



REVIEW

REVISED Cellular agriculture in the UK: a review [version 2; peer review: 4 approved]Neil Stephens ¹, Marianne Ellis ²¹Social and Political Sciences, Brunel University London, Uxbridge, UB8 3PH, UK²Department of Chemical Engineering, University of Bath, Bath, BA2 7AY, UK

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Abstract

This review details the core activity in cellular agriculture conducted in the UK at the end of 2019, based upon a literature review by, and community contacts of the authors. Cellular agriculture is an emergent field in which agricultural products—most typically animal-derived agricultural products—are produced through processes operating at the cellular level, as opposed to (typically farm-based) processes operating at the whole organism level. Figurehead example technologies include meat, leather and milk products manufactured from a cellular level. Cellular agriculture can be divided into two forms: ‘tissue-engineering based cellular agriculture’ and ‘fermentation-based cellular agriculture’. Products under development in this category are typically valued for their environmental, ethical, and sometimes health and safety advantages over the animal-derived versions.

There are university laboratories actively pursuing research on meat products through cellular agriculture at the universities of Bath, Newcastle, Aberystwyth, and Aston University in Birmingham. A cellular agriculture approach to producing leather is being pursued at the University of Manchester, and work seeking to produce a palm oil substitute is being conducted at the University of Bath. The UK cellular agriculture companies working in the meat space are Higher Steaks, Cellular Agriculture Ltd, CellulaRevolution, Multus Media and Biomimetic Solutions. UK private investors include CPT Capital, Agronomics Ltd, Atomico, Backed VCs, and Breakoff Capital. The UK also has a strong portfolio of social science research into diverse aspects of cellular agriculture, with at least ten separate projects being pursued over the previous decade. Three analyses of the environmental impact of potential cellular agriculture systems have been conducted in the UK. The first dedicated third-sector group in this sector in the UK is Cultivate (who produced this report) followed by Cellular Agriculture UK. International groups New Harvest and the Good Food Institute also have a UK presence.

Open Peer Review

Reviewer Status

	Invited Reviewers			
	1	2	3	4
version 2 (revision) 12 Oct 2020	 report	 report		
version 1 24 Jan 2020	 report	 report	 report	 report

1. **Sissel Beate Rønning** , Nofima AS, Ås, Norway
2. **Elisabeth Abergel** , University of Quebec at Montreal (UQAM), Montreal, Canada
3. **Joshua Flack**, Mosa Meat, B.V., Maastricht, The Netherlands
Mark J. Post , Maastricht University, Maastricht, The Netherlands
4. **Mariana Petronela Hanga** , Aston University, Birmingham, UK

Any reports and responses or comments on the article can be found at the end of the article.

Keywords

Cellular agriculture, Cultured meat, Clean meat, Cell-based meat, Cultivated meat, UK, Palm oil

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Author roles: **Stephens N:** Conceptualization, Investigation, Methodology, Project Administration, Writing – Original Draft Preparation, Writing – Review & Editing; **Ellis M:** Conceptualization, Investigation, Writing – Review & Editing

Competing interests: NS is a founding member of Cultivate, a third sector multi-voiced forum for discussing cellular agriculture from UK perspectives, and this publication forms part of the work of Cultivate. ME is a founding member of Cultivate, a third sector multi-voiced forum for discussing cellular agriculture from UK perspectives, and this publication forms part of the work of Cultivate. ME is also of co-founder of Cellular Agriculture Ltd, a start-up company active in cellular agriculture.

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REVISED Amendments from Version 1

This new version of the paper has been updated in response to the reviewers' comments in the following ways:

An extended introductory paragraph expanding upon the paper's aim and key audiences.

A clarification that 'tissue engineering-based cellular agriculture' includes structured and unstructured products.

Note that the entire replacement of animal agriculture is only a possibility.

Additional overview information on some technical challenges facing cellular agriculture.

Additional notes on the anticipated benefits of fermentation-based palm oil.

A reordering of the text about the historical context of cellular agriculture.

Additional paragraph about Dr Mark Kotter's work at the University of Cambridge.

Additional content in the social science section providing extra detail on the content of the work discussed and detailing their funding sources.

Additional notes on the funding of Cultivate.

Additional reflection upon the role of the University of Bath in UK cellular agriculture.

Additional note on the limited formal relationships between the social scientists and those working in laboratories.

Any further responses from the reviewers can be found at the end of the article

Introduction: What is cellular agriculture?

Cellular agriculture is an emergent field in which agricultural products—most typically animal-derived agricultural products—are produced through processes operating at the cellular level, as opposed to (typically farm-based) processes operating at the whole-organism level. This review details the cellular agriculture landscape in the UK at the time of publishing, providing an overview of key actors in the sector from a range of backgrounds, including university and corporate laboratory research, private investors, social science, Life Cycle Analyses, and policy work. The aim of the review is to collate information on the UK context in a form that is not currently available in the public domain. It provides a brief overview of the key groups and individuals involved, and identifies each by the sector in which they operate. The goal is to provide a brief and accessible review that, where possible, signposts readers to further sources that can be pursued for additional information. As such it is not intended as a detailed overview of the technical aspects of the work discussed. Instead, the review provides a basis for subsequent discussion both within and beyond the UK about activity in the country. We anticipate it will have value for policy-makers, academics, NGOs, and other actors interested in learning about and engaging with cellular agriculture in the UK, and will form a building block upon which subsequent discussion can be conducted.

The term cellular agriculture was first coined in 2015 by Isha Datar, Executive Director of US-based 3rd sector group New

Harvest. Potential future products bracketed under the label cellular agriculture include meat produced through tissue engineering (variously known as cultured meat, clean meat, cell-based meat and cultivated meat (referred to herein as CM)), and animal-derived products such as milk, leather and egg white produced through recombinant DNA fermentation techniques (Datar *et al.*, 2016; Stephens *et al.*, 2018). As these examples suggest, cellular agriculture is typically divided into two types, based on the technology form used. The first has been called 'tissue engineering-based cellular agriculture' (Stephens *et al.*, 2018) and involves taking cells from live (or recently deceased) animals and culturing these cells so as to control their cell proliferation and differentiation to direct the formation of increasing quantities of a desired cell type (e.g. muscle and fat for meat, skin for leather). We use this term to capture work on both structured and unstructured products (e.g. mincemeats and full tissue meats). The second type of cellular agriculture has been termed 'fermentation-based cellular agriculture' (*ibid*) and involves genetically modifying typically bacteria, yeast or algae by adding recombinant DNA so that when they are fermented in sugars they produce organic molecules that can subsequently be processed to biofabricate familiar products such as milk and leather.

While the term cellular agriculture is less than five years old, the technologies it describes have a longer history. In terms of tissue engineering-based cellular agriculture, the first work to increase the mass of *in vitro* muscle under laboratory conditions happened around the millennium (Benjaminson *et al.*, 2002; Catts & Zurr, 2002), with further work in the following decade (Puy *et al.*, 2010; Wilschut *et al.*, 2008). In terms of fermentation-based cellular agriculture, some suggest the historical lineage can be drawn as far back as industrially-produced rennet used in manufacturing cheese, which has used recombinant DNA techniques since the 1990s to replace enzymes taken from ruminant mammals, typically after their slaughter. However, manufacturers using this technique have not adopted the term cellular agriculture and do not feature within the emergent cellular agriculture community, so we do not include rennet in our review. Similarly, some products that are naturally produced in plants can be made using fermentation, such as flavour molecules and oils like vanillin, but these have not generally be classed as cellular agriculture to date. It could be argued that they fall under the same umbrella if their goal is the same (i.e. sustainable production), as is the case of the palm oil substitute discussed later.

The call for cellular agriculture is generally motivated by a set of related concerns about the impacts of animal agriculture as it exists today and the challenges of the increased global population in the coming decades. Cellular agriculture can be said to be directed at addressing UN Sustainable Development Goal Two (Zero Hunger) and Goal Twelve (Responsible Consumption and Production). While the exact form the potential contribution of cellular agriculture may take varies from case to case, the recurrent themes are a concern with the environmental impact of animal agriculture (in terms of land use, greenhouse gas emissions, impact on biodiversity etc., see

Bhat *et al.*, 2015; Mattick, 2018), as well as animal ethics concerns about livestock living conditions and slaughter (Milburn, 2018; Schaefer & Savulescu, 2014), and the impact on human health of animal agriculture through issues such as animal-borne disease and antibiotic use (Arshad *et al.*, 2017; Specht *et al.*, 2018). The view is that cellular agriculture will allow the continued production of familiar animal products while using either fewer or no animals in the process. The aim is that this would result in either reducing (or perhaps entirely replacing) animal agriculture, or that it would slow the increase in global use of animals in agriculture to meet global rising demand for animal products driven by population and wealth increases. This given, while there is optimism within the community, a number of substantial technical hurdles remain. This includes producing culture media at a lower cost; developing cell lines that have the capacity for indefinite propagation and have a high culture-efficiency to maximise product yield; developing reliable automation and bioreactor systems to enable scale-up that is net-zero carbon; and reproducing the taste, texture and nutritional profile of familiar meat products (Stephens *et al.*, 2018; Thorrez & Vandenburg, 2019).

In this review we suggest the common-use definition of cellular agriculture could be expanded to also include the cellular production of agricultural goods that are not sourced from animals, here reflecting upon the example of fermentation-based palm oil production (an active area of research in the UK). Intuitively this makes sense, as this fermentation-based work is producing agricultural products at the cellular level. This work also ties to environmental and animal welfare concerns, specifically around deforestation and its impact upon greenhouse gases and biodiversity, that are also seen expressed in different ways elsewhere within the cellular agriculture community. However, at this stage, we raise this as just a possibility, and do not seek to assert a new definition upon the field.

Global context

The leading nations in cellular agriculture today arguably are the US, the Netherlands, and Israel, although work is conducted in numerous other countries, including the UK. In terms of CM, the first larger scale project was conducted in the Netherlands from 2005 onwards. One member of this initial consortia, Prof Mark Post of Maastricht University, went on to secure funding from Google co-founder Sergey Brin to produce the world's first laboratory-grown hamburger, which was cooked and tasted at a press conference in London in 2013 (O'Riordan *et al.*, 2017; Post, 2014). The interest this generated fed into a change of culture within the international CM community, as the first 10–15 years of largely university-based research shifted towards the emergence of a start-up culture (Stephens *et al.*, 2019). While University research has continued, the focus has shifted to the swiftly increasing number of early stage companies in the area, seeking and securing venture capital seed funding for their work. Among the highest profile in the US are Memphis Meats, who were the first CM company to secure series A funding of \$17m, and the vegan-mayonnaise and liquid egg company Just (formally Hampton Creek) who have also established a CM R&D initiative. Others include Mission Barns, Wild Type, and

Bluefin tuna-focused Finless Foods. Outside of the US, the Netherlands has remained a key site with Post following his burger press conference with the establishment of a start-up, Mosa Meat, which in 2018 announced a funding round of €7.5m. A second company, Meatable, also runs out of Leiden. Israel also has a strong base, with companies including Future Meat Technologies and Aleph Farms, who recently completed a funding round of \$11.65m. Other examples include Japan-based Integriculture, Singapore-based Shiok Meats, and Canada-based Appleton Meats. As private entities, it is not always clear exactly what proprietary technology each company is developing, or how advanced their technology is.

In terms of fermentation-based cellular agriculture, the international context is dominated by US companies, particularly those based in the San Francisco Bay area. Key examples include Geltor, who produce gelatin, Clara Foods, who produce egg white, and both Perfect Day and New Culture, who produce animal-free dairy products. Outside of California, the most prominent company is Modern Meadow, who ferment collagen to use in manufacturing leather-like products. Modern Meadow were initially the first company to work on CM, but later focused exclusively on leather. Beyond the US, the main example would be Japan-based Spiber, who make spider silk. Further information on the global context can be found in State of the Industry Reports for CM and plant-based meats, eggs and dairy from the Good Food Institute.

Histories of cellular agriculture often include two key UK-related components, both related to CM. The earliest is a regularly repeated quotation from Winston Churchill in a 1931 article titled 'Fifty Years Hence', in which he states "[w]e shall escape the absurdity of growing a whole chicken in order to eat the breast or wing, by growing these parts separately under a suitable medium" (Churchill, 1931). Typically, people from the community follow the quotation by noting it is taking longer than Churchill predicted, but the trajectory was correct. The second UK-related historical milestone is the 2013 London press conference in which Post and his team at Maastricht University unveiled the world's first cultured burger, which had been grown in his laboratory in the Netherlands and transported to the UK just before. The burger was a proof of concept as opposed to a product launch, as it was reported to have cost around \$300,000. It was tasted by two independent food journalists from Austria and the US, after being cooked by chef Richard McGeown, patron of Couch's Great House Restaurant in Cornwall, UK (O'Riordan *et al.*, 2017; Post, 2014).

Review methodology

This review is rooted in a ten-year social science project conducted by N.S. This project has involved over 50 interviews with experts internationally in CM, as well as attendance at key meetings and media analysis of reporting on the subject. N.S. and M.E. are part of a group that co-founded an organisation named 'Cultivate' in 2016 to act as a multi-voiced forum for discussing issues around cellular agriculture in the UK. Cultivate organises an annual event to bring together the UK cellular agriculture community. During its November 2018 event a draft document produced by N.S. on UK activity in this

area was circulated and commented upon by those present. After this, N.S. followed up the suggestions made in that discussion and conducted further desk-based research and direct contact with groups involved to develop the work reported here. This exercise was addressed again during Cultivate event in November 2019 to up-date and finalise the review.

As noted above, cellular agriculture is an emerging field, and much of the leading research has been conducted within private companies that do not typically publish their research. As such, this review includes fewer references to peer-reviewed sources than would be the case in a typical review article. This is by necessity, as there are only a limited number of peer-reviewed papers available on this novel area of research. Subsequently this review combines references to peer-reviewed research with grey literature found in reports, institutional websites, and media reporting.

We note that we ourselves are among the most active in this field in the UK, and as such we review our own work as part of this text. We also note that cellular agriculture can sometimes seem a fast moving field, with new entrants appearing frequently. Often in the commercial sphere such entities operate in what is termed ‘stealth mode’, to indicate a low profile. As such, it is possible our account may miss some UK activity, and can only claim to capture the context as we know it to be at the time of publication.

In the following sections we review key aspects of UK cellular agriculture activity, focusing upon different clusters of activity in turn.

University laboratory research

The most active university in the UK is the University of Bath. Dr Marianne Ellis and Dr Chris Chuck are the bioprocessing strand lead and director, respectively, in the Centre for Integrated Bioprocessing Research (CIBR). The Ellis group focuses on tissue engineering-based cellular agriculture; the Chuck group focuses on fermentation-based cellular agriculture, specifically production of a palm oil substitute from yeast. Ellis began her research career in regenerative medicine and has applied her bioprocess design techniques to the expansion of muscle cells for CM. Given her experience with *in vitro* liver models (Luetchford *et al.*, 2018; Storm *et al.*, 2016) and her early-career work on scaffold development for mesenchymal stem cell expansion (Morgan *et al.*, 2007), she has positioned herself to develop platform technologies for a wide range of tissue engineered cellular agriculture products, specifically based around scalable bioreactor design (Allan *et al.*, 2019). She has a research group, with funding from New Harvest amongst others, developing bioreactors and scaffolds for CM, and gives Chemical Engineering undergraduate students the opportunity to carry out major project work in this space, having now supervised over 30 Masters of Engineering student projects on the topic of cultured meat bioprocess design. The work combines tissue engineering with established biotechnology process design with the addition of novel approaches to scaling up tissue engineering cultures. Focus is on bioreactor configuration; given the early stage of this work, much effort is going into

understanding the metabolic stoichiometry, i.e. how much raw material is consumed by the cells to produce a given amount of protein as well as the waste products. This is intimately linked to efficient scale up due to it being the basis for media recipes and amounts required, which is likely to be affected by cell type and culture conditions.

Aberystwyth University has recently started working on cellular agriculture via a PhD student co-funded by M.E.’s start-up, Cellular Agriculture Ltd, the Institute of Biology, Environment and Rural Sciences (IBERS) at Aberystwyth University and the Pedigree Welsh Pig Society. The project is examining cell sourcing and harvest for cultured pig meat. To our knowledge this is the first and only study in the world exploring the properties of primary porcine cells to find the most efficient for CM production. This type of research is commonplace in traditional meat production, albeit for the whole animal, and it follows that there will be particular breeds whose cells are more conducive to the bioreactor culture environment than others, thus leading to a more efficient production process, like the broiler chicken, and even a customer-preferred source likened to prime cuts of meat like Aberdeen Angus beef.

Also, in 2019, US-led third sector group [the Good Food Institute provided \\$210,088 funding to Petra Hanga](#), lecturer in Biological Engineering at Aston University, to work on bioprocessing and scale-up. Her focus is upon microtissues composed of fat and muscle in a scalable bioreactor platform. Working with bovine mesenchymal stem cells, the project aims to optimise protocols for increased cell production.

From 2018 until late 2019, US-based third sector group [New Harvest have also been funding Dr Ricardo M. Gouveia at Newcastle University](#) to investigate how substrate curvature effects the migration, proliferation and self-organisation of cells within a matrix, and how controlling this could support targeted bio-fabrication of tissues that reproduce the texture of meat. This work is based within the lab of Prof Che J. Connon, which is also connected to the start-up CellulaREvolution discussed in the next section.

At the University of Cambridge, academic neurosurgeon Dr Mark Kotter has developed work on human induced pluripotency stem cells to produce neurons and skeletal myocytes for biomedical purposes (Pawlowski *et al.*, 2017). Kotter’s new technology – named OPTi-OX – has been licensed to the Netherlands-based company Meatable, who are using it to develop a CM system. Kotter co-founded Meatable, along with Krijn de Nood and Daan Luining, in 2018, with its aims including producing a pork prototype.

Returning to the University of Bath, and moving away from CM, Chuck has been working on the scale up of oleaginous yeasts grown on waste resources for the production of a palm oil substitute (Parsons *et al.*, 2018; Whiffin *et al.*, 2016). Funded by a £3.9m grant from the EPSRC and Innovate UK, this MP² Project is a collaboration between the University of Bath, University of York, Croda, and AB Agri. They seek to create a sustainable biorefinery

that uses food waste biomass that has been broken down with a one-step and additive-free microwave technology to hydrolyse the materials into fermentable sugars. Then, using oleaginous yeast as a platform mechanism, the MP² Project group seek to develop a pilot-industrial scale bioreactor to produce larger quantities of single cells oils that can operate as a palm oil substitute for some purposes. Their current research involves optimising the yeast strain being used, and assessing the mechanics and economics of a scale-up system. The long-term goal is to produce a palm oil substitute—the world’s most widely used oil crop—with a system involving less deforestation and the associated habitat destruction.

Finally, moving away from food but remaining with cellular agriculture, in 2019 an Engineering and Physical Sciences Research Council-funded PhD project commenced at the University of Manchester. Supervised by Dr Celina Jones, Dr Olga Tsigkou and Dr Lucy Bosworth, the project aims to pair a synthetic scaffold with 3D cell culture techniques to produce a new uniformed textile-cell construct, or ‘leather’. The vision is to enable traditional fibre-scaffolds to be transformed into unique fabrics using textile processes. These biodegradable fabrics would then be cultured with fibroblasts, which should secrete extracellular matrix proteins (including collagen and elastin), and eventually be modified to be comparable to the dermis layer of the skin. This ‘artificial’ skin would then be subjected to traditional tanning processes, minus a number of previously essential steps, in an attempt to create a mechanically stable, uniform leather material.

Companies

The most visible CM company in the UK is [Higher Steaks](#), founded by Benjamina Bollag (CEO), Dr Stephanie Wallis (CSO), and Prof David Hay (Scientific Director) in 2017. Higher Steaks is a ‘full stack’ company, meaning its focus is upon producing a consumer ready CM product, as well as working on all the intermediary steps in a vertically integrated form. They are developing a technology that could use skin biopsies or blood samples from pigs to which an induced pluripotency technique is applied to create cells that could produce any type of tissue including muscle and fat for use in pork products. Pork has been chosen as the initial focus as porcine biology is close to human biology, allowing biomedical insights to be more easily translated, and because of Higher Steaks’ concern that pigs in the meat industry have a higher exposure to antibiotics than cattle. However, they also expect their technology to be applicable to other species in the future. Like many full stack CM start-ups, they are also working to develop methods for reducing the cost of the media in which their cells are grown, as media is the highest costing input to the process. On this, they have already established culturing protocols that work sufficiently well without fetal bovine serum (an animal-derived blood product), but are continuing research efforts in this area. In mid-2019, the team was made up of Bollag and Wallis and a stem cell scientist, while Hay contributed in parallel to his role as the chair of the Tissue Engineering department at MRC Centre for Regenerative Medicine at the University of Edinburgh. They also have a team of advisors. Higher Steaks raised a pre-seed round

and are currently preparing for their seed round and anticipate expanding once further capital is secured.

While Higher Steaks have been more visible, the first CM company to be established in the UK was [Cellular Agriculture Ltd](#), founded in 2016 by Illtud Dunsford and Ellis. The company is in some regards distinct internationally: co-founder Dunsford’s background is in farming as the owner of a successful meat production and processing business set on the family farm of 300 years (Charcutier Ltd), giving the company an unusual grounding in traditional meat production. Cellular Agriculture Ltd has not adopted a ‘full stack’ business model and does not seek to produce meat themselves. Instead they are commercialising the bioprocess with focus on the bioreactor technology, developed in the Ellis laboratory at the University of Bath, to enable the industry to manufacture their products on a commercial scale. The company is leveraging its university contacts, and co-funds two PhD students alongside US-based 3rd sector group New Harvest and the University of Bath for bioreactor design, and Aberystwyth University for cell sourcing and harvesting. It has also developed its own proof of concept bioreactor via InnovateUK funding. In mid-2019 they were preparing their seed round.

There have been, and continue to be, other companies with UK links active in the field. [CellulaREvolution Ltd](#) are a new spin out company from Newcastle University co-founded by Leo Groenewegen CEO, Dr Martina Miotto CSO and Prof. Che Connon CTO. The team work with peptides for multiple purposes. This includes developing methods for continuous bioprocessing in which cells automatically self-detach from their growing surface to allow other cells to subsequently grow in the same space. This substantially increases production yields, all within a serum-free environment whilst reducing media volume and footprint ([Miotto et al., 2017](#)). Their research was originally developed for medical uses, particularly the cornea, but they are now exploring applications in both biomedicine and CM ([CellulaREvolution, 2018](#)). In November 2019, CellulaREvolution announced a £380,000 investment via the North East Angel R&D programme, managed by Northstar Ventures.

Also recently established, [Multus Media](#) are seeking to produce animal-free, sustainable and cheap media for the CM industry. [Their approach](#) is to use genetically engineered yeast to produce mammalian cell growth factors. Based out of Imperial College Advanced Hackspace (ICAH) in London, the project is led by Kevin Pan with a team of 13 other scientists.

Another start-up, [Biomimetic Solutions](#), is also exploring developing enabling technologies with applications in both CM and biomedicine. Starting in Brazil, [the company moved to London in 2018 and participated in the RebelBio accelerator programme](#). Currently Biomimetic Solutions retains links to both Brazil and the UK. They have patented a scaffold called Nano3D that is edible and pH neutral that could provide a framework for muscle cells to grow into as CM is produced. The scaffold has been trialled by US CM company [Finless Foods \(Benz, 2018\)](#).

Private investors

The most active private funder of cellular agriculture work in the UK is CPT Capital, a dedicated investor in the alternative protein sector. It is run through the family office of Jeremy Coller, a successful financial executive. They have invested in both plant-based proteins (including famous names like Beyond Meat and Impossible Foods) as well as a string of cellular agriculture companies, including Geltor (gelatine), Perfect Day and New Culture (both dairy products), Modern Meadow and Vitro Labs Inc (both leather), and Blue Nalu, Aleph Farms, Memphis Meats, and Mosa Meat (all CM). While these are largely US-based companies, CPT Capital are now “[looking to expand the geographic representation](#)” of their portfolio. They look for pre-seed to Series B stage companies with a view to long-term support.

The second most active investor in the sector that we are currently aware of is Agronomics Limited, who focus specifically on nascent modern foods that target environmental benefits. [Their listed investments](#) include BlueNalu, New Ages Meats, Shiok Meats and Meatable. Other single company investments from the UK include [Atomico's investment in Memphis Meats](#), Backed VC's investment in the Dutch company Meatable, and [Breakoff Capital's investment in Finless Foods](#). Other UK-related investors include Richard Branson, who famously [invested in Memphis Meats Series A round](#), and, as reported above, biotech incubator RebelBio (backed by global venture capital firm SOSV), who supported Biomimetic Solutions.

Social science

The UK has a broad range of social science analyses of cellular agriculture. The earliest was an economic forecast produced by [eXmoor pharma concepts \(2008\)](#). This work was funded by the Dutch-led In Vitro Meat Consortium project, and predicted CM could be produced for €3300–3500 per tonne, compared to about €1800 per tonne for chicken meat.

At this time, sociologist Dr Neil Stephens began an extended project, still continuing today, tracking the long-term development of CM and the community that supports it. His early work identified the ontological ambiguity over what CM actually is—as meat, or as meat alternative, or even not as food at all—and has subsequently documented the technical and cultural moves that have sought to define its status and politics ([O’Riordan et al., 2017](#); [Stephens, 2010](#); [Stephens, 2013](#); [Stephens & Ruivenkamp 2016](#); [Stephens et al., 2018](#); [Stephens et al., 2019](#)). Stephens’ work has received funding from the Economic and Social Research Council, the Wellcome Trust, and via a larger FP7 project (titled EPINET). It has stressed the symbolic work conducted by those within the cultured meat community to assert frames of reference that position the politics of cultured meat in specific ways.

Continuing the interdisciplinary theme, lawyer [Dr Ludivine Petetin \(2014\)](#), then of the University of Hull, published work

identifying key questions about the politics and policy landscape of CM, before arguing EU regulation needed strengthening in response to CM, in order to strike a balance between ensuring risk management is accomplished effectively, while avoiding stifling innovation.

In more work funded by the Wellcome Trust, bioethicists [Dr Owen Schaefer and Prof Julian Savulescu \(2014\)](#), then of the University of Oxford, argued CM is permissible and worth promoting. They found potential moral objections – disrespect towards animals, reduction of happy animal numbers, and risks of cannibalism – are insufficiently serious to undermine the potential positives offered by the technology.

2014 also saw the first UK academic meeting dedicated largely to CM. Titled ‘The Ethics of *In-Vitro* Flesh and Enhanced Animals’ and hosted by Dr Jan Deckers in the small Northumberland Town of Rothbury, the two-day event featured a range of social science papers addressing the issue. Along with Stephens and Schaefer, another attendee was geographer Dr Alexandra Sexton, now of the University of Oxford and a co-founder of Cultivate. Funded initially by the ESRC, and then as part of the broader Wellcome Trust funded Livestock, Environment and People (LEAP) Project, Sexton has analysed the political framing of CM in relation to similar narratives found among emerging plant-based meat companies. Her work documents the narratives through which CM is presented as an edible, and transformative, technology, and how political notions of what constitutes ‘good’ food and ‘good consumers’ are articulated through this ([Sexton, 2016](#); [Sexton, 2018](#); [Sexton et al., 2019](#)).

Over the next couple of years, a number of reports on public perceptions of CM were published. The first was by an international group including staff at the University of Bath ([Marcu et al., 2015](#)). Funded as part of a European Union FP7 project, this work looked at perceptions in the UK, Portugal and Belgium, and found participants’ accounts often connected CM to existing reference points to make sense of it, be that familiar metaphors, science fiction, or their existing opinions on the politics of food technology and commercialisation. A second study, funded by and conducted with the Tyndall Centre for Climate Change Research at the University of Manchester ([O’Keefe et al., 2016](#)), looked at focus group responses to a range of food practices intended to address climate change, including CM. It found consumers did not strongly link food choices to climate change, but were more likely to embrace changes that fit more closely to their existing competencies and practices. More recently, Christopher Bryant, working with the Bath group and funded by the UK Economic and Social Research Funding Council, has published a further set of survey-based consumer analyses ([Bryant & Barnett, 2018](#)). His findings include the observation that consumer positivity towards CM increases when it is called ‘clean meat’ as opposed to ‘lab grown meat’ ([Bryant & Barnett, 2019](#)), and, in work funded by the Animal Advocacy Research Fund, that India and China have

higher levels of acceptance for cultured meat than the USA, and higher familiarity predicted higher acceptance (Bryant *et al.*, 2019). Finally on public perceptions, Professor Frank Vriesekoop of Harper Adams University has worked with a team of international colleagues on consumers perspectives in the UK, Spain, Brazil and the Dominican Republic (Gómez-Luciano *et al.*, 2019). They found readiness to consume alternative proteins was greater in higher income countries, and that consumers found plant-based proteins more attractive than CM.

Recently, Dr Josh Milburn, of the University of Sheffield, has also written supportively on the ethics of cultured meat and milk. On CM, Milburn argues appropriate safeguards can be put in place to prevent harm to animals from which cells are extracted, and hierarchies between humans and animals can be overcome by using humans as the cell source for CM (Milburn, 2016). Milburn then argues cultured milk has key differences ethically to CM in that milk is unambiguously food, and never part of an animal's body. Cultured milk, Milburn argues, should be supported while ensuring it does not stand to legitimate the current milk industry, while again noting that cultured human milk would undermine any concerns about reasserting human-animal hierarchies (Milburn, 2018).

Finally, John Miller, also of the University of Sheffield and another attendee of the 2014 Rothbury event, is writing on the literary history of CM. He identifies science fiction narratives concerning CM as early as 1881, and analyses in detail a depiction from the 1952 novel 'The Space Merchants' (Pohl & Kornbluth, 1984) that on one hand gestures towards a politics that values traditional meat production over CM, but on the other engages with the problems of capitalism that frame meats produced in any form (Miller, 2019).

Environmental life cycle analyses

Life cycle analyses (LCA) assess the environmental impact across the lifecycle of a particular product or output. Such work has inherent difficulties in the context of cellular agriculture as the products being modelled are still early in their research and development process, and have not yet entered scale-up processes. As such LCAs on the topic involve making multiple assumptions, or the use of the closest real-world example in the absence of empirical material on actual cellular agriculture processes. However, potential environmental benefits are key motivators for many cellular agriculture products, so a number of attempts have been made to quantify what this benefit would be. Three of these have been produced in the UK. The earliest of these was the first LCA of CM produced anywhere in the world, by Dr Hannah Tuomisto, then of Oxford University, working with Dr Joost Teixeira De Mattos of the University of Amsterdam. As well as the first, this LCA has to date remained the most optimistic, suggesting that compared to conventionally produced European meat, a CM system could result in 7–45% lower energy use, 78–96% less greenhouse gas emissions, 99% lower land use, and 82–96% lower water use (Tuomisto & de Mattos, 2011). Four years later, Dr Mark Steer of the University of the West of England conducted an LCA of milk produced through cellular agriculture, based on the work of San Francisco start-up Muufri

(now Perfect Day). The modelling here found Muufri's milk could use 35% of the energy, 16% of the greenhouse gases, 1% of the land and 2% of the water compared to the conventional dairy industry (Steer, 2015). Finally, more recently in 2019, another Oxford University group published an LCA of CM comparing a wider set of potential production and use contexts than previous work, and looked across multiple timeframes, up until 1,000 years in the future. The study found that, while in many instances CM is climatically superior to conventional livestock production, some scenarios may exist in which this is not the case (Lynch & Pierrehumbert, 2019).

3rd sector groups, charities and think tanks

There are two dedicated UK-based third sector groups in the UK, as well as UK representation of international (generally US-based) groups and a level of interest among UK third sector groups with a broader remit. The first dedicated UK third sector group was 'Cultivate', founded in 2016 by an interdisciplinary and cross-sector team of five (that include the authorship team of this review). It describes itself as "a multi-voiced forum intended to support informed dialogue about the emergent field of cellular agriculture from UK perspectives". It formed after the group who went on to become its founders were invited to a number of discussions at 10 Downing Street about UK policy in this area, during which they produced a review of UK activity and a set of policy recommendations, one of which was to establish the networking group that became Cultivate. A significantly reedited version of their report went on to be published as Stephens *et al.*, (2018). Cultivate have hosted an annual meeting since 2016 and produce written outputs on the topic. The organisation operates without external funding and functions with low costs. Events are supported by attendee entrance fees and founder contributions.

A second dedicated UK third sector group was established in 2018. 'Cellular Agriculture UK' seeks to "provide a clear, central hub and contact point for those who have independently developed interest in the space" and to "reach out to potential interested parties and support their engagement in the space" (Cellular Agriculture, 2018) and held their first activities in early 2019. Beyond these UK-based groups, three US based groups also have UK representation. The Cellular Agriculture Society have UK-based volunteers. The Good Food Institute now has a representative in the UK, having recently employed its first UK-based staff member, Richard Parr, as their Managing Director (EU); as noted previously, they have funded Hanga's research at Aston University. Another leading US-based third sector group—New Harvest—fund PhD research at the Ellis lab at the University of Bath and Gouveia's work at Newcastle University, as well as earlier work at King's College London and the University of Oxford.

Additionally, a number of UK groups with broader focus have produced reports about CM, including the Adam Smith Institute (Hollywood & Pirie, 2018), the Food Ethics Council (2015) and the Nuffield Council on Bioethics (2019). Among the most detailed is a report by Chatham House (Froggatt & Wellesley, 2019) that specifically articulates considerations for the EU. In particular, they raise issues relating to how regulation and

labelling decisions made by policy-makers could frame future direction and pace of growth.

Conclusion

Cellular agriculture, both as a term and as a field of activity, remains relatively new. Those developing the technologies associate it with a range of significant benefits, but the technology remains early-stage in many cases, and the capacity of these technologies to deliver these benefits remains unknown and subject to the social context of their introduction. The technologies have garnered support over the last five years from a set of technology investors, often with links to Silicon Valley finances or modes of working. UK activity, in this context, is increasing but remains smaller than that found in countries such as the US, Israel and the Netherlands.

The longest-standing UK work has been university-based. The University of Bath is a leading institution among these, in part as it was an early-mover, and due to its existing track-record in bioprocessing, but also partly due to chance in that Bath has three separate groups (one of which is based in the Department of Psychology, two based in the Department of Chemical Engineering) that have independently chosen to work in this area. More recently the number of companies has been growing. Unlike many of the American, Israeli and Dutch companies, all but one UK company have adopted a business-to-business model, seeking to supply components necessary for CM production to other CM companies. The exception is Higher Steaks, who have adopted the full-stack model of seeking to produce marketable CM products. We also note that all of the UK companies are focused upon CM, with none of them addressing the broader set of cellular agriculture products. These companies are either seeking, or have gained, initial seed funding, but have attracted less finance than the leading companies globally. Also notable is that the UK-based investors have most frequently directed their finance outside of the UK, primarily to the US, and have invested less domestically.

We have demonstrated that the UK has a long history of lively work on the social and policy aspects of cellular agriculture, covering key but diverse topics including the production of meaning, consumer responses, economics and regulatory

analysis. This is not, we suggest, anything specific to cellular agriculture, but instead represents a strong UK body of work on the analysis of emerging technologies in general. This academic work has fed into the emerging policy discussion, about how cellular agriculture should be regulated and what role it might have in society if realised as a commercial reality. However, beyond the organisation Cultivate, there are few formal links between the social scientists and those conducting laboratory work.

We detailed the two examples of UK cellular agriculture laboratory work beyond CM; the leather work and Manchester University and the MP² Project. As we noted, the MP² Project—focused upon a fermentation-based palm oil system—demonstrates that cellular agriculture approaches need not be limited to animal-derived products and suggests that the common-use definition of cellular agriculture could be expanded to include non-animal agricultural products, including oils.

Overall, our review has shown that the UK is not the leading country in the world in cellular agriculture, but it does have an active and diverse community. Given the knowledge base within relevant fields in the UK, there is also significant potential for this body of work to increase in the coming years. We have provided this review to inform interested parties about who is active and what they are doing in the UK as 2020 begins, both for the benefit of audiences keen to engage in 2020, and to record this moment of emergence for the historical record. The future of cellular agriculture is indeterminate, but it seems likely the UK will continue to be involved in the coming years.

Data availability

No data are associated with this article.

Acknowledgements

Both Dr Alexandra Sexton (Oxford Martin School, Oxford University) and Illtud Dunsford (Cellular Agriculture Ltd) commented on early plans and late stage drafts of this document. Both are also co-founders of Cultivate, and we acknowledge their contribution.

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 **Sissel Beate Rønning** 
Nofima AS, Ås, Norway

I have no further comments to make, thank you for this revised version.

Competing Interests: No competing interests were disclosed.



Reviewer Expertise: Food Sciences, cultured meat, muscle cell biology.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 19 October 2020

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 **Elisabeth Abergel** 
Department of Sociology and Institute for Environmental Science, University of Quebec at Montreal (UQAM), Montreal, Canada

The revised article has addressed a lot of the comments and seems more focused in some parts, most notably the section dealing with social science and the involvement of the University of Bath in Cellular Meat. The authors have included more details and have provided satisfactory responses to reviewers. I, therefore, think the article is ready for indexing.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Sociology of science and technology, biotechnology and the bioeconomy, agricultural technologies, sustainable food systems, food future, gender and food, and food ethics.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 14 February 2020

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Mariana Petronela Hanga 

School of Life and Health Sciences, Aston University, Birmingham, UK

This manuscript is a comprehensive review detailing the cellular agriculture landscape with a focus on the UK. It covers information about current relevant academic research including social science and life cycle analysis, companies acting in this area, private investors and other organisations with an interest. The authors have carried out a thorough investigation covering all stakeholders in the UK, but within the worldwide context. I liked very much that the authors have included a section on global context as it is important to acknowledge that the current leaders in the cellular agriculture scene are USA, Netherlands and Israel, while the UK at the moment is still in the early stages with only one start-up company aiming to commercialize a cultivated meat product and a handful of academic groups actively involved in this area.

The manuscript starts by defining cellular agriculture as covering 2 approaches: “tissue-engineered based” and “fermentation-based cellular agriculture” providing examples of types of products for each. I liked that a classification of the different approaches to cellular agriculture products was attempted as cultivated meat is often presented in the media, thus ignoring the other types of cellular agriculture products. However, in my opinion, the term “tissue engineered based” is perhaps slightly misleading as it implies only one type of cultivated meat product which is structured meat. It does not cover the non-structured meat (*e.g.* minced meat) that is obtained without the need of a scaffold specific to tissue engineering approaches. Perhaps a different, more inclusive term would be more appropriate.

The authors state that the aim of cellular agriculture is “to reduce (or entirely replace) animal agriculture”, however I don’t agree in totality with this statement as it is highly unlikely that complete replacement of animal agriculture will be achieved with the existing capacity. A partial replacement is more realistic.

An interesting proposal was made by the authors to extend the current definition of cellular agriculture to include cell-based agricultural goods that are not sourced from animals with a particular reference to fermentation-based palm oil from yeast. This is an interesting concept that falls within a different product category with potential benefits, however I would have liked to read more about these benefits, as there is only a brief statement saying that “this work ties to typical environmental and animal welfare concerns”, but doesn’t explicitly describe those benefits, particularly from the animal welfare point of view.

The manuscript is very well written and structured in a logical manner, being very easy to follow from one section to another. The conclusions are meaningful and summarize nicely the findings of this investigation. There is a lack of peer-reviewed published manuscripts in this domain which was acknowledged by the authors. Additionally, the majority of active players in this domain worldwide belong to the private sector and don’t publicize their proprietary technology or the stage of development that they are at. As such, it is difficult to assess the timeline to a marketable cellular agriculture product, it being cultivated meat or other (e.g. leather, milk).

Is the topic of the review discussed comprehensively in the context of the current literature?

Yes

Are all factual statements correct and adequately supported by citations?

Partly

Is the review written in accessible language?

Yes

Are the conclusions drawn appropriate in the context of the current research literature?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Bioprocessing of stem cells, cultivated meat, bioreactors, scale up, cell therapy manufacturing.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 01 May 2020

Neil Stephens, Brunel University London, Uxbridge, UK

We thank the reviewer for these useful and positive comments. We have made three specific edits to the paper in response to the comments.

First, we have clarified our use of “tissue engineering based” cellular agriculture to show that we include non-structured cultured meat within this. We did not want to use a different term as that phrase has already been used in published work elsewhere.

Second, we made a slight edit to acknowledge that partiality of animal agriculture replacement by saying one aim of cellular agriculture is “perhaps entirely replacing” animal agriculture.

Thirdly, we have added a short line on the claimed benefits of a cellular agriculture approach to palm oil production, noting it is: “specifically around deforestation and its impact upon greenhouse gases and biodiversity”.

Competing Interests: No competing interests were disclosed.

Reviewer Report 11 February 2020

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Joshua Flack

Mosa Meat, B.V., Maastricht, The Netherlands

Mark J. Post 

Department of Physiology, Maastricht University, Maastricht, The Netherlands

This review provides a timely record of the current state of the Cellular Agriculture field in the United Kingdom. As the authors surmise, the UK is a leading nation in terms of scientific research, but arguably has been somewhat ‘behind the curve’ in terms of Cellular Agriculture. As the authors detail, this is now changing, although the developments in the UK are more below the radar than the activities in the US, Israel and several European nations, such as the Netherlands.

The overview constitutes a useful resource for those looking for an entry point into understanding the UK-based Cellular Agriculture landscape. It provides a good cross-sectional view of all activities in this space in the UK, with some comparison to other nations.

The authors struggle with the inclusivity of the term cellular agriculture, more specifically whether to include all biotechnology using recombinant technology in micro-organisms, i.e. fermentation. The existing industry in this space, that historically predates cellular agricultural activities by some decades and which focusses on many applications in addition to agricultural products and food, will likely not recognize itself in this qualification. Fortunately, to date there is no practical confusion over the term cellular agriculture, but with advancing technologies and the emergence of cross-over technologies as well as applications, the term will become less defining.

As in most other countries, the rapid emergence of cellular agriculture in the UK, depends on privately funded initiatives in the absence of public funding. As reported, there were some government initiatives to get a clear understanding of the field during the Cameron

administration, but this apparently has faded in the wake of government changes and obvious focus on other subjects. In various countries on the continent and indeed in Brussels itself, consultations have started and political views are being formed, hopefully followed by funding or permissive legislative activities. In this respect it will be interesting and challenging how the recent political developments in the UK will affect the current or future collaborative projects in the Cellular Agriculture space with European partners. This will especially be important for future regulation. Europe has been leading the way in defining how cellular agriculture products, specifically cultured meat, will be regulated. It is unknown how the UK will manage regulation of novel food products in the near future. The authors might want to speculate or have insight into what is a likely regulatory scenario.

Nevertheless, it is encouraging to learn that there are many academic groups involved in cellular agriculture, one way or the other. This is attested by the relatively large number of scientific publications coming out of UK academic groups, a majority of them on social science aspects. On the laboratory science level, it should be mentioned that the Dutch start-up Meatable was co-founded by a UK-based academic, Mark Kotter, and is making use of stem cell technologies developed in his laboratory in Cambridge.

The discussion related to the 'full-stack' nature of Higher Steaks as a Cellular Agriculture company is an interesting point, and one that might warrant further discussion should the authors wish. Do the authors foresee that such vertically integrated companies will ever come to dominate the UK-based Cellular Agriculture scene? Vertical integration seems to be a business model from the past and the current attempts to vertical integration by startup companies should be viewed as the result of a lack of suppliers active in this space. It would therefore be good to define what the strength of UK-based companies or academic groups is and how they would fit in an eventual cellular agricultural industry.

In this rapidly changing field, any publication is inevitably out of date at the time of publication. For example, Memphis Meats recently announced a large Series B funding round (\$161M).

The authors are in an excellent position to suggest future paths that Cellular Agriculture research in the UK might take, and what strategies should be employed to maximize the efficacy of the current projects and thus improve or accelerate the growth of Cellular Agriculture in the UK and the rest of the world.

Is the topic of the review discussed comprehensively in the context of the current literature?

Yes

Are all factual statements correct and adequately supported by citations?

Yes

Is the review written in accessible language?

Yes

Are the conclusions drawn appropriate in the context of the current research literature?

Yes

Competing Interests: The reviewers are employees of Mosa Meat, B.V. a Dutch startup that aims to commercialise cultured meat

Reviewer Expertise: Tissue engineering; cultured meat; Physiology.

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 01 May 2020

Neil Stephens, Brunel University London, Uxbridge, UK

We thank the reviewers for their comments on the paper. We acknowledge that the paper was published just prior to Memphis Meat's \$161 Series B, but we have not included this as the review is intended to be accurate as of the end of 2019.

We have edited the paper following this review in that we have now included a paragraph about Mark Kotter's work with Meatable, and we thank the reviewers for highlighting this to us.

Competing Interests: No competing interests were disclosed.

Reviewer Report 06 February 2020

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Elisabeth Abergel

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The article sets out to provide an inventory of the field of Cellular Agriculture in the UK including the private and public researchers and companies, investors as well as a very broad overview of the types of products they are developing. There is also a section on social science, which aims to situate how academics studied and were instrumental in opening up various aspects of CM in several disciplinary contexts such as sociology, bioethics, law, political framing, environmental assessments, etc.

There is a very synthetic but well crafted introduction which retells the story of CM and includes some notable UK references, notably Winston Churchill's famous quotation as well as the highly publicized tasting of the first "lab-grown burger" which took place in London.

The paper highlights current and recent developments in the UK within the Cell Agriculture space

in relations to other countries (US, Holland and Israel for instance). The authors also describe three studies of the environmental impact assessments of potential Cellular Agriculture systems emanating from the UK. Hence, readers get a snapshot of the UK's involvement in and contributions to Cellular Agriculture since its beginning until the end of 2019.

The article is very descriptive and offers very little analytical perspective as is expected from the authors' stated objectives. In terms of the review methodology and the purpose of the article, the contents are coherent and follow a logical order. The authors are extremely knowledgeable in the field of Cellular Agriculture in the UK on the scientific and social science side. They have been involved in this issue since its beginnings in the UK and internationally. Their involvement in the field is acknowledged in the review methodology.

However, one cannot help question the purpose of this paper from an academic and scholarly point of view. While it spans, it seems, a great variety of actors and players in Cellular Agriculture, it lacks in depth and possibly critical distance as the authors feature prominently in the article. It is on some level very self-referential. One also wonders who the intended target audience might be as the article provides some technical details of scientific developments but leaves out broader information about key findings of studies from its "portfolio" of social science research.

For instance:

- While the paper discusses scientific research and social sciences contribution to the field, what are the links between these communities, if any (besides the Cultivate organization and the authors)?
- One would have liked to have known the role of UK scientists, entrepreneurs and/or investors who promote Cellular Agriculture at the international level through association meetings, start-up events and conferences? The scope of influence of people like Illtud Dunsford for example (Cellular Agriculture Ltd) who represents the farmer's perspective at CM events organized outside the UK (he is mentioned in the paper as coming from a farming background but he is also partnered with M.E. one of the authors).
- What are the ties between university researchers and private companies in terms of shared levels of expertise, within the UK and outside the UK and in terms of funding besides funding doctoral students?
- Does the UK demarcate itself in terms of expertise, technologies, areas of research, patented technologies, expected products, infrastructure, etc.? Why is the University of Bath such a leader?
- What might be occurring in terms of government involvement? What regulatory developments, if any?
- How and who funded the social sciences research conducted in the UK? Who funds Cultivate (created by both authors as a forum for discussing UK cellular agriculture)?
- Who are the institutional actors and related industries supporting cellular agriculture in the UK? And what roles do they play in the development of the field?

The paper reads almost as a promotional piece, it doesn't delve into deeper questions. It is, as

stated earlier, an inventory of sorts. One of the interesting points raised in the article is the brief discussion about potentially expanding the definition of cellular agriculture to include non-animal sourced products. This could have been discussed further as definitions and language are very strategic in Cellular Agriculture but also, to not leave readers with the impression that including fermentation based palm oil production was placed there because it is an active area of research in the UK. It raises questions about how far the definition of Cellular Agriculture can be expanded.

Is the topic of the review discussed comprehensively in the context of the current literature?

Yes

Are all factual statements correct and adequately supported by citations?

Yes

Is the review written in accessible language?

Yes

Are the conclusions drawn appropriate in the context of the current research literature?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Sociology of science and technology, biotechnology and the bioeconomy, agricultural technologies, sustainable food systems, food future, gender and food, and food ethics.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 01 May 2020

Neil Stephens, Brunel University London, Uxbridge, UK

We thank the reviewer for their thoughtful comments, and we have made a number of improvements to the paper in response. We respond to each of the major points in turn below.

- one cannot help question the purpose of this paper from an academic and scholarly point of view. While it spans, it seems, a great variety of actors and players in Cellular Agriculture, it lacks in depth and possibly critical distance as the authors feature prominently in the article. It is on some level very self-referential. One also wonders who the intended target audience might be as the article provides some technical details of scientific developments but leaves out broader information about key findings of studies from its "portfolio" of social science research.

This critique mirrors the comments of another of the reviewers, and we have responded by extending the opening paragraph to give a clear statement of what the paper aims to achieve, and who we think will benefit from it. In terms of purpose, for us, the paper is one

stage in a set of activities that we are engaged in that will support a deeper and more critically engaged discussion about cellular agriculture in the UK. In this regard this paper is very important to us as a baseline for a broader discussion. Finally on this, one reason this journal is a good fit for this specific paper is its requirements in terms of purpose: "All new findings supported by original source data are welcome, regardless of the perceived interest and the extent of novelty".

- While the paper discusses scientific research and social sciences contribution to the field, what are the links between these communities, if any (besides the Cultivate organization and the authors)?

We are not aware of any further links, but we cannot definitively say there are none. We have added a line to the paragraph in the conclusion about the social science work on CM noting that these links are limited.

- One would have liked to have known the role of UK scientists, entrepreneurs and/or investors who promote Cellular Agriculture at the international level through association meetings, start-up events and conferences? The scope of influence of people like Iltud Dunsford for example (Cellular Agriculture Ltd) who represents the farmer's perspective at CM events organized outside the UK (he is mentioned in the paper as coming from a farming background but he is also partnered with M.E. one of the authors).

This paper was not intended to detail the activities of UK groups in the international context, or judge their influence (although we do note the role of UK investors in non-UK companies). So we have not addressed this point as it is beyond the paper's remit.

- What are the ties between university researchers and private companies in terms of shared levels of expertise, within the UK and outside the UK and in terms of funding besides funding doctoral students?

The paper identifies multiple ties between universities and private companies. Cellular Agriculture Ltd is developing technology from the University of Bath, CellulaREvolution is developing technology from Newcastle University, Higher Steaks is working with the University of Edinburgh, and (featured in this revised version) Meatables is commercialising technology from Cambridge University.

- Does the UK demarcate itself in terms of expertise, technologies, areas of research, patented technologies, expected products, infrastructure, etc.? Why is the University of Bath such a leader?

This is an interesting question but we do not believe that 'the UK' is close enough to a singular organised group that does actively demark or self-define itself. As the paper shows, activity in the UK is characterised by a relatively small number of groups, many of which are relatively early in their operations. We have added a new line to the conclusion that comments on the University of Bath: "The University of Bath is a leading institution among these, in part as it was an early-mover, and due to its existing track-record in bioprocessing, but also partly due to chance in that Bath has three separate groups (one of which is based in the Department of Psychology, two based in the Department of Chemical Engineering) that have independently chosen to work in this area".

- What might be occurring in terms of government involvement? What regulatory developments, if any?

The government has said very little formally on this topic. As noted in the new introduction, this paper has been produced in part to allow stakeholders such as the government to more easily identify activity in the UK in anticipation of possible future policy discussion in the UK.

- How and who funded the social sciences research conducted in the UK?

Following this comment and that of another reviewer, the section on UK social science has been edited substantially to both increase the coverage of the content of the social science work, and identify its funding sources where they are known. However, this has been done while working to retain the succinct overview quality of the paper.

- Who funds Cultivate (created by both authors as a forum for discussing UK cellular agriculture)?

The paragraph overviewing Cultivate now includes these details: "The organisation operates without external funding and functions with low costs. Events are supported by attendee entrance fees and founder contributions."

- Who are the institutional actors and related industries supporting cellular agriculture in the UK? And what roles do they play in the development of the field?

We are a little confused by this comment, as the paper primarily functions to list the key institutional actors and the role they play in the development of the field, so we feel this is already addressed across the paper.


Thanks again for your comments, we hope you agree this is now an improved manuscript.

Competing Interests: No competing interests were disclosed.

Reviewer Report 03 February 2020

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? **Sissel Beate Rønning** 
Nofima AS, Ås, Norway

This manuscript gives an overview of the cellular agriculture in UK, and it presents information on a relatively unexplored subject where publication of data is still limited. The manuscript summarizes nicely the research activity, and the commercial activities in the UK, and I hope the authors will extend this work to include rest of Europe in their next review. As the authors are among the most active researchers in the UK on the topic, this unfortunately implies they review and refer to much of their own work. This is a limitation of the manuscript, and although the authors address this in the review methodology the authors must be careful to provide a balanced and comprehensive overview of the research field. I think this manuscript is important, well performed and I recommend it for indexing if the authors address my comments.

Comments:

- Could the authors emphasize even more the objective of this review? Why is it necessary with this review and most importantly: who is it for?

- I am surprised there is such limited research (and investments) on fermentation-based cell agriculture in UK. According to reports such as the RethinkX report, these types of products are more likely to reach the market sooner compared with tissue-based cell agriculture. Perhaps the authors could comment on this interesting fact? Also, in this report the authors predict a total collapse of food production as we see it today, and how to handle post-animal production is not something we should ignore in the future. Who will/should produce cultured meat (local farmers, agribusiness, bioscientists, pharmaceutical business)? What effect will synthetic protein production/cellular agriculture have on the conventional agricultural sector? How to prepare for its arrival? And what about other markets, such as production of growth factors, fish feed, pet food? According to White Paper from World Economic Forum in 2019, “public support for alternative proteins will most likely be suppressed if the social costs of their adapter are seen to high”. Perhaps some of these questions could be addressed in this manuscript?
- The text is sometimes incoherent and unfocused. For example, a short historical introduction to cell agriculture is given in the beginning of introduction. Then another historical section, describing Churchill and the first burger is described in another chapter; cell agriculture-related work in UK. In my opinion this could be moved to the introduction, keeping the chapters more focused.
- I missed information on the technology transfer between medical field and the field of cell agriculture. i.e. production of vaccines, tissue engineering, production of insulin and so on. What is similar, and what differs?
- The authors point out that “substantial technical hurdles remain”. In order to help the reader, could the authors perhaps describe briefly those challenges, not just refer to them?
- In my opinion the readability of the manuscript will increase with tables and graphics.
- Obviously, Stephens is an expert in social science, and I think the manuscript will benefit from extending the chapter on social science to not just mention all the studies and reports of social sciences, but also the results and conclusions of these works.

Is the topic of the review discussed comprehensively in the context of the current literature?

Yes

Are all factual statements correct and adequately supported by citations?

Yes

Is the review written in accessible language?

Yes

Are the conclusions drawn appropriate in the context of the current research literature?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Food Sciences, cultured meat, muscle cell biology.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 01 May 2020

Neil Stephens, Brunel University London, Uxbridge, UK

Thank you for your review of our paper. We have edited the text to address the issues raised. Below we detail our response to the core comments in turn:

- Could the authors emphasize even more the objective of this review? Why is it necessary with this review and most importantly: who is it for?

We have more than doubled the length of the opening paragraph to state explicitly the purpose of the review. We also note that we believe it will be useful for diverse actors within the UK policy and practice as a building block for subsequent discussion. We plan to use the review as a resource in future work we will be conducting in this context ourselves.

- I am surprised there is such limited research (and investments) on fermentation-based cell agriculture in UK. According to reports such as the RethinkX report, these types of products are more likely to reach the market sooner compared with tissue-based cell agriculture. Perhaps the authors could comment on this interesting fact? Also, in this report the authors predict a total collapse of food production as we see it today, and how to handle post-animal production is not something we should ignore in the future. Who will/should produce cultured meat (local farmers, agribusiness, bioscientists, pharmaceutical business)? What effect will synthetic protein production/cellular agriculture have on the conventional agricultural sector? How to prepare for its arrival? And what about other markets, such as production of growth factors, fish feed, pet food? According to White Paper from World Economic Forum in 2019, "public support for alternative proteins will most likely be suppressed if the social costs of their adapter are seen to high". Perhaps some of these questions could be addressed in this manuscript?

We do not have a robust answer to the question of why there is limited fermentation-based cellular agriculture in the UK. The core role of this paper is simply to note that this is the case. It is also beyond the remit of this paper to devise an account of what impact cellular agriculture may have on food production and other markets going forward. However, as we noted above and in the edited introduction, in the UK context we hope this paper will be one step in supporting an informed discussion that can start to address these issues.

- The text is sometimes incoherent and unfocused. For example, a short historical introduction to cell agriculture is given in the beginning of introduction. Then another historical section, describing Churchill and the first burger is described in another chapter; cell agriculture-related work in UK. In my opinion this could be moved to the introduction, keeping the chapters more focused.

We have moved this text as suggested, and agree it improves the paper.

- I missed information on the technology transfer between medical field and the field of cell agriculture. i.e. production of vaccines, tissue engineering, production of insulin and so on. What is similar, and what differs?

This is an interesting topic, but we feel this is beyond the focus of this particular paper in

terms of the objectives it has set out.

- The authors point out that “substantial technical hurdles remain”. In order to help the reader, could the authors perhaps describe briefly those challenges, not just refer to them?

We have added a brief description as requested, in which we note: “This includes producing culture media at a lower cost;; developing cell lines that have the capacity for indefinite propagation and have a high culture-efficiency to maximise product yield;; developing reliable automation and bioreactor systems to enable scale-up that is net-zero carbon;; and reproducing the taste, texture and nutritional profile of familiar peat products”.

- In my opinion the readability of the manuscript will increase with tables and graphics.

We have decided not to include any additional tables or graphics, as we were unable to think of what data would appropriately and succinctly be captured in table form.

- Obviously, Stephens is an expert in social science, and I think the manuscript will benefit from extending the chapter on social science to not just mention all the studies and reports of social sciences, but also the results and conclusions of these works.

This section has been extended substantially, more than doubling the text to provide further information on the context of these social science projects and signposting some key findings. It would be possible to expand further on each example, however we believe the current form maintains the right balance between detail and succinctness.

Competing Interests: No competing interests were disclosed.