discussion, but was still considered important to the respondent. Notes were taken during the discussion portion of the workshop by a dedicated note-taker who wrote down quotes that could be used to illustrate the nuances of the ideas discussed, but did not identify the speaker in order to preserve anonymity. Hence, the workshops encouraged a dynamic, spontaneous flow of ideas that drew on participants' personal and professional knowledge and linked the technical and social aspects of the technology. The resulting novel and vivid future scenarios were captured in the workshop notes and participant questionnaires.

Participants in each workshop were asked to discuss how a transition away from agricultural meat in favor of ubiquitous cultured meat might affect five aspects of US society: food in general, human health, family and education, culture and ethics, and general demographics. While the United States was the focus of the workshops, participants were also invited to comment on a sixth category, global development.

Discussions were not limited to these areas, however. Participants were encouraged to indicate additional variables that they felt would be most significant or important as tissue engineering techniques develop. Further, discussions of economic and environmental impacts were not discouraged, though participants were informed that studies of economic and environmental variables were being accomplished via alternative methods.

The data collected from the workshops should be interpreted as future scenarios for consideration and discussion only. The complex nature of technological development and its interactions with other systems preclude the ability to accurately assess causal relationships and make deterministic predictions. Moreover, the participants were predominantly American scholars; their views are thus not representative of a global population, nor even all American cultural groups. Nonetheless, the results presented here are meant to introduce novel information to discourses and decision-making around cultured meat development and commercialization.

Findings

The discussions during the three workshops did not result in a unified prediction of social changes that will accompany a transition from slaughtered meat to *in vitro* meat. But that was not the goal. Instead participants discussed a wide variety of possible futures. Some of the vignettes described could occur simultaneously. In other cases it was clear that only one of the options could happen. Discussants did not spend a large amount of time debating the likelihood of specific changes. Rather stories were built as a group – with one person positing a possibility and others contributing facts or suggestions that developed a broader picture of the original idea. This section does not exhaust everything that was discussed, but outlines some of the common themes that arose.

Adoption and consumption decisions. Even though factors influencing cultured meat adoption were not a focus of the research, the workshop groups often could not help but speculate about future diffusion patterns. In general, people expected an uneven global adoption rate and thought that Americans and Chinese would be open to the technology much more than Europeans. In Europe, they said, people are more concerned with the source of their food whereas, in the United States, food is already highly modified and processed, with a very tenuous connection to the natural source. Even in the case of meat, they said, the shift to an “unnatural” product has already happened. It was further speculated that a lot of Americans “wouldn’t even know the difference” between cultured and real meat. Others thought that cultured meat would appeal to Americans’ attempts to remove themselves from the animal. As one participant noted, “People don’t want meat that looks like meat necessarily. We want it to appear sterile, wrapped in plastic, in the grocery store.” On the other hand, a few people expressed dissenting opinions and suggested that, not only do Americans eat a substantial amount of natural food, the amount of processing required to produce cultured meat would inhibit people from eating it even if they are eager to try novel foods. The “yuck factor” associated with cultured meat could play an important role in how cultured meat is diffused, packaged, and marketed.

Additional factors associated with adoption were religion and identity. Some participants thought that religious rules about food would probably remain. Some even foresaw religious groups with extensive rules about meat – like Judaism, Islam, and

Hinduism – to play a role in resistance to *in vitro* meat. One participant stated, “Religions (e.g. Hindu) that consider the cow to be one of their goddesses will not like the idea of their god being produced or created in petri dish[es].”

In general, American values and cultural myths became a prominent point of debate in one of the workshops where, as one participant pointed out, if the narratives surrounding cultured meat oppose an important myth or cultural value, as with GMOs in Europe, adoption could be arrested. For example, Americans value independent farming; therefore, a perceived further erosion of Jeffersonian Agrarianism or elimination of the cowboy might dissuade Americans from adopting cultured meat. However, another participant countered that our society has historically been through many shifts in agricultural practices, particularly with respect to labor: “Shifts associated with cultured meat would not be very different from what we have seen in the past, and would be unlikely to influence cultured meat adoption. In fact,” the participant said, “the cowboy is already a myth, along with the family farm. Neither of these lifestyles exists anymore, yet their stories persist in romanticized form. Myths remain incredibly stable in the face of constant cultural flux and generally do not prevent social change.” The panelists felt that cultural touchstones will likely be used in the discussions around in vitro meat in the future – in fact the cowboy myth has already been used in futurist projects on the topic (see Figure 6) – but exactly how they are used and which configurations will become predominant is unclear.

Figure 6. Hypothetical marketing campaign for cultured meat brand. As part of his online portfolio, designer Grant Parinello (not affiliated with this research) developed a marketing campaign for a hypothetical food product called Supermeat (Parrinello, 2011) that featured a cowboy as a spokesperson.

Cultural effects. Just as cultural values will almost certainly influence the adoption and development of cultured meat, the technology will likewise impact cultures and religions. Specifically, one participant thought that cultured meat might shift both secular and religious lifestyles, enabling the “spread of neo-Buddhist systems and increase romanticization of nature and animals.”

Additional questions arose around traditions and ceremonies involving preparing and sharing meals, particularly if cultured meat requires less preparation. On this point, however, many foresaw adaptation: “Cultural norms would adapt to accommodate it – Thanksgiving would still occur, but with cultured turkey.” Moreover, participants imagined that food-based traditions and rituals such as potluck dinners would continue to draw people together in much the same way in 2050. One argued that “they will serve as an opportunity to eat with like-minded people i.e. a group of vegetarians… or people who want to eat meat from animals."

Coevolution of food and food preferences. At the core of all focus group discussions were perceptions and expectations for how cultured meat will appear when it reaches restaurants and grocery stores. Participants imagined variations in quality & type of IVM products, from commodity "vat" meat constituting nothing more than a basic protein source to specialized luxury and designer products (e.g., "Atkins®-Approved Slim-Meat") with a corresponding range of prices. A number of participants concurred that meat of the future would be significantly altered due to greater flexibility in production methods, with variable characteristics including nutrients, flavors, textures, exotic and extinct species, species mixtures, and even products grown from human explants. It was further suggested that cuisine diversity would lead to inevitable pushback and desire for "natural" food products, opening up new markets as animals are raised on a small scale or hunted to appease "meat purists."

While some participants expressed concern that people would miss eating meat off the bone, others highlighted human adaptability. For example, "growing meat in an aseptic environment and testing it for pathogens and parasites could result in meat that does not need to be cooked. This could lead people to develop a taste for tender meat that does not need to be exercised as much." Another suggested that, "while 40 years is too short of a timeframe for significant change to take place, by 2150 meat could be radically different – perhaps humans would even lose the psychological need to chew." This last scenario illustrates how continuous feedback loops between changing food technology and evolving consumer preferences could result in radical changes to both, perhaps even new human psychological and physiological norms.

Human health. When asked about the health effects of cultured meat, participants provided an array of possible outcomes. Several respondents optimistically foresaw increases in overall health status and longevity in developed nations due to a “clean” (sterile) product with less fat, higher nutrient density, and possibly smaller portion sizes. More specifically, one claimed: “There will be vast declines in obesity, infectious diseases, food-borne illnesses, auto-immune ailments and health expenditures per capita as the system transitions to focus on lifelong [disease] prevention.”

Some participants went one step further and imagined meat becoming a health delivery system where food containing additives such as vitamins, vaccines, antibiotics, and other pharmaceuticals would be recommended or prescribed by doctors. Ultimately, one participant suggested, meat could be designed for particular human genomes (similar to the way some medicines are given to people based on their genotype).

Still others believed that cultured meat would theoretically enable people to become more health-conscious, but were dubious that human health would unequivocally improve due to behavioral issues. For example, if people do not exercise or eat healthfully, obesity will persist. One participant wondered, even if food is tailored to meet individuals’ specific physiological needs, will it matter? “That is, will someone with a tendency towards high blood pressure buy a burger designed for him/her?” Another indicated that there might be negative effects associated with consuming too much protein.

Some respondents were more skeptical that cultured meat would indeed be healthier. One participant noted “It really depends on what the cultured meat is infused with – more fat, less fat, or just different fat.” Another respondent warned, “Perhaps there will be *more* obesity as additives are used to make cultured meat more desirable and marketable.” Some participants saw a sinister side to additives: They could have mildly addictive properties such as meat with caffeine (“Wakin’ Bacon”), and other, perhaps undisclosed, properties. Moreover, some participants expressed concern regarding the long term health effects of cultured meat itself: It could cause both physical and genetic abnormalities that could be passed from one generation to the next, limiting personal development and, on an aggregate basis, national economic growth.

Population & lifestyle. Workshop participants generally assumed that producing meat in factories would lead to decreased agricultural employment which would in turn cause an uptick in urbanization. From there, some then reasoned that people would respond to decreased urban living space by forming more diverse and extended family units. At the same time, participants imagined that cultured meat would be more conducive to prepared and take-out (mobile) meals than conventional meat. They therefore believed this might lead to more independent lifestyles, smaller families and looser, more fragmented family structures even in rural settings.

Education. Participants were queried about how IVM might impact trends in standardized test scores as an indicator of education and intelligence. Those who responded were slightly and tentatively optimistic. Assuming that academic test scores are correlated with nutrition, they said, increasing school lunch quality could have a positive impact on test scores. Another participant simply foresaw an “increased educational emphasis on the food science, engineering and biological fields required to generate and support the new cultured meat industry.” As with health care delivery, one participant suggested that food might become an integral part of career preparation. The participant postulated that in the future, “Children’s diets [will] become as strictly controlled as their exposure to strangers has been: scholars, athletes, and models [will all be] raised on custom diets from infancy.” This scenario highlights the possibility that greater flexibility in food design will facilitate its integration and coevolution with existing human institutions.

Ethics and animal cruelty. Workshop participants believed that cultured meat would reduce animal cruelty and suffering, and then went on to suggest that animal rights movements might be spurred by cultured meat. One respondent put it this way: “My sense is that we will see increasing sensitivity and expansion of ethical concerns as regards sentient beings, especially higher order mammals (cows, etc.). We may even see widespread acceptance of rights for animals and with this various mechanisms, legal and social, to minimize the pain of animals and possibly even protect some from killing for the purpose of food.” Another respondent put it more starkly: “There will be a different relationship with ‘the farm’ – [we will come to see it] as an inhumane slaughterhouse…”

Some respondents extended these views to human relations, theorizing that enhanced “ethical consciousness may transcend to human interactions, possibly leading to fewer violent crimes.” But views on this issue were mixed. Pessimistic participants imagined that diverse adoption decisions could be a polarizing factor, leading to increased tensions among religions, cultures, and nations: “On the human side I can see a backlash against ‘real’ meat eaters as savages, which could lower intercultural relations.”

Still others imagined that the elimination of animal slaughter would similarly eliminate the need for ethical reflection and forestall change: “I think it will prop up a lack of reflexivity in our culture about where the products we consume come from. It could slow down the changes in values the vegan community wishes to see in terms of [ethical treatment of] animals, humans, and ‘nature’.” Another participant made the same point: “If we don’t have to address the violent ways animals are treated in society today, will that be an overall loss to cultural values? Or would a transition to cultured meat open up this discussion?” A final participant observed that some cultures view nature as being separate from human society and, further, that the distinction can lead to political clashes. To illustrate the point, the participant queried, “Will we get over the epistemic divide engrained in our mindsets between nature and culture, or will cultured meat reinforce this great divide and lead to more GMO-like conflicts?” The implication that IVM, an animal-derived food source cultivated with industrial technology, could incite a shift toward integrated views of nature and human society or facilitate institutionalized animal rights illustrates the powerful links between technology, personal mental models, and cultural values. Simultaneously, the diversity of plausible scenarios discussed by the panels reflects the complex and unpredictable nature of these large-scale sociotechnical interactions.

Environment and land use. Workshop participants were not specifically asked to comment on the environmental impacts of cultured meat, but many emphasized the importance of, and potential for, improvements in environmental sustainability via reduced resource consumption (water, fertilizers, etc.), fewer greenhouse gas emissions, and decreased pollution due to animal wastes. In addition, they noted that the reduction (but not elimination) of agricultural feedstock requirements for cultured meat as compared to livestock could increase availability of arable land. Optimistically, it was noted that factory meat production might facilitate enhanced environmental life cycle management of food production via water recycling, wastewater treatment, etc. By contrast others expressed concern that, even though cultured meat production might be less environmentally-damaging than traditional meat production on an equivalent mass basis, significantly greater demand (possibly driven by larger, more affluent populations that view IVM as inherently sustainable) could lead to higher production rates and therefore more environmental impacts than a “business as usual” scenario with livestock production only.

An important theme also emerged over use and management of the land that cattle currently occupy. Participants observed that grazing animals like cattle perform landscape management services that reduce vegetation and reduce the risk of wildfires. They suggested that cultured meat could result in a kind of landscape unlike anything seen in generations, if ever. Hence alternative range management activities might need to be adopted. While the potential exists for conversion of grazing land to low-carbon uses, some participants believed that the “appropriate balance of land use” would require national oversight.

Economics in the United States. As with many other topics, uncertainty and lack of consensus was the result of the economics discussion. The prospect of a shift toward cultured meat caused two participants to express concern over a general “employment crunch” and other financial challenges in the agricultural supply chain. However, others imagined a number of national economic benefits ranging from avoided food-related expenditures to new business opportunities. Avoided expenditures, they said, might stem from lower overall food prices due to reduced demand for livestock feed; fewer losses associated with animal disease and adverse weather; and fewer cases of food-borne illness that can lead to lost wages, lower aggregate labor productivity, and increased healthcare expenditures. New business opportunities could take the form of novel food products and the application of complementary technologies from other industries such as tasty though unnatural flavor additives or self-cooking packages.

Some participants also discussed the byproducts of animal slaughter (e.g. gelatin, soap, pet food, leather, etc.) and the surrounding economic uncertainty. On the one hand, development of functional equivalents for these products could lead to economic growth; on the other hand, such equivalents could be more expensive than the animal-sourced substances. It is also possible that animals could continue to be raised for these products, making them both more expensive and, by some standards, ethically questionable. As with all areas, the workshop findings stressed that there will be economic opportunities and challenges associated with a shift away from agricultural meat in favor of IVM. The trends highlighted here are likely only a few, but preparation and monitoring of the downstream effects could serve to mitigate the most significant losses.

Economic equity. Workshop participants generally agreed with the notion that technology and society coevolve, but due to the nature of the research, discussions often began with a description of a technological change and was followed by a scenario describing its downstream social consequences. For example, optimistic individuals believed that IVM diffusion would lead to increasing wealth for the rich *and* poor, whereas another wondered if there are politics inherent in cultured meat (like Langdon

Winner’s bridges in Long Island example (Winner, 1980)) and went on to pessimistically imagine that the IVM industry itself might contribute to inequity by building polluting factories in impoverished communities, thereby negatively impacting health. However, on this topic, other participants started with projected social behavior and then considered what role cultured meat might play. According to this future scenario, the rich might self-segregate into enclaves according to food values, some of which would procure local and organic food whereas others would favor IVM and other engineered fare. It would follow that food designed for optimal nutrition would increase in price but impart consumers with superior health and productivity. This would in turn widen the gap between rich and poor within the United States as well as worldwide. Based on the vision of communities segregated by economic class, one member predicted an associated gap in education and a less skillful American workforce overall. Reflecting on how the social classes might react to such a divide, a final participant predicted that the desire for equity would be a defining characteristic of the sustainable development discourse in the future.

Global hunger and development. With respect to global poverty and hunger, many respondents indicated deep uncertainty regarding impacts on developing nations. Those who did express opinions were divided. The most optimistic held that IVM would provide inexpensive protein to the poor and alleviate global hunger. Other respondents predicted little to no change in global hunger and listed three possible reasons. First, according to participants, the problem of global hunger is one of distribution rather than production and IVM would not impact food distribution. Second, should a company try to build a production facility in a developing nation, it would be limited to those nations that have a preexisting industrial infrastructure, thereby limiting economic benefits to nations where development is already underway. Third, cultured meat could remain very expensive, possibly due to the presence of intellectual property rights, and therefore remain unaffordable to the poor. The most pessimistic workshop members reflected on the topic of intellectual property rights and feared that IVM could be seen as an economic tool for “global corporate crackdowns on rogue producers” and that famines might be seen by corporations as opportunities “to lock in brand commitments.”

Food system security. Uncertainty also surrounded the impact of cultured meat on food security, but focused on two factors: vulnerability and centralization. Factory production of cultured meat was judged to be less vulnerable to disease and environmental changes than livestock operations, and it was therefore determined to be more secure. Others considered the role of centralized production in food security, but found it to be an ambiguous factor. One respondent associated large, central carneries with ease of protection and thus greater security. By contrast, others placed greater emphasis on the risk of food supply disruption in the event of a successful attack on a large, centralized plant and suggested that building many small carneries would lessen the severity of any given attack. This discussion proved to be interesting introduction to the issue of food system security, but may serve primarily to highlight the need for additional analysis.

Regulation. The need for adequate regulation of cultured meat was noted around two major concerns: sanitary conditions and labeling requirements. Many participants wanted to be certain that the meat products were made in clean facilities but acknowledged that some standards might favor industrial production and put smaller artisan producers at a financial disadvantage.

Participants hoped that labeling requirements would reduce ambiguity associated with the sources and production methods of natural and cultured meat products. While concern was expressed that companies would try to label meat as “real” when, in fact, it was cultured, the labeling objective was reversed when it came to selling meat from endangered species: Participants were concerned that meat would be labeled cultured when in fact an animal had been killed. Simultaneously, participants acknowledged that there was no guarantee that the ability to engineer meat from endangered species would diminish the culling of protected animals.

However, some participants anticipated greater regulation of traditional meat production. In particular, they said, confined feeding operations (“factory farming”) would be made illegal due to animal rights protests, so any livestock meat produced would be on the cottage industry level. Yet another expressed concern that these “specialty growers of real meat” would also come under scrutiny for a variety of tainting problems experienced by those who receive insufficient training in “natural” food preparation, i.e. the need to cook it thoroughly.

Discussion

The stated goals of this investigation were twofold: to identify previously unacknowledged implications of cultured meat in areas already under discussion (human health, environmental impacts, global hunger, and ethics), and to consider possible consequences in systems that are less obviously and less directly coupled to food production. Discussants in three workshops expressed skepticism regarding one-sided, entirely positive views of cultured meat; they raised important points regarding the coevolution of this technology with the world at large; and expressed uncertainty about all developmental steps related to the emerging technology.

Among the points of uncertainty was whether IVM would be commercialized and adopted at all. Technical challenges remain, but even if these are overcome, consumer acceptance is not guaranteed. Food has important meanings for many individuals and is often closely related to personal and cultural identities. For this reason, cultured meat could be scorned if it comes into conflict with important values and myths. In the United States, for example, myths of the family farm and the cowboy lifestyle figure prominently. For others, such as many Europeans, the agrarian landscape holds great value (Ford, 2011). Elsewhere, the livelihoods of pastoral communities could be a pivotal factor (Gathura, 2013).

Assuming factory production of meat is adopted, it will introduce the potential for food to become increasingly designed due to flexible manufacturing practices as well as genetic modification. As the technology advances, both humans and human institutions are likely to shift in unpredictable ways. For example, human food preferences will almost certainly shift to embrace novel food products. Equally possible, though less certain, is the potential for designer food to become more integrated with existing social institutions, perhaps serving as a pharmaceutical delivery system or an integral part of educational curricula. In a longer-term scenario, IVM could eventually contribute to modified human physiologies.

Regulation and policy will play an important role in adoption decisions and influence food safety and security. At a basic level, standards of cleanliness and manufacturing practices will play a role in human health and perceptions of IVM in general. The need for, and impact of, labeling rules is uncertain. As with genetically-modified organisms (GMOs), a lack of labeling requirements might not hinder adoption, but could incite protests from some groups. While it is also possible that manufacturers will voluntarily label cultured meat in order to tout its beneficial properties, labels of any kind would have an unforeseeable effect on consumption. In terms of food security and range management, specific policies could serve to enhance both if IVM becomes ubiquitous, but the complexity and possible unintended consequences of these systems suggest that more analysis is required prior to implementing any regulation.

The workshop participants made one final point not yet discussed in this article: they warned that many risks associated with cultured meat production simply cannot be conceptualized at this point in the development process. While the authors believe that investigations such as this one serve to reduce uncertainties, and so-called "unknown unknowns," they do not alleviate the need for ongoing monitoring of emerging technologies and their impacts as they progress. Technologies as potentially significant as cultured meat will have equally significant impacts on the world. The complex and interconnected nature of global systems ensures that, for every shift in the nature of food production, there will be reactions in human norms, cultures, institutions, and landscapes. Identifying undesirable consequences before or as they arise can facilitate stabilizing decisions that result in more tempered technological transitions.

Chapter 5

Life Cycle Analysis

On August 5, 2013, a hamburger prototype made from cultured, or *in vitro*, meat was tasted at a well-publicized event in London (“Cultured beef: The event,” n.d.). The meat used for preparation of this hamburger was not grown in an animal, but rather from bovine skeletal muscle stem cells in Dr. Mark Post’s laboratory at Maastricht University. The event may foreshadow a day when traditional livestock production has given way to large-scale growth of meat in factories, or carneries. While Dr. Post has suggested that commercialization of cultured meat could be ten to twenty years away (“Cultured beef: The event,” n.d.), the environmental implications are profound: A life cycle analysis published in 2011 acknowledged significant uncertainty, but suggested that, as compared to traditionally-produced beef, sheep meat, pork, and poultry, cultured meat would require significantly less land, water, and energy (except poultry), and emit fewer greenhouse gases (Tuomisto & Teixeira de Mattos, 2011).

Goal

This investigation seeks to evaluate previously-published findings by performing a similar life cycle assessment using different assumptions (please see Table 21 on page 175 for a model comparison). It will further estimate the acidification potential, eutrophication potential, human toxicity, and ozone-depletion potential of cultured meat production that were not included in the original study. Focusing on the United States and modeling a large-scale production facility in line with contemporary cell cultivation practices, this study will confirm some of the possible benefits of cultured meat while highlighting areas for potential caution or targeted innovation.

At the heart of this analysis is a model of a large-scale cultured meat production plant. It was based on the present state of the art of cell culture techniques, but this model does not represent the only cell cultivation method available, and technological improvement are likely to change rapidly in the coming years. Inherent in anticipatory assessments is a tension between building a model that represents a workable process given existing knowledge and estimating how the future commercial process will differ. Thus, anticipatory LCAs should be viewed as possible future scenarios for cultured meat production but not predictions. Nonetheless, they can provide valuable insight into how the technology might evolve and affect other, coupled systems.

Scope

Formation of skeletal muscle tissue for cultured meat is a multi-step process (shown in Figure 7) that begins with the isolation of myosatellite cells (adult stem cells) from a sample of donor animal tissue. Once activated, the myosatellite cells become myoblasts (precursors to muscle fibers). When placed in a culture medium containing the necessary factors, the myoblasts proliferate, resulting in increased cell number and culture biomass. Next, the culture medium is modified to induce myoblast differentiation to non-proliferative myocytes, which fuse into multinucleated myotubes. Facilitated by physiological stimuli (i.e., mechanical, chemical), myotubes mature into contractile myofibers that comprise skeletal muscle tissue. For the purposes of this analysis, it will be assumed that all of these steps occur in a single bioreactor and that the culture medium is not significantly changed or altered during the phases. Further, it is assumed that all metabolic consumption and waste production occurs during the proliferation phase. That is, inputs and outputs associated with activation, differentiation, and physiological stimuli phases are ignored.

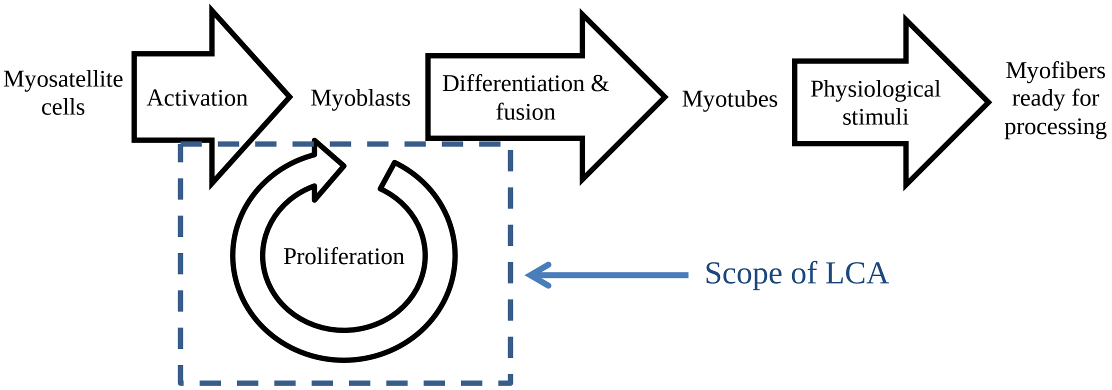


Figure 7. Phases of skeletal muscle fiber development. This LCA is limited to the proliferation phase.

Media for animal cell cultures typically contains a number of inputs including water, glucose, the amino acid glutamine, and predefined mixtures called “basal media” that consist of additional amino acids, lipids, vitamins and salts (Hu, 2012). In addition, animal serum such as fetal bovine serum (FBS) is generally added to the culture because it contains “a cocktail of most of the factors required for cell attachment, growth and proliferation and is thus used as an almost universal growth supplement effective for [many cell] types” (Brunner et al., 2010, p. 53). However, for a number of reasons including high costs, unsteady supplies, lot variation, and the possible presence of transmissible diseases such as bovine spongiform encephalopathy (BSE) (Brunner et al., 2010; Girón-Calle et al., 2008), chemically-defined animal- or serum-free media (SFM) is preferred over animal serum. Unfortunately, efforts to develop effective serum-free media often result in decreased cell growth as compared to cell culture containing serum. As a result, hydrolysates (enzymatic or acid digests) of yeast, rice, soy, and other plant and microbial materials have been added to basal media as a supplementary source of amino acids, peptides, vitamins, and trace elements (Sung et al., 2004). This investigation will assume that soy hydrolysate will supplement the culture medium, and that it will remain serum-free.

In addition to culture medium, tissue engineering must provide a scaffold or “structural and informational template for cell attachment and division” (Kosztin et al., 2012, p. 1792). Scaffolds mimic the extracellular matrices found *in vivo* and may be composed of natural or synthetic polymers (Kosztin et al., 2012). A number of challenges surround scaffold material for cultured meat since it must be edible, dissolve or degrade prior to consumption, or be easily excluded from cell harvest. Though various proposals have emerged such as collagen mesh or spheres to which cells may adhere (Bhat & Bhat, 2011), this component has been excluded from the life cycle inventory due to uncertainty associated with the solution that will eventually be utilized. A diagram of the cultured meat production model is given in Figure 3 on page 19.

Functional Unit

The life cycle assessment described herein is a cradle-to-gate analysis of animal tissue growth and maturation. Metabolic requirements specific to muscle cell cultivation could not be located; therefore the life cycle inventory was constructed based on Chinese Hamster Ovary (CHO) cells. Thus, the functional unit is 1 kg of CHO tissue which is assumed to have the physical characteristics of a typical animal cell, with a dry mass of 17% and a protein content of 7% (42% on a dry mass basis) (Hu, 2012). The life cycle impacts from this model will be compared to the results for cultured meat production obtained by Tuomisto and Teixeira de Mattos (2011) as well as beef (Pelletier, Pirog, et al., 2010), pork (Pelletier, Lammers, et al., 2010), and poultry (Pelletier, 2008) LCAs published by Pelletier and coauthors.

Allocation Procedures

In order to be consistent with the livestock LCA procedures (Pelletier, Lammers, et al., 2010; Pelletier, Pirog, et al., 2010; Pelletier, 2008), process impacts were allocated to co-products on a gross chemical (calorific) energy basis (unless otherwise stated). For example, corn wet milling produces not only starch that can be made into glucose, but also corn steep liquor, corn gluten feed, fiber, and germ from which oil is extracted. Allocation fractions were computed as the mass of each co-product, c, multiplied by the gross chemical energy per unit mass (see Table 23 in the supporting information) divided by the total gross chemical energy contained in all process outputs. This can be expressed according the formula:

$$Allocation\ Fraction = \frac{mass_c \left(\frac{energy}{unit\ mass}\right)_c}{\sum_{n=1}^{\#\ of\ co-products} mass_n \left(\frac{energy}{unit\ mass}\right)_n} \tag{1}$$

The gross chemical energy allocation approach becomes less straightforward when comparing cultured meat production to processes such as livestock rearing that produce both human-edible and non-edible outputs. While roughly half of livestock live weights are edible (Pelletier, Lammers, et al., 2010; Pelletier, Pirog, et al., 2010; Pelletier, 2008; Smil, 2013), only about 14% of bovine and 11% of hog carcasses are lost through shrinkage or waste (Marti, Johnson, & Mathews, 2011). Byproducts of slaughter are used in leather production, pet food, cosmetics, and pharmaceuticals, among many other household and industrial products (Marti et al., 2011). If animal production was replaced with engineered processes, substitutes for the byproducts would almost certainly have environmental impacts. For example, Modern Meadow, a start-up firm in Missouri, is already attempting to produce leather via a tissue engineering process similar to the one modeled herein (M. Keller & Txchnologist, 2012). At the same time, culturing tissue also produces non-edible substances such as ammonia, lactate, and alanine that may or may not be recycled for industrial applications. In lieu of the substantial undertaking that would be required to account for all displaced products associated with both processes, this analysis will present the environmental impacts of beef, pork, and poultry primarily on a live-weight basis but also include values computed on an edible-weight basis.

Impact Assessment

All impacts were calculated using the SimaPro 8 LCA software package from PRé Consultants (PRé Consultants, 2013). Energy use was computed using the Cumulative Energy Demand method (Frischknecht et al., 2007) which converts final energy inputs to primary energy. Land use was found via the Ecological Footprint method (Frischknecht et al., 2007), but reported results were limited to land occupation (nuclear and carbon dioxide components were excluded). Water intake was computed via the Building for Environmental and Economic Sustainability (BEES) method (Gloria, Lippiatt, & Cooper, 2007; Lippiatt, 2007). All other impacts were found via the CML (Center of Environmental Science of Leiden University) 2001 (World 1995) method. These methods were chosen to be consistent with the beef, pork, and poultry life cycle analyses (see Table 4 for comparison). The livestock LCA publications did not report water consumption; therefore, data from Mekonnen and Hoekstra (2012) was used instead.

Table 4

Life Cycle Impact Methods

Impact category	Beef [a]	Pork [b]	Poultry [c]	Cultured meat
Energy use	Cumulative energy demand	Cumulative energy demand	Cumulative energy demand	Cumulative energy demand v1.08
Land use	Ecological footprint (land occupation portion only)	Ecological footprint (feed production portion only)	N/A	Ecological footprint v1.01 (land occupation portion only)
Greenhouse gas emissions	IPCC 2007, 100a	CML 2001, 100a	CML 2 Baseline 2000	CML 2001 v2.05, 100a[d]
Eutrophication	CML 2001	CML 2001	CML 2 Baseline 2000	CML 2001 v2.05
Acidification	N/A	N/A	N/A	CML 2001 v2.05
Human toxicity, 100a	N/A	N/A	N/A	CML 2001 v2.05
Ozone layer depletion, steady state	N/A	N/A	N/A	CML 2001 v2.05
Water intake	N/A	N/A	N/A	BEES v4.02

[a] (Pelletier, Pirog, et al., 2010)

[b] (Pelletier, Lammers, et al., 2010)

[c] (Pelletier, 2008)

[d] Total greenhouse gas emissions for this study, as computed by the IPCC 2007 and CML 2001 methods, differed by only 0.3%.

Unless otherwise stated, processes for which a life cycle inventory is not included in this chapter or APPENDIX B were taken from the US LCI (Norris, 2003) and ecoinvent v2 (EcoInvent, 2008) databases. However, one modification to ecoinvent processes should be noted: Substantial values of water for turbine use were omitted since water for that purpose was assumed to be recycled. In addition, the electricity process from the US LCI database was used but modified to include 7.6 L of water per kWh used at the consuming facility (2.1 L/MJ of delivered energy) (Torcellini, Long, & Judkoff, 2003).

Life Cycle Inventory Analysis

It bears repeating that no large-scale cultured meat production facilities currently exist. The sections below include detailed descriptions of components of the hypothetical system depicted in Figure 3. They should be viewed as approximate and subject to change as the art and practice of tissue engineering progresses.

Cell proliferation. Cells in culture typically demonstrate three phases of growth: The first is an initial lag phase where cells acclimate to the new culture environment; this is followed by a period of rapid or exponential growth; and finally, cells reach a stationary phase where growth diminishes. For the purposes of this analysis, it is assumed that the cell culture remains at the exponential growth rate (μ) for the duration of the cell proliferation period. Moreover, it is assumed that all cells are viable and that no cell death or lysis occurs. While both assumptions are unrealistic in practice, it indicates that the results of this life cycle analysis are representative of an ideal system with minimal material and energy losses.

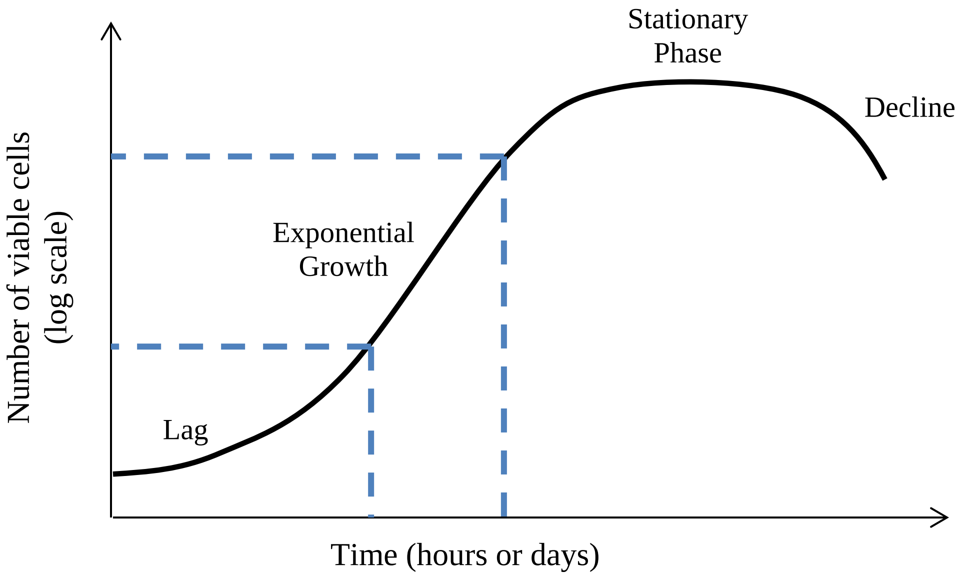


Figure 8. Phases of cell culture growth. This life cycle model assumes that cells grow at an exponential rate throughout the growth period.

As modeled, cultured meat production will begin with a seed culture density, X_0, of 1×10^5 cells/mL and proceed in stirred-tank bioreactors until the estimated maximum attainable cell density, X_1, of 1×10^7 cells/mL (Yang, Luo, & Chen, 2004) is reached. The growth cycle time, t, can then be computed with the following expression (Paredes et al., 1999):

$$t = \frac{1}{\mu} ln\left(\frac{X_1}{X_0}\right) \tag{2}$$

where μ is the specific growth rate of cells in cells/(cell-hour). It is assumed that each cell has a mass of 3500 pg (Hu, 2012) so biomass production is given by the equation:

$$Biomass\ production\ per\ batch$$

$$= (X_1 - X_0) * \frac{3500\,pg}{cell} * \frac{1kg}{10^{15}\,pg} * \frac{1000\,mL}{L} * \frac{15{,}000\,L}{batch} \tag{3}$$

Between each growth cycle, all bioreactors have a period of 3 days for cleaning and preparation for the next growth cycle.

Feedstocks and waste products. Due to the complexities of intracellular reactions, deterministic models of cell metabolism including growth rate, nutrient consumption, and waste production are difficult to develop (Hermann, 2003). Ideally, a model based on the proliferation and differentiation of myoblast cells (precursors of skeletal muscle cells) would form the basis of this life cycle analysis. However, because good-quality data for myoblasts could not be located, the well-studied Chinese hamster ovary (CHO) cell will serve as the primary cell model for inputs, outputs, and growth rate of cultured meat. The reader should be cautioned, however, that CHO tissue is typically cultured, not for its biomass, but for its ability to produce human therapeutic proteins such as human thrombopoietin (hTPO) (Sung et al., 2004). These cells may thus differ significantly from skeletal muscle cells. Nonetheless reasonable nutrient uptake rates and waste production rates, q, in the presence of soy hydrolysate were found in Sung et al. (2004) and listed in Table 5. The CHO cells were assumed to have a specific growth rate, μ, of 0.0254 cells/(cell-hour) (equivalent to a doubling time of about 27 hours) which results in a dry mass yield of 0.49 g cells/g glucose. This value is typical for animal cells (Sung et al., 2004).

Based on Sung et al. (2004), the primary feedstocks or metabolic inputs to cell culture are assumed to be glucose, oxygen, and the amino acid glutamine. Glutamine is singled out from other amino acids in this model because it is delivered to cells in a higher concentration, and because a specific uptake rate is available for CHO cells.

Hence the requirement for glutamine can be estimated with greater accuracy than other amino acids.

Mole fluxes for the primary feedstocks and waste products (lactate, alanine, and ammonia) are computed according to the expression (based on Paredes et al., [1999]):

$$S = \frac{10^{-15} q_S X_0}{\mu} (e^{\mu t} - 1) \tag{4}$$

where S is the consumption or production of the compound of interest in moles, X_0 is the initial cell concentration in cells/mL, q is the specific consumption or production rate in nmol/(10^6 cells· hour), and t represents time in hours. Mass fluxes are then computed as:

$$Mass_S = S \cdot MW_S \tag{5}$$

where MW is the molecular weight of compound S in grams/mole. Please see Table 5 for a list of specific production/consumption rates and molecular weights.

Table 5

Mass Fluxes and Molecular Weights of Nutrients and Waste Products

Substance	CHO production/consumption rate, q_S (nmol/10^6 cells/hour) (Sung et al., 2004)	MW (g/mole)
Inputs		
Glucose	174.2	180.16
Glutamine	18.0	146.14
Oxygen	332.2	32.00
Waste Products		
Lactate	279.5	90.08
Alanine	6.3	89.09
Ammonia	13.5	17.03

Direct consumption rates for basal medium and hydrolysates were not readily available; however, the basal medium for CHO cells is typically Iscove's modified Dulbecco's Medium (IMDM) (Sung et al., 2004) which is a standard formulation (see Table 30 on page 192). In the case of the Sung et al. (2004) study, the IMDM was supplemented with additional amino acids and other components (also given in Table 30). It is assumed that the basal medium and supplemental components are purchased as dry matter and mixed at the appropriate concentrations at the production facility.

Studies have shown that a hydrolysate concentration of 5 g/liter yields optimal biomass growth (Chun, Kim, Lee, & Chung, 2007; Sung et al., 2004); therefore it was assumed that soy hydrolysate is added to the culture medium in this concentration. Even though soy hydrolysates contain quantities of amino acids, the amino acid profile can vary across products so, for the purposes of this LCA, they were assumed to supplement, rather than replace, the amino acid quantities listed in Table 30.

The life cycle inventory associated with the cultured meat production model is summarized in Table 7 on page 61. Inventories for the primary feedstocks (glucose, glutamine and other amino acids, soy hydrolysate, and basal medium) are provided in APPENDIX B starting on page 176. All of these substances are derived from either corn or soybeans; the inventories used for crop production can also be found in APPENDIX B on page 195.

Production facility. The livestock LCAs referenced in this study include on-farm energy use but not energy embodied in buildings or capital equipment. For consistency, this study will follow the same approach. Energy use within the cultured meat production facility was included and estimated using the pharmaceutical and beer production industries as guides. Both industries utilize many of the same processes required by tissue engineering including cultivation of cell cultures, but have very different facility models. The bioreactor configuration in this study was modeled on the Biogen IDEC large-scale pharmaceutical manufacturing plant in Research Triangle Park, NC, since it is a flexible facility with the ability to produce monoclonal antibodies (MAb) derived from mammalian cell cultures (“Biogen’s LSM plant; on line, on time, on budget,” 2003; Hu, 2012). This facility houses six 15,000 liter (L) stirred-tank reactors on 245,000 ft^2 of floor space. However, due to significant uncertainties associated with cultured meat production and its need for cleanroom facilities and other subsystems, the plant size will be modeled on the brewing industry and its smaller bioreactor-capacity-to-floorspace ratio. Thus the plant will be assumed to have 7,717 ft^2 (717 m^2) of floorspace; the derivation of this value can be found in APPENDIX B on page 198.

Table 6

Delivered Energy for Breweries by Fuel

Component	Percent of total	Physical units	Physical units
Total	100.0%	1 MJ	1,000 BTU
Electricity (final/delivered)	15.7%	0.04 kWh	0.05 kWh
Natural gas	43.1%	0.44 ft^3	0.46 ft^3
Coal	33.3%	1.6×10^{-5} short tons	1.7×10^{-5} short tons
Steam	7.8%	0.07 lbs	0.07 lbs
Water for electricity production		0.3 L	0.38 L

Note. Adapted from Galitsky, Martin, Worrell, & Lehman (2003).

The baseline facility energy required for HVAC and other purposes will be assumed equivalent to that of a warehouse: 513.3 MJ/m^2/year (45.2 kBTU/ ft^2/year)

(D&R International Ltd., 2012). The mix of fuels for cultured meat production processes was assumed to be the same as for the brewing industry. This mix was derived from Galitsky, Martin, Worrell, and Lehman (2003) and shown in Table 6. Per Torcellini et al., (2003), water associated with electricity production is also included at the rate of 7.6 L/kWh (2.1 L/MJ).

Bioreactor processes. In addition to the facility energy, the cultured meat plant will require energy for aerating and mixing the culture medium. Aeration, also known as oxygenating or "sparging," is the process of delivering oxygen to the bioreactor tank. It is typically accomplished by pumping ambient air first through a filter to remove contaminants and then into the tank via fine-bubble diffusers. The energy required for aeration is computed in APPENDIX B on page 196.

Once air has entered the tank, it must be distributed to ensure all cells receive sufficient oxygen. This is accomplished by mixing, or agitating, the fluid in the tank via impeller rotation. Stirred-tank reactor (STR) design requires that the impeller speed be fast enough to distribute oxygen throughout the culture medium but not so fast that cells are damaged (Yang et al., 2004). This is typically accomplished by limiting impeller speed to 1.5 m/s (Nienow, 2006), which is equivalent to 0.56 revolutions per second for an impeller having a diameter of 0.85 m. However, this mixing rate restricts cellular growth to a maximum density of about 10^7 cells/mL (Yang et al., 2004). The steps involved in computing agitation energy are presented in APPENDIX B on page 196.

Sterilization of culture medium. In order to avoid contamination of the cultured meat, sterile techniques must be employed throughout the production process. These techniques require that the culture medium be sterilized before any cells are introduced.

In batch sterilization approaches, the entire volume of culture medium is heated in the bioreactor and maintained at approximately 121°C for 10 to 20 minutes (Heinzle, Biwer, & Cooney, 2006, p. 34). However, for the purposes of this model, the culture medium is assumed to be heated to 140°C for 2 to 4 minutes as it flows into the bioreactor. Energy consumed by this "continuous" method can reportedly be 80% lower than that required for batch sterilization (Heinzle, Biwer, & Cooney, 2006, p. 34). Further, heat from the continuous process may be recovered by preheating cold incoming medium using the waste heat given off by the sterilized medium as it cools to the optimal temperature for cell proliferation (37°C for mammal cells) (Heinzle, Biwer, & Cooney, 2006, p. 34). The modeled process reflects the assumption that culture medium is heated from 25 to 67.5°C using waste heat; the life cycle inventory therefore includes only the energy required to heat the medium from 67.5 to 140°C at the beginning of the batch cycle.

It is assumed that no further energy is required to maintain the culture medium at the optimal temperature while cell proliferation is proceeding. Depending on the thermal properties of the bioreactor, this may or may not be a valid assumption: Heat could be lost via a number of pathways including transfer through the bioreactor walls. At the same time, each cell can be expected to produce heat at the rate of about 23 pW (Flickinger, 2013). Thus it is possible that both heating and cooling will be required at different points in the batch cycle (see analysis on page 207).

Bioreactor cleaning-in-place. Bioreactors must be cleaned and sanitized between each batch cycle to ensure sterile production conditions. Large bioreactors are typically cleaned-in-place (CIP) in order to reduce the time and expense associated with disassembling the system, cleaning each component, and then reassembling the reactor.

This LCA assumes that CIP procedures follow the "water – NaOH (0.5 M) – water" sequence described in Flickinger (2013, p. 1596). This means that the tank is first rinsed with deionized water and drained; a caustic sodium hydroxide solution is then added, heated from 25 to 50°C, and drained; finally, the tank is rinsed once more with deionized water. In addition, the agitator and aerator will operate for the duration of the 4-hour cleaning process. Values for all modeled energy inputs are summarized in Table 7 and detailed calculations can be found in APPENDIX B.

Table 7

Inventory Required to Produce 1 kg Cultured Meat

Substance	Per year	Per batch	Per 1 kg of cultured meat
Inputs			
Land use for production facility	717 m^2		0.007 m^2
Seed culture (not included in LCA)		$1x10^5$ cells/mL	350 μg
Water for cell culture (deionized [a] and sterilized)		15,000 L	28.9 L
Glucose		183.3 kg	352.7 g
Glutamine		15.4 kg	29.6 g
Oxygen (not included in LCA but used for aeration energy computation)		60.2 kg	115.9 g
Soy hydrolysate (dry matter)		75 kg	144.3 g
Basal medium (dry matter)		15,000 L	28.9 L
Energy			
Facility	368,034 MJ		3.56 MJ
Heating water for sterilization		3,981 MJ	7.7 MJ
Heating water for cleaning		1,567 MJ	3.0 MJ

(continued)

Table 7

Inventory Required to Produce 1 kg Cultured Meat

Substance	Per year	Per batch	Per 1 kg of cultured meat
Agitation		293MJ	0.56 MJ
Aeration		48.2 MJ	0.09 MJ
Deionization		390 MJ	0.75 MJ
Water for cleaning (deionized [a])		45,000 L	86.6 L
Sodium hydroxide (NaOH) for cleaning		300 kg	577 g
Transportation (all dry ingredients travel 500 km by diesel truck)		337 tkm	0.65 tkm
Outputs			
Cultured meat	103,463 kg	1×10^7 cells/mL or 520 kg	1 kg
Lactate		147 kg	283 g
Alanine		3.3 kg	6.31 g
Ammonia		13.4 kg	27.3 g
Sodium hydroxide (NaOH) for cleaning		300 kg	577 g
Materials and processes not included in the inventory			
Piping, tubing, and pumps required to transport nutrients to the cell culture			
Nutrient containers			
Materials required to acquire and maintain the cell line			
Production and maintenance of buildings and capital equipment (this is consistent with the livestock LCAs referenced)			

[a] An ecoinvent v3 process, “Water, deionised, from tap water, at user {GLO}| market for | Alloc Def, S,” provided the inventory for deionized water (less water for turbine use) (EcoInvent, 2013).

Results

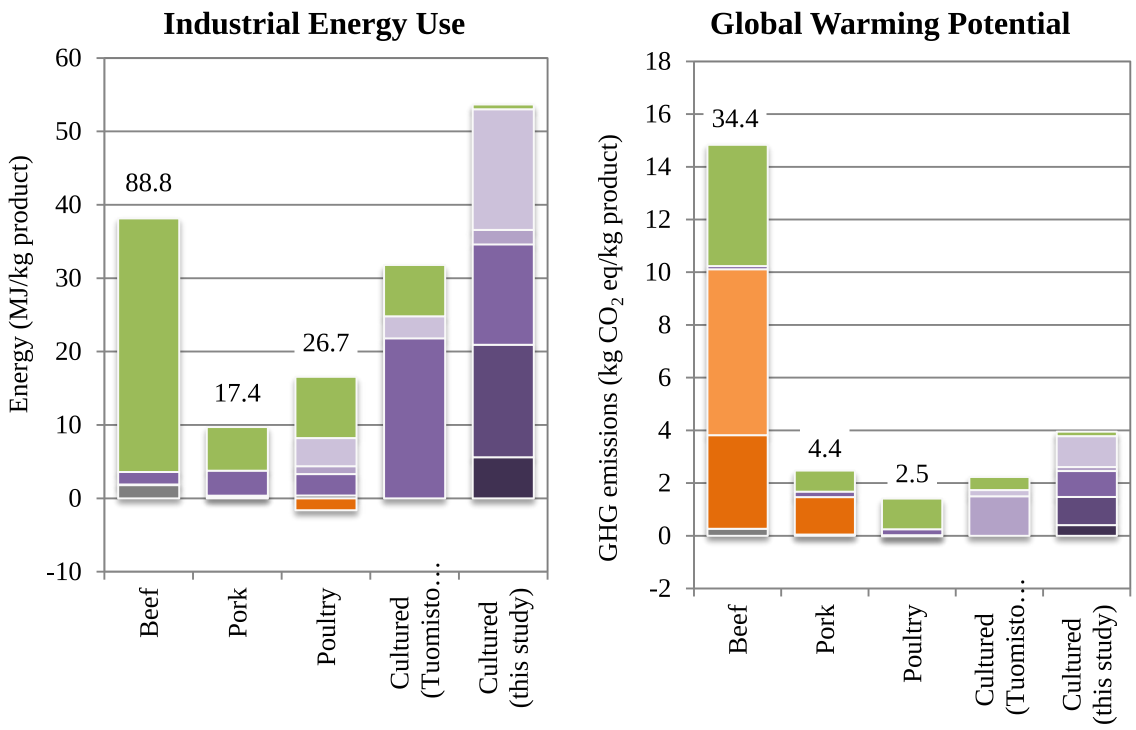
The environmental impact comparisons for energy, eutrophication, greenhouse gas emissions, and land use are depicted in Figures 9 and 10. Detailed results for all impact categories are provided in APPENDIX B beginning on page 202. Figures 9 and 10 are designed to depict agricultural processes in green, industrial processes in purple, and waste products in orange.

Comparison of this study with prior LCA. Energy consumption and GHG emissions in this study exceed that of the Tuomisto and Teixeira de Mattos study by about 70 percent. This is due to the inclusion of facility energy in this study, deionized water, the bioreactor cleaning cycle, as well as flows associated with production of multiple feedstocks including synthetic amino acids. Land use requirements for this study total almost ten times that of the previous cultured meat LCA, due solely to the different assumptions made with respect to feedstocks.

Comparison of this study with Agricultural Meat. Based on the color scheme followed in Figure 9, it is apparent that cultured meat, as modeled in this study, will require more industrial energy than beef on a live-weight basis, but for different purposes. Most of beef's energy is involved in primary production of feed, whereas cultured meat requires much smaller feedstock quantities, and therefore occupied land (see Figure 10), than animals. This is due to a number of factors including an ideal cell growth model that assumed no cell death and a relatively short growing cycle: 7.6 days for cell proliferation (excluding differentiation, fusion, physiological stimuli, and processing) versus finishing times of more than 303 days for beef (Pelletier, Pirog, et al., 2010), 151 days for pork (Pelletier, Lammers, et al., 2010), and 48 days for poultry

(Pelletier, 2008). However, cultured meat also requires significantly more energy for the *processing* of feedstocks. That is, whereas cows and pigs eat the relatively unprocessed byproducts of corn and soybean milling, cultured meat is likely to require additional, energy-intensive steps including saccharification of corn starch, hydrolysis of soybean meal, and fermentation of glucose into synthetic amino acids. A similar phenomenon applies to poultry. As modeled and discussed by Pelletier (2008), poultry feed is relatively energy intensive because it contains fishmeal, poultry fat, and poultry byproduct meal. All of these are energetically expensive to produce and to process. This is why poultry appears to be more energy-intensive than pork.

In addition, Figure 9 suggests that cultured meat, despite its significant energy requirement, may emit fewer greenhouse gases than beef. This is due to the GHG-intensive nature of methane emissions and manure management for cattle that are absent for cultured meat. Cultured meat is not without waste products, however. Ammonia emissions are the primary source of its eutrophication potential and will be discussed further in the next section.



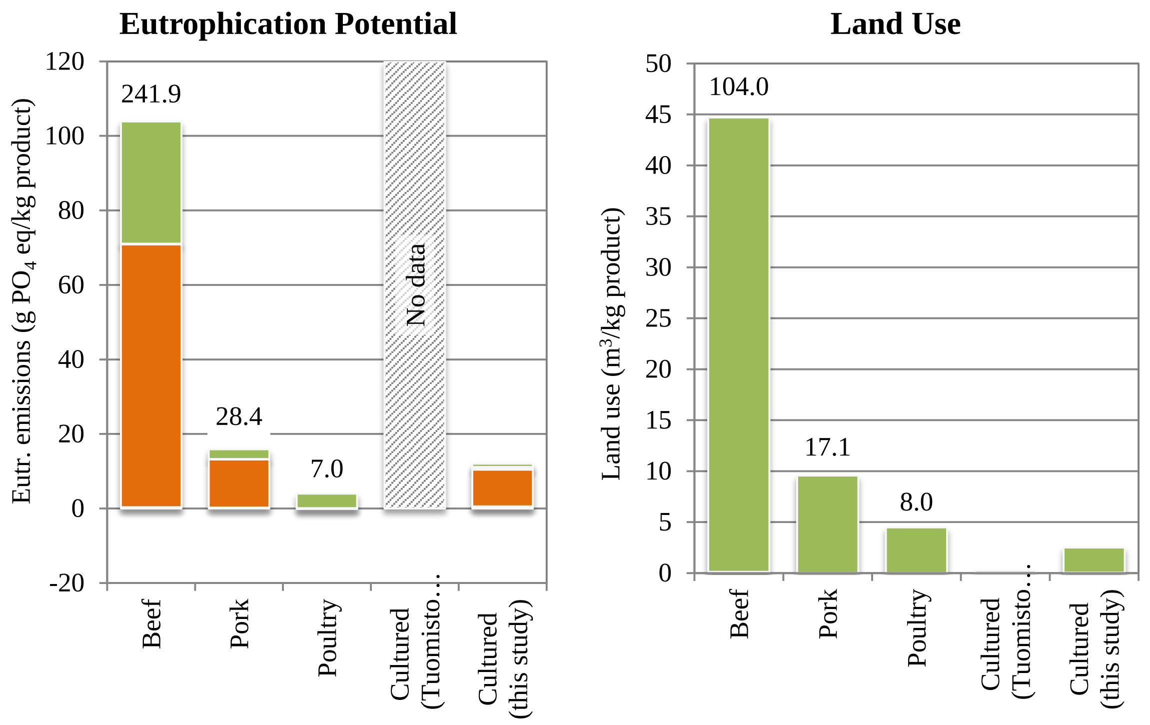
Legend			
Livestock production		Cultured meat production	
🟩	Feed primary production (includes processing and transport for beef and pork)	🟩	Feedstock primary production
🟪	Feed processing	🟪	Feedstock processing
🟪	Feed transport	🟪	Feedstock transport
🟪	On-farm energy (water) use	🟪	Cell cultivation
🟧	Enteric methane	🟪	Cleaning
🟧	Manure management	⬛	Facility
⬛	Other	🟧	Waste products

Figure 9. Results: Industrial energy use and global warming potential. Results are compared to those of feedlot beef (Pelletier, Pirog, et al., 2010), commodity high-profit pork (Pelletier, Lammers, et al., 2010), poultry (Pelletier, 2008), and cultured meat produced in California per Tuomisto and Teixeira de Mattos' (2011) LCA. Numbers

above the livestock column indicate impacts on an edible-weight basis (see Table 38 on page 207 for edible portions). The "other" category is predominantly the cost of bull production for beef (Pelletier, Pirog, et al., 2010), sow replacement for pork (Pelletier, Lammers, et al., 2010), and hatchery chicks for poultry (Pelletier, 2008).

Eutrophication potential. As shown in Figure 10, this study found that the eutrophication potential associated with cultured meat is slightly less than that of pork on a live-weight basis. The relatively small quantity of required feedstock serves to reduce the need for fertilizer application and therefore agricultural runoff. However, ammonia is a byproduct of cell culture and therefore contributes to this impact category. It could be argued that, even though cultured meat has a slightly smaller eutrophication potential than pork, the ability to better manage the waste stream emanating from a factory versus farm runoff makes the industrial process significantly more advantageous. It is even possible that ammonia could be recycled for amino acid production, though the energy requirements for such a recovery process are uncertain.

Just as treatment of waste from slaughterhouses was outside the boundaries of the livestock LCAs, this study similarly excluded treatment of waste from cultured meat production. However, it is worth mentioning that unmetabolized portions of soy hydrolysate, glucose, amino acids, vitamins, and salts will be present in the bioreactor waste stream, in addition to the ammonia, lactate, and alanine.



Legend			
Livestock production		Cultured meat production	
🟩	Feed primary production (includes processing and transport for beef and pork)	🟩	Feedstock primary production
🟧	Manure management		

Figure 10. Results: Eutrophication potential and land use. Results are compared to those of feedlot beef (Pelletier, Pirog, et al., 2010), commodity high-profit pork (Pelletier, Lammers, et al., 2010), poultry (Pelletier, 2008), and cultured meat produced in California per Tuomisto and Teixeira de Mattos' (2011) LCA. Numbers above the livestock column indicate impacts on an edible-weight basis (see Table 38 on page 207 for edible portions). Land use consists of land occupation values for beef and feed production values for pork; it excludes the area required to sequester atmospheric CO_2 emissions and the area required by nuclear energy. Land occupation for poultry sourced

from Williams, Audsley, & Sandars (2006a) and converted to live weight basis based on data given therein.

Water use. As depicted in Figure 11, water requirements for this study as compared to the Tuomisto and Teixeira de Mattos LCA depend on whether green water (rainwater) is included in the inventory. In total, water use in this study is 2.2 times that of the Tuomisto and Teixeira de Mattos LCA, but blue water (ground and surface water) withdrawals are slightly less than in the Tuomisto and Teixeira de Mattos model. The same phenomenon is evident for livestock: Beef, pork, and poultry are more water-intensive than cultured meat on a total basis, but comparable in terms of blue water. This can be explained by livestock's larger consumption of feed which contains corresponding amounts of embedded water. Most of this water is in the form of rainwater, however, and is not sourced from ground or surface sources.

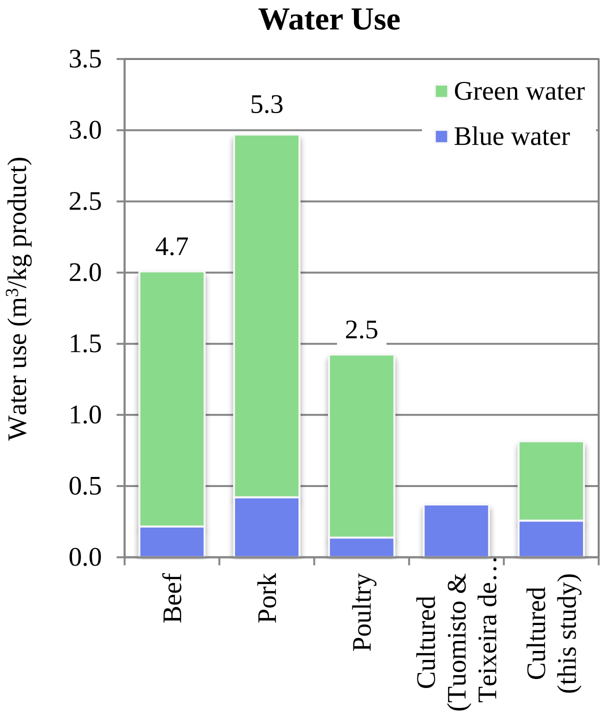


Figure 11. Water use comparison. Beef, pork, and poultry values were estimated based on Mekonnen and Hoekstra (2012) and converted to a live weight basis using data given in Table 38. Numbers above the livestock column indicate impacts on an edible-weight basis. Tuomisto and Teixeira de Mattos (2011) included both green and blue water in their LCA, but the California production model presented here required no green water.

Energy return on investment. Energy return on investment (EROI) is a means to demonstrate how much useful food energy is produced from invested energy. Whereas Figure 9 compares the impacts of cultured meat with those of livestock on a *live weight* basis, EROI focuses on *edible weight* and gross chemical (calorific) energy produced. Figure 12 depicts human-edible energy output divided by various types of energy inputs. It further underscores the phenomenon discussed above where cultured meat will utilize agricultural feedstocks more efficiently than animals at the expense of industrial energy inputs. Whereas cultured meat produces a great deal more food energy per food energy input (human-edible EROI), in terms of return on industrial energy, it is much lower – less than that of chicken.

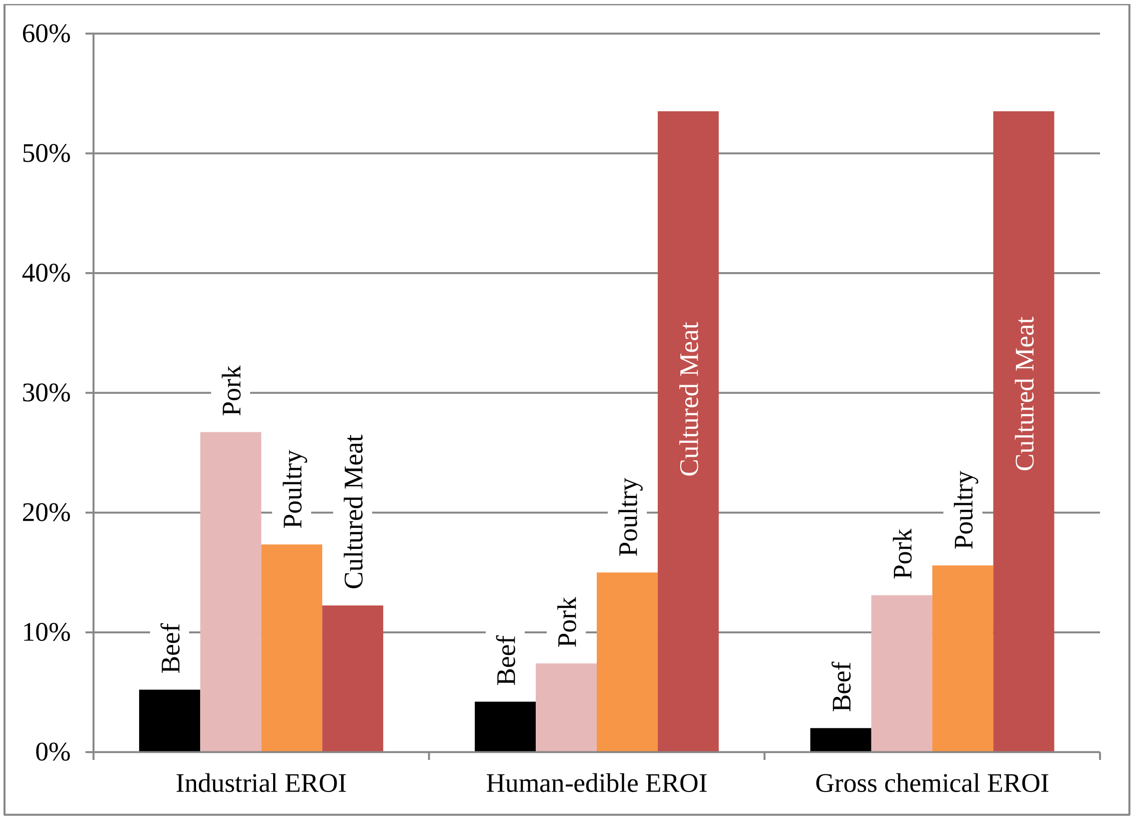


Figure 12. Energy return on investment (EROI). Industrial EROI is the human edible energy return on industrial energy investment; human-edible EROI is the human-edible energy return on human-edible caloric energy investment; and gross chemical EROI is the gross chemical energy return on gross chemical energy input (Pelletier, Pirog, et al., 2010). Please see Table 35 on page 204 for a detailed description of the sources and assumptions inherent in this chart.

These energy dynamics may be better understood through the analogy of the Industrial Revolution: Just as automobiles and tractors burning fossil fuels replaced the external work done by horses eating hay on roads and farms, tissue engineering of cells will similarly substitute industrial processes for the internal, biological work done by animal physiologies. That is, meat production in animals is made possible due to internal biological functions (temperature regulation, digestion, oxygenation, nutrient distribution, neutralization of pathogens, etc.). These are accomplished at the expense of biological (feed) energy inputs. Producing meat in a bioreactor means that these same functions must be performed at the expense of industrial energy, rather than biotic energy. As such, tissue engineering could be viewed as a new wave of industrialization.

Even though industrial energy is required to produce agricultural crops, Figure 12 indicates that a transition away from livestock rearing (particularly swine and poultry) in favor of cultured meat would simultaneously shift energy consumption away from agricultural feedstocks and toward industrial energy inputs. Therefore innovations that reduce the necessary industrial energy demand of cultured meat would be advantageous. The modeled processes that consume the most industrial energy, and therefore present significant opportunities for energy reduction, are discussed next.

Energy Consumption and Process Uncertainty

As Figure 9 showed, processing of feedstocks, cell proliferation, and bioreactor cleaning are the largest consumers of energy as modeled by this study. Figure 13 shows the same data broken down by specific input rather than product stage. The figure suggests that bioreactor cleaning is responsible for the bulk of the life cycle energy embodied in 1 kg of cultured meat, followed by deionizing and sterilizing the water for cell culture, basal medium production, glutamine production, and facility energy. All of these are important components of cultured meat production and are not likely to be eliminated in the near future: cleaning and sterilization procedures, for example, are followed to prevent the growth of microorganisms and essentially do the work that would otherwise be accomplished by the animal's immune system. Nonetheless, a great deal of uncertainty surrounds the methods that will be employed and, in some cases, there is uncertainty associated with industrial process inventories.

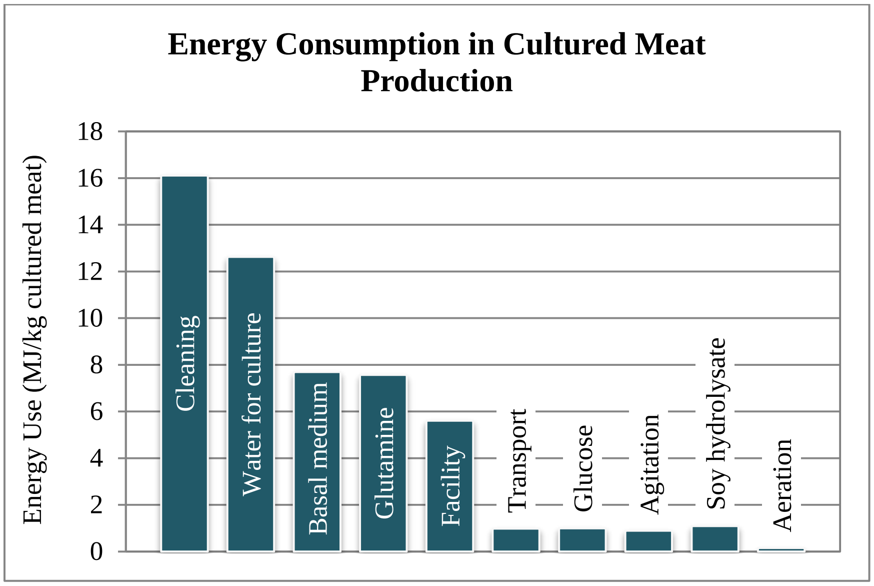


Figure 13. Energy consumption in cultured meat production by input. Water for culture includes sterilization and deionization.

As modeled for this LCA, the bioreactor cleaning process is the largest contributor to energy consumption for cultured meat production. Its sub-processes are shown in greater detail in Figure 14. While the chart underscores the energy-intensive nature of some chemical inputs such as sodium hydroxide, ongoing gains in industrial efficiency could serve to reduce life cycle energy consumption. Moreover, different sources provide different estimates of energy consumption inherent in the sodium hydroxide manufacturing process. This LCA used the inventory from the US LCI database (Norris, 2003) which reports that 15.4 MJ are required to produce 1 kg of sodium hydroxide. By contrast, other sources suggest that the energy might be closer to

3.5 MJ (Thannimalay, Yusoff, & Zawawi, 2013). If this were the case, the total energy required to produce 1 kg of cultured meat would be closer to 46.5 MJ (versus 53.6).

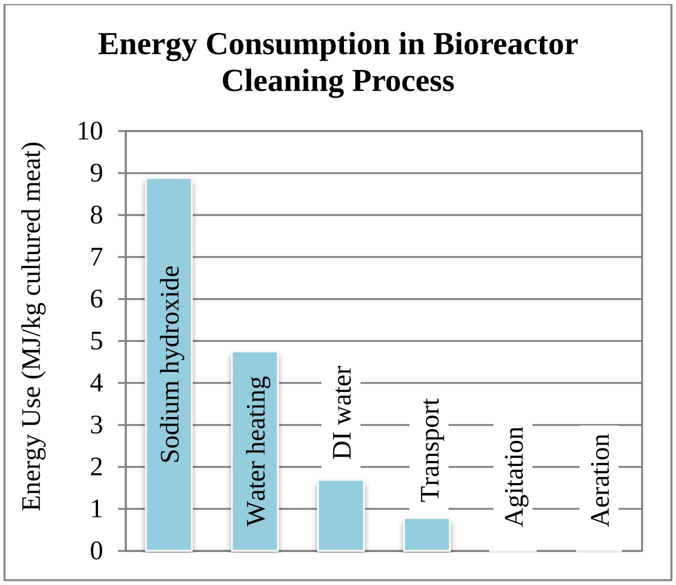


Figure 14. Energy consumption associated with bioreactor cleaning process.

Other contributors to the energy-intensive nature of cultured meat include the need to sterilize the culture medium prior to the batch cycle. Heating the water makes up 96% of the 12.6 MJ of energy associated with the water for culture. However, cultured meat facilities might adopt alternative techniques to heat such as sterile filtration via reverse osmosis. This would reduce the required energy by an uncertain amount, though it could have more significant environmental impacts in other categories.

Amino acids also contribute significantly to energy consumption. The amino acid glutamine plus the amino acids that constitute about 23% of the dry mass of the basal medium as modeled (shown in Table 30 on page 192) were assumed to be produced via a synthetic process. Synthetic amino acid production is a multi-step process involving corn production followed by milling, saccharification of the corn starch, and fermentation of the glucose in the presence of a nitrogen source such as ammonia or ammonium sulfate. All of these processes require additional industrial energy and contribute to the total energy intensity of cultured meat. However, it is possible that amino acids synthesized via fermentation could be replaced with a formulation of plant-based hydrolysates designed to meet the specific nutritional needs of proliferating muscle cells. This would have the advantage of reducing the number of industrial steps required for amino acid production, and therefore embedded energy, but could also increase the necessary agricultural inputs, and therefore land requirements. Additional uncertainty associated with the basal medium comes from the exclusion of vitamins and other compounds from the life cycle inventory (see Table 30). Depending on the manufacturing process for vitamins and chemicals like sodium bicarbonate, the life cycle energy consumption for cultured meat could be much higher than the estimation presented herein.

Finally, uncertainty surrounds the facility size and energy consumption estimates. It was assumed that the facility would be similar in size to a brewery and draw relatively little baseline energy for heating, ventilation, air conditioning, and lighting. However, the need to follow aseptic protocols could mean that a carnery could require clean room facilities that would not only require more baseline energy, but also require more floorspace. This and other points of uncertainty are explored in the sensitivity analysis.

Sensitivity Analysis

Factors modified for the sensitivity analysis reflect several areas of uncertainty in the model. In addition to questions associated with sterilization methods and facility energy requirements discussed above, uncertainties surrounding cell growth are explored. In particular, the seed cell density is lowered to account for additional energy associated with cell line maintenance and the maximum cell density is increased to simulate growth in an optimized bioreactor. Finally, the cell growth rate is increased to simulate one way that cells might be modified for more efficient meat production. All variable factors are summarized in Table 8. To assess model sensitivity to these factors, a Monte Carlo Analysis (MCA) was performed using SimaPro 8. Each simulation consisted of 1000 samples.

Table 8

Factors Modified for the Sensitivity Analysis

Variable	Probability distribution	Distribution parameters	Comments
Facility size	Triangular	Minimum: 500; most common: 717; maximum: 22,761 m^2	Most common corresponds to a brewery and maximum corresponds to a pharmaceutical model. Minimum value allows for uncertainty.
Facility energy consumption (lighting, HVAC, etc)	Uniform	513.31 to 1033.44 MJ/year	Minimum corresponds to a warehouse; maximum corresponds to an average commercial building (D&R International Ltd., 2012)
Sodium hydroxide life cycle energy	Uniform	3.5 to 15.4 MJ	Represents uncertainty associated with different sources
Sterilization temperature/energy	Triangular	Minimum: 0; maximum and most common: 63.5°C	Maximum corresponds to a culture medium sterilization process via heating to 140°C; minimum corresponds to sterile filtering of medium via reverse osmosis and a cell culture that proliferates well at ambient temperature.

(continued)

Table 8

Factors Modified for the Sensitivity Analysis

Variable	Probability distribution	Distribution parameters	Comments
Minimum cell density (X_0)	Triangular	Minimum: 1; maximum and most common: $1x10^7$ cells/mL	Minimum value is meant to capture environmental impacts of cell line maintenance. Maximum and most common value corresponds to initial density given by Sung et al.(2004)
Maximum cell density (X_1)	Triangular	Minimum and most common: $1x10^7$; maximum: $1x10^8$ cells/mL	Most common value corresponds to typical limits of STRs (Yang et al., 2004). Maximum value corresponds to densities achievable with hollow fiber bioreactors (Shipley et al., 2011).
Cell growth rate (μ)	Triangular	Minimum and most common: 0.0254; most common: 0.047 nmol/(10^6 cells·hr)	Most common value is based on experimental data (Sung et al., 2004). Maximum value corresponds to a yield of 0.9 g cell dry mass/g glucose dry mass

As shown in Figure 15, the greatest uncertainty is associated with energy use, global warming, acidification, and human toxicity. These factors are most closely related to energy consumption which could be significantly higher if factors such as facility energy requirements have been underestimated by the model. By contrast, the analysis indicates that, given most Monte Carlo scenarios, both land use and water use could be significantly reduced with respect to the baseline model. These are most strongly correlated with cell growth rate which, over time, could be increased as cells are selected or genetically modified to use feedstocks more efficiently for biomass production.

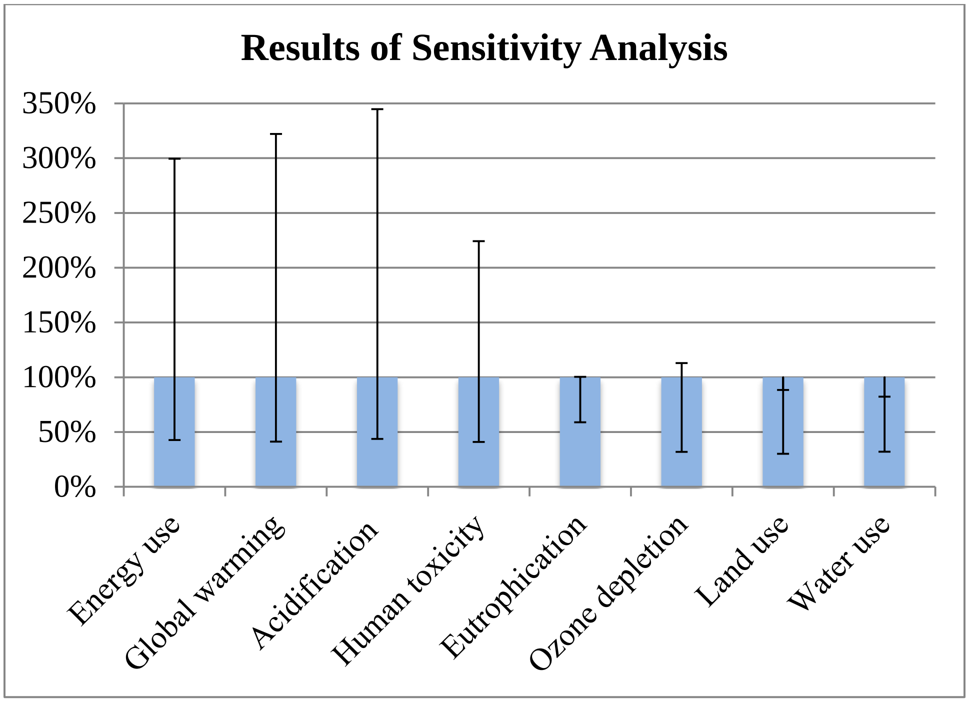


Figure 15. Results of the sensitivity analysis. Uncertainty bars reflect the 90% confidence interval.

Discussion

None of the findings presented in this chapter are meant to suggest that cultured meat should not be the subject of ongoing research and development. On the contrary, cultured meat is likely to come with many advantages including human health benefits and reductions in animal suffering. Nonetheless, an understanding of the potential environmental, economic, and social implications of emerging technologies can facilitate perception and mitigation of unintended consequences prior to and during commercialization.

Pros and cons of industrialization. The study presented herein should not be considered complete. Its scope was limited to one step (cell proliferation) of what will be a multistep process required to bring cultured meat to stores and restaurants. While the realized environmental impacts of large-scale cultured meat production are as yet highly uncertain, it nonetheless suggests that tissue engineering may constitute a new phase of the Industrial Revolution. Moreover, further industrialization of meat production will potentially come with many pros and cons that extend beyond the environmental realm. Even though industrial energy consumption may rise slightly, waste products emanating from meat factories may be easier to treat or recycle than those leaching into farm runoff. Yet, the manure and litter from animal rearing will similarly be lost as sources of fertilizer, leaving the farms more dependent on synthetic nitrogen and phosphorus. Decreased feedstock demands for meat production may reduce the cost of crops such as soy and cereal grains while increasing availability of these commodities for biofuel production. A possible concomitant decline in agricultural land use could bring environmental and economic challenges including disruption of certain farm economies and declining land prices.

Anticipatory life cycle analysis. The model underlying this LCA indicates that energy consumption, GHG emissions, land use, and total water use could be more intensive than those indicated by Tuomisto and Teixeira de Mattos. Much of this difference was attributed to diverse feedstock models: this study included glucose, soy hydrolysate, and basal medium including synthetic amino acids whereas Tuomisto and Teixeira de Mattos relied on cyanobacteria hydrolysate alone. Due to the seemingly burdensome nature of the feedstock model used in this study, one might be tempted to conclude that it is the inferior choice compared to cyanobacteria hydrolysate. However, the feedstock model developed for this LCA was based on peer-reviewed studies demonstrating its effectiveness for supporting cell growth. More research and analysis would be required to assess the nutritional adequacy of cyanobacteria hydrolysate alone for large-scale cell culture.

More broadly, the disparate feedstock choices in the two models serve to underscore an important point about anticipatory LCA: Until processes have become manifested in working manufacturing facilities, the models associated with life cycle analyses can be only approximate. Both of the models discussed herein serve to provide insight into how diverse manufacturing decisions could impact the environment at large. Moreover, they suggest that every production decision will have environmental trade-offs; being cognizant of those trade-offs can aid in developing a production process that is least detrimental to the surrounding region.

Even though significant uncertainty surrounds this analysis, anticipatory analyses can nonetheless be valuable in highlighting the possible implications of, and tradeoffs associated with, emerging technologies as they are maturing and before plant development manifests undesirable environmental impacts. As industrial bioengineering technologies advance, significant leaps forward in cell culture techniques will undoubtedly be made. Ongoing reviews of the state of the art will help to illustrate their benefits and highlight areas for improvement.

Chapter 6

Economic Input-Output Analysis

The *in vitro* hamburger served in London on August 5, 2014, reportedly cost over €250,000 (“Cultured beef: Frequently asked questions,” n.d.) (about $350,000), but a study published in 2008 suggested cultured meat could one day be as inexpensive as unsubsidized beef (eXmoor Pharma Concepts, 2008). This investigation seeks to explore the impacts on the US economy if cultured meat were substituted for traditional beef, pork, and poultry.

Output Multipliers

An output multiplier is defined as “the total value of production in all sectors of the economy that is necessary in order to satisfy a dollar’s worth of final demand for [one sector’s] output” (Miller & Blair, 1985, p. 245). This can be better understood with an example. A hypothetical graduate student decides to have a hamburger for lunch at a local restaurant. She pays the restaurant $15 and leaves a $3 tip for the waiter. Because of the extra work the waiter did to serve the student’s hamburger, he uses the student’s $3 to purchase potato chips from a deli as a snack. The deli, in turn, must purchase additional potato chips from its supplier. The supplier must then purchase additional potato chips from a processor who must purchase more potatoes from a farm. The farm must plant additional potatoes, buy more fertilizer, hire more employees, and so on. In fact, even though the student paid the waiter only $3, the total economic activity required to produce the $3 snack was much greater than $3.

This dynamic can be quantified in aggregate via output multipliers. By adding down the columns in national input-output tables, the direct impact of spending $1 more in that industry can be ascertained. This is its simple output multiplier. Meat production requires a large number of economic inputs including feed, water, energy, and medicine which in turn require additional inputs. As such, meat production might be expected to have a large multiplier effect, and it does. As shown in Table 9, animal-production industries make up two of the ten industries with the largest economic multipliers. Animal and byproduct processing industries make up another four. Therefore it is hypothesized that a shift away from agricultural meat production in favor of cultured meat would result in a net decline in economic activity, at least temporarily.

Table 9

Industries with the Largest Economic Multipliers

NAICS code	Industry	Multiplier
31161A	Animal (except poultry) slaughtering, rendering, and processing	3.33424
316100	Leather and hide tanning and finishing	3.29754
311513	Cheese manufacturing	3.2088
112300	Poultry and egg production	3.19034
311225	Fats and oils refining and blending	3.18257
311615	Poultry processing	3.1692
1121A0	Cattle ranching and farming	3.04904
311119	Other animal food manufacturing	3.04349
31131A	Sugar cane mills and refining	3.03402
31122A	Soybean and other oilseed processing	3.01651

Note. Data derived from 2002 benchmark industry by commodity total requirements table (United States Bureau of Economic Analysis, 2008).

Approach

The hypothesis that replacing agricultural meat with cultured meat would result in an aggregate economic decline will be tested by developing an inventory of inputs required to produce cultured meat. This will be scaled up to the equivalent of all meat produced in the United States in 2002. Using input-output tables for 2002 published by the BEA (United States Bureau of Economic Analysis, 2008), a scenario can be developed that would simulate replacement of all traditional meat production with cultured meat.

In order to estimate the economic flows associated with cultured meat, a hypothetical production facility and an inventory of material inputs for cultivation were developed based on cell nutritional requirements published in Sung et al. (2004) and large-scale cell production techniques common in the United States at the present time (Hu, 2012). A summary of the hypothetical cultured meat production model is presented in Figure 16 and described below. This is a simplified version of the model used for the life cycle analysis shown in Figure 3 on page 19. It bears repeating that no large-scale cultured meat production facilities currently exist. The model described herein should be viewed as approximate and subject to change as the art and practice of tissue engineering progresses.

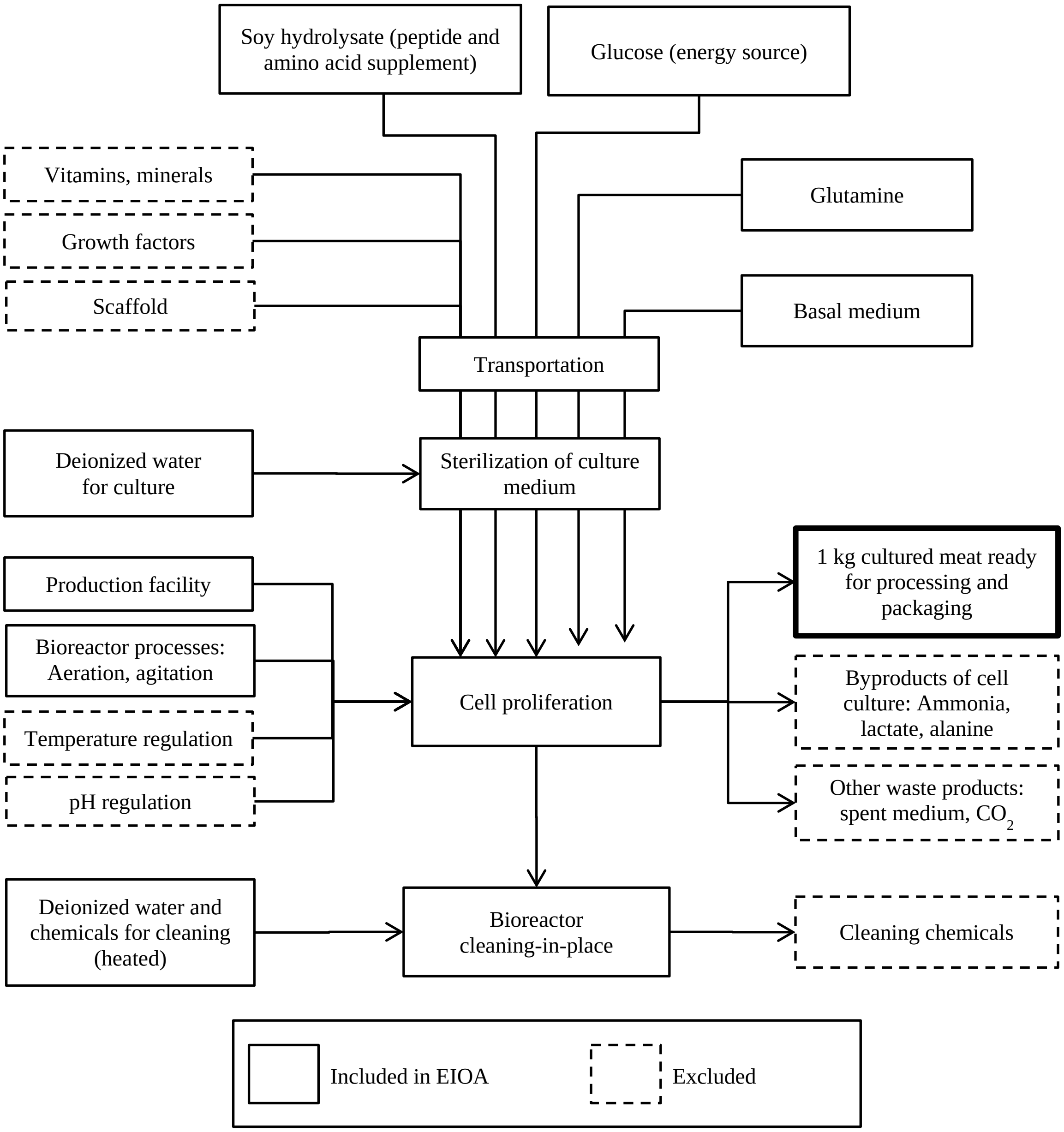


Figure 16. System diagram for hypothetical cultured meat production process. Separation of cultured meat from the broth (possibly via centrifugation) as well as cultured meat processing and packaging are not included in this study.

Inventory Overview

The production model for the economic analysis is identical to the life cycle inventory discussed in Chapter 5 except that labor costs were added in the economic inventory. As with the model for required facility floorspace (discussed in APPENDIX C on page 217), the brewing industry was used as a guide for estimating necessary labor costs. Please see APPENDIX C on page 218 for details of the labor model. A summary of all characteristics of the production model can be found in Table 10.

Table 10

Inventory to Produce 1 kg Cultured Meat

Substance	Per year	Per batch	Per 1 kg of cultured meat
Inputs			
Seed culture (not included in analysis)		1×10^5 cells/mL	350 μg
Facility floorspace	717 m^2		0.007 m^2
Number of employees	3.74		0.000036
Water for process (deionized and sterilized)		15,000 L	28.9 L
Glucose		183.3 kg	352.7 g
Glutamine		15.4 kg	29.6 g
Oxygen (not included in cost of production but required for aeration energy calculation)		60.2 kg	115.9 g
Soy hydrolysate (dry matter)		75 kg	144.3 g
Basal medium (dry matter)		15,000 L	28.9 L
Energy			
Facility	368,034 MJ		3.56 MJ
Heating water for sterilization		3,981 MJ	7.7 MJ

(continued)

Table 8

Factors Modified for the Sensitivity Analysis

Substance	Per year	Per batch	Per 1 kg of cultured meat
Heating water for cleaning		1,567 MJ	3.0 MJ
Agitation		293MJ	0.56 MJ
Aeration		48.2 MJ	0.09 MJ
Deionization		390 MJ	0.75 MJ
Transportation		337 tkm	0.65 tkm
Sodium hydroxide (food grade) for cleaning		300 kg	577 g
Water for cleaning (deionized)		45,000 L	86.6 L
Outputs			
Cultured meat	103,463 kg	$1x10^7$ cells/mL or 520 kg	1 kg
Lactate (excluded from analysis)		147 kg	283 g
Alanine (excluded from analysis)		3.3 kg	6.31 g
Ammonia (excluded from analysis)		13.4 kg	25.8 g
Sodium hydroxide (excluded from analysis)		300 kg	577 g
Materials and processes not included in the inventory			
Piping, tubing, and pumps required to transport nutrients to the cell culture			
Nutrient containers			
Construction of the facility and other capital expenditures			
Materials required to acquire and maintain the cell line			

Economic Analysis

In preparation for use with the 2002 benchmark tables published by the US Bureau of Economic Analysis (BEA) (2008), 2013 retail prices and 2002 producer prices for all material and energy inputs were compiled. These are summarized in Table 11 with sources and exceptions noted. In general, it was assumed that inputs would arrive in ready-to-use condition. The exception to this is water which is assumed to be deionized and sterilized in the cultured meat facility. Energy costs associated with deionization and sterilization are included but outlays for the purchase of deionization resin were not. Energy quantities were converted to physical units using the brewery energy mix presented in Table 6 on page 58. Capital expenditures, cost of capital, and value added were not considered in this analysis.

Table 11

Inputs and Prices for Production of 1 kg Cultured Meat

Substance	Units	2013 retail price per unit quantity	2002 producer price per unit quantity
Industrial space (lease)	$/m^2/year	$61.68 [b]	$43.06 [c]
Labor, average total compensation for breweries (NAICS 312120)	$/employee /year	$86,909 [d]	$71,436 [e]
Tap water for process	$/L	$0.0023 [f]	$0.00041 [g]
Glucose	$/g	$0.02 [h]	$0.00033 [i]
Glutamine	$/g	$0.44 [j]	$0.25523 [a]
Soy hydrolysate (dry matter)	$/g	$0.07 [k]	$0.04101 [a]
Basal medium (IMDM)	$/L	$8.10 [l]	$4.69863 [a]
Energy			
Electricity (final/delivered energy for industrial use)	$/kWh	$0.07 [m]	$0.04830 [n]
Natural gas	$/ft^3	$0.0034 [o]	$0.00248 [p]
Coal	$/short ton	$55.64 [q]	$17.52 [r]
Steam	$/lb	$0.0023 [s]	$0.0023 [s]
Transportation	$/tkm	$0.26 [t]	$0.18 [u]

(continued)

Table 11

Inputs and Prices for Production of 1 kg Cultured Meat

Substance	Units	2013 retail price per unit quantity	2002 producer price per unit quantity
Tap water for cleaning	$/L	$0.0023 [f]	$0.00041 [g]
Sodium hydroxide	$/g	$0.0024 [v]	$0.0014 [a]

[a] Computed based on 2013 retail price, 2013 and 2001 consumer price indices (CPIs) (U.S. Department of Labor Bureau of Labor Statistics, 2013) and 2002 gross margin for NAICS industry 4246 (chemicals and allied products) (United States Census Bureau, n.d.-c) according the formula

$$\text{2002 producer price}=(\text{1-2002 gross margin})\left[\left(\frac{\text{2002 CPI}}{\text{Sept 2013 CPI}}\right)(\text{2013 retail price})\right]$$

[b] (CBRE Global Research and Consulting, 2013)

[c] (Kelly, 2004) for Raleigh, NC

[d] (United States Census Bureau, n.d.-b)

[e] (United States Census Bureau, n.d.-a)

[f] (North Carolina League of Municipalities & UNC Environmental Finance Center, 2013)

[g] (“Central Arizona groundwater replenishment district final 2013/14 - 2014/15 rate schedule,” n.d.)

[h] (“Glucose, powder,” n.d.)

[I] (Economic Research Service of the USDA, 2013)

[j] (“L-Glutamine,” n.d.)

(continued)

Table 11

Inputs and Prices for Production of 1 kg Cultured Meat

[k] (“Peptone Hy-Soy® T,” n.d.)

[l] (“IMDM, Powder,” n.d.)

[m] (US Energy Information Administration, n.d.-a)

[n] (US Energy Information Administration, 2004)

[o] (“Today in energy: Daily prices,” 2013)

[p] (US Energy Information Administration, 2004)

[q] (“Today in energy: Daily prices,” 2013)

[r] (US Energy Information Administration, 2004)

[s] (*How to calculate the true cost of steam*, 2003)

[t] (Bureau of Transportation Statistics, n.d.) for 2012

[u] Computed from (Bureau of Transportation Statistics, n.d.); assumes a profit margin of 5% (Ostria, 2003).

[v] (Duda Energy LLC, n.d.)

Based on the input quantities modeled multiplied by the unit prices, cultured meat would be expected to cost $267 per kg ($121/lb) in 2013 retail prices and $153 per kg ($69/lb) in 2002 producer prices. A comparison with contemporary prices of common cuts of agricultural meat is given in Table 12.

Table 12

Computed Cultured Meat Costs Compared with Beef, Pork, and Poultry Prices as of August 2013

	Ground beef	Sirloin steak	Pork chops	Broiler composite	Boneless chicken breast	Cultured based on 2013 retail prices
Price ($) per kg	7.61	14.56	7.79	4.41	7.93	267

Note. Adapted from United States Department of Agriculture (n.d.).

Scaling of input costs. The high computed price for cultured meat is somewhat problematic for an economic analysis. High prices represent large economic flows and substituting these for agricultural meat on a mass-equivalent basis would produce unrealistic economic growth in the model. Moreover, assuming cultured meat is ever widely adopted, the price will almost certainly need to be comparable to existing meat products. For this reason, the prices for cultured meat inputs were scaled down significantly in order to be equivalent to a computed composite price of $2.02 per kg for agricultural meat as produced in the United States. The meat composite is summarized in Table 13 and computed as follows.

$$Quantity\ of\ beef\ (or\ pork\ or\ poultry) in\ composite$$

$$= \frac{Quantity\ of\ beef\ produced\ in\ 2002}{Beef\ quantity + Pork\ quantity + Poultry\ quantity} \times 1\ kg \qquad (6)$$

$$Composite\ price\ =$$

$$\frac{(Beef\ price)(Beef\ quantity) + (Pork\ price)(Pork\ quantity) + (Poultry\ price)(Poultry\ quantity)}{Beef\ quantity + Pork\ quantity + Poultry\ quantity}$$

$$= \$2.02\ per\ kg \qquad (7)$$

The results of a study by eXmoor Pharma Concepts (2008) suggested that cultured meat may one day match the price of unsubsidized beef. It may therefore never reach the composite price of $2.02 per kg. Nonetheless this value was chosen to facilitate the exploration of impacts associated with cultured meat without introducing economic growth into the model. For this reason, scaling factors were applied to prices of inputs inconsistently but based on the logic that cultured meat producers are unlikely to receive discounts on commodities such as energy and water. By contrast, large scaling factors were applied to the processed and chemical inputs including glutamine, soy hydrolysate, and basal medium. These components lend themselves to large volume discounts, if not production within the cultured meat facility itself. Moderate discounts were applied to industrial space, labor, and the commodity glucose. All of these might be subject to small variations in price depending on geographic location and quantity purchased.

Table 13

Composite Price for 1 kg of Meat Produced in the United States, 2002 Producer Prices

Value	Beef	Pork	Poultry	Composite
2002 production, dressed weight basis	12.3 billion kg	8.9 billion kg	17.5 billion kg	
2002 producer price	$3.57/kg	$1.44/kg	$1.23/kg	$2.02/kg
Amount in composite	0.318 kg	0.230 kg	0.451 kg	1 kg

Note. Adapted from National Agricultural Statistics Service of the USDA (n.d.).

Table 14

Scaling Factors for Cultured Meat Input Prices

Substance	Units	2002 producer price per unit quantity	Scaling factor	Scaled price per unit quantity, 2002 producer cost
Industrial space (lease)	$\$/m^2/year$	43.06	0.5	21.53
Labor for breweries (NAICS 312120)	$/employee /year	71,436	0.5	35,718
Tap water for culture	$/L	0.00041	1.0	0.00041
Glucose	$/g	0.00033	0.2	0.00007
Glutamine	$/g	0.25523	0.005	0.00128
Soy hydrolysate (dry matter)	$/g	0.04101	0.005	0.00021
Basal medium (IMDM)	$/L	4.69863	0.0008	0.00377
Energy				
Electricity (final/delivered energy for industrial use)	$/kWh	0.04830	1.0	0.04830
Natural gas	$\$/ft^3$	0.00248	1.0	0.00248
Coal	$/short ton	17.52	1.0	17.52
Steam	$/lb	0.0023	1.0	0.0023
Transportation	$/tkm	0.18	1.0	0.18
Tap water for cleaning	$/L	0.00041	1.0	0.00041
Sodium hydroxide	$/g	0.00141	0.2	0.00028

Economic input-output. The input costs for 100,000 kg of cultured meat were allocated to NAICS industries as shown in Table 15. Simultaneously, the beef, pork, and poultry costs associated with the composite described in Table 13 were assigned to the corresponding NAICS code. Using Microsoft Excel, this information was formatted into a matrix of 430 rows and 1 column. It was then multiplied by the 2002 benchmark industry by commodity total requirements table (427 rows x 430 columns) (United States Bureau of Economic Analysis, 2008) in order to determine the industries impacted by the commodity substitution.

Table 15

Commodity Substitution Matrix for Input-Output Analysis

Commodity	Change in final demand based on 100,000 kg substitution ($)	NAICS Code	NAICS Industry
Beef	-113,447	1121A0	Cattle ranching and farming
Pork	-33,144	112A00	Animal production, except cattle and poultry and eggs
Poultry	-55,721	112300	Poultry and egg production
Industrial space (lease)	14,918	531000	Real estate
Labor	129,000	814000	Private households
Tap water for culture	1,189	221300	Water, sewage and other systems
Glucose	2,341	311221	Wet corn milling
Glutamine	3,773	325414	Biological product (except diagnostic) manufacturing
Soy hydrolysate (dry matter)	2,959	31122A	Soybean and other oilseed processing
Culture medium (IMDM)	10,868	325414	Biological product (except diagnostic) manufacturing

(continued)

Table 15

Commodity Substitution Matrix for Input-Output Analysis

Commodity	Change in final demand based on 100,000 kg substitution ($)	NAICS Code	NAICS Industry
Energy			
Electricity (final/delivered energy for industrial use)	3,291	221100	Electric power generation, transmission, and distribution
Natural gas	1,707	221200	Natural gas distribution
Coal	430	324199	All other petroleum and coal products manufacturing
Steam	242	221300	Water, sewage and other systems
Transportation	11,787	484000	Truck transportation
Tap water for cleaning	3,566	221300	Water, sewage and other systems
Total economic change [a]	0.00		

[a] Numbers may not add to total due to rounding error.

Results

As shown in Figure 17, the hypothesis that substituting cultured meat for agricultural meat would result in diminished economic output was confirmed. The model predicts that total output would fall $3.16 per kg of cultured meat substituted for agricultural meat. Industries where growth is observed are those that provide direct inputs to cultured meat production: inorganic chemical manufacturing provides the sodium hydroxide for cleaning the bioreactors, biological product manufacturing provides glutamine and basal medium, and government enterprises provide water for the process.

Contracting industries include those directly related to livestock production. These include cattle, pork, and poultry production, and animal food manufacturing. Projected declines in crop production and processing industries (crop farming, grain farming, and support activities for agriculture) indicate that cultured meat will require fewer feedstock inputs than livestock. This is supported by the projected decline in the real estate industry and was confirmed to be the case in the life cycle analysis. The presence of petroleum refineries among the declining industries indicates that cultured meat will require less energy than livestock. Despite this seeming contradiction of the life cycle analysis results, it is important to remember that the EIOA is based on economic allocations, rather than mass allocations as reported by the life cycle analysis. Because edible meat makes up the bulk of livestock value, the EIOA is effectively applying most of the environmental impacts to the edible weight of the animal. This same approach is approximated in the numbers above the livestock columns in Figure 9 on page 65. The discrepancy is likely further exacerbated by the scaling down of costs associated with energy-intensive cultured meat inputs such as sodium hydroxide, glutamine, and basal medium. For that reason, it is likely that this analysis does not provide an accurate reflection of relative energy consumption.

Wholesale trade and monetary industries indicate less obvious trends. Wholesale trade is relatively strongly correlated with animal food production which indicates simply that it will be negatively impacted as animal food production declines. Industry 52A000, monetary authorities and depository credit intermediation, is part of the finance and insurance sector and is relatively strongly correlated with cattle farming and ranching as well as other crop producing industries. While this is an important relationship to consider, the presence of this industry among those projected to decline may simply be the result of the exclusion of the cost of capital from the cultured meat production model.

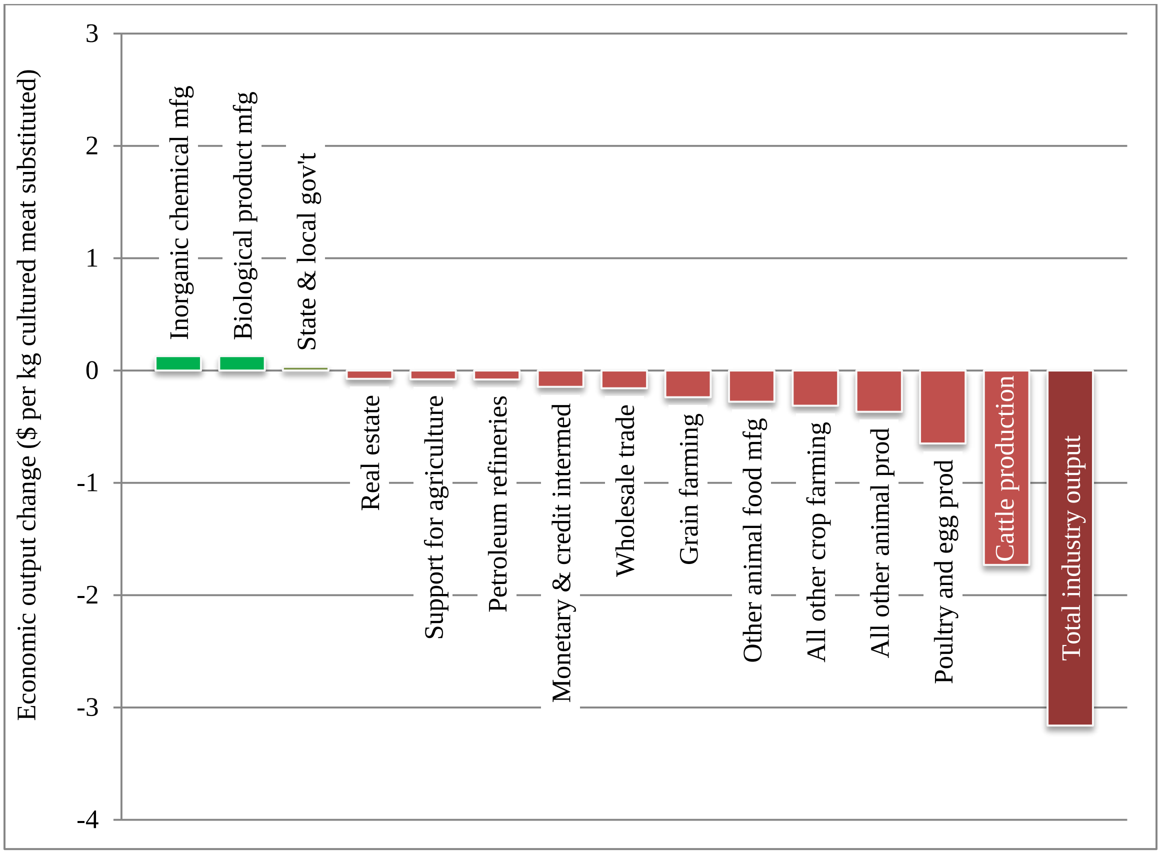


Figure 17. Effects of substituting cultured meat for agricultural meat composite. Only industries contributing at least 1% of the total change are included in this chart. Some industry names are abbreviated for legibility.

Discussion

This analysis suggested that a shift away from livestock production in favor of cultured meat would result in economic contraction. However, this should be considered in light of the conclusions from the life cycle analysis indicating that cultured meat might be a continuation of the Industrial Revolution. As has been the general trend of industrialization historically, innovations that would be expected to cause economic decline have instead led to growth. Given that cultured meat production will replace the internal work done by livestock with industrial energy, any economic contractions associated with cultured meat as a substitute for livestock rearing could be expected to be temporary. A similar counterintuitive cause-effect relationship is known as Jevons' paradox which refers the tendency for a reduction in factor inputs to result in greater overall consumption of that resource. Because cultured meat production could result in more productive use of corn and other feedstocks for meat production, it could counterintuitively lead to greater overall consumption of those agricultural commodities. More investigation is required to ascertain whether one or both of these counterintuitive trends might be likely.

In addition, this economic analysis was based on an economic input-output model that was open with respect to private households. This means that changes in wages associated with the shift in commodity production would not be reflected in the results. This unfortunately renders the model somewhat incomplete and limits the information available from it. Despite the need for further investigation, this analysis suggests that substituting cultured meat for livestock could result in economic contraction – particularly in the agricultural sectors.

Chapter 7

Impact Evaluation: Implications of Cultured Meat

This chapter considers the results of the environmental analysis in a national context and highlights areas that could be significantly impacted by a general replacement of livestock with bioengineered products. Social projections are excluded from this section because they are addressed as thoroughly as possible in Chapter 4. Moreover, economic projections were not developed because the structure of the US economy would shift significantly in response to commercialization of cultured meat. An economic projection based on transactions in 2002 would fail to capture these adaptions and render it inherently and unavoidably unhelpful.

Environmental Projections

Based on the results presented in Chapter 5, projections associated with shifts in energy consumption, GHG emissions, eutrophication potential, land use, and water use were computed for the three cultured meat production scenarios shown in Figure 2. It should be noted that the projections are computed for livestock on a live weight basis which reflects an assumption that substitutes for all byproducts of slaughter will be produced via a process similar to cultured meat production. The projections also assume that all other factors remain unchanged, including technology that could facilitate increasing crop yields.

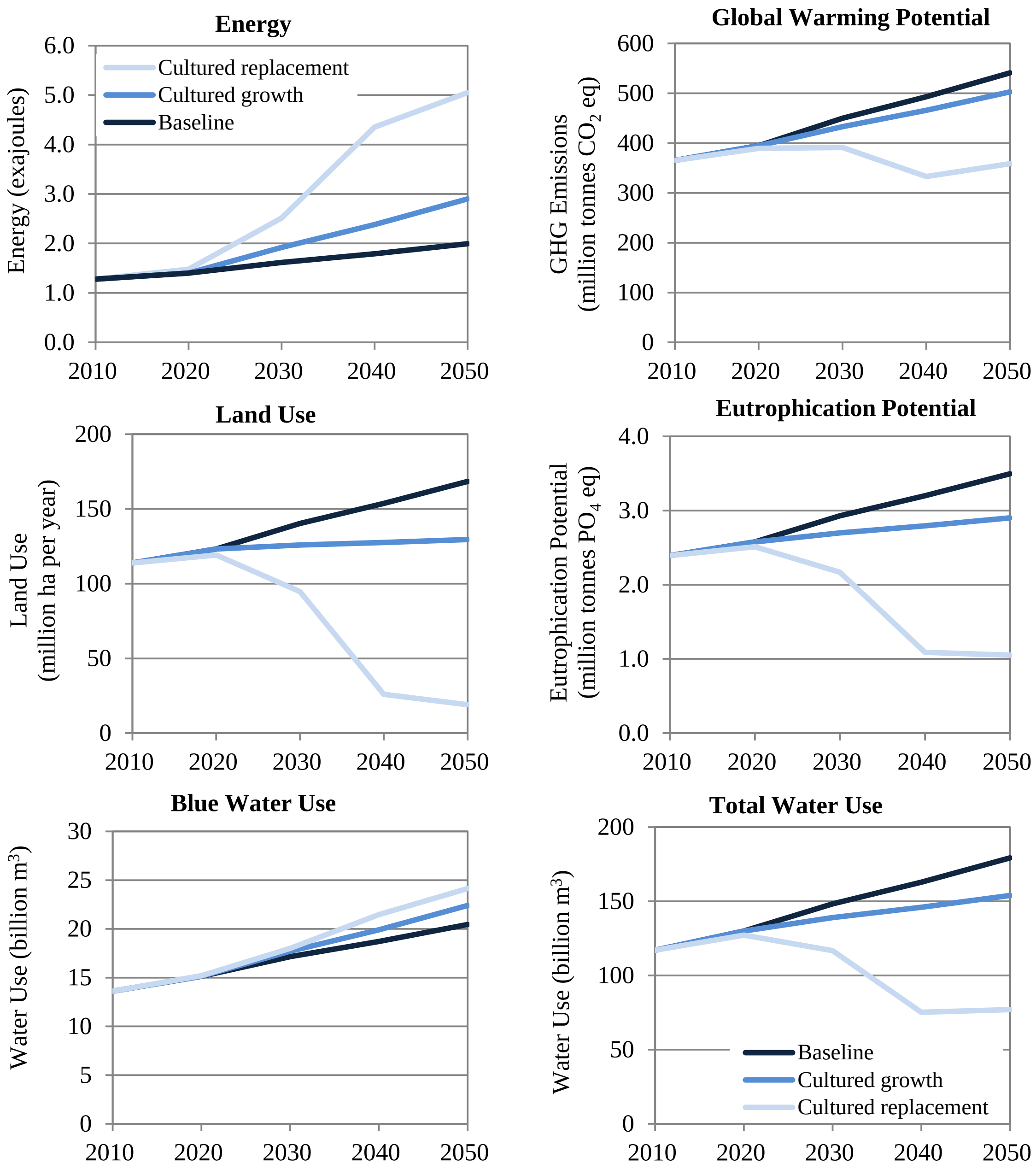


Figure 18. Possible shifts in environmental impacts associated with cultured meat transition scenarios. Projections are computed by multiplying the results of the life cycle analysis discussed in Chapter 5 by the quantities of cultured meat, beef, pork, and poultry (on a live weight basis) associated with the transition scenarios shown in Figure 2.

Given these caveats, the environmental projections are depicted in Figure 18. Due to anticipated increases in US meat production, all environmental impacts could be expected to increase in the Baseline scenario. As compared to that projection, the Cultured Replacement scenario suggests that energy use and blue water consumption would increase even more dramatically. However, GHG emissions could be expected to remain roughly stable, and land use, eutrophication potential, and total water consumption might decline if cultured meat completely replaces livestock.

These trends mean little outside the context of aggregate national use, however. For this reason, the projected changes in impacts were compared to national aggregate values from recent years. As shown in Table 16, cultured meat would have only small effects on national energy consumption, GHG emissions, and fresh water withdrawals (blue water only). Land use effects could be much more significant, however. The Baseline case where US meat production grows from 59 billion kg in 2007 and 2010 to 94 billion kg (live weight) in 2050 suggests that land use would expand by 6% if all other factors remained unchanged. This is equivalent to a 35% increase in cropland. By contrast, the Cultured Replacement scenario implies that land use could decline even more dramatically, releasing 10% of total US land area (58% of cropland) for other uses.

Both of these scenarios represent diverse but challenging environmental and economic trends. Assuming cultured meat does not offset any anticipated increases in meat production, land use devoted to livestock rearing could expand, leading to rising land and food prices. On the other hand, a rapid shift toward cultured meat production could result in falling land and food prices, as well as continued declines in agricultural employment. At the same time, a number of factors could preempt these intuitive effects.

Expansion of biofuel production, for example, could absorb agricultural surpluses and lead to continued agricultural expansion.

Table 16

Environmental Implications of Cultured Meat in a National Context

Value	US aggregate	Approximate increase (decrease) in 2050 with respect to present: Baseline projection	Approximate increase (decrease) in 2050 with respect to present: Cultured Replacement projection
2007 energy consumption (PJ)	106,892 [a]	0.7%	3.5%
2007 GHG emissions (million tonnes CO_2-eq)	7,263 [b]	2.5%	0.2%
2005 fresh water withdrawals (billion m^3)	483.5 [c]	1.6%	2.4%
2007 total land (million hectares)	936 [b]	6.0%	(9.5%)
2007 crop land (million hectares)	159 [b]	35.1%	(55.7%)

Note. Fresh water values include blue water only.

[a] Source: (US Energy Information Administration, 2013)

[b] Source: (US Environmental Protection Agency, 2013)

[c] Source: (United States Geological Survey, n.d.)

The potential shift being described here is reminiscent of a time in the early 20th century when horses and mules were replaced by tractors and automobiles. In 1913, 28% of all harvested land (37 million hectares) was devoted to growing feed for horses and mules (United States Census Bureau et al. 1997, Series K 496-501). This area slowly diminished in the decades that followed, but total cropland did not begin to decline as a general trend until 1950 (United States Census Bureau et al. 1997, Series J 52-53). Thus, even though a transition to cultured meat could exceed the land use changes seen as tractors and automobiles replaced animals for work and transportation, afforestation or reforestation is not guaranteed. Other factors including gains in productivity, economic cycles, changes in agricultural exports, and increasing biofuel production would all play important roles in land use.

Potential Tradeoffs Associated with Cultured Meat

A number of important challenges and tradeoffs are presented elsewhere in the document, particularly in the social assessment discussion in Chapter 4. However, a number of implications were not highlighted specifically by other assessments and are therefore included here. These remain speculative and are included for the purposes of further consideration and discussion.

Environment and economy. An important realization that resulted from performing both environmental and economic analyses was that, despite the energy-intensive nature of cultured meat production, energy is likely to account for only a small portion of total costs. This is also reflected in other industries. For example, despite being “the second largest user of energy in the manufacturing sector” (US Energy Information Administration, n.d.-b), chemical producers as a whole (NAICS 325) spend only about 3% of their operating budget on fuels and electricity (United States Census Bureau, n.d.-a). This rather subtle incentive structure inherent in the economy may serve to derail efforts to improve environmental sustainability of cultured meat and other industrial production processes.

Ethics. Many people might find it objectionable to use embryonic stem cells for purposes other than propagating a complete organism. Yet growing meat from embryonic stem cells could theoretically produce a great deal of cultured meat while reducing or eliminating the need to acquire tissue explants from donor animals. A similar dynamic may form around propagating genetically-modified cells. While genetic modification of animal cells is not a prerequisite for culturing meat, genetic modification is among the techniques that can render a cell line immortal, thus reducing the frequency that tissue samples would need to be taken from a donor animal. Hence a dilemma may arise between reducing donor animal suffering and eating food from embryonic or genetically modified stem cells. Genetic modification could also be used to impart specific characteristics to the muscle and fat tissue. Some of these might enhance the flavor or texture of the meat, while others might increase the growth rate or resource efficiency of the culturing process, thus modifying environmental impacts and/or economic costs.

Species and energy. As discussed in the heat transfer analysis in APPENDIX B (page 207), both heating and cooling of the cultured meat bioreactors might be required to keep cells at a temperature optimal for growth. For mammals, optimum temperature is around 37°C and “variations of 1°C can reduce cell growth, viability, and/or product production” (Flickinger, 2013, p. 874). However, other cell types such as those from insects or fish have different optimal growth temperatures and may also proliferate well over a wider range of temperatures. For this reason, energy required to produce muscle and fat tissue may be reduced if consumers were willing to accept meat from non-traditional species.

Antibiotics. Overuse and misuse of antibiotics has been linked to antibiotic-resistant bacteria and the use antimicrobials to promote growth of livestock has been discouraged by the Food and Drug Administration (FDA, 2013). Tissue engineering practices dictate that cultured meat would be grown in sterile conditions, thereby not only decreasing the risk of food-borne illness, but also antibiotic use. However, it remains possible that some producers might introduce antibiotics, antivirals, and antifungals in tissue cultures to reduce the energy required to sterilize the culture medium and other inputs for cultured meat. On the other hand, antibiotic production itself may be energy-intensive. Therefore this is another area that is deserving of more analysis.

Chapter 8

Metrics for Ongoing Dialog and Management

The practice of Earth Systems Engineering and Management (ESEM) encourages a dialog between humans and emerging technologies. ESEM principles indicate that "major shifts in technologies and technological systems should be evaluated before, rather than after, implementation" (Allenby, 2012). Moreover, these principles recommend that a set of metrics be developed that can be used to assess and guide development of a technology on an ongoing basis. The investigations discussed in this document represent at least a partial evaluation of the emerging technology of cultured meat prior to commercialization. As such, it forms the basis for recommending metrics for ongoing monitoring and management of the technology if and when large-scale production facilities are constructed. It is important to understand the characteristics and impacts of these production plants for two reasons. First, they represent workable processes that could be copied many times over as production expands. Second, technological diffusion often follows a characteristic S curve where growth begins slowly and then enters a phase of exponential growth before the growth rate finally begins to decline. Any undesirable effects associated with cultured meat should be addressed early in the commercialization and diffusion process since they will become greatly exacerbated during the exponential growth phase.

It follows that trends in meat products produced and consumed should be monitored for signs that cultured meat production might be entering an exponential growth phase. This warning would allow outstanding environmental, economic, or social concerns to be addressed. The remaining recommended metrics are arranged here according to their primary domain of concern (environment, economy, society). To the extent possible, future trajectories and implications are noted.

Environmental Metrics

First and foremost, the production characteristics of cultured meat should be monitored in order to assess how large-scale production might impact the environment. For reference, Table 17 provides environmental impacts associated with the cultured meat plant model developed for the life cycle assessment discussed in Chapter 5, excluding the effects of upstream processes. Significantly larger impacts could be cause for process review and may represent opportunities for strategic innovation. However, it is also likely that some plants will attempt to reduce costs by consolidating production of feedstocks, nutrients, and other inputs in the same facility, thus shifting upstream impacts into the cultured meat plant itself.

At the same time, it would be prudent to monitor the primary feedstocks of cell culture. The model described herein assumed that glucose made from corn with the addition of soy hydrolysate and synthetic amino acids would serve as the primary nutrient sources. However, this might not be the case for all processes: Alternative recipes might call for inputs that require complex manufacturing processes which could have detrimental environmental characteristics; other ingredients might originate from relatively scarce sources that disrupt established supply chains. Finally, life cycle impacts of other inputs such as vitamins and growth factors fell outside the scope of the life cycle analysis described herein, but should be considered for future study.

Waste streams should not be neglected. Eutrophying emissions and other pollutants should also be monitored in plant effluents. Cultured meat facilities might benefit from recycling byproducts of cell culture such as ammonia and lactate; otherwise waste water is likely to require special handling and/or coordination with water treatment plants.

Table 17

Example Monitoring Metrics for Cultured Meat Production Processes.

Factor input	Quantity per 1 kg cultured meat (this model)
Direct energy consumption	16 MJ
Direct water withdrawals (blue water only)	115 Liters
Feedstocks, dry mass basis	Glucose: 353 g Soy hydrolysate: 144 g Synthetic amino acids (including basal medium): 74 g
Eutrophying emissions (including cleaners)	10 g PO_4 eq

Note. Values in this table represent factors associated with a cultured meat plant only and exclude upstream life cycle impacts.

Land use. Because cultured meat production could serve to reduce the land required for grazing and feed production, the quantity of land in farms should be monitored carefully. Moreover, a significant decline in land managed by ranchers could result in overgrowth of vegetation and an increased risk for wildfires. For this reason, rangelands in the United States would benefit from a monitoring program. At the same time, in the event that commercial production of cultured meat fails to materialize, the anticipated increase in livestock production over the coming years could expand agricultural land significantly.

Water use. Due to its relatively small requirement for agricultural feedstocks, cultured meat requires much less total water than livestock. However, it is roughly equivalent to livestock in terms of fresh water withdrawals. For this reason, it would be beneficial to monitor ground and surface water supplies to ensure production facilities are not overly taxing available resources and existing infrastructure. On the other hand, the industrial nature of cultured meat production presents the opportunity for treatment and recycling of waste water flows.

Nitrogen and phosphorus. Both nitrogen and phosphorus are components of agricultural fertilizer as well as animal wastes; they are also responsible for some of the environmental degradation associated with food production (Xue & Landis, 2010). Once released into the environment, they can contribute to eutrophication of water bodies and lead to aquatic dead zones (US Environmental Protection Agency, 2012). Both nutrients can also contaminate drinking water sources and increase treatment costs (US Environmental Protection Agency, 2012). An increase in livestock production could be accompanied by a concurrent increase in the need for synthetic fertilizers. By contrast, a shift toward cultured meat could reduce this demand.

Economic Metrics

Economic contraction. The economic input-output assessment presented in Chapter 5 suggested that economic contraction would accompany a transition away from livestock in favor of bioengineered meat. Moreover, it predicted that the agricultural sectors would be hardest hit. Even though agriculture represented only 1.2 percent of the US GDP in 2012 (United States Bureau of Economic Analysis, 2014b) and supported only 2.1 million jobs (1.4% of the total) (United States Bureau of Labor Statistics, 2013), a downturn in this sector could be disruptive to rural economies. For this reason, economic output as well as employment in these sectors should be monitored for significant declines and increased economic hardship. At the same time, economic growth may emerge in new industries such as those related to biotechnology. Through early identification of sectors experiencing growth, strategic education and training may serve to smooth the transition of workers from agriculture to other industries.

Economic inequality. The social assessment workshops highlighted the possibility that food based in biotechnology might exacerbate economic divisions between groups in the United States, particularly if it remains expensive while imparting other benefits such as better nutrition. This represents a second metric that could be monitored for signs of economic division and inequity.

Substitutes for byproducts of slaughter. If livestock production diminishes, so will the availability of byproducts of slaughter such as blood, fat, internal organs, and hide or feathers. These are used for a variety of purposes including pharmaceuticals and other therapeutic applications. Supply chains should be monitored for changes in price of byproducts of slaughter as well as the identification of non-animal substitutes. Some of these substitutes might have significant environmental impacts that should be investigated as well.

Social Metrics

Human health. A host of factors associated with cultured meat consumption could impact human health. Health could be enhanced by sterile culture conditions that reduce food-borne illness; declining human-animal interaction could reduce the incidence of zoonotic diseases, and limited fat consumption (particularly saturated fat) could lessen individuals’ risk of cardiovascular disease and obesity. On the other hand, the iron content of cultured meat is currently uncertain but may be lower than agricultural meat due to the lack of blood. Moreover, cultured meat may not inherently contain vitamin B12, so supplements may be advisable. At the same time, overconsumption of cultured meat and its potential additives could result in a variety of ailments. For this reason, per capita consumption of cultured meat should be monitored as well as obesity rates, cardiovascular illness, and cases related to overconsumption of protein. Moreover, cultured meat additives such as caffeine, vitamins, and supplements should be catalogued. The need to assess the health effects of food supplements and their interactions might also be prudent as foods that increasingly contain previously-unavailable substances such as resveratrol in high concentrations.

Need for regulation. Due to the risk of serious illness associated with contamination of the cell culture, inspection of facilities to ensure the use of sterile protocols is advisable. However, due to the sterile culture conditions, there may be less of a need to cook the meat thoroughly. This might not be the case for agricultural meat; therefore, labels with proper cooking instructions might need to be added to packages of agricultural meat.

Intergroup conflict. The ability to produce meat without killing an animal presents the opportunity to afford greater protections to animals, up to and including the benefit of sentient rights such as the right to life and freedom of movement. It follows that conflict might arise between groups with different views on animal rights. Monitoring rhetoric surrounding the issue of animal rights could aid in managing intergroup conflict before it escalates to violence or impacts international relations.

Chapter 9

Methodology Review

This chapter represents a reflection on the methodology utilized for this research and includes lessons learned throughout the course of the investigations.

Social Assessment

As described in Chapter 2, the workshops were structured with a technology briefing, followed by a discussion meant to stimulate "out-of-the-box" thinking, and were concluded with time allotted for participants to complete a written survey to capture unique and diverse individual viewpoints on the implications of cultured meat. Overall, this approach worked well and yielded a great deal of compelling information. Several techniques and recommendations for future investigations are worth noting, however, and are discussed below. These are organized in the order they occurred during the workshops: briefing, participant discussion, and questionnaire. This section will conclude with a discussion of alternative approaches to social assessment.

Technology briefing. Of the three analyses that comprise this overall investigation (social, environmental, economic), the social assessment was undertaken first. As a result, anticipated environmental and economic impacts of the technology were not available for presentation in the first workshop with the exception of speculation taken from popular media coverage. Subsequently, high-level environmental and economic implications were compiled for an extreme case where US livestock production is completely eliminated along with the associated greenhouse gas emissions, water consumption, land use, and economic growth/decline. These estimates were presented in workshops 2 and 3.

The outcomes of this addition were mixed. The primary benefit was that participants could factor these potential environmental and economic shifts into their discussions. However, the workshop notes and questionnaire responses did not indicate that this information significantly influenced the participants' thought processes. Moreover, during the third workshop, a participant questioned the relevance and quality of the data used for the economic analysis, thereby diverting workshop time away from the primary goal and perhaps even invalidating that portion of the briefing in the minds of the participants. Finally, due to the approximate nature of the environmental and economic data presented, as well as the uncertainty associated with future technology trajectories in general, there is no guarantee that the information presented was accurate. Therefore, it could have influenced the course of the conversation in a direction that will prove to be irrelevant as the technology advances.

One can further speculate that holding the social assessment workshops last (after the environmental and economic analyses have been completed and the data compiled) could serve to provide participants with more accurate projections in the environmental and economic arenas. However, even with detailed analyses of emerging technologies, the same challenges are present: Participants may question the data and/or methodology, and the results may prove inaccurate and therefore reduce the value of the social assessment that was partly based on them. A possible compromise could be achieved by an iterative process where two rounds of the social assessment occur: One without the inclusion of environmental and economic implications, and a later round based strongly on the results of complementary analyses.

Participant discussions. The observation of the Chatham House Rule (participants were free to use the information received, but could not reveal the identity nor the affiliation of any other participant) facilitated the flow of uninhibited conversation. Whereas an audio or video recording of the sessions might have preserved a more accurate account of the discussion, both would have eliminated the element of anonymity (assuming technology will one day allow voices to be identified).

Group discussions were encouraged and guided through the use of specific questions designed to produce scenarios related to cultured meat in the future. For example, “You are a cultured meat designer. What kind of cultured meat would you design? What kind of cultured meat would you not want to have a part of?” Moreover, each workshop also included a role-playing session where participants were asked to play a role as if it was 2050 and cultured meat was ubiquitous. Options were provided such as a high school student, a doctor, a recent immigrant to the US, a farmer, etc. Participants were allowed to choose one of the suggested roles or another of their liking. Participants were then given a few minutes to develop a scenario before each shared their story with the group. The researcher, research advisers, and other participants also followed up on the narratives with additional questions; participants were invited to respond from the perspective of their chosen character.

The role-play portion proved to be particularly productive since the workshop participants imagined themselves in a future world and explained how cultured meat had impacted their lives. Moreover, the researcher and advisers were able to ask questions that elicited further details about the hypothetical person’s life. In workshops 2 and 3, two additional blank pages were added to the questionnaire for participant notes. This had the benefit of allowing the researcher to capture the notes being made by participants during the preparatory period. These included details and thought processes that might not have been verbalized or captured by the note taker.

Questionnaires. The participants' written responses to questions about the implications of cultured meat were beneficial to the reported results. While anonymity protocols prevented verbal comments from being correlated with the same participant's written responses, the overall results are believed to be more comprehensive due the available written responses. However, the questionnaires were not without challenges. Time was reserved at the end of the workshop for participants to complete the questionnaires, and most people did complete the questionnaires before leaving the workshop, but a few asked to take them away so they could complete them later. Unfortunately, once the questionnaires left the meeting room, the probability that responses would be obtained from that participant declined. Moreover, participants who did complete and return the questionnaire at a later date reported perceiving the questionnaire to be quite long and time-consuming. Even though a total of 20 completed questionnaires were received from 23 participants, the overall process might benefit from preventing questionnaires from leaving the room while inviting participants to complete only the parts they feel are the most important to them.

Environmental Assessment

Life cycle analysis is a relatively mature and reliable means of assessing the environmental impacts of agricultural and industrial processes. Its application provided significant insight into the implications of a shift from livestock rearing to cultured meat. However, the LCA described herein suffered from a number of challenges. Above all, a great deal of energy was spent compiling inventories for feedstocks such as soy hydrolysate, but a number of inputs were necessarily excluded from the inventory simply because process descriptions were unavailable. This was the case with vitamins, recombinant human insulin, and sodium bicarbonate – all of which will constitute important inputs to cultured meat production. Additional challenges are discussed below and include the need to perform a material flow analysis (MFA) to assess the flows of nitrogen and phosphorus, as well as the need for a more comprehensive comparison with livestock is needed to fully understand the implications of a shift in technological paradigms.

Nitrogen and phosphorus. Both nitrogen and phosphorus are components of agricultural fertilizer as well as animal wastes; they are also responsible for some of the environmental degradation associated with food production (Xue & Landis, 2010). Once released into the environment, they can contribute to eutrophication of water bodies and lead to aquatic dead zones (US Environmental Protection Agency, 2012). Both nutrients can also contaminate drinking water sources and increase treatment costs (US Environmental Protection Agency, 2012). The LCA discussed in Chapter 5 compared cultured meat's eutrophication potential with that of livestock. This metric is indicative of nitrogen and phosphorus waste products, but not necessarily process inputs.

The phosphorus cycle is further complicated by the reliance of industrial agricultural systems on phosphate rock, mined from a few limited deposits around the world. Estimates regarding how long supplies will last vary, but one source suggests that production could peak as soon as 2033 (Neset & Cordell, 2012). A shift in meat production technology could affect the dynamics of nitrogen and phosphorus in a number of ways, including decreasing overall fertilizer demand and pollution associated with animal wastes while increasing point sources of nutrient waste streams. A material flow analysis (MFA) is thus more useful than LCA for determining the direct changes in demand for all process inputs including nitrogen and phosphorus. In addition, an MFA of meat products would help to identify categories of pollution that would accompany a transition from agricultural to industrial technology, including concentrated streams of ammonia and lactate.

Functional unit and TINA. The inherent need to make assumptions when performing an LCA may introduce uncertainty into the reported results. For example, the study presented herein compared cultured meat to the live weight of livestock. However, in the case of the Tuomisto and Teixeira de Mattos (2011) LCA, the environmental impacts of cultured meat were compared to the edible meat obtained from livestock. Specifically, that study assumed that all environmental impacts were associated with the relatively small portion of the animal considered to be edible by humans (see Table 18 row 1). However, other sources report larger edible portions of beef, pork, and poultry (see Table 18 rows 2-3) and varying this percentage has a significant influence on the computed environmental impacts of the products being compared. As shown in Figure 19, assuming a larger edible livestock percentage serves to decrease the reported impacts of livestock production and suggests that cultured meat is less advantageous on a relative basis.

Table 18

Estimates of Human-Edible Portions of Livestock from Various Sources

Row	Description	Beef	Pork	Poultry	Source
1	Edible wt as % of live weight	20%	33%	35%	Tuomisto & Teixeira de Mattos (2011)
2	Edible wt as % of live weight	40%	53%	60%	Smil (2013 p. 140)
3	Edible wt as % of live weight	43%	56%	56%	(Pelletier, Lammers, et al., 2010; Pelletier, Pirog, et al., 2010; Pelletier, 2008)

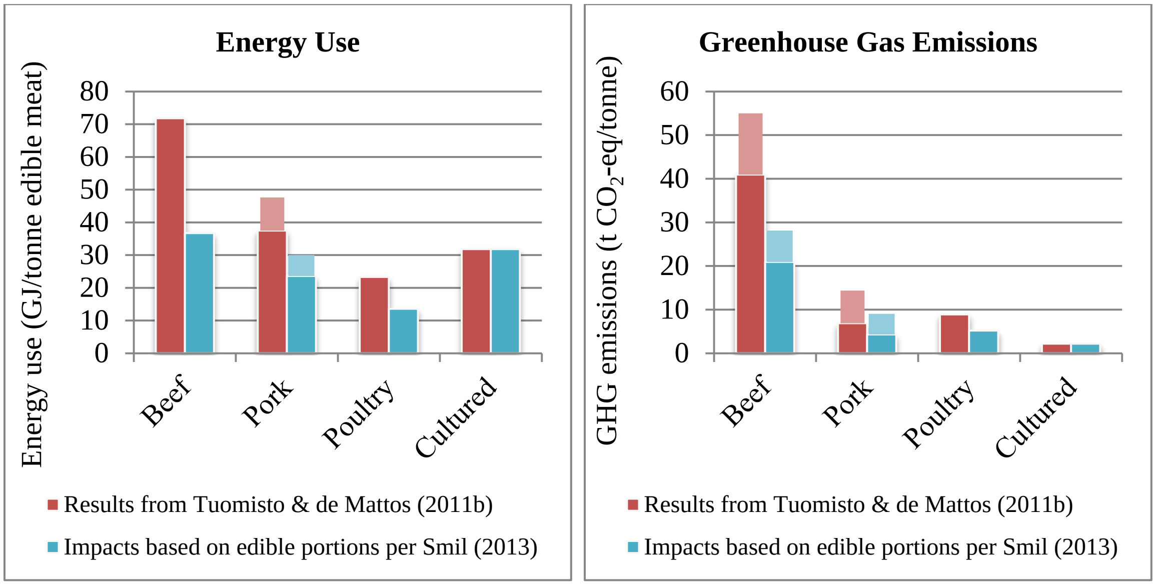


Figure 19. Impact of functional unit assumptions on LCA results. Selected results reported by Tuomisto & Teixeira de Mattos (2011) compared with the same results assuming larger edible livestock portions given by Smil (2013, p. 140). Column extensions indicate a range of values given by the source.

To complicate matters further, much of the inedible byproducts of animal slaughter are not thrown away, but rather sold for productive purposes, implying that at least some environmental impacts should be allocated to them. Marti, Johnson, and

Mathews (2011) report that only about 14.1% of cows and 11% of hogs is lost through shrinkage or waste. The remaining byproducts are used in leather production, pet food, cosmetics, and pharmaceuticals among many other household and industrial products (Marti, Johnson, and Mathews 2011). For poultry, waste products from slaughter include offal (heads, feet, and intestines totaling about 17.5% of live weight), feathers (7% of live weight), and blood (3.5% of live weight) (Ockerman and Hansen 1999, p. 440). All but the feathers can be dried and processed into byproduct meal suitable for animal feed (Ockerman and Hansen 1999, p. 440). Feathers and down “may be utilized for clothing, insulation, bedding, decorations, sporting equipment, feather meal, and fertilizer” (Ockerman and Hansen 1999, p. 441).

Were production of the primary source of meat byproducts to diminish, a number of scenarios might play out. One of these might be the continued raising of livestock specifically for commercial and industrial purposes – possibly inflating the cost of the final products in the process. Another scenario might be the use of synthetic substitutes for the byproducts. Such substitutes would have unforeseen but possibly significant environmental impacts or other unintended consequences of their own. For this reason, there is value in considering the holistic context in which the technology is emerging – not only to more accurately assess the potential environmental impacts, but the economic and practical downstream effects as well.

A more extensive LCA framework is needed in order to better understand technological transitions at a system level, including the secondary effects associated with co-products. To meet this need, the “Technological Innovation Network Analysis”, or TINA, is proposed. This is a novel method that applies both LCA and MFA techniques to technological transitions at a system level. As shown in Figure 20, it provides insight into not only the impact of a new technology, but also the secondary effects associated with co-products. In the case of a transition from livestock production to bioengineered meat, for example, the edible components of an animal are co-produced, and perhaps subsidize, a wide variety of secondary products.

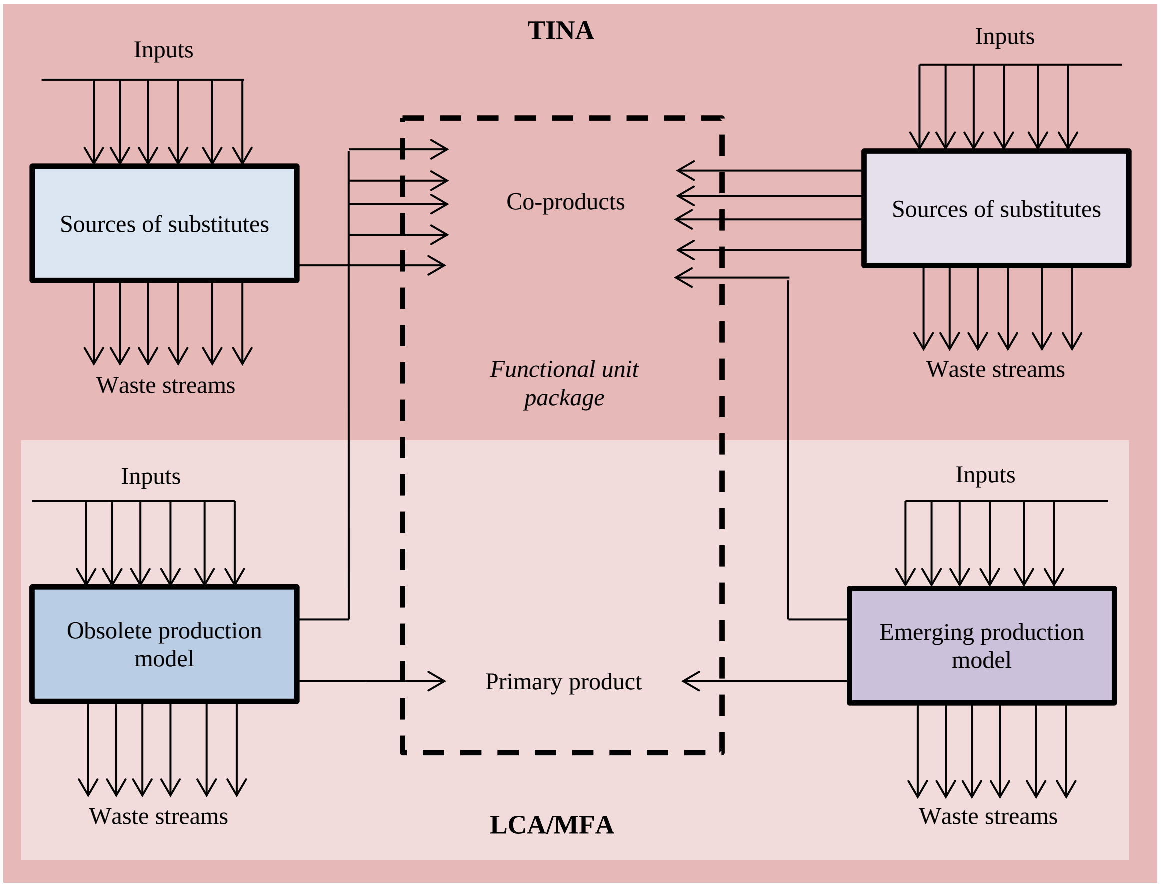


Figure 20. Technology innovation network analysis (TINA). TINA is a means to assess the impacts associated with a technological transition.

Unfortunately, compiling such an inventory for livestock may not be as straightforward as it seems: Designer Christien Meindertsma tracked a single pig from an industrial slaughterhouse in the Netherlands through sales of all of its component parts (Meindertsma, 2010). She discovered that byproducts of pig slaughter find their way into wide variety of everyday products including bread, concrete, human medical devices and therapies, renewable energy sources, and even bullets. Moreover, a preliminary compilation of cattle byproducts shown in Table 19 suggests a similarly diverse range of uses. Hence a reduction or elimination of livestock production could have surprising downstream effects including raising prices for vaccines and other therapeutic substances: According to Marti et al. (2011), “In many of these treatment uses, no other synthetic products function or perform equally well” (p. 4). Hence, despite the required investment, a more comprehensive technology innovation network analysis could produce a more precise environmental comparison while highlighting areas for targeted innovation.

Table 19

Preliminary Technology Innovation Network Inventory for Beef Production and Byproducts of Slaughter

Product	Cattle yield (kg)[a]	Primary uses	Known substitutes
Live weight	455		
Dressed carcass	273		
Retail cuts	190	Human consumption	Cultured meat
Byproducts			
Hide or pelt	36	Leather	Cultured leather, fabric, or plastic
Edible fats	50	Shortening and biodiesel	Cultured fat, fossil fuels
Variety meats	17	Pet food, animal feed, some is exported for human consumption[b]	Cultured meat, fish byproducts, vegetables and grains

(continued)

Table 19

Preliminary Technology Innovation Network Inventory for Beef Production and Byproducts of Slaughter

Product	Cattle yield (kg)[a]	Primary uses	Known substitutes
Blood	18		
Thrombin		Blood coagulation, skin graft procedures [b]	To be investigated
Fibrin		Surgical repair of internal organs [b]	To be investigated
Fibrinolysin		Wound-cleaning agent, minor burn treatment [b]	To be investigated
Other	80		
Inedible fats		Soap	Vegetable sources
Bone		Therapeutic hormones, enzymes [b]	Some substances may be produced by recombinant cells; others may not have ready substitutes [b]
Glands & other tissues		Serums, vaccines, antigens, antitoxins, xenotransplants [b]	
Unaccounted items (stomach contents, shrinkage, etc.)	64	N/A	N/A

[a] Source: Ockerman and Hansen (1999, p. 19)

[b] Source: Marti et al. (2011)

Economic Assessment

As discussed in Chapter 6, the economic input-output assessment failed to consider the effect of changing household incomes and spending. In addition, it did not consider the employment effects of substituting cultured meat for livestock. The reason for this was simply that the economic tables were taken directly from the Bureau of Economic Analysis (BEA) and, as published, the tables were open with respect to households. This means that any secondary economic effects induced by gains or losses in household income would not be reflected in the tables or models incorporating them. A great deal of additional time and effort would have been required to develop a closed model based on the information available. The same was true for employment data. Employment data is available from the Bureau of Labor Statistics, but significant additional time and effort would have been required to build a complete model that included employment figures.

A preferable alternative approach would have been to utilize IMPLAN software and datasets. These have a number of benefits over data from the BEA. Primarily, they contain not only open and closed models, but employment data as well. IMPLAN also compiles detailed tables annually whereas the BEA releases detailed benchmark tables only once every five years, and each is typically delayed five years. The IMPLAN software and datasets were not utilized for this investigation because the cost exceeded the budget available for the project.

Technological evolution

The analyses presented in this document were anticipatory in nature: One of the most common challenges facing assessments of emerging technologies is the availability of a working commercial-scale process on which to base an analytical model. As a result, it is less accurate to think of anticipatory assessment results as predictions than as scenarios that could be realized as the technology advances. In this way, anticipatory analyses can provide insight into the implications of new products, but they should not be interpreted as conclusive or definitive. In addition, whereas this assessment was based on a hypothetical model of cultured meat production that might be reasonable given existing knowledge, the techniques that ultimately enable the large-scale production of cultured meat are likely to deviate significantly and perhaps fundamentally from those in use for cell culture today. Moreover, the model will become less realistic the further into the future one looks. As depicted in Figure 21, while path dependencies constrain evolution in the short-term, complex interactions between natural, human, and technological systems become compounded over time, rendering the far future much less predictable than the near future. This points to the need to revisit the analyses on an ongoing basis as the technology advances and commercial plants are designed.

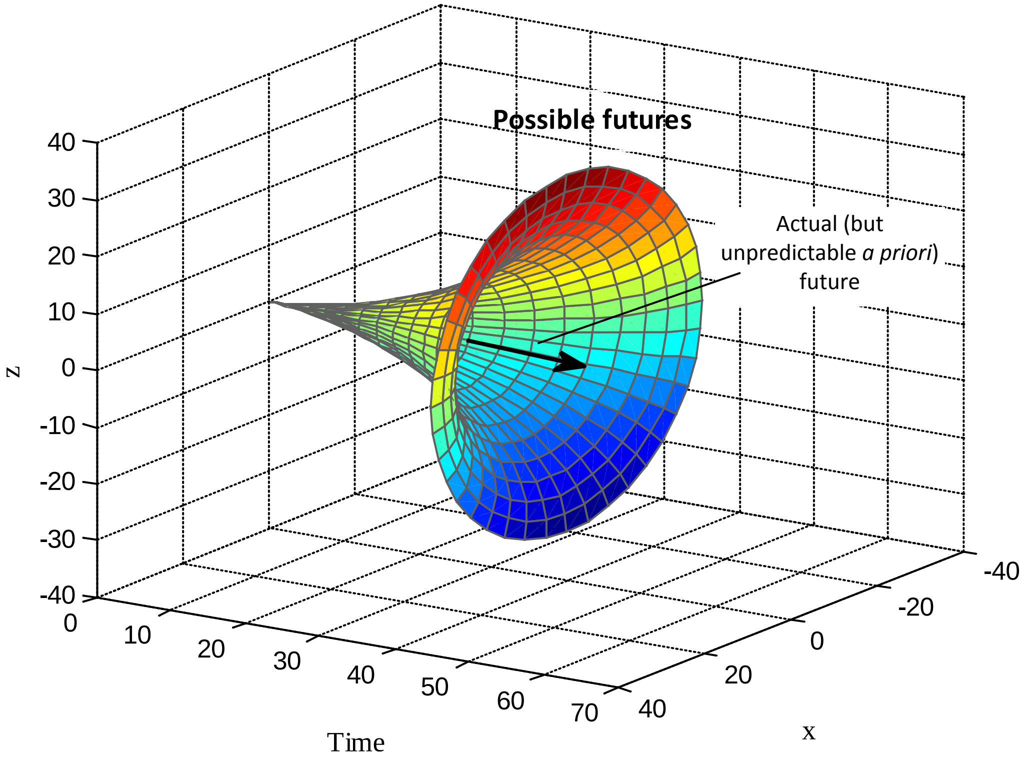


Figure 21. Path dependency and unpredictability inherent in the evolution of complex systems over time. Source: Allenby (2012).

Uncertainty

Any anticipatory technology assessment is inherently fraught with uncertainty. In this section, an attempt is made to quantify the degree of uncertainty associated with the primary conclusions from each of the three analyses. The estimates listed in Table 20 are meant to express the ability of the methods and models used to predict specific outcomes. For example, based on the life analysis discussed in Chapter 5, there is a relatively high degree of certainty that cultured meat will reduce GHG emissions associated with meat production in the short term. In the longer term, however, other factors such as cells genetically engineered for rapid growth may require additional energy inputs for active cooling, thus increasing GHG emissions once again. In all cases, the certainty estimate reflects the ability of cultured meat to influence the trend. For example, the table suggests great uncertainty regarding the ability of cultured meat to reduce global hunger in all timeframes. This does not preclude the emergence of other effects that do indeed improve nourishment among poor populations, but they may have little or nothing to do with cultured meat. Thus, uncertainty regarding cultured meat's ability to address the problem remains high.

Table 20

Estimates of Assessment Uncertainty

Projection	Short term (< 20 years)	Medium term (20-50 years)	Long term (> 50 years)
Social trends in the United States			
Cultured meat is commercialized	3	2	1
Cultured meat is adopted on a large scale	4	2	1
Human health improves	4	4	4

(continued)

Table 20

Estimates of Assessment Uncertainty

Projection	Short term (< 20 years)	Medium term (20-50 years)	Long term (> 50 years)
Intra- and inter-group conflict decline	4	4	4
Animal cruelty diminishes	5	3	3
Global hunger declines	5	5	5
Food systems become more secure	5	5	5
Food becomes increasingly regulated	4	4	4
Food becomes integrated with other systems	4	3	2
Environmental factors associated with meat production			
Industrial energy use increases (live weight basis)	2	3	4
Global warming potential decreases	2	3	3
Eutrophication potential decreases	2	2	2
Land use decreases	2	2	2
Blue water use increases	3	4	5
Economic shifts in the United States			
Overall economic contraction	3	5	5
Contraction in agricultural sectors	2	2	2
Expansion of biotechnology sectors	2	1	1

Note. The primary conclusions associated with each assessment are ranked on a scale from 1 (most certain) to 5 (least certain) over different time horizons. Excluding the first social entry regarding commercialization of cultured meat, all estimates assume that cultured meat has been commercialized and is widely manufactured and available in the United States.

Synergies

Despite the isolated nature of the three analyses performed, taken together, they produced more information than each would have by itself. For example, the environmental and economic assessments together showed that cultured meat production will be a relatively energy-intensive process, but energy will likely make up only a small portion of production costs. This may create conflicting environmental and economic incentives.

Additional synergies emerged from the social assessment. Even though participants in the workshops were not asked to focus specifically on environmental and economic issues (since separate analyses were being done in these areas), important points in both of these areas were nonetheless identified that would not have been perceived otherwise. Specifically, from an environmental standpoint, participants suggested that eliminating cattle grazing from rangelands in the United States could allow unchecked growth of vegetation over large areas and result in severe wildfires. This could in turn lead to a need for regulation and/or active management of rangelands and a consequent public cost. Economically, participants pointed out that foodborne illness places a burden on the American economy that could be avoided via cultured meat grown in sterile conditions. Neither of these would have been identified via the LCA or EIOA, but they constitute potentially significant consequences associated with a technology transition. It should be noted that neither of these phenomena were subject to further analysis as part of this project, but could be explored in subsequent analysis. From this perspective, they further support the value of an iterative approach for technology assessments.

Potential Benefits of Iteration

As implied by Figure 5 on page 28, it is impossible to segregate environmental changes from social and economic effects in the real world. All human and natural systems are interdependent in ways that are difficult, if not impossible, to predict. Thus the analyses that made up this investigation are incomplete by their very nature. Yet they provided a basic set of technological implications. An additional round of investigations aimed at further refining and understanding their results would approximate a more comprehensive assessment approach.

Potential Applications of the Framework

The approach taken in this study has applications in a number of realms, but this discussion will focus on sustainable engineering. The concept of sustainable engineering has emerged to characterize an engineering practice that extends beyond the scope of traditional boundaries to encompass environmental and social concerns from a local to global scale (Allenby, 2012). This means that engineers and managers are charged with meeting customer requirements while balancing profitability, concern for natural systems, and social equity. In short, sustainable engineering necessitates that social and environmental effects of new technologies be assessed prior to commercialization and then monitored as they diffuse through diverse populations. However, accepted methods for accomplishing these goals are elusive. Before constructing a production plant, firms undertake extensive financial analyses. Concurrent environmental and social assessments such as those completed as part of this investigation could help them better understand economic-environmental tradeoffs as well as how the product might impact diverse stakeholders.

Chapter 10

Hypothetical Future Narratives

Scenarios have to be plausible, but reality is under no such constraints.

- William Gibson

As discussed in Chapter 9, the relatively isolated nature of the social, environmental, and economic analyses do not accurately reflect the interdependent nature of human and natural systems, but the application of an iterative approach can approximate a more integrated methodology. Further, while the social assessment workshops did cross boundaries to address environmental and economic issues, and their relatively unstructured nature was effective for encouraging new ideas to emerge, the identified impacts tended to be simple forecasts limited to one area of interest at a time. For these reasons, an additional exercise was pursued in order to illustrate how a number of seemingly isolated and insignificant phenomena resulting from cultured meat could interact and bring about sweeping changes at a global scale. The narratives that appear below do not adhere to established scenario planning procedures such as those discussed by Amer et al. (2013), Becker (1983), and List (2007), but rather are the product of reflection on the part of the researcher and each incorporate a number of the metrics for ongoing dialog and management listed in Chapter 8.

The narratives are not meant to be predictions, or even cautionary tales, but rather to illustrate how seemingly implausible – and perhaps undesirable – futures can become reality. Further, they are meant to emphasize the power of technology to reshape the world as it appears: “From the structure of our economies to the evolution of our environment to our ethical standards, a world whose protein supply is significantly provided by factory-grown meat technologies will probably be different in kind from a world without these technologies" (Mattick & Allenby, 2013). As such, the stories further illustrate the need to maintain a dialog with technologies such as tissue engineering in order to better perceive and address unforeseen and unintended consequences as they arise.

Narrative 1: Vital Meat and the Corn Economy

The first cultured meat plant opened in 2024 near Columbia, Missouri, with very little fanfare or press coverage. About the same time, a major fast food chain introduced the Om Sandwich™ – a hamburger infused with Omega-3 fatty acids and resveratrol, marketed to aging Generation Xers who wanted to preserve cognitive function and overall well-being. It cost more and was said to be a bit more dense than the chain's traditional fare, but the public saw value in food that would improve quality of life and quickly acquired a taste for so-called "vitality food". The sandwich became a top seller and soon thereafter a competing chain introduced the Essential Taco™ which featured edible flowers instead of lettuce and meat that smelled vaguely of cardamom and lavender.

This was followed by various lines of fresh and frozen ready-made meals featuring meats tailored to a bewildering array of demographics. These included experimental lines of "vital meat" dinners aimed specifically at vegetarians and vegans. Despite the early support of the People for the Ethical Treatment of Animals (PETA) for cultured meat, many vegetarians and vegans still expressed significant reservations about the culturing process: Did it require the input of animal byproducts? How were donor animals treated? Most vegan societies gave vital meat their reluctant approval after a long series of Web-based dialogs and, ultimately, the ability to tour production facilities according to a predefined schedule.

Livestock producers tried to compete with vital meat by adding vitamins and minerals, but they ultimately lost market share since they could not control the marbling the way the bioprinters could, nor could any partner firms produce the same aesthetic qualities with sauces that the bioreactors could infuse into the very meat cells themselves. The price of animal meat fell and producers began to rely more and more on what were previously secondary markets such as pet food, cosmetics and pharmaceuticals – all of which became more expensive. Some livestock producers lobbied against vital meat and proposed regulating it as a pharmaceutical, rather than a food, since the production process resembled pharmaceutical production much more closely than food production. These proposals died in committee, however, since many constituents enjoyed vital meat and those that did not made arrangements with farm cooperatives to purchase “natural” meat. The USDA and FDA, both sympathetic to the livestock producers’ arguments, signed a memo of understanding that gave the FDA jurisdiction over vital meat factories. They instituted a policy of periodic inspection of production facilities, but generally did not interfere with operations unless an illness was reported.

With fewer animals eating corn and soybeans, the price of agricultural commodities dropped quickly, followed by land prices. The Farm Bill, having lapsed in the early 2020s, was revived to purchase farms that failed and provide subsidies to the growers that remained. Farmers’ enthusiastic supported for these measures was matched by those with a stake in vital meat and ethanol since corn was a primary input in both. More and more vital meat and ethanol plants sprung up across the Midwest as ethanol was becoming economically competitive with gasoline. Acres of farmland were brought back online as the so-called “corn economy” flourished. Meanwhile, even though marine dead zones declined in severity due to increased fertilizer application efficiency, demand for nitrate and phosphate fertilizer grew, sparking continued concern over fossil fuel use and declining global supplies of the latter.

In most Western nations, at the urging of vital meat marketers, eating animals came to be viewed as barbaric. The problem of what to serve at Thanksgiving and Christmas never even materialized since vital meat manufacturers paid grocery stores to effectively replace commodity turkey and ham with Grateful Table Tom™ roast and Mindful Meal Sal™ loaf in the meat case. (Tom the Turkey and Sal the Hog had become world-renowned as delicious tissue donors. They could be seen lounging and playing in their respective habitats during prearranged factory tours. However, doubt remained as to whether they were the actual tissue donors.) Disapproval of the perceived suffering of food animals grew and activists began to stage euthanization raids on the remaining concentrated animal operations. In an attempt to resolve the conflict, the USDA enhanced, and strictly enforced, its animal welfare guidelines. The consequence of this fell mostly on the price of meat exports and healthcare (particularly pharmaceuticals). Health care was already forcing chronically-ill individuals into bankruptcy. Despite the industry’s promises that vital meat “promoted lean vibrancy”, obesity rates continued to rise. Many suspected that vital meat contained unhealthy – possibly addictive – additives.

In contrast to the West, most Asian nations – particularly China – viewed natural meat as a status symbol and continued to produce and import meat from around the world. This was aided by a botched marketing campaign that inadvertently implied that eating vital meat would make people lonely. As livestock-rearing became more and more contentious in Western nations such as the US, Canada, Brazil, and Australia, African countries seized the opportunity to set up import tariffs on vital meat and subsidized exports of natural beef, pork, and mutton. With their new agriculture-based economy, Africa thrived. Its close relationship with China, cemented by a strong trade relationship (natural meat for consumer and electronic goods), created a new global alliance. The objections of nations committed to eliminating animal suffering set up a Northwest-Southeast global political divide. It was this alignment that allowed China to secure a steady flow of petroleum from the Middle East.

The United States turned inward, choosing to rely on agriculture as its primary source of food and fuel. It began recycling phosphorus from waste streams to reduce its dependence on imports that were increasingly being claimed by African livestock. For energy, it relied more and more on ethanol and national sources of natural gas. It eventually became clear, however, that the Northwestern global region had reached an economic plateau. The population had become tired and overweight. It became eclipsed by the growth of the Southeast, fueled by a large, industrious population and abundant fossil fuel resources.

Narrative 2: The Global Meat Debates

Soon after the first prototype factory was constructed in The Netherlands in 2017, agricultural companies, livestock producers, and slaughterhouses in the United States formed an “anti-bioreactor” coalition and hired a strategic marketing firm. Billboards and food magazines were soon dotted with nostalgic pictures of family farms and cowboys with captions that read, “This nation was founded on hard work and real food. Support the farms that support the nation. Eat real.” Other variations displayed images of a bioreactor and a cow and asked, “Do you know what’s in your hamburger? Eat real.” Simultaneously, lobbyists made convincing arguments to Congress that allowing meat to be grown in factories (versus farms) would bring swift economic decline, high rural unemployment, and rapid urbanization that would quickly overwhelm city infrastructures. Controversial but successful legislation reminiscent of Prohibition soon banned the nationwide sale, production, importation, and transportation of meat grown by artificial means.

Debates over cultured meat were more heated in Europe where many argued that environmental benefits necessitated a shift away from livestock whereas others favored preservation of the agrarian landscape and artisan traditions. Arguments suggesting that cultured meat was a “gateway process” to genetic design of animals and humans ultimately caused the European Union, like the United States, to ban cultured meat. The Netherlands, wishing to expand its meat industry without increasing grain imports, ultimately seceded from the European Union.

Given its large population and increasing industrialization and affluence, China watched cultured meat research and development efforts in the rest of the world intently and began its own nascent production program in 2020. In many ways the process was a natural fit for China since the primary feedstock (glucose) could be made from the starch in rice, so very few agricultural adaptations were required. Factories sprung up all over the landscape and an enterprising government, following established precedent, began to subsidize and export its cultured meat. China’s meat became a reliable, inexpensive staple item and nations such as India and many in the Middle East could not get enough of it.

As soon as the first cultured meat plant began production, environmental groups began increasing pressure on Brazil to curtail its beef industry in order to limit rain forest destruction associated with crop production and cattle grazing. Based on the assumption that cultured meat requires fewer agricultural inputs to produce a unit of edible meat, they reasoned that a shift away from livestock rearing would slow, or ideally reverse, deforestation of the Amazon rainforest. The Brazilian government was cautiously optimistic and invested in a pilot plant that used sugar cane as the primary feedstock for cultured meat. Realizing that this strategy could divert some sugar away from ethanol production (the nation's primary transportation source), they asked for ongoing updates that included quantitative accounting of inputs and outputs and did not actively encourage exports.

Other nations also took up cultured meat production and found specific market niches: Japan, for example, was known for its high-quality, bioprinted cuts that were almost indistinguishable from natural meat (apparently they cultured bone marrow and infused the meat with red blood cells). Japanese exports were expensive and available only in high-end restaurants. Australia specialized in cultured meat from wild and endangered species and its government had to create a special task force to ensure that endangered species were not being killed or otherwise adversely affected. A few specific companies advertised meat cultured from human tissue – particularly from celebrities. Some famous individuals happily donated tissue and endorsed their products. Due to lingering doubt, the American firm 23 and Me began certifying meat products as being genuinely sourced from a specific individual. Less accommodating celebrities had to hire additional security to prevent their DNA from being stolen by "gene paparazzi" trying to make a living selling unauthorized but viable tissue samples. This practice slowly subsided as precedents were set in most countries granting individuals (or the estate in the case of the deceased) legal ownership of their genetic material.

As bioprocess engineering continued to advance, so did the food it produced. In most of the world, surf and turf had come to be understood as steak marbled with lobster meat. In the US and Europe, deprivation took its toll. Amateur bioengineers set up small-scale carneries in their basements and garages. Organized crime rings built tunnels under the Canadian border specifically for moving meat into the United States. Restaurants quietly began purchasing cultured delicacies from the black market and converting to so-called "eat-easies". Unfortunately the illegal culture conditions were often unsterile and many people died of food poisoning before personal contamination testers were developed. Eventually China threatened to recall US government debt if it did not begin accepting cultured meat imports and the ban was lifted. The subsequent decline in US agricultural sales and land values did precipitate a mild recession, but it was short-lived due to a surge in biotech-related economic activity.

Most of Europe continued to avoid cultured meat and people took pride in the sustainable balance that had been achieved between people and their land. Historians, noting patterns of history, began to warn that military complacency might leave them vulnerable to invasion or colonization by nations hoping to acquire productive agricultural land and sources of fresh water. The Netherlands used its revenue from meat exports to expand its military, reinforce its borders, and enter into talks with Belgium to secure grain imports in exchange for armaments.

Meanwhile Chinese pride and prestige soared as it came to be viewed as the world's dinner table. However, problems were already becoming apparent: The need for large amounts of sterilized, industrial water taxed the nation's infrastructure; the growing need for supplies of rice to feed the nascent muscle and fat cells diminished availability for the poor. Even workers at non-meat factories began to suffer and national productivity slowed. China struggled to compete with other industrial nations in the export markets. Many people lost their jobs. The hungry and thirsty rural population began to stage riots outside cultured meat factories. When farmers collectively agreed not to grow rice for a year, the Chinese meat industry finally collapsed. Urban populations returned to farms still operated by relatives. Chickens once again became common sights in China as it withdrew from the world stage.

About the same time, Brazil's monitoring program was beginning to pay off. Experts noted that for every kilogram of sugar consumed, about ½ kg of meat was produced. Realizing that cultured meat required relatively little supporting agricultural land, they discouraged further deforestation by creating tax incentives for sugar production on existing farms and construction of new cultured meat plants. As factory meat replaced livestock, the government continued to monitor a number of variables including national ethanol prices, land prices, energy use, water use, employment, and water eutrophication. They noticed a slight upward trend in fossil fuel use, but chose to take no action since this was being imported and paid for by the cultured meat manufacturers. Analysts commented that, due to its cautious management, cultured meat eventually replaced livestock as one of Brazil’s primary exports with little social or economic disruption.

Narrative 3: Global Adoption

The first cultured meat plants were built simultaneously in the United States and The Netherlands. Canada, China, Brazil, and Australia built their first-generation plants soon after. In all cases, the appropriate regulatory bodies were notified well in advance and were kept informed regarding process modifications. No regulators pushed for mandatory labeling, but due to the substantial intellectual property involved in cultured meat production and the premium being charged for the products, branding and sales necessitated that cultured meat be labeled anyway – and typically touted unique and special features. The first products were somewhat tough and dry but were released with great fanfare regarding their low-environmental impact and lack of saturated fat. Moreover, the sterile production conditions meant that they could be kept in grocery stores and refrigerators much longer which partially made up for their higher prices.

As quality improved and prices declined, cultured meat products became more and more pervasive and livestock numbers in confined operations fell. As the bottom fell out of the natural meat market, some producers in the United States found it cheaper to set their animals free than to pay for slaughter. Herds of feral cattle now roamed free on public lands. In Australia, the last animals were wiped out in the severe drought of 2030. Water recycling and desalinization allowed the cultured meat plants to run at normal capacity. Twenty years after the first carneries had been built, food animals were confined to specialty farms that kept a very low profile and catered to “meat purists”. Most people could no longer imagine eating meat from an animal, and most had forgotten how to cook it. Some textbooks now claimed that it was evolving human morals that caused a decline in animal consumption.

The need for grain inputs to meat production fell which resulted in annual surpluses. Many people anticipated a surge in population due to the excess food production but this never fully materialized. Birth rates remained low, possibly due to continued industrialization. On the other hand, death rates also fell due to fewer cases of cancer, Alzheimer’s disease, cardiovascular diseases. Some credited these trends to the emerging ability to tailor food to specific individuals and others credited less exposure to viruses and other pathogens carried by animals.

The last continent (other than Antarctica) to receive a carnery was Africa. This was due to national governments colluding to protect their burgeoning agricultural sectors and traditional pastoralists. Once they saw the global price of grains decline significantly, however, they set up cultured meat factories to utilize locally-grown corn as a feedstock and further protect agriculture-dependent populations. Many African farmers complained that removing livestock from the land broke the circle of life and forced them to purchase synthetic fertilizers versus the application of naturally-occurring manure, but the governments saw no other way to preserve the agriculture that they had worked so hard to foster.

Thirty years after the first carnery was built, the world was a very different place in some ways: Less cultivation and few animals allowed landscapes to adapt to different purposes– some were managed and some achieved a new natural state; a decline in farming and treatment of carnery waste meant that water pollution had declined. Yet some familiar problems remained: Fossil fuel consumption continued to increase and, despite the grazing of fewer ruminants, greenhouse gas emissions were still a global concern. Fresh water supplies were still limited, but continued to be adequately managed.

Chapter 11

Conclusion

In July, 2011, a life cycle analysis (LCA) was published comparing cultured meat to conventionally-produced meat (Tuomisto & Teixeira de Mattos, 2011). It acknowledged significant uncertainty, but found that, “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” (Tuomisto & Teixeira de Mattos, 2011, abstract). These results have been cited extensively, and it is now commonly believed that cultured meat will be an environmentally-friendly alternative to livestock- rearing. While there is nothing wrong with the results and the subsequent acceptance, for a number of reasons discussed below, it would premature to consider the environmental discussion closed.

At the same time, a number of other claims have emerged suggesting that cultured meat address global hunger issues (Tuomisto & Roy, 2012), promote human health by eliminating harmful contents such as saturated fats and pathogens (Siegelbaum, 2008), and alleviate the ethical concerns associated with industrial livestock operations (Bartholet, 2011). This assessment acknowledged these claims, but found a great deal of uncertainty surrounding each of them. Moreover, it identified other concerns that may become more obvious if and when cultured meat becomes ubiquitous.

Main Findings

Significant social implications of cultured meat include the possibility that food will become more of a design space than it is currently and, consequently, more integrated with existing human institutions. Cultured meat could also lead to greater ethical concern for, and possibly extension of sentient rights to, animals. On the other hand, divergent views on animal consumption could lead to increased intra- and inter-group conflict among humans. Finally, over the long term, changing patterns of consumption could lead to eventual changes in human physiology.

The LCA performed by this assessment found that cultured meat will have more significant environmental impacts than previously shown. More importantly, it indicated that cultured meat will effectively replace a predominantly biological production (muscle and fat production) with a predominantly industrial one. This comes with specific advantages including a reduced reliance on agricultural feedstocks and the ability to better manage input flows and waste streams. At the same time, it comes with challenges such as the potential to use industrial energy more intensively and the possible need to actively care for vegetation on land that is no longer managed by cattle grazing.

Economic effects may include a general contraction affecting the agricultural sectors most directly. Historical trends suggest that the national impacts will likely be temporary but it could facilitate a continuation of existing declines in agricultural value-added and employment as a percentage of national aggregates. An important area to monitor will be the potential loss of byproducts of slaughter as inexpensive inputs for household, industrial, and healthcare products. A great deal of uncertainty surrounds the availability of substitutes for substances extracted from blood and internal organs, but secondary markets for animal byproducts may prove to be the primary markets affected in terms of scarcity and rising prices.

Future Work

Anticipated follow-on work associated with this research falls primarily into four categories: complementary environmental analyses; a continuing economic assessment of cultured meat; larger trends associated with industrialization and innovation; and development of a more integrated assessment approach.

Environmental analyses. As discussed previously, the life cycle analysis did not indicate what changes in applied fertilizer such as nitrogen and phosphorus might be realized as a result of cultured meat adoption. A shift in meat production technology could affect the dynamics of nitrogen and phosphorus in a number of ways, including decreasing overall fertilizer demand and pollution associated with animal wastes. A material flow analysis (MFA) would be more useful than LCA for determining the direct changes in demand for all process inputs including nitrogen and phosphorus. Moreover, a technology innovation network assessment (TINA), as described in Chapter 9, would provide more insight into the holistic implications of a technology shift, including substitutes for animal byproducts.

Economic assessment. As discussed in Chapter 5, further investigation of a transition to cultured meat is possible. This might include the development of a new model using the recently-released 2007 benchmark input-output tables from the Bureau of Economic Analysis (2014a) or acquisition of IMPLAN national data. Thereafter, a closed model could identify the indirect effects of household income as well as employment changes associated with the cultured meat commercialization. More subtly, an investigation into the anticipated secondary economic impacts of livestock elimination would be valuable. These include, as the social assessment implied, an investigation into the economic benefits of reducing food-borne illness as well as the downstream effects of eliminating byproducts of slaughter. Specifically, byproducts of slaughter have very little economic value compared to meat and therefore do not figure prominently in the input-output tables. However, it is possible that an economic input-output model could be constructed to identify the effects of scarcity and price increases, as well as substitutes for the byproducts.

Larger trends. This technology assessment has suggested that a transition away from livestock production and toward cultured meat would be reminiscent of the shift from draft animals to automobiles and tractors in the early 20th century. A more extensive investigation of this era and other aspects of the Industrial Revolution could provide greater insight into what lies ahead as industrial processes continue to replace biological ones. For example, the Luddite fallacy refers to the observation that technological innovation does not lead to higher unemployment in the overall economy. Could this phenomenon be identified using economic input-output analysis? In addition, Jevons' paradox refers to the tendency of increasing technological efficiencies to result in greater overall consumption rather than conservation. It implies that more efficient use of corn for meat production could lead to greater corn consumption, but more investigation could serve to support this hypothesis.

Integrated assessment. Even though the three analyses performed as part of this research were pursued largely independently, there may be opportunities to develop a more integrated framework going forward. This would more accurately simulate the interdependent nature of real-world systems and possibly serve to highlight less-obvious secondary and tertiary effects. For example, as pointed out in one of the workshops, food-borne illness, while primarily a human health issue, also has associated economic costs including health care expenditures and lost economic productivity. Could an integrated assessment methodology, perhaps incorporating complexity principles, be developed that would automatically identify such subtle effects?

Finally, as also indicated by the social assessment, technological transitions are likely to have less measurable impacts on the food system such as enhanced food security and/or decreased resilience. For example, cultured meat is expected to require smaller quantities of agricultural feedstocks per unit output. As a result, it will also require less rainwater. This, in turn, could mean that a food system incorporating more cultured meat and fewer animals is less vulnerable to drought. Metrics such as vulnerability are difficult to quantify, but ongoing research could provide additional insight into these important but intangible systemic effects.

Anticipatory Technology Assessment

Emerging technologies such as cultured meat may not be viewed as earth systems engineering projects – nor even large-scale engineering projects at all. Rather, they are more likely to be viewed as isolated corporate production decisions or as simple purchasing decisions made by individuals visiting their local grocery stores. As such, there is no perceived need for any particular institution to identify or take responsibility for the far-reaching consequences of such seemingly minor and innocuous actions. In aggregate, however, millions of uncoordinated but nonetheless congruent individual decisions can have significant and widespread impacts on coupled human and natural systems at a global scale.

The investigation discussed in this document represents one attempt to develop tools for anticipating the aggregate global impacts of incremental technological decisions for purpose of perceiving, and ultimately managing, those impacts. The results presented in this document do not represent predictions of the future, but are merely scenarios meant for consideration and discussion. Even though significant uncertainty surrounds this analysis, anticipatory analyses are nonetheless valuable in highlighting the possible implications of, and tradeoffs associated with, emerging technologies as they are maturing and before plant development manifests undesirable environmental impacts. It is the hope of the researcher that such methodologies continue to be developed, refined, and applied. The value of this research lies in its ability to aid human society to respond rationally, ethically, and responsibly to the implications of new technologies as they emerge.

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APPENDIX A

SOCIAL ASSESSMENT: WORKSHOP QUESTIONNAIRE

WORKSHOP QUESTIONNAIRE	Participant: WX-XX
IRB Approval Date:	1/17/2013
IRB Protocol #:	1301008706

Part 1

Please complete before or after the workshop interaction.

Assuming that cultured meat is not widely adopted anywhere in the world, what changes would you expect to see in the United States by 2050? (For example, changes in food supply, religion, education, family structures, etc.)

By default, your responses will be associated only with the participant number that appears in the upper right hand corner of this page. However, if you are willing to provide additional personal information including your profession, employer, position/title, or name, please do so here. This information may be repeated in the reporting of the research and in associated publications and presentations.

(optional)

Part 2
Social Narrative

Please complete part 2, 3, or 4 (or any combination) after the workshop interaction.

What social changes might occur in the United States if cultured meat generally replaced traditional meat products by 2050? What concerns do you have about such a future?

Part 3
Specific Social Impacts

Please complete part 2, 3, or 4 (or any combination) after the workshop interaction.

What do think are the ***most important*** changes that could arise in the United States if cultured meat generally replaced traditional meat products by 2050?

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Food

In terms of food and the food system in general, what changes might occur in the United States if cultured meat generally replaced traditional meat products by 2050? Some factors to consider might be:

- Food prices
- Cuisine diversity
- Cuisine quality
- Food consumption patterns (quantitative or qualitative differences)
- Vegetarian or vegan diets
- Food security
- Food system sustainability
- Food system resilience: the ability of a system to maintain its functions and structure in the face of internal and external change (e.g., drought or rising energy prices) and to degrade gracefully when it must

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Human Health

What changes in human health and nutrition might occur in the United States if cultured meat generally replaced traditional meat products by 2050? Some factors to consider might be:

- Obesity
- Malnourishment
- Life expectancy
- Health expenditure per capita
- Infectious diseases
- Food-borne illnesses
- Cancer rates
- Mental health

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Family and Education

What changes in family dynamics and education might occur in the United States if cultured meat generally replaced traditional meat products by 2050? Some factors to consider might be:

- Family size
- Marriage rate
- School graduation rate
- Standardized test scores

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Ethics and Culture

What shifts in ethics and culture might occur in the United States if cultured meat generally replaced traditional meat products by 2050? Some factors to consider might be social trust and social tolerance.

Do you think cultured meat could have an impact on the cultural identity of some groups? If so, what groups and how could they be impacted?

Demographics and General Statistics

What changes in population dynamics might occur in the United States if cultured meat generally replaced traditional meat products by 2050? Some factors to consider might be:

- Population and growth rate
- Median age
- Fertility rate (births per woman)
- Immigration
- Urban population
- Poverty rate and the poor
- Income per capita
- Employment patterns
- Income equality (GINI index)
- Gender equity (wages and leadership roles)
- Leisure time

Global Impacts

What global changes might occur if cultured meat generally replaced traditional meat products by 2050?

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What effects do you think the availability of cultured meat would have on developing nations, particularly global poverty and/or hunger?

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Part 4
Social Indicators

Please complete part 2, 3, or 4 (or any combination) after the workshop interaction.

Please fill in values for factors of interest, indicating whether they will increase or decrease, and the importance of change.

Factors of interest	**Present state**	**No cultured meat in 2050** (↑ -- ↓)	**All cultured meat in 2050** (↑ -- ↓)	**Importance of change** 1 = very important 2 = important 3 = trivial
Food in General				
Food prices, weekly food cost of a nutritious diet, family of 4 in 2010 (USCB)	$221			
Cuisine diversity (qualitative index)	100			
Cuisine quality (qualitative index)	100			
Consumption, avg Cal/day (USDA)	2067			
Food insecure households, 2009 (UCSB)	14.7%			
Food system resilience (index)	100			
Food system sustainability (index)	100			
Fill in additional factors here				
Human Health				
General nutrition (index)	100			
Overweight population,	67%			

Factors of interest	**Present state**	**No cultured meat in 2050** (↑ -- ↓)	**All cultured meat in 2050** (↑ -- ↓)	**Importance of change** 1 = very important 2 = important 3 = trivial
2007-2008 (USCB)				
Undernourished population (WB)	5%			
Life expectancy at birth (WB)	78			
Health expenditure per capita, 2009 (USCB)	7,578			
Food-borne illnesses, 2011 (FoodNet)	18,964			
Cancer, new cases, 2010 (USCB)	1.53 million			
Suicides (mental health), per 100,000 persons (WB)	4.9			
Family & Education				
Avg family size, 2011 (USCB)	3.25			
Married population, 2011 (USCB)	48.3%			
High school completion rate, 2011 (USCB)	85.9%			
Avg SAT Critical Reading Score, 2011 (IES)	497			
Avg SAT Math Score, 2011 (IES)	514			
Avg SAT Writing Score, 2011 (IES)	489			

Factors of interest	**Present state**	**No cultured meat in 2050** (↑ -- ↓)	**All cultured meat in 2050** (↑ -- ↓)	**Importance of change** 1 = very important 2 = important 3 = trivial
Ethics and culture				
Social trust, people expressing high level of trust in others, 2008 (OECD)	49%			
Community tolerance index of minority groups, 2010 (OECD)	76%			
Demographics and General Statistics				
Population, 2010 (USCB)	308.7 million			
Population growth rate (WB)	0.7%			
Median age, 2010 (USCB)	37.2[2]			
Urban population (WB)	44.7%			
Net migration (WB)	4.95 million			
Fertility rate, births per woman (WB)	2.1			
Poverty rate, 2011 (USCB)	15.9%			
Income equality between rich and poor, GINI index, 2011 (USCB). 0 = perfect equality; 1 = maximum inequality	0.475			
Gross national income per capita (WB)	48,620			
Labor force participation	64%			

Factors of interest	**Present state**	**No cultured meat in 2050** (↑ -- ↓)	**All cultured meat in 2050** (↑ -- ↓)	**Importance of change** 1 = very important 2 = important 3 = trivial
rate, 2011 (USCB)				
Unemployment rate, Jan 2013 (BLS)	7.9%			
Gender equity, women's earnings as % of men's, 2010 (BLS)	81%			
Leisure time, avg hours per day, 2011 (BLS)	5.21			
General happiness, % of population reporting they are "Very Happy", 2006 (NORC)	32.4%			
Global Impacts				
Global poverty headcount ratio, 2008 (% of people living on < $1.25 per day, WB)	22.4%			
Undernourished population (WB)	12.7%			

BLS = US Bureau of Labor Statistics
IES = Institute of Educational Sciences
NORC = National Opinion Research Center
USCB = US Census Bureau
USDA = US Department of Agriculture
WB = World Bank

NOTES

NOTES

APPENDIX B

LIFE CYCLE ANALYSIS: SUPPORTING INFORMATION

Comparison of this Study with Tuomisto and Teixeira de Mattos (2011)

Table 21

Comparison of This Study with Tuomisto & Teixeira de Mattos (2011)

Model component	This study	Tuomisto & Teixeira de Mattos (2011)
Feedstocks	Glucose, glutamine, soy hydrolysate, and basal medium	Cyanobacteria hydrolysate
Cell respiration	Aerobic	Anaerobic
Initial cell density in bioreactor	1x10^5 cells/mL	Not stated
Maximum cell density	1x10^7 cells/mL (Yang et al., 2004)	~ 1x10^7 cells/mL
Mass of one cell	3.5x10^{-12} kg 17% dry mass 7% protein (42% on a dry mass basis).	3.33 x10^{-12} kg (1x10^{-12} kg dry mass) 30% dry mass 19% protein
Batch duration	7.6 days + 3 day cleaning cycle	60 days
Facility energy	Included Size: 717 m^2 Baseline energy demand: 513.3 MJ/m^2/year	Excluded
Bioreactor	6x15,000 L stirred-tank reactors Height: 4.25 m Diameter: 2.125 m Impeller speed: 0.56 rps Filling capacity: 100% Weight: not computed	30x1,000 L Stirred-tank reactors Height: 1.72 m Diameter: 0.86 m Impeller speed: 1.67 rps Filling capacity: 80% Weight: 93 kg

(continued)

Table 21

Comparison of This Study with Tuomisto & Teixeira de Mattos (2011)

Model component	This study	Tuomisto & Teixeira de Mattos (2011)
Agitation / mixing	Included: 449.1 W (29.9 W/m^3) Impeller power number: 5.75	Included: 16 W/m^3 Impeller power number: 2.14
Aeration / sparging	Included: 4.5 kg O_2/MJ (Xylem, 2012)	Included: 0.05 vvm
Sterilization and deionization of culture water	Included. Sterilization included via continuous heating to 140°C.	Sterilization included via autoclaving
Bioreactor cleaning-in-place	Included	Excluded
Culture temperature	37°C	37°C
Energy to maintain cell culture temperature	Excluded	Excluded
Capital equipment	Excluded	Included
Allocation basis for livestock impacts (for comparison purposes)	Live weight	Edible weight

Inventories for Primary Feedstock Production

Glucose and Corn Steep Liquor via Corn Wet Milling

Glucose is a white crystalline solid (Silla, 2003) that has a number of applications including ethanol production. It is also a common source of carbon for cell cultures. Glucose can be obtained from a number of sources including fruits, sugarcane, and sugar beets; however, in the United States, it is primarily produced by the hydrolysis of corn starch (Renouf, Wegener, & Nielsen, 2008; Silla, 2003). Corn starch, in turn, is an output of both dry and wet milling of corn. According to Dale and Tyner (2006), “when producing ethanol, dry milling has a higher efficiency and lower capital and operating costs. For this reason, most of the ethanol plants within the U.S. are dry milling operations" (p. i). However, wet milling is a more versatile process that can produce a wider variety of products including corn starch, corn syrup (Dale & Tyner, 2006), and corn steep liquor. Because corn steep liquor is an input to glutamine production (Rose, 1978) which is also required for cultured meat production, it will be assumed that both corn starch and corn steep liquor are produced via corn wet milling for the purposes of this life cycle model. The process of corn wet milling is shown in Figure 22. Starch may be converted to glucose via an additional hydrolysis step.

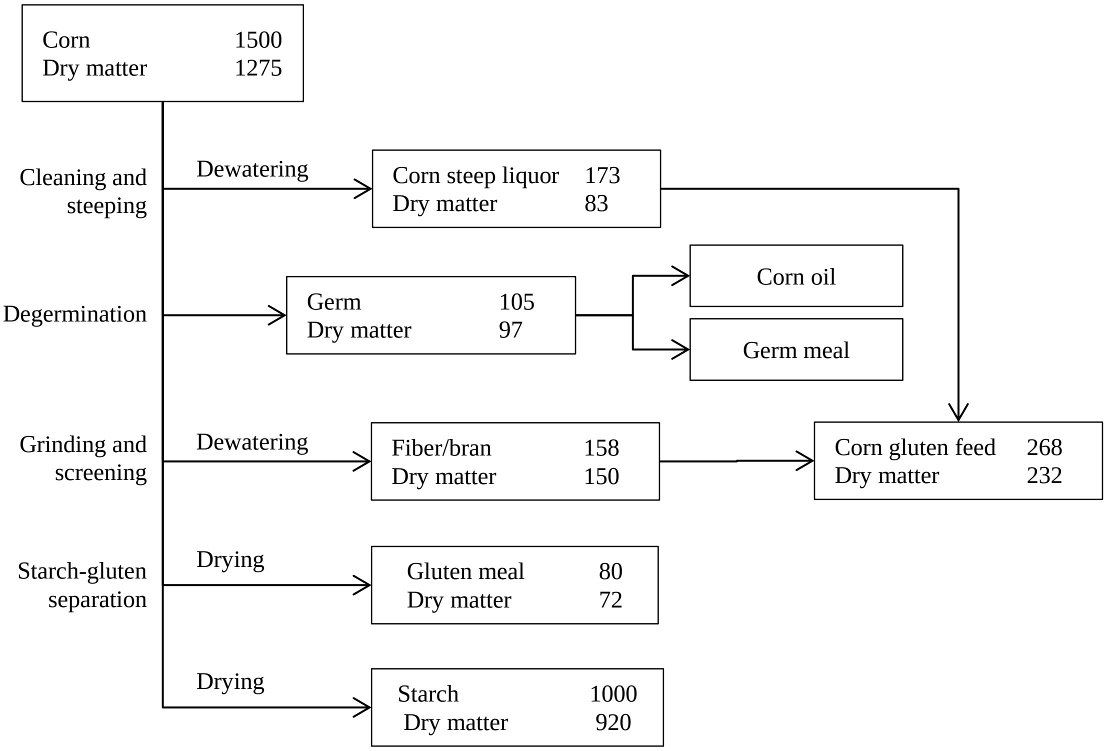

Figure 22. Schematic diagram of the corn wet milling process. Adapted from Renouf et al. (2008) and van Zeist et al. (2012). Corn steep liquor and the bran/fiber are often combined and sold as corn gluten feed, but they may remain separate.

Except as otherwise noted, life cycle inventory data for this process were obtained from Renouf et al. (2008). This model is believed to represent a consistent and conservative estimate of corn wet milling impacts. However, this source indicates that the energy required to produce 1000 kg of glucose (including hydrolysis) is 3115 MJ. This is rather low compared to Galitsky, Worrell, & Ruth (2003), who estimate final energy inputs associated with 1000 kg of starch (excluding hydrolysis) to be about 4734 MJ of electricity and fuel plus about 1839 MJ of steam.

Table 22

Inventory for Glucose Production

Substance	Units	Quantity	Impact allocation
Inputs			
Harvested corn	kg	1500	
Energy			
Electricity	MJ	934	
Water (for electricity production)	L	1972	
Natural gas	MJ	2181	
Chemicals			
Lime (CaO)	kg	0.3	
Sulphuric acid (100%)	kg	0.45	
Sulphur dioxide	kg	3.06	
Urea	g	208	
Sodium hydroxide (50%)	g	282	
Sodium chloride	g	65	
Cyclohexane	g	55	
Chlorine	g	12	
Water	m^3	4.9	

(continued)

Table 22

Inventory for Glucose Production

Substance	Units	Quantity	Impact allocation
Outputs			
Glucose	kg	1000	64.0%
Co-products			
Bran/fiber	kg	158 [a]	13.5%
Corn steep liquor	kg	173 [a]	5.8%
Corn gluten meal	kg	80	7.3%
Corn germ	kg	105 [a]	9.4%
Air emissions			
Particulate (PM10)	g	0.7	
Water emissions			
BOD5	g	0.2	
Chlorides	g	118.8	
Sulphate	g	0.2	
Suspended matter	g	0.7	

Note. Unless otherwise stated, inventory values were taken from Renouf et al. (2008). Impacts were allocated to the products of wet corn milling on a gross chemical energy basis computed from dry mass and energy contents of corn products listed in Table 23.

[a] Computed from Renouf et al. (2008) and van Zeist et al. (2012)

Table 23

Energy Content of Cultured Meat Inputs

Substance	Dry matter (%)	Gross energy (mcal/kg)
Glucose	92 [a]	3.75 [b]
Corn gluten meal	90 [a]	5.467 [c]
Corn steep liquor	48 [a]	3.79 [d]
Corn bran	95 [a]	4.847 [c]
Corn germ	92 [a]	5.224 [c]
Soybean meal (as fed basis)		4.084 [e]
Soybean oil		9.4 [f]

Note. Energy values are given on a dry mass basis except as noted.

[a] Source: van Zeist et al. (2012)

[b] Source: Food and Agriculture Organization of the United Nations (2002)

[c] Source: Anderson, Kerr, Weber, Ziemer, and Shurson (2012)

[d] Source: Chovatiya, Bhatt, and Shah (2010)

[e] Source: Pelletier, Pirog, et al. (2010)

[f] Source: Almeida and Godoi (2011)

Synthetic Amino Acids

L-glutamine is a non-essential amino acid synthesized in the body predominantly by muscle cells; however, it must be added to *ex vivo* cellular cultures (Hu, 2012). As of 2001, approximately 2000 tons of glutamine were produced worldwide for use in pharmaceuticals and health foods, entirely through fermentation of glucose and ammonia and/or ammonium sulfate by glutamic bacteria (Kusumoto, 2001). The process for industrial production is given in Figure 23.

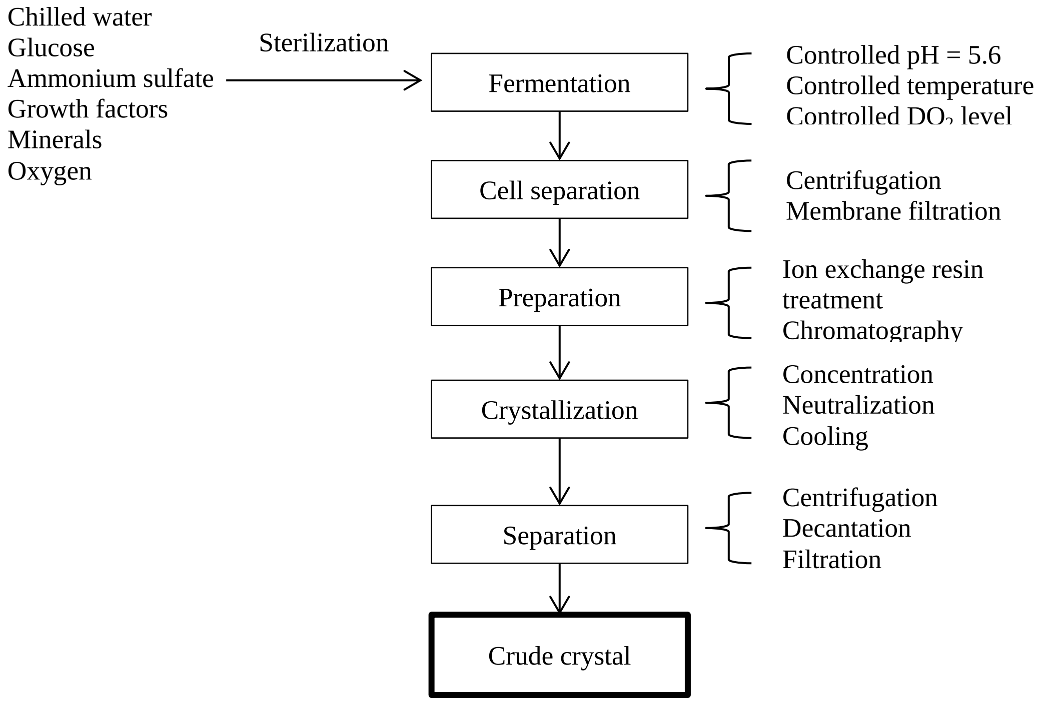

Figure 23. Diagram of l-glutamine production. Based on Kusumoto (2001).

A published life cycle analysis for glutamine could not be located. Therefore, the inventory was assembled from an article reporting experimental results as well as a life cycle analysis of threonine, another amino acid produced via fermentation. Most material flows were derived from a cost optimization study published by Li et al. (2007). Using a combination of methods, the author attempted to minimize overall glutamine production costs by varying primary inputs (glucose and ammonium sulfate) in order to maximize glutamine-to-byproduct ratios. Data for the inventory, presented in Table 24, is based on the most economical optimal medium (OM-2) scenario. Energy and additional material flows were taken from a life cycle analysis of lysine, threonine, and methionine conducted by Marinussen and Kool (2010). Threonine was chosen as the model for glutamine production since, similar to glutamine, it is crystallized via ion-exchange resins

(Hermann, 2003; Marinussen & Kool, 2010) and both have similar amino acid to glucose yields of 0.35 (Li et al., 2007; Marinussen & Kool, 2010). Uncertainty regarding the differences between threonine and glutamine production remains, however. The life cycle analysis for threonine (Marinussen & Kool, 2010) reflects the typical process of acidification after the cell separation phase: hydrochloric acid or sulfuric acid is added "to ease adsorption of the amino acid to the ion exchange resins" (Hermann, 2003, p. 167). However, acids are not specifically mentioned in the industrial production model published by Li et al. (2007) and fermentation of glutamine occurs at a weakly acidic pH of 5.6. It will therefore be assumed that no additional acid is added to the fermentation liquor and that a cationic ion exchange resin is used. This assumption should be revisited as more information becomes available.

Table 24

Inventory for Glutamine Production

Substance	Units	Quantity
Inputs		[a]
Corynebacterium glutamicum G32, ATCC 13032		--[a]
Stirred-tank fermentors of 100 m^3		--[a]
Glucose	g	2881.3[a]
Ammonium sulfate	g	2044.8[a]
Corn steep liquor	g	253.5[a]
Monopotassium phosphate, KH_2PO_4 †	g	52.8[a]
Magnesium sulfate heptahydrate, $MgSO_4 \cdot 7H_2O$	g	29.6[a]
Manganese sulfate monohydrate, $MnSO_4 \cdot H_2O$ †	g	0.1[a]
Zinc sulfate heptahydrate, $ZnSO_4 \cdot 7H_2O$ †	g	0.1[a]
Water for process (fermentation/cleaning)	g	21033.0[b]

(continued)

Table 24

Inventory for Glutamine Production

Substance	Units	Quantity
Water for cooling	g	8961.3[c]
46% Caustic (NaOH) for cleaning-in-place	g	200[c]
Resin	g	228[d]
Energy		
Steam for fermentation, evaporation, and drying	kg	20[c]
Electricity for fermentation, evaporation, and drying	kWh	12.05[c]
Outputs		
Glutamine	g	1000.0[a]
Glutamate	g	76.7[a]

Note. All impacts were allocated to glutamine production.

[a] OM-2 results from Li et al. (2007).

[b] Computed from Li et al. (2007). It is assumed that purification and sterilization are done in the facility.

[c] Threonine inventory from Marinussen & Kool (2010).

[d] Computed from Marinussen & Kool (2010) and Dow Chemical (2000).

† Compound unavailable in SimaPro databases.

Table 25

Inventory for Lysine Production

Substance	Units	Quantity
Inputs		
Glucose syrup (70% dry matter)	kg	3500
Corn steep liquor (48% dry matter)	kg	300
Ammonia	kg	155
Ammonium sulfate	kg	95
Sulfuric acid (96%)	kg	320
Phosphoric acid (85% w/w)	kg	25
Vitamins, amino acids (as glutamine)	kg	4
Salts (as magnesium sulphate)	kg	5
Antifoam	Liters	10†
Water for process (fermentation/cleaning)	m^3	4.6
Water for cooling (fermentation/evaporation)	m^3	68
46% Caustic (NaOH) for cleaning-in-place	kg	4.5
Nitric acid (67%) for cleaning	kg	1.5
Energy		
Steam for fermentation, evaporation, and drying	tonne	2.3
Electricity for fermentation, evaporation, and drying	kWh	3935
Outputs		
Lysine.HCL	kg	1000
Effluent waste water (low BOD assumed to be 10 mg/L)	m^3	4

Note. All impacts allocated to lysine. Source: Marinussen & Kool (2010).

† Compound unavailable in SimaPro databases

Table 26

Inventory for Threonine Production

Substance	Units	Quantity
Inputs		
Glucose syrup (100% dry matter)	kg	3000
Corn steep liquor (48% dry matter)	kg	1000
Ammonia	kg	700
Sulfuric acid (96%)	kg	1500
Phosphoric acid	kg	4
Vitamins, amino acids, salts, antibiotics (as glutamine)	kg	5
Water for process (fermentation/cleaning)	m^3	120
Water for cooling (fermentation/evaporation)	m^3	9
46% Caustic (NaOH) for cleaning-in-place	kg	200
Nitric acid (67%) for cleaning	kg	250
Resin	L	300
Energy		
Steam for fermentation, evaporation, and drying	tonne	20
Electricity for fermentation, evaporation, and drying	kWh	12,050
Outputs		
L-Threonine	kg	1000

Note. All impacts allocated to threonine. Source: Marinussen & Kool (2010).

Soy Hydrolysate

Protein hydrolysates serve as a nitrogen source for biotechnology applications and provide “vitamins, minerals and unknown growth factors resulting in higher yields and productivities” (Pasupuleti & Braun, 2010, pp. 11-12). For this reason, hydrolysates from a number of plant sources including soy, rice, yeast, and wheat have been investigated as replacements for animal serum, but results have been mixed (Chun et al., 2007; Girón-Calle et al., 2008; Sung et al., 2004). While yeast hydrolysates have been shown to increase therapeutic protein production (Sung et al., 2004) and soy hydrolysates have increased cell biomass growth (Chun et al., 2007), both fail to achieve performance equal to media containing fetal bovine serum. Nonetheless, it will be assumed that soy hydrolysate is added to the cultured meat broth at the rate of 5 g/L to supplement the synthetic amino acids in the basal medium. This concentration has been shown to produce the highest viable cell densities (Chun et al., 2007; Sung et al., 2004).

Hydrolysis of proteins may be accomplished via acids, alkalis, or enzymes, but enzymatic hydrolysis using selective proteases is becoming the more common method because the reaction takes place in milder conditions, is safer with few or no undesirable side products, and is easier to control than other methods, providing a more uniform product (Marinova, Cuc, & Tchorbanov, 2008; Pasupuleti & Braun, 2010; Sun, 2011). Hydrolysis of soy protein typically begins with soybean meal (discussed in the next section) or soy protein isolate to which enzymes are added (Sun, 2011). Due to their large scale availability, enzymes used for industrial hydrolysis are typically of plant or microbial origin such as bromelain, papain or ficin (Sun, 2011); however, animal-sourced enzymes such as pancreatin, trypsin, and pepsin could also be applied to soy protein (Pasupuleti & Braun, 2010; Sun, 2011). Depending on the desired products, mild acid (0.2 N HCl) might be added to the slurry, and it might be pressurized or subjected to ultrasonic waves (Sun, 2011). Petersen (1981) described a two-step process by which soy white flakes (similar in composition to soybean meal) are first washed in an acid bath to produce soy protein concentrate. The concentrate is then diluted with water to an 8% substrate concentration and enzyme is added to achieve a 2% enzyme:substrate ratio. The mixture is heated to 55°C while NaOH is added to maintain a pH of 8. Once the desired degree of hydrolysis has been achieved, the enzyme is inactivated by the addition of acid to lower the pH to 4. Centrifugation is then used to separate the hydrolysate from the unconverted soy protein to achieve an overall hydrolysate yield of approximately 70%.

No life cycle analysis of soy protein hydrolysis could be located, so the process described above was used to estimate the LCA of soy hydrolysate. However, due to significant uncertainties in the process details, only the soybean meal, enzyme, water, and energy inputs associated with heating will be included. Therefore, because this estimate ignores the acid, base, centrifugation, cleaning, and facilities, it underestimates the full environmental impact of hydrolysis. This abbreviated life cycle inventory for soy hydrolysate is shown in Table 27. The inventory for the enzyme is shown in Table 28.

Table 27

Inventory for Soy Hydrolysate Production

Substance	Units	Quantity
Inputs		
Soybean meal	g	1428.6
Chemicals		
Enzyme	g	28.6
NaOH	g	Unknown
HCl	g	Unknown
Water for process	g	17,857
Energy for heating water (brewery fuel mix)	MJ	2.24
Outputs		
Soy hydrolysate	g	1000
Air emissions		Unknown
Water emissions		Unknown

Note. Computed from Petersen (1981).

Table 28

Inventory for Enzyme Production

Substance	Sub-compartment	Units	Quantity
Inputs			
Energy, from coal	resource/in ground	MJ	52.1
Transformation, from pasture and meadow	resource/land	m^2	0.723
Transformation, to industrial area	resource/land	m^2	0.723
Water, unspecified natural origin/m3	resource/in ground	m^3	0.0209
Outputs			
Enzyme, Cellulase, Novozyme Celluclast		kg	1
Air emissions			
Carbon dioxide, fossil	air/unspecified	kg	4.09
Ethene	air/unspecified	kg	0.002
Sulfur dioxide	air/unspecified	kg	0.00937
Soil emissions			
Phosphate	soil/unspecified	kg	0.0153

Note. Adapted from Inman (2013).

Soybean Meal

Soybean meal is a product of soybean milling and is essentially the flour that remains after the soybeans are dehulled and defatted (see Figure 24). The life cycle inventory for this process was obtained from Dalgaard et al. (2008) and shown in Table 29.

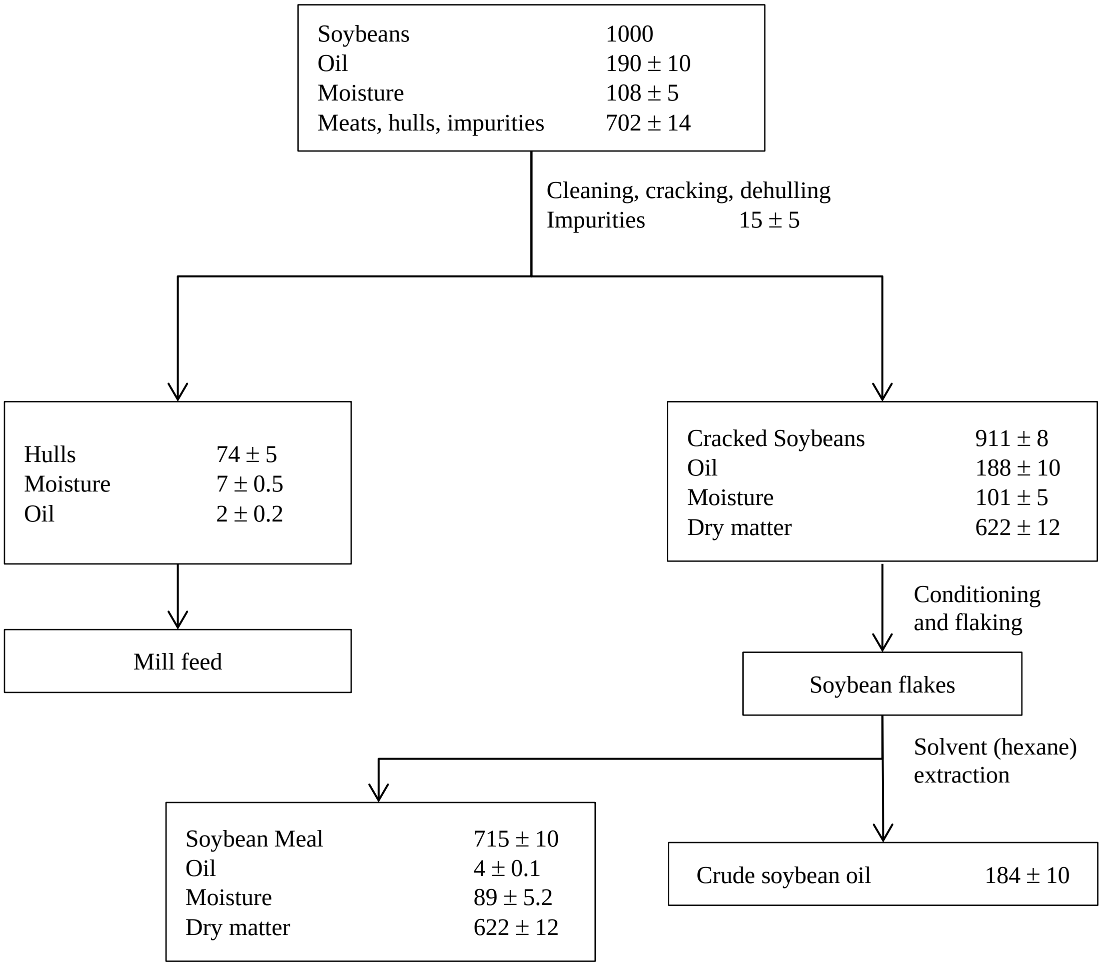

Figure 24. Diagram of the soybean milling process. Based on Keller (n.d.). Note that the values given in this figure were derived from a different source, and therefore differ from, those given in Table 29. Product values given here are for information purposes only and were not used in the life cycle inventory.

Table 29

Inventory for Soybean Meal Production

Substance	Units	Quantity	Impact allocation
Inputs			
Harvested soybeans	kg	1000	
Energy			
Transport to mill (28 t lorry)	tkm	500	
Electricity (natural gas)	kWh	12	
Heat (oil)	MJ	145	
Heat (gas)	MJ	282	
Chemicals			
Hexane	g	400	
Outputs			
Soybean meal (87.5% dry matter, 3.2% oil)	kg	826.45	70%
Co-products			30%
Soybean oil	kg	157.85	
Air emissions			
Hexane	g	200	
Water emissions			
BOD5, biological oxygen demand	g	0.017	
COD, chemical oxygen demand	g	0.061	
Nitrate	g	0.004	

Note. Source: Dalgaard et al. (2008). Impacts were allocated to the products of soybean milling on a gross chemical energy basis based on energy contents of soy products listed in Table 23.

Basal Medium

Basal media are widely available commercially and contain a number of ingredients necessary for cell growth including amino acids, vitamins, and salts. The CHO cell metabolic data used in this study was obtained in the presence of Iscove's Modified Dulbecco's Medium (IMDM) (Sung et al., 2004). While commercial-scale cultured meat production is likely to use a medium designed and optimized specifically for skeletal muscle cells, IMDM supplemented as noted in Sung et al. (2004) serves as a reasonable estimate of the compounds that will be necessary for cell proliferation.

The standard formulation for Iscove's Modified Dulbecco's Medium (IMDM) includes glucose and glutamine. For the purposes of this LCA, those are removed from the IMDM inventory since quantities for both substances are computed based on specific cellular uptake rate. Because inventories are not available for all amino acids listed, and synthetic amino acids are generally produced via fermentation, threonine and lysine in equal portions will be used as proxies for the spectrum of amino acids listed. Other compounds that do not exist in SimaPro databases are ignored. Thus, even though the concentration of IMDM would actually be 20,686 mg/L, for the purposes of this study, the components comprise only 6,747 mg/L including supplementary components.

Table 30

Inventory of Iscove's Modified Dulbecco's Medium (IMDM)

Components	IMDM Concentration (mg/L)	Supplementary components (mg/L) [a]	Quantity in inventory (mg/L)
Amino Acids			
Glycine	30		30 [b]
L-Alanine	25	12.5	37.5 [b]
L-Arginine hydrochloride	84		84 [b]
L-Asparagine (freebase)	25		25 [b]
L-Aspartic acid	30		30 [b]
L-Cystine 2HCl	91.4		91.4 [b]
L-Glutamic Acid	75		75 [b]
L-Glutamine	584		--
L-Histidine hydrochloride-H2O	42		42 [b]
L-Isoleucine	105		105 [b]
L-Leucine	105	105	210 [b]
L-Lysine hydrochloride	146	146	292 [b]
L-Methionine	30		30 [b]
L-Phenylalanine	66		66 [b]
L-Proline	40		40 [b]
L-Serine	42		42 [b]
L-Threonine	95		95 [b]
L-Tryptophan	16	16	32 [b]
L-Tyrosine disodium salt	104		104 [b]
L-Valine	94		94 [b]

(continued)

Table 30

Inventory of Iscove's Modified Dulbecco's Medium (IMDM)

Components	IMDM Concentration (mg/L)	Supplementary components (mg/L)[a]	Quantity in inventory (mg/L)
Vitamins			
Biotin	0.013		†
Choline chloride	4		†
D-Calcium pantothenate	4		†
Folic Acid	4		†
Niacinamide	4		†
Pyridoxal hydrochloride	4		†
Riboflavin	0.4		†
Thiamine hydrochloride	4		†
Vitamin B12	0.013		†
i-Inositol	7.2		†
Inorganic salts			
Calcium Chloride ($CaCl_2$) (anhyd.)	165		165
Magnesium Sulfate ($MgSO_4$) (anhyd.)	97.67		97.67
Potassium Chloride (KCl)	330		330
Potassium Nitrate (KNO_3)	0.076		0.076
Sodium Bicarbonate ($NaHCO_3$)	3024		†
Sodium Chloride (NaCl)	4500		4500
Copper(II) Chloride ($CuCl_2$)		0.0025	†
Sodium Phosphate Monobasic (NaH_2PO_4-H_2O)	125		125
Sodium Selenite (Na_2SeO_3-$5H_20$)	0.0173	0.017	†

(continued)

Table 30

Inventory of Iscove's Modified Dulbecco's Medium (IMDM)

Components	IMDM Concentration (mg/L)	Supplementary components (mg/L) [a]	Quantity in inventory (mg/L)
Ferric Nitrate ($Fe(NO_3)_3$-$9H_2O$)		2	†
Ferric Citrate		2	†
Zinc Sulfate Heptahydrate, ($ZnSO_4 \cdot 7H_2O$)		1	1
Other components			
Recombinant Human Insulin		5	†
Ethanolamine		3	3
Phosphatidylcholine		5	†
Pluronic F68		1,000	†
Putrescine		1	†
D-Glucose (Dextrose)	4500		--
HEPES	5958		†
Phenol Red	15		†
Sodium Pyruvate	110		†
Total concentration	20,686		6,747

[a] (Sung et al., 2004)

[b] Excluding glutamine, which is modeled separately, the basal medium utilized by Sung et al. (2004) contained 1524.9 mg/L of amino acids. For modeling purposes it was assumed that half of these amino acids were produced following a process similar to lysine and the other half threonine.

† Compound unavailable in SimaPro databases

Inventories for Crop Production

Table 31

Inventory for Corn and Soybean Production

Substance	Corn	Soybeans
Inputs		
Fertilizer (kg)		
N	145	4.2
P_2O_5	51	11.0
K_2O	65	17.3
Sulfur	4.2	
Lime	321	
Energy		
Diesel (l)	43.0	31.8
Gas (l)	11.2	10.2
LPG (l)	67.3	
Electricity (kWh)	41.5	
Herb/Pesticides (kg active ingredients)	2.8	1.3
Seed (kg)	216	144
Green (rain) water (m^3) [a]	5585	4992
Blue (ground and surface) water (m^3) [a]	674	294
Outputs		
Yield (tonnes)	10.7	3.2
Nitrous Oxide (kg)	4.7	1.1
Ammonia (kg)	21.8	8.6
Nitric Oxide (kg)	3.1	0.1
Carbon Dioxide (kg) [b]	142.7	1.8

Note. Based on Pelletier, Pirog, et al. (2010).

[a] Source of water inputs: Mekonnen & Hoekstra (2010).

[b] From lime and urea fraction of N fertilizer as per IPCC (2006).

Bioreactor Energy Calculations

Aeration / Oxygenation

Based on oxygen uptake rate given in Table 5 and equation (4) on page 56, the total oxygen requirement for a batch of cultured meat can be determined to be 60.2 kg. Standard aeration efficiencies (SAE) range from 2-8 kg O_2/kWh for diffused systems (Xylem, 2012). Assuming an efficiency of 4.5 kg O_2/kWh, then the power required to deliver 60.2 kg of oxygen the bioreactor can be computed as follows:

$$E_{sp} = \frac{kg\ O_2}{SAE} = \frac{60.2\ \ kg\ O_2}{\left(\frac{4.5\ kg\ O_2}{kWh}\right)\left(\frac{kWh}{3.6\ MJ}\right)} = 48.2\ MJ \tag{8}$$

Mixing / Agitation

Dimensionless numbers are often used to aid in bioreactor design. One of these is the Reynolds number (abbreviated “Re”), which is “the ratio of inertial to viscous forces” (Taghavi, Zadghaffari, Moghaddas, & Moghaddas, 2011, p. 282). In the bioreactor reactor design given herein,

$$Re = \frac{\rho_b N D^2}{\mu} = \frac{(993.1 kg/m^3)(0.56/s)(0.85m)^2}{0.653x10^{-3}\ Ns/m^2} = 617{,}228 \tag{9}$$

where ρ_b is the density of the culture medium (assumed to be equivalent to water), N is the impeller angular velocity in revolutions per second, D is the impeller diameter, and μ is the fluid dynamic viscosity (also assumed to be that of water). Any Reynolds number greater than 10,000 in a stirred vessel is said to be turbulent.

Another dimensionless number is referred to as the power number (N_p) which has a well-accepted correlation with the power (P) imparted in the bioreactor by the impeller. Power number, N_p, is given by:

$$N_p = \frac{P}{\rho N^3 D^5} \tag{10}$$

This number is a function of the type of impeller and is essentially constant for turbulent fluids (Re > $1x10^4$). Assuming the bioreactor includes a Rushton impeller with a power number of 5.75 (Fusion Fluid Equipment, 2012), then the power and energy imparted to the impeller during one batch cycle are computed as follows.

$$P_{ag} = N_p \rho_b N^3 D^5 = 5.75\left(\frac{993.1kg}{m^3}\right)\left(\frac{0.56}{s}\right)^3 (0.85\,m)^5$$

$$= 449.1\,\frac{kgm^2}{s^3} = 449.1\,W \tag{11}$$

$$E_{ag} = P_{ag}(batch\ duration)$$

$$= 449.1\,W(181.2\ hours)\left(\frac{3600\,s}{hour}\right)\left(\frac{MJ}{1x10^{\,6}J}\right) = 293\ \mathrm{M}J \tag{12}$$

Heating Water

Animal cells proliferate well at 37°C. However, the culture medium must be sterilized at the beginning of each batch cycle. It assumed that 50% of waste heat associated with cooling the sterilized medium is captured in a step that preheats the new, incoming media to 67.5°C. Given this scenario, energy must be expended to heat the culture medium from 67.5 to 140°C. Assuming each batch requires a total of 15,000 L of water, then the energy required to heat the water is 4,545 MJ per batch:

$$E_{H2O} = C_v V \Delta T = 4179.6\,\frac{J}{LK}(15{,}000\,L)(140 - 67.5K)\left(\frac{MJ}{1x10^{\,6}J}\right)$$

$$= 4{,}545\ \mathrm{M}J \tag{13}$$

A similar computation is performed to estimate the energy required to heat 15,000 L of water from 25 to 50°C for the bioreactor cleaning cycle.

Calculation of Facility Floorspace

In the absence of a full-scale working carnery, the brewing industry was used as a model for estimating the required floorspace required for a cultured meat plant. However, it is impossible to equate cultured meat to beer production directly: Not only are they different substances with different densities, but they also have different batch cycle times. However, both products require a common commodity: space and time in a bioreactor, expressed here as “bioreactor liter-hours”. Therefore, if it takes 10 days (excluding aging) (MillerCoors LLC, n.d.) and 1 liter of bioreactor volume to produce 1 liter of beer, then it takes 240 bioreactor liter-hours to make 1 liter of beer. It follows that, if a brewery can ferment 248,000,000 gallons (“Packaging is as golden as MillerCoors’ brews,” 2011) or 939 million liters of beer per year, the brewery has a capacity of 225 billion bioreactor liter-hours per year:

$$1\ liter\ of\ beer\ requires\ 10\ days * 24\frac{hours}{day} = 240\ liter - hours \tag{14}$$

$$939\ million\ liters\ beer\left(\frac{240\ liter-hours}{liters\ of\ beer}\right) = 225{,}000{,}000{,}000\ liter - hours \tag{15}$$

If the same brewery takes up 2.3 million square feet (213,677 m^2) (“Packaging is as golden as MillerCoors’ brews,” 2011), then the facility can support 98,000 bioreactor liter-hours per square foot. Similarly, the carnery model offers 756 million liter-hours per year:

$$6 * 15{,}000L\left(50\frac{weeks}{year} * 7\frac{days}{week} * 24\frac{hours}{day}\right) = 756\ million\ liter - hours \tag{16}$$

Again assuming the industrial brewery model, the carnery would need 7,717 ft^2 (717 m^2) of floor space:

$$756\ million\ carnery\ liter - hours\left(\frac{2{,}300{,}000\ brewery\ ft^2}{225{,}000{,}000{,}000\ brewery\ liter{-}hours}\right)$$

$$= 7717\ ft^2 \tag{17}$$

For reference, a typical 15,000 L bioreactor would have a diameter of about 2 meters (6.5 feet) so the six bioreactors would actually take up only about 200 ft^2.

Based on this assumption and the life cycle analysis results presented in Chapter 5, the energy consumption of a cultured meat plant can be computed. As shown in Figure 25, if feedstocks were processed offsite and ready to add to the bioreactor upon arrival, then the cultured meat plant would require significantly less energy than a pharmaceutical plant and brewery per unit of floorspace (dark purple). Depending on how similar cultured meat production will be to pharmaceutical and beer production, this could indicate that the carnery model developed herein understates the energy that will be required. However, assuming that breweries prepare the feedstock, or wort, that provides nutrients to the yeast themselves, then they could be said to perform some of the feedstock processing onsite. For this reason, the light purple portion of the cultured meat plant column was added to indicate the energy per facility square foot required to prepare the basal medium and other inputs. Even with this significant addition, it still appears that the energy required for cultured meat production may be underestimated.

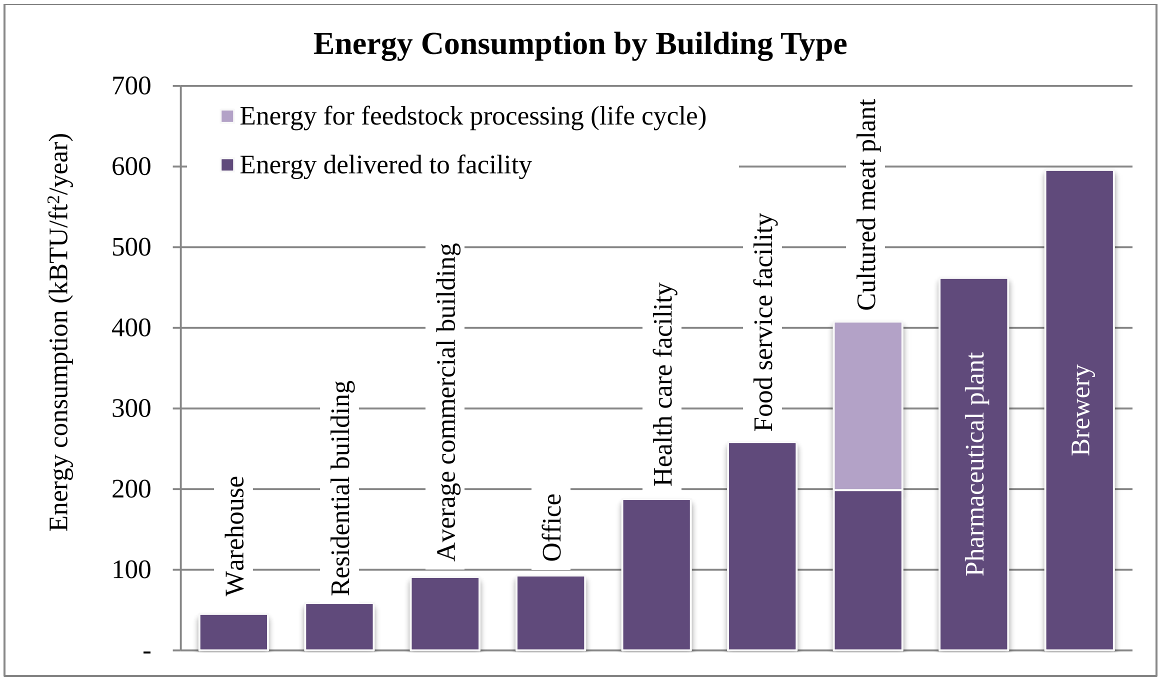

Figure 25. Energy consumption by building type. Data for the cultured meat plant was computed from the results presented in Chapter 5. Dark purple indicates direct energy required by the model plant including baseline facility energy, cleaning-in-place, sterilization and deionization of water, agitation, and aeration of the bioreactors; light purple represents energy required for processing of cultured meat feedstocks. Source for other building types: D&R International Ltd. (2012).

Cell Information

Table 32

Physical Characteristics of a Typical Animal Cell

Characteristic	Value	Units
Cell mass	3500	pg
Cell dry mass	600	pg
Protein mass	250	pg
Cell water mass	2900	pg
Cell volume	4000	μm^3

Note. Source: Hu (2012).

Conversion Factors

Table 33

Conversion Factors

Quantity			Conversion factor	Units
Unit conversion factors				
Energy				
	1 BTU	=	0.00029307	kWh
	1 BTU	=	0.001055056	MJ
	1 kWh	=	3412.14163	BTU
	1 kWh	=	3.6	MJ
	1 MJ	=	238.85	kcal
Area				
	1 acre	=	4046.86	m^2
	1 m^2	=	10.7639	ft^2
	1 ft^2	=	0.092903	m^2

(continued)

Table 33

Conversion Factors

Quantity			Conversion factor	Units
Volume				
	1 acre-foot	=	1233481.84	liters
	1 beer barrel	=	119.24	liters
	1 m^3	=	1000	liters
	1 gal	=	3.78541	liters
Mass				
	1 lb	=	0.453592	kg
Physical characteristics				
Water				
Density of water at 37.8C		=	993.112	
Energy content of fuels				
Diesel:	1 gallon	=	130500	BTU
Natural gas:	1 ft^3	=	930	BTU
Coal:	1 short ton	=	20140000	BTU
Steam:	1 lb	=	1078.9	BTU
Oil:	1 toe	=	41.7	GJ
Energy content of biomass				
Beef (live weight):	1 kg	=	4.63	MJ
Pork (live weight:	1 kg	=	4.63	MJ
Poultry (live weight:	1 kg	=	4.63	MJ
Cultured meat:	1 kg	=	6.57	MJ

Detailed Results

Table 34

Environmental Impact Comparison with Prior LCA, Beef, Pork, and Poultry Production

Impact category	Units	Beef [a]	Pork [b]	Poultry [c]	Cultured meat [d]	This study
Industrial energy use	MJ	38.2 (88.8)	9.7 (17.4)	15.0 (26.7)	31.8	53.7
Global warming potential (100a)	kg CO_2 eq	14.8 (34.4)	2.5 (4.4)	1.4 (2.5)	2.2	3.9
Eutrophication potential	g PO_4 eq	104 (241.9)	15.9 (28.4)	3.9 (7.0)	N/A	12.0
Land use	m^2a	44.7[e] (104.0)	9.6[e] (17.1)	4.5[f] (8.0)	0.2	2.5
Acidification potential	g SO_2 eq	N/A	N/A	N/A	N/A	37.3
Human toxicity (100a)	kg 1,4-DB eq	N/A	N/A	N/A	N/A	0.36
Ozone layer depletion (steady state)	µg CFC-11 eq	N/A	N/A	N/A	N/A	214

Note. Functional unit is 1 kg cultured meat and1 kg live weight of beef, pork, and poultry.

(Impacts on edible weight basis are shown in parentheses.)

[a] Feedlot (Pelletier, Pirog, et al., 2010)

[b] Commodity High Profit (Pelletier, Lammers, et al., 2010)

[c] (Pelletier, 2008)

[d] California (Tuomisto & Teixeira de Mattos, 2011)

[e] Estimated based on data provided in the source. Consists of land occupation values for beef and feed production values for pork.

[f] Source: Williams, Audsley & Sandars (2006) converted to live weight basis.

Table 35

Energy Return on Investment (EROI)

Type	Beef (Feedlot)	Pork (Commodity High Profit)	Poultry	This study
Industrial EROI	5.2% [a]	26.7% [b]	17.3% [d]	12% [g]
Human-edible EROI	4.2% [a]	7.4% [b]	15% [e]	54% [g]
Gross chemical EROI	2.0% [c]	13.1% [c]	16% [f]	54% [g]

Note. Industrial EROI is the human edible energy return on industrial energy investment; human-edible EROI is the human-edible energy return on human-edible caloric energy investment; and gross chemical EROI is the gross chemical energy return on gross chemical energy input (Pelletier, Pirog, et al., 2010).

[a] "Assumes 43% yield of boneless meat per live-weight kg produced and an energy density of 4.63 MJ/kg of raw, boneless beef." (Pelletier, Pirog, et al., 2010)

[b] "Assumes 56% yield of boneless meat per live-weight kg produced and an energy density of 4.63 MJ/kg of raw, boneless pork." (Pelletier, Lammers, et al., 2010)

[c] Assumes 100% yield of boneless meat per live-weight kg produced and an energy density of 4.63 MJ/kg of raw, boneless pork." (Pelletier, Lammers, et al., 2010)

[d] Computed based on data given in source. Assumes 56% of live weight poultry is edible and an energy density of 4.63 MJ/kg (Pelletier, 2008)

[e] Source: Smil (2013, p. 140). Assumes all poultry feed is human-edible.

[f] Computed from Smil (2013, p. 140). Assumes an energy density of 4.63 MJ/kg.

[g] Assumes 100% edible yield of cultured meat and an energy density of 6.56 MJ/kg based on Savinell & Palsson (1992) and Pagan (n.d.). Human-edible and gross chemical inputs consist of glucose and soybean meal used at all stages of production.

Table 36

Water Use Comparison with Prior LCA, and US Beef, Pork, and Poultry Production

Water disposition	Units	Beef [a]	Pork [a]	Poultry [a]	Cultured meat in California[b]	This study
Water, industrial meat production	L	2008 (4670)	2969[b] (5303)	1424 (2542)	371	815
Green water		1,792	2,548	1,285		558
Blue water		216	421	139	371	257
Water, weighted average meat production	L	8177	3553[b]	1421		
Green water		7,858	3,071	1,283		
Blue water		319	483	139		

Note. Functional unit is 1 kg of cultured meat and live weight for agricultural meat. (Impacts on an edible weight basis are shown in parentheses.) All values include green (rainwater) and blue water (surface and groundwater) but exclude grey water (freshwater required to assimilate pollutants) (Mekonnen & Hoekstra, 2012).

[a] (Mekonnen & Hoekstra, 2012)

[b] (Tuomisto & Teixeira de Mattos, 2011)

Table 37

Environmental Impact for Cultured Meat by Product Stage

Impact category	Units	Feedstock production: Agriculture	Feedstock production: Processing	Material transport	Cell cultivation & waste products	Facility	Cleaning
Industrial energy use	MJ	0.66	16.5	1.99	13.7	5.60	15.3
Global warming potential (100a)	kg CO_2 eq	0.17	1.17	0.15	1.0	0.41	1.07
Eutrophication potential	g PO_4 eq	0.90	0.55	0.13	9.9	0.11	0.46
Land occupation	m^2a	2.47	0.01	--	--	0.02	0.01
Acidification potential	g SO_2 eq	3.20	11.3	0.75	8.86	3.67	9.54
Human toxicity (100a)	kg 1,4-DB eq	0.02	0.11	0.01	0.08	0.03	0.11
Ozone layer depletion (steady state)	µg CFC-11 eq	11.9	5.03	--	23.8	1.84	172
Water use	L	633	55.6	--	33.2	1.18	92.3

Note. Functional unit is 1 kg of cultured meat.

Table 38

Livestock Dressed and Edible Portions

Portion	Beef	Pork	Poultry
Dressed weight as % of live weight [a]	60%	75%	75%
Edible weight as % of live weight [b]	43%	56%	56%

[a] Based on 2010 data from National Agricultural Statistics Service of the USDA (n.d.).

[b] Based on livestock LCA sources (Pelletier, Lammers, et al., 2010; Pelletier, Pirog, et al., 2010; Pelletier, 2008).

Heat Transfer Analysis

The optimum temperature for CHO cells is 37°C and "variations of 1°C can reduce cell growth, viability, and/or product production" (Flickinger, 2013, p. 874). The total heat flux associated with a large-scale cell culture in a stirred-tank bioreactor can be expressed as follows:

$$Q_{acc} = Q_{met} - Q_{sen} + Q_{sp} + Q_{ag} - Q_{evap} - Q_{ex} \tag{18}$$

where Q_{met} represents heat produced by cell metabolism, Q_{sen} is sensible enthalpy gain by flow streams (outlet-inlet), Q_{ag} is heat generated by power input from agitation, Q_{sp} is heat generated by sparging, Q_{evap} is heat removed by evaporation, and Q_{ex} is heat transferred by the heat exchanger (Flickinger, 2013, p. 875).

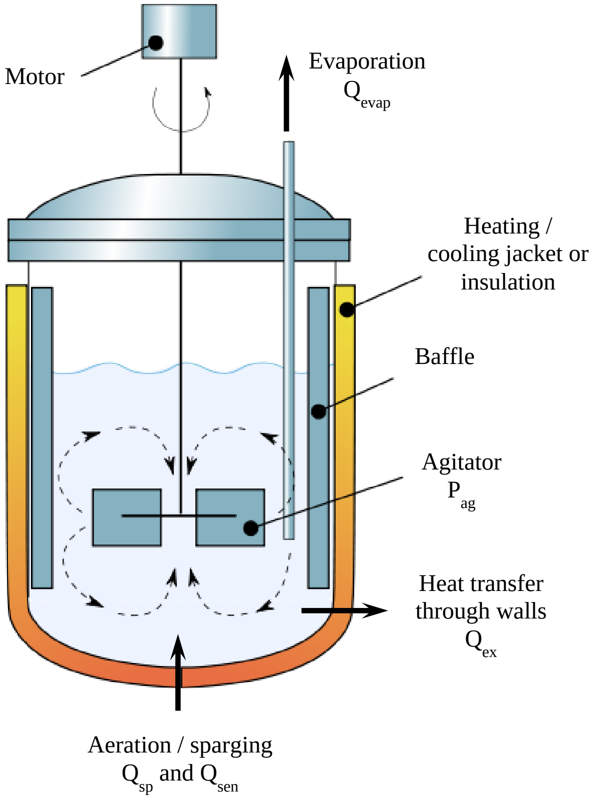

Figure 26. Heat transfer in a stirred-tank bioreactor. Adapted from Flickinger (2013) and (Auschulz, 2009).

Metabolic Heat Flux

While metabolic heat flux can vary significantly by cell type and environmental conditions, the specific heat flux for recombinant CHO cells of ~23 pW/cell will be used here (Flickinger, 2013, p. 875).

$$Q_{met} = \frac{23pW}{cell} \cdot X \tag{19}$$

where X is the cell density.

Sensible Enthalpy Gain

The primary substance added to the bioreactor during growth is assumed to be air for oxygenation. The heat transfer associated with this flow is

$$Q_{sen} = MC_p\rho_g\left(T_b - T_g\right) \tag{20}$$

where M is the mass flow rate, C_p is the heat capacity of the air (1,012 J/kgK), ρ_g is the density of the air entering the bioreactor (1.6735 kg/m^3 at 1.41 atm), T_b is the temperature of the bioreactor (37°C or 310.15K) and T_g is the air (25°C or 298.15K).

$$Q_{sen} = MC_p\rho_g\left(T_b - T_g\right) = \ M\left(1012\frac{J}{kgK}\right)\left(\frac{1.6735kg}{m^3}\right)(12K) \tag{21}$$

Aeration

Power input due to sparging is given in Flickinger (2013, p. 876) as

$$P_{sp} = M\rho_g\left(\frac{RT_b}{MW}ln\frac{p_1}{p_2} + \alpha\frac{u_{Go}^2}{2}\right) \tag{22}$$

where R is the ideal gas constant, MW is the molecular weight of air (28.97 g/mol), p_1 is the pressure at the sparger (1.41 atm), p_2 is the pressure at the top of the bioreactor (1 atm), and $\alpha\frac{u_{Go}^2}{2}$, which represents the jet kinetic energy developed at the sparger holes, is small and can be neglected for well-designed spargers (Flickinger, 2013).

$$P_{sp} = M\left(\frac{1.6735kg}{m^3}\right)\left(\frac{\left(8.3144621\frac{m^3\,Pa}{K\,mol}\right)(310.15K)}{\frac{0.02897kg}{mol}}ln\frac{1.41}{1}\right) \tag{23}$$

Agitation

Power input due to agitation is given by (Flickinger, 2013):

$$P_{ag} = N_p\rho_bN^3D^5 \tag{24}$$

where N_p is the impeller power number which is essentially constant for turbulent flow. ρ_b is the density of the culture medium, N is the impeller rotation rate (0.56 rev/s), and D is the impeller diameter (0.85 m). Assuming a Rushton impeller with a power number of 5.75 (Fusion Fluid Equipment, 2012),

$$P_{ag} = N_p \rho_b N^3 D^5 = 5.75 \left(\frac{993.1 kg}{m^3}\right) \left(\frac{0.56}{s}\right)^3 (0.85\, m)^5$$

$$= 449.1 \frac{kgm^2}{s^3} = 449.1\, W \tag{25}$$

Evaporation

For heat transfer due to evaporation, it will be assumed that the compressed air entering the bioreactor is dry. This will be the case if it has been sterilized (Riet & Tramper, 1991). The outflowing air will be fully saturated, however (Riet & Tramper, 1991).

$$Q_{evap} = MC_v \left(\frac{p_{in}}{p_{out}} \rho_{v,out} - \rho_{v,in}\right) \tag{26}$$

where C_v is the heat of vaporization (2260 kJ/kg), $\rho_{v,out}$ is the equilibrium water vapor concentration at bioreactor temperature and exit pressure (0.04 kg/m^3), $\rho_{v,out}$ is the water vapor concentration of the inflowing air (assumed to be 0).

$$Q_{evap} = M \left(\frac{2{,}260{,}000\, J}{kg}\right) \left[1.4 \left(0.04 \frac{kg}{m^3}\right)\right] \tag{27}$$

Bioreactor Walls

Heat loss through the walls of the bioreactor is given by (Riet & Tramper, 1991) as

$$Q_{ex} = U_b A_b (T_b - T_a) \tag{28}$$

where U_b is the heat transfer coefficient of the bioreactor walls (assumed to be 2.5 W/m^2/C, but Nienow [2012] suggests that typical values are 2000-3000 W/m^2/°C), A_b is the bioreactor surface area (= $\pi TH + \pi T^2/4$ = 31.9 m^2), T_b is the bioreactor temperature (37°C), and T_a is the ambient temperature outside the bioreactor (25°C).

$$Q_{ex} = \frac{2.5W}{m^2 C} (31.9 m^2)(12℃) = 958\, W \tag{29}$$

Overall Heat Flux

The overall heat flux can then be computed for each of the above factors. For simplicity, all values have been plotted over the course of a typical batch process and presented here. The largest drivers of heat flux are the cellular metabolic processes and the transfer through the walls of the bioreactor. While it is likely that some active heating and cooling will need to be applied to the bioreactor, achieving an overall heat transfer coefficient through the walls of the bioreactor of 2.5 $W/m^2/C$ would maintain a culture temperature between about 35°C and 39°C (± 2°C of the optimal temperature). For this reason, it will be assumed that, once the water has been heated to 37°C initially, no further energy for active heating or cooling will be required.

$$\Delta T = \frac{Q_{total}}{Vc_v} = \frac{Q_{total}}{15{,}000\ L\left(4179.6\ \frac{J}{L-K}\right)} \tag{30}$$

where c_v is the volumetric specific heat capacity of water, assumed to be 4.1796 $J/(cm^3\text{-}K)$ or 4179.6 J/(L-K) at 25°C and V is the volume of liquid. This gives an increase in temperature per unit second.

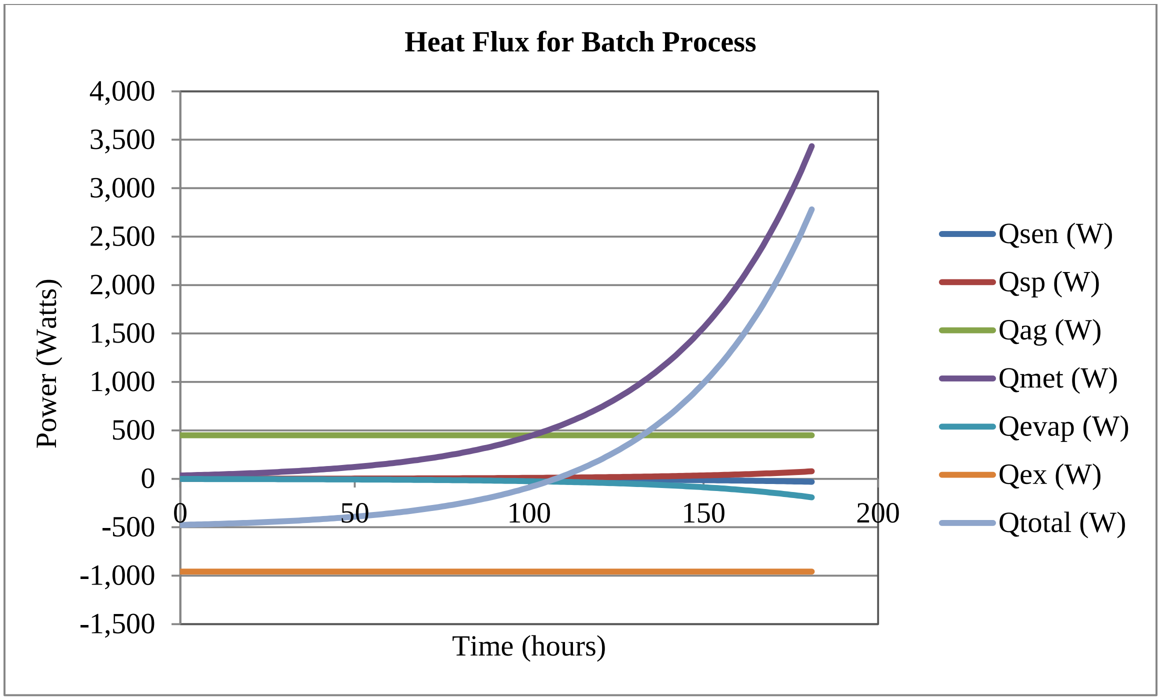

Figure 27. Heat fluxes associated with cultured meat batch production process.

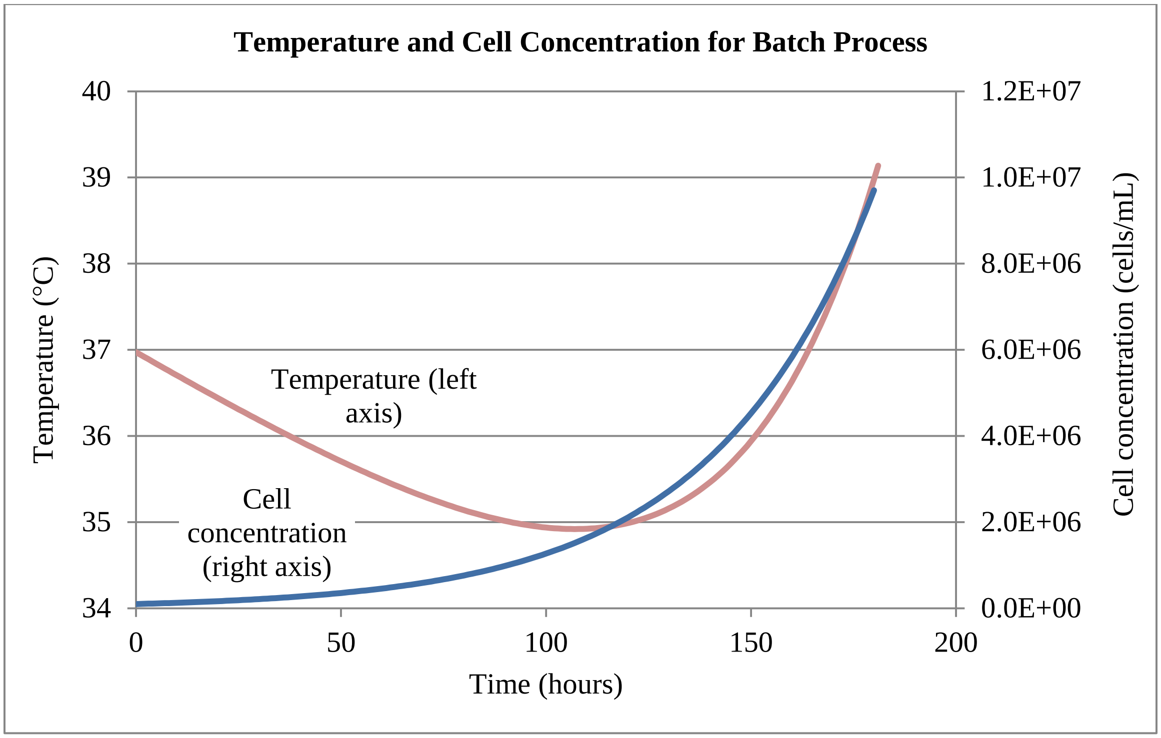

Figure 28. Cell concentration and expected temperature profile of the cultured meat production batch process.

APPENDIX C

ECONOMIC ANALYSIS: SUPPORTING INFORMATION

Overview of Economic Input-Output Assessment

Economic input-output assessment (EIOA), sometimes known as interindustry analysis, was developed by Wassily Leontief in the late 1930s and later earned him the 1973 Nobel Prize in Economic Science in (Miller & Blair, 1985). It is a widely-applied method of economic analysis, even having been extended to model energy consumption, environmental impacts, industrial employment, as well as inter-regional trade flows (Miller & Blair, 1985).

At its core, however, are tables of economic data relating industrial sectors by their flows of production and consumption (Miller & Blair, 1985). That is, during normal economic activity, each industrial sector requires primary and intermediate inputs of goods and services from other sectors. Their output may then be sold to still other intervening sectors before ultimately being purchased by end customers. Economic input-output models aggregate the links between industries in order to quantify and elucidate the interdependencies within the economy as a whole. A brief introduction is presented below but more comprehensive overviews can be found in Leontief (1986) and Miller and Blair (1985).

Table 39 shows economic flows between sectors in a very simple economy. Total economic output (X_i) from each sector includes both intermediate flows to other sectors (x_{ij}) and the final products and services sold to end customers (Y_i).

Table 39

Hypothetical Economic Flows. Values could be measured in terms of units of output or currency units.

		To purchasing sectors		Final Demand	Total Output
		Sector 1 (x_{i1})	Sector 2 (x_{i2})	(Y_i)	(X_i)
From selling sectors	Sector 1	150	500	350	1000
	Sector 2	200	100	1700	2000
Wages paid to labor		1000	2000	3150	6150

If there are n sectors in the economy, then total sector output (X_i) can be written in equation form as

$$x_{i1} + x_{i2} + \cdots + x_{in} + Y_i = X_i \tag{31}$$

If we let

$$a_{ij} = \frac{x_{ij}}{X_j} \tag{32}$$

then a table of structural coefficients can be computed based on Table 39.

Table 40

Coefficient Matrix of the Hypothetical Economy.

		To purchasing sectors	
		Sector 1	Sector 2
From selling sectors	Sector 1	$a_{11} = \frac{150}{1000} = 0.15$	$a_{12} = \frac{500}{2000} = 0.25$
	Sector 2	$a_{21} = \frac{200}{1000} = 0.20$	$a_{22} = \frac{100}{2000} = 0.05$

Solving equation (32) for x_{ij} $\left(x_{ij} = a_{ij}X_j\right)$ and substituting into equation (31) gives the following:

$$\begin{gathered}
a_{11}X_1 + a_{12}X_2 + \cdots + a_{1n}X_n + Y_1 = X_1 \\
a_{21}X_1 + a_{22}X_2 + \cdots + a_{2n}X_n + Y_2 = X_2 \\
\vdots \\
a_{n1}X_1 + a_{n2}X_2 + \cdots + a_{nn}X_n + Y_n = X_n
\end{gathered} \tag{33}$$

Rearranging gives

$$\begin{gathered}
(1 - a_{11})X_1 - a_{12}X_2 - \cdots - a_{1n}X_n = Y_1 \\
-a_{21}X_1 + (1 - a_{22})X_2 - \cdots - a_{2n}X_n = Y_2 \\
\vdots \\
-a_{n1}X_1 - a_{n2}X_2 - \cdots + (1 - a_{nn})X_n = Y_n
\end{gathered} \tag{34}$$

This may be written in matrix form as

$$\left(\begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix} - \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}\right) \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix} = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix} \tag{35}$$

or more simply

$$(I - A)X = Y \tag{36}$$

where

$$I = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}, A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}, X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix}, and\ Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix}$$

Finally, equation (36) can be solved for X gives the following form:

$$X = (I - A)^{-1}Y \tag{37}$$

This is a very useful result because once the elements of $(I - A)^{-1}$, often referred to as the Leontief inverse, are known, then total output of each sector can be determined under various demand conditions.

Once constructed, these economic input-output models facilitate the exploration of “what if” scenarios whereby a hypothetical condition is allowed to propagate through the economy at large. It lends itself well to a variety of studies including policy analysis and technology assessment. Economic input-output scenarios have historically predicted a number of surprising trends. For example, due to a high demand for steel in the 1945 construction and durable-goods industries, it was shown that “a flourishing postwar economy would require even more steel than the peak of the war effort” (Leontief, 1986, p. 13).

Calculation of Facility Floorspace

In the absence of a full-scale working carnery, the brewing industry was used as a model for estimating the required floorspace required for a cultured meat plant. It is impossible to equate cultured meat to beer production directly: Not only are they different substances with different densities, but they also have different batch cycle times. However, both products require a common commodity: space and time in a bioreactor, expressed here as “bioreactor liter-hours”. If it takes 10 days (excluding aging) (MillerCoors LLC, n.d.) and 1 liter of bioreactor volume to produce 1 liter of beer, then it takes 240 bioreactor liter-hours to make 1 liter of beer. It follows that, if a brewery can ferment 248,000,000 gallons (“Packaging is as golden as MillerCoors’ brews,” 2011) or 939 million liters of beer per year, the brewery has a capacity of 225 billion bioreactor liter-hours per year:

$$1\ liter\ of\ beer\ requires\ 10\ days * 24\frac{hours}{day} = 240\ liter - hours \qquad (38)$$

$$939\ million\ liters\ beer\left(\frac{240\ liter-hours}{liters\ of\ beer}\right)$$

$$= 225{,}000{,}000{,}000\ liter - hours \qquad (39)$$

If the same brewery takes up 2.3 million square feet (213,677 m^2) ("Packaging is as golden as MillerCoors' brews," 2011), then the facility can support 98,000 bioreactor liter-hours per square foot.

Similarly, the carnery model offers 756 million liter-hours per year:

$$6 * 15{,}000L\left(50\frac{weeks}{year} * 7\frac{days}{week} * 24\frac{hours}{day}\right) = 756\ million\ liter - hours \qquad (40)$$

Again assuming the industrial brewery model, the carnery would need 7,717 ft^2 (717 m^2) of floor space:

$$756\ million\ carnery\ liter - hours\left(\frac{2{,}300{,}000\ brewery\ ft^2}{225{,}000{,}000{,}000\ brewery\ liter-hours}\right)$$

$$= 7717\ ft^2 \qquad (41)$$

For reference, a typical 15,000 L bioreactor would have a diameter of about 2 meters (6.5 feet) so the six bioreactors would actually take up only about 200 ft^2.

Calculation of Employee Requirements

The brewing industry fermented 200,406,545 barrels or 23.9 billion liters of beer in 2002 (Beer Institute, 2013). Following a procedure similar to the floorspace calculation, the industry therefore has a capacity of 5.7 trillion bioreactor liter-hours per year:

$$1\ liter\ of\ beer\ requires\ 10\ days * 24\frac{hours}{day} = 240\ liter - hours \tag{42}$$

$$23.9\ billion\ liters\ beer\left(\frac{240\ liter-hours}{liters\ of\ beer}\right) = 5.7\ trillion\ liter - hours \tag{43}$$

If breweries employ 28,347 people (United States Census Bureau, n.d.-b), then the facility requires $4.94\text{x}10^{-9}$ employees per liter-hour. Similarly, the carnery model offers 756 million liter-hours per year (see above section); therefore, again assuming the industrial brewery model, the carnery would need 3.74 employees:

$$756\ million\ carnery\ liter - hours\left(\frac{28{,}347\ brewery\ employees}{5.7\ trillion\ brewery\ liter-hours}\right)$$

$$= 3.74\ employees \tag{44}$$

The carnery produces 103,000 kg of cultured meat per year. Therefore 0.000036 employees are required per kg.

Summary of Cultured Meat Production Model for Economic Analysis

Table 41

Summary of Hypothetical Cultured Meat Production Model for the Economic Analysis

System component	Description
Facility	Floorspace: 717 m^2
	Baseline energy demand: 513.3 MJ/m^2/year
Employees	3.74
Type of bioreactor	6x15,000 L stirred-tank reactors
	Height: 4.25 m
	Diameter: 2.125 m
	Impeller speed: 0.56 rps
	Filling capacity: 100%
Initial cell density in bioreactor	1x10^5 cells/mL
Maximum cell density	1x10^7 cells/mL (Yang et al., 2004)
Batch duration	7.6 days + 3 day cleaning cycle
Feedstocks	Glucose, synthetic amino acids, soy hydrolysate, and basal medium
Water for culture	15,000 L, deionized and sterilized via heating from 25 to 140°C with partial recovery of waste heat
Agitation / mixing power requirement	449.1 W, impeller power number: 5.75
Aeration / sparging efficiency	4.5 kg O_2/MJ (Xylem, 2012)
Culture temperature	37°C (energy to maintain cell culture temperature is excluded from this analysis)
Bioreactor cleaning-in-place	30,000 L deionized water + 0.5 M sodium hydroxide solution, heated from 25 to 50°C
Capital equipment	Excluded

BIOGRAPHICAL SKETCH

Carolyn Mattick recently finished a Ph.D. in Environmental Engineering at Arizona State University where she also completed an M.S. degree in Sustainability. Her dissertation research focused on developing a forward-looking analytical framework for better understanding the possible large-scale environmental, economic, and social implications of tomorrow's engineered products. As a demonstrative case study, this framework was applied to the emerging technology of cultured, or *in vitro,* meat: edible muscle and fat tissue grown from animal stem cells in a laboratory or factory. In addition to this research, Carolyn enjoyed being a teaching associate for CEE/SOS 181 – Technology, Society, and Sustainability. Carolyn plans to continue her research into the implications of emerging technologies in the field of sustainable engineering. Carolyn also holds an MBA in Entrepreneurship from the University of Colorado and a B.S. in Aerospace Engineering from Purdue University. She has held positions in industry, working as both an Integration and Test Engineer at Orbital Sciences Corporation and a Program Manager at E*TRADE.