Cultured Meat: The Systemic Implications of an Emerging Technology

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***Abstract*— Cultured meat – edible muscle tissue grown in a laboratory or factory (carnery) without the need of a whole animal – was shown to be feasible in 2000 [1] and several researchers have since suggested that large-scale production is possible [2–5]. Using ESEM principles as a guide, this investigation represents a preliminary attempt to shed light on some of the environmental, economic, and social implications of this emerging technology. The ultimate goal is to facilitate adaptive management of its commercialization and diffusion in order to prevent or mitigate sub-optimal lifecycle impacts.**

***Index Terms*—Cultured meat, *in vitro* meat, carneries, earth systems engineering and management, emerging technologies.**

I. Introduction

THE world consists of interconnected webs of complex systems, interacting at scales from local to global. As a result, the commercialization of new technologies has the potential to cause unintended consequences – both positive and negative – at seemingly remote locales, especially if widely adopted on a global scale. For this reason, considering the potential unintended consequences associated with new products before they reach large-scale markets can serve to provide some intelligence regarding how to best manage these technologies before sub-optimal lifecycle processes become locked in.

Cultured meat – edible muscle tissue grown in a laboratory or factory (called a carnery) without the need of a whole animal – was shown to be feasible in 2000 [1] and several researchers have since suggested that large-scale production is possible [2–5].

Many researchers and funding sources believe that cultured meat is ultimately a benign technology. Indeed, the media often portray it as reducing the environmental impact of meat production (including the reduction of greenhouse gas emissions), making people healthier (by eliminating the harmful contents such as saturated fats and pathogens) [6], addressing global hunger issues[7], and alleviating the ethical concerns associated with industrial livestock operations [8].

However, a closer look suggests that the adoption of cultured meat would be more nuanced in its effects. Obviously, it could significantly disrupt the status quo associated with food production in general. There will be both winners and losers in nations that begin producing cultured meat, as well as in farming regions. Shifts in national economies and employment patterns, in import and export markets, and in food security policies, could potentially be significant. At a global level, implications – particularly for developing nations – are more difficult to discern, but are no less important to consider.

In addition, a number of factors, including culture and regulatory matters, suggest that global adoption might be mixed [8], [9]. Policies that serve to encourage or discourage consumption will be highly contentious. Thus, this paper seeks to shed light on some of the possible implications of cultured meat before they are realized, and perhaps identify relevant metrics that may be used to adaptively manage development and diffusion of cultured meat production. By drawing from historical cases and simple economic and policy models, this paper highlights the positive implications and identifies possible negative impacts associated with cultured meat so they can be more effectively managed in accordance with the principles of Earth Systems Engineering and Management (ESEM) [10].

II. Factory-Grown Meat

While many tout the potential benefits of factory-grown meat, it is worth noting that many barriers to commercialization still exist. At least three methods for culturing mature skeleton muscle cells (myocytes) have been proposed, but all have inherent challenges. The first requires an explant to be taken from the muscle of a donor animal and grown in a nutrient medium. This was shown to be feasible in 2000, when tissue samples were taken from a goldfish and placed in four different growth media: fetal bovine serum, fishmeal extract, shiitake mushroom extract, and maitake mushroom extract [1]. In the case of the latter nutrient medium, explants increased 13.1% in area over 7 days [1]. The authors of the study chose the explant method because they believe it will result in tissue that most closely resembles meat (that is, containing not only muscle cells, but also fat and other cells in familiar proportions) and because this composition best mimics the *in vivo* environment and will therefore reduce the potential for muscle cells to transform into other, undesirable types of cells [1]. The problem with this approach is that its proliferation potential is limited; new

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biopsies would be required from donor animals on a regular basis.

Another method (some would say the most promising [11]) of culturing meat involves adult stem cells which can be obtained from a variety of tissues [11]. However, a method of reliable differentiation would be needed and, as with the explant approach, adult stem cells are believed to have a limited lifespan and proliferation capacity *in vitro* [12].

A third method for cultured meat production begins with embryonic stem cells. This approach has the advantage that these cells have, at least theoretically, an unlimited self-renewal capacity and a single embryo could, again in theory, produce enough meat to feed the world [11]. In practice, genetic mutations would accrue over time, limiting the total production potential of a single embryonic stem cell [11]. In addition, this method would necessitate that embryonic stem cells lines would have to be established from farm animal species, a task that has not yet been accomplished [11]. Moreover, once these lines have been established, differentiation into the desired cell types (primarily skeletal muscle and fat) would necessarily be induced and maintained – this is a further challenge facing tissue engineers [11].

It should be noted that other proposed methods exist that involve genetic manipulation of the culture cells. However, discussion of these methods in the literature is often accompanied by caveats noting the possibility of consumer rejection [12], [13].

Culture methods aside, additional challenges exist. One of these is the inability to grow tissue in a three-dimensional matrix that would mimic cuts of meat such as steak. Cells that are farther than 0.5mm from a nutrient supply for a significant period of time, they will become necrotic [11]. For this reason, the first generation of cultured meat will be grown in sheets on a substrate or in bioreactors that keep culture cells in a perpetual state of freefall in the growth medium [11] and will lend itself to processed or ground meat products such as hamburgers, hot dogs, and sausages. Even growth of tissue cultures for these products is not straightforward. In order to achieve the texture and consistency of traditional meat, factory-grown cells will have to be exercised. This may be accomplished by either mechanically stretching the cells or applying electrical stimulation, but one will be necessary for developing a palatable product.

Another challenge is the development of nutrient cultures in sufficient quantities to support market demand. Currently cell cultures are typically grown in animal-based media such as fetal bovine serum. This is not only expensive, but has a highly variable composition which can include pathogens, and is not likely to be acceptable to consumers looking for a animal-free protein source [11]. Hence the availability of serum-free growth culture (likely from an algal or mushroom source) will be a critical co-production factor for cultured meat, as will a concomitant cocktail of hormones and growth factors [13].

Despite these challenges, researchers continue to make progress. Hence, now is the time to consider the economic, social, and environmental implication of cultured meat. Please note that, while it is possible to produce fish tissue via the same process, this paper will focus on agricultural meat: beef, pork, mutton, and poultry.

III. Economic Implications

A. *Cost of cultured meat*

Mark Post, a researcher at Eindhoven University in the Netherlands, expects to produce the first cultured hamburger in October, 2012 [11], and he projects that it will cost about $345,000 [12]. Part of the reason for the high price is the growth medium. At €7000 – 8000 / tonne [13], it currently makes up about 90% of the production cost [14]. However, a 2008 European study [13] projected that cultured meat (at €3300/tonne) could become competitive with conventional beef (at €3500/tonne) if economies of scale bring the cost of growth media to about one tenth of its current price. They maintain that, even under those conditions, agricultural poultry would remain more affordable, at about €1800/tonne (unsubsidized).

B. *Impact on Traditional Meat Producers and Agriculture*

As the price of factory-grown meat falls, it could hurt the business of traditional meat producers – particularly more expensive beef and pork. The impact could be more profound if factory-grown products are perceived as safer (free from food-borne illness) and healthier (lower in fat).

Declines in purchases of traditional meats would likely ripple through the agricultural supply chain and impact feed growers as well, reducing aggregate demand. Depending on the speed with which it occurred, such a scenario might lead to a dramatic drop in global grain prices (in a dynamic opposite that associated with the 2007 food riots blamed in part on expanding biofuel production [15]). However, even at a slower pace, meat and feed producers could be faced with significant declines in employment, and uncertain compensatory hiring in the cultured meat supply chain (which would necessarily include large-scale production of growth media). Among those negatively impacted could be exporters of meat such as the United States, Canada, and Brazil [16]. More specific predictions with regard to global impacts of such a technology shift are difficult to make because they depend heavily on regional patterns of cultured meat production and adoption. However, with regard to developing economies, theories exist regarding the role of agriculture that can lend useful insight into the possible implications of cultured meat on the world's poor.

C. *Global Development Implications*

The ability to grow meat in a factory has been proposed as a potential solution to address global hunger and perhaps prevent the hunting of endangered species for food [7]. While this may seem like an obvious solution, the United Nations maintains that food insecurity is an issue of poverty and not scarcity [17]. Moreover, while the FAO projections to 2050 do acknowledge continued growth (though slowing rates of increase) in food demand, including greater per capita meat consumption, they similarly argue that the food requirements of an anticipated 9.1 billion people can be met given that appropriate investments and policies are put in place [18].

To complicate matter further, at a global scale the economics of food and national development are quite complex and the introduction of cheap (perhaps subsidized) factory-produced meat to feed the poor could actually have the opposite of its intended effect.

In general, despite its small role in global GDP, the livestock sector is nonetheless socially and politically important in the world's developing nations. Not only does it generate income and livelihoods for "one billion of the world's poor" [19], it also provides food security, fertilizer, building materials, and fuel [20]. Analysis has shown that "GDP growth originating in agriculture is, on average, at least twice as effective in benefiting the poorest half of a country's population as growth generated in non-agricultural sectors" [21]. Moreover, a healthy agricultural sector is believed to have played a vital role in the transformation of many of today's developed economies: Europe, the United States, and perhaps even China, Taiwan, and other Asian nations [21]. Therefore policies that disrupt smallholder agricultural activities, such as an attempt to provide cheap meat to a nation's poor, could have a counterintuitive and potentially devastating impact on individual livelihoods as well as economic growth on a national level.

On the other hand, very rapid growth in a livestock industry can be equally detrimental. For example, in the 1960s and 70s, market forces in the United States (including the increasing demand for fast food) resulted in rising beef imports from Costa Rica. Consequently, between 1959 and 1972, beef production in Costa Rica doubled [22]. Yet, over the same period, annual beef consumption *within* Costa Rica actually declined from 30 to 19 pounds per person as local consumers began competing with US importers for livestock products [22]. Because US companies were paying higher prices for beef, local beef prices rose, and many Central American families were no longer able to afford it [22]. Further, as a result of poor soil quality, livestock production served to increase pressure on rain forests in that area. In the early 1980s, Costa Rican rain forests were being converted to agricultural uses at the rate of 600 km^2 per year – a rate that would have left the nation devoid of forests in less than 30 years [22].

Beef exports from Costa Rica have since declined [23] and rainforest destruction has slowed, though a recent news story indicates that ranching may be ramping up in Paraguay, with similar implications for its Chaco forest [24]. These examples highlight the complexities of international trade linkages and underscore the need to encourage appropriate economic growth that does not disadvantage local populations and damage the environment. They also suggests that cultured meat could be a relatively benign addition to the food portfolio of industrialized nations, but caution should be exercised where international development and trade policies are concerned.

IV. Social Implications

A. *Policy and Adoption*

Any discussion of the social implications of an emerging technology must consider the factors that would influence commercialization and adoption patterns associated with that technology. Aside from cost, the diffusion of cultured meat into common use still faces many obstacles. These include national regulatory environments and public perception.

From a regulatory perspective, there is still uncertainty in terms of approval and standards for meat factories. To the best of the authors' knowledge, no cultured meat product has been submitted for regulatory approval in any nation as of the publication date. However, Neal Fortin, Professor and Director of the Institute for Food Laws & Regulations at Michigan State University, considers cultured meat to be rather conventional from a policy perspective. In the United States, for example, cultured meat products would be regulated by the Food and Drug Administration and the Department of Agriculture "under the general provisions of the statutes the agencies enforce" [25], implying that no new statutes would be required specifically targeting factory-produced meat. However, history has shown that existing regulation is subject to change and is not the only barrier to sales. The European Union, for example, has moved to stifle genetically modified organisms (GMOs) since 1999 [26]. At that time, 18 GMO products had been approved with no mandatory labeling requirement. Thereafter, its laws became highly restrictive and, coupled with unfavorable public opinion, GMO seeds were planted on less than 100,000 hectares in the EU in 2007; for comparison, 58 million hectares of GMOs were planted in the United States the same year [26]. A number of explanations for this shift have been suggested, including the influence of certain interest groups [26].

While cultured meat does not necessarily involve genetic manipulation, it is likely to involve other forms of biotechnology, including the use of embryonic and adult stem cells [27]. Coupled with growth in a bioreactor, this could have the effect of alienating non-governmental organizations or consumers who perceive cultured products as artificial or processed and therefore unnatural [28]. Moreover, groups who stand to lose economically from the approval and adoption of cultured meat could wage public campaigns against it.

On the other hand, it is also possible that people would not perceive cultured meat as a substitute for traditional meat, but rather as a complement, eaten by vegetarians and those ethically opposed to industrial meat production and animal slaughter. One such group, People for the Ethical Treatment of Animals (PETA), is seeking to spur cultured meat commercialization by offering a prize of $1 million to the first individual or group to successfully sell 2,000 pounds of federally-approved, cultured chicken meat for human consumption [29]. It should be noted, however, that the deadline to claim the prize is June 30, 2012, and no one is on track to win it.

Another important factor associated with the adoption of cultured meat will be religion. That is, what rules and norms associated with religious beliefs would prevent their followers from consuming factory-grown livestock products? While it has been reported in literature [30] that the bioreactor cultivation process does not conflict with Sikh and Muslim traditions, more research into this question is warranted.

B. *Health*

It goes without saying that meat is nutritionally important. It provides not only protein, but also vitamin B12, bioavailable, iron, and omega-3 fatty acids [30]. Yet the fat in animal products simultaneously contributes to so-called "lifestyle" health issues such as obesity, diabetes, cancer, and cardiovascular diseases [30], [31]. Further, incidents of food-borne illnesses caused by contaminated food products continue to increase in developed nations [30]. It has been suggested that TSEs (Transmissible Spongiform Encephalopathy diseases) may be acquired by humans after ingesting prions from beef [32]. Finally, the close contact between animals and their human keepers can lead to outbreaks of influenza and other diseases [30].

In terms of health, cultured meat has clear advantages. The elimination of the slaughterhouse, for example, simultaneously reduces the risk of food-borne pathogens. A reduction in number and density of farm animals also reduces the risk of inter-species disease transmission. Cells taken from an animal can be tested for TSEs prior to cultivation in order to prevent human infection. Further, fat content can not only be regulated in cultured meat, but the *kind* of fatty acids present can be preselected (i.e., ratio of polyunsaturated fat versus saturated fat) [30]. It should be noted that muscle cells alone do not contain iron (this comes from blood) or vitamin B12 (this is produced by microorganisms living in the animal), but both of these, and other, nutrients can be added to the cultured product to make it, for all intents and purposes, designed to be healthier [30].

Of course, such a seemingly beneficial product might not be free of unintended consequences. In particular, people might be tempted to overconsume cultured meat to the exclusion of a well-balanced diet and suffer from the side-effects of too much protein. By contrast, the ability to engineer meat with specific properties opens the door to a multitude of commercial possibilities. Most obviously, it becomes theoretically possible to tailor products to meet the specific dietary needs of men, women, and other demographic groups. But this is just the beginning. Once factory food begins production, there are far fewer potential barriers to significant and fundamental redesigns of food products, which heretofore have necessarily generally depended on the plant or animal production system.

C. *Culture*

Agricultural practices have been recognized as playing a role in preserving cultural heritage [33]. Even though the total agricultural populations in Europe and the Americas have been declining for some time [23], a transition away from traditional meat production could hasten this trend – and the loss of rural traditions as well. Indeed, biologist Brian J. Ford has cited the artificial but romantic landscapes of Europe as being one reason why cultured meat will never render livestock rearing completely obsolete [34]. While he acknowledges that sheep and cattle grazing is important in maintaining the ecological balance of agricultural systems, Dr. Ford also underscores the social importance of "lush meadows" and "wild vistas" for recreation [34]. He does not say it explicitly, but one cannot help but assume that such aesthetically-pleasing, though entirely managed, landscapes also play an important role in cultural identity.

D. *Ethical Challenges*

Along with the ability to grow beef, pork, mutton, and poultry, comes the possibility of growing tissues from other species – including humans. While it is difficult to determine how serious of an issue this will become, it is nonetheless acknowledged as a possibility in the literature [30]. On a practical note, cannibalism practiced in some tribal cultures, as in Papua New Guinea, is known to spread a prion disease called kuru. As with animals, firms growing human tissue for food could simply test the culture sample for prions prior to cultivating additional cells. Indeed, safe, victimless cannibalism may be coming to a restaurant near you.

E. *Resilience*

Although not of immediate concern, it is worth considering the sustainability of national and global food supplies. Specifically, given the possibility that cultured meat could replace a significant portion of livestock production, could such a scenario serve to increase or decrease overall resilience as well? That is, developing a food production process that is dependent on a modern electricity infrastructure could make that food supply more vulnerable to large-scale failures in electricity distribution; alternatively, having a number of factories producing meat may reduce the impacts of a particular disease in a country's herds (e.g., mad cow disease and the culling of many UK cattle).

V. Environmental Implications

The livestock sector has been called "one of the top two or three most significant contributors to the most serious environmental problems, at every scale from local to global" [19]. Indeed, in spite of its slight contribution to global gross domestic product (less than 2 percent), grazing and feed production for livestock currently require an estimated 70% of all agricultural land and 30% of total emerged land area (land not covered by water or ice). It also consumes roughly 8 percent of human water use (predominantly for irrigation of feed crops), and produces about 18 percent of anthropogenic greenhouse gas (GHG) emissions (measured in CO_2 equivalent) [19]. Further, livestock production is believed to be a contributing factor to deforestation in some areas of the globe, as well as to eutrophication in coastal areas, and pollution in general due to waste products [19].

It is important to point out that not all of the aforementioned livestock impacts are the direct result of meat consumption:

Milking animals constitute about 20% of cows, buffalo, sheep and goats; laying hens make up about 32% of all poultry (computed from [23]). Nonetheless it is generally believed that a transition to cultured meat will ease the stresses that livestock place on the environment. This view was supported by a 2011 lifecycle analysis conducted by Tuomisto and de Mattos [35]. Their findings indicated that a transition to cultured meat could reduce 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 [35]. In addition, energy consumption for cultured meat is expected to be lower than for beef, mutton, and pork production, but greater than for chicken.

A. *Cultured Meat as a Geoengineering Strategy*

The above results suggest that a complete conversion from agricultural meat production to factory processes could result in significant shifts in land use and the potential for rapid reforestation. As Allenby points out, such a large-scale manipulation of earth systems could effectively constitute a geoengineering project. In a follow-up editorial to her lifecycle analysis, Tuomisto put the reforestation potential into a global context, saying that "if cultured meat constituted half of all meat consumed we could halve the greenhouse emissions, and increase the forest cover by 50%, which is equivalent to four times of Brazil's current forest area" [7]. Such a transition could be a significant step forward in climate management – but are these findings realistic and could this revolutionary technology also come with unintended consequences?

B. *Livestock Industry Byproducts*

Lifecycle analysis is a useful tool for environmental assessment, but the results often do not tell the entire story. To illustrate this point, consider that the above referenced lifecycle analysis allocates all resources used by livestock production to the relatively small percentage of the animal carcasses that are eaten by humans. This ranges from 38.6% for beef to 51.5% for poultry [35]. In reality, however, little of the animal carcass is wasted. In the United States, for example, only about 11% of hogs' liveweight and 14% of steers is lost through waste or shrinkage [36]. The remaining byproducts are sold by the livestock industry for use in leather, pharmaceuticals, cosmetics, pet food, and other household and industrial products [36]. While excluding byproducts from lifecycle analyses is certainly a valid and simplifying approach, there is also value in considering the holistic context in which the technology is emerging. Were production of the primary source of byproducts (livestock) 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 raising 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. It is also possible that the cultured meat industry would be called on to grow not only edible muscle and fat tissue, but also skin for leather; organs, glands, and blood for medicines; meat for pet food; and so on.

The important message here is that realistic scenarios matter. If, for example, animal byproducts, as well as meat, were considered integral to agricultural livestock production, then the projected degree to which cultured meat could alleviate environmental concerns might be less optimistic.

VI. Cultured Meat as an Earth Systems Engineering Endeavor

Emerging technologies such as cultured meat may not be viewed as earth system 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.

ESEM principles indicate that "major shifts in technologies and technological systems should be evaluated before, rather than after, implementation" [37]. Moreover, they caution that intervention should occur only when necessary and only to the extent required. In short, ESEM encourages a dialog between humans and emerging technologies.

Using ESEM principles as a guide, investigations can shed light on some of the implications of emerging technologies, highlight possible unforeseen consequences, and make recommendations regarding possible management strategies. This document represents a very high-level consideration of cultured meat in an ESEM framework. Follow-on work will necessarily require a more detailed study of its potential economic, social, and environmental impacts. Ultimately, a set of metrics is slated to be developed so that the impacts of cultured meat can be assessed in real-time, as it diffuses to the global population.

VII. Conclusion

If commercialized, cultured meat has the potential to significantly reduce the energy, water, and land required to produce some animal-derived commodities [35], as well as lessen greenhouse gas emissions [35]. Less obviously, it could shift supply chain requirements, and impact livelihoods around the globe.

At the present time, there is still a great deal of uncertainty surrounding regulatory, adoption, and production decisions associated with factory-produced meat. Regardless, due to the potential impacts, now is the time to begin developing a framework in which to monitor and adaptively manage its development, commercialization, and diffusion.

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