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RESEARCH ARTICLE

Gene editing of livestock: Sociotechnical imaginaries of scientists and breeding companies in the Netherlands

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Gene editing technologies allow users to make in vivo (live) changes to an organism's DNA. Advances in the field of gene editing have made it arguably more precise, efficient, flexible, and cheaper compared to previous technologies. This has generated an upsurge of interest in gene editing and its governance, including in livestock applications. Although gene editing in livestock promises benefits, it also raises technical, ethical, and societal questions alongside the prospect of (radical) transformation. Since the technology is still to be developed into marketable products, it is the designs, visions, or what we term "sociotechnical imaginaries" that shape gene editing technologies and that represent an important site for sociological inquiry. In this article, based on an analysis of interviews with breeding company representatives and agricultural scientists in the Netherlands, we analyze the assumptions, values, and commitments that underpin their imaginaries. These imaginaries matter, since their negotiation will help structure how the technology develops and how it will subsequently transform livestock and human–animal relations. In our analysis, we analyze the discursive practices from the interview data distilling three sociotechnical imaginaries that shape and underpin how respondents discuss gene editing in livestock. Elaborating the sociotechnical imaginary concept to make it more amenable to the emerging dynamics of gene editing in livestock, we show how imaginaries need to be studied "in place" and in terms of "material practices." Even though each of the imaginaries frame livestock gene editing as desirable and beneficial, they nevertheless have differential effects in how they structure industry, researcher, government, and consumer/citizen relations. We conclude by discussing how and why sociotechnical imaginaries on livestock gene editing matter and their implications for governance and research.

Keywords: Gene editing, Livestock, Sociotechnical imaginary, Visions, Responsible innovation, Materiality

1. The policy debate on gene editing

A daunting global policy challenge for the 21st century is to achieve food security for a growing world population, while simultaneously grappling with biodiversity protection, ecosystem function and services, animal welfare, and climate change (Godfray et al., 2010). For a number of agricultural scientists, gene editing, and in particular the CRISPR-Cas system, is framed as perhaps *the* most significant technological advance that will facilitate solutions to this global challenge (Ruan et al., 2017; Ricroch, 2019). Novel approaches to gene editing are claimed to have made "editing of the genome much more precise, efficient, flexible, and less expensive relative to previous strategies" (National Academies of Sciences Engineering and Medicine, 2017, p. 1). More specifically, these techniques enable researchers to activate or deactivate genes, insert DNA from the same or other species with desirable traits, and/or remove parts of DNA that contain undesirable traits (Netherlands Commission on Genetic Modification, 2018). Since gene editing can be used on many living organisms that contain DNA, this seemingly opens up the possibility to use the technology in many species and for multiple functions.

The plant sector has played a principal role in shaping the policy debate on gene editing, not least on account of its historical role in developing and commercializing genetically modified (GM) crops. During the 1990s, when the GM debate started to develop, the dominant frame used for GM in plants was that it provides a promissory solution to many of our societal and environmental problems (Conway, 1999; Lipton, 2001). However, this frame proved fallible when it was realized that in practice the technology was not being used to develop crops explicitly with the aim of producing environmental or health or consumer benefits (Economic and Social Research Council, 1999), but rather to enable farmers to reduce labor costs and to farm larger acreages of crops such as soya and maize (Buttel, 2005). Later, the technology came under intense scrutiny from NGO and civil society groups,

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leading to societal unrest and controversy based on societal concerns[1] and dynamics that remained poorly understood in policymaking and risk assessment procedures (Wynne, 2002; Macnaghten, 2004; Sykes and Macnaghten, 2013; Macnaghten and Carro-Ripalda, 2015). GM technology did not become the savior of the planet for citizens but instead a highly potent symbol for wider unease with technological modernity (Grove-White, 1991). In the GM debate on plants, a resulting policy response, particularly prominent in the European Union (EU), was to tighten assessment procedures on the risks and safety of the technology with the precautionary principle as an underlying guide. This led to new legislation from the EU in the form of the 2001/18/EC GM organism (GMO) Directive in which, alongside monitoring, traceability, and labeling requirements, several (long-term) risk assessments have to be completed before new GM crops are allowed onto the market. Notwithstanding such broadening of focus, the policy context governing the regulation of gene editing in Europe is one that stubbornly prioritizes questions of risk and safety (Eckerstorfer et al., 2019), reducing the conversation to quantifiable known risks.[2]

Returning to the policy debate on gene editing, there has been considerable pressure, including some backroom lobbying from plant breeding companies, aimed at ensuring that the technique does not fall under the EU GMO Directive (Hartung, 2020). Since gene editing has been developed in the wake of GM technology, a dominant promissory policy imaginary strongly backed by a number of plant scientists and breeding companies has revolved around the argument that gene editing and products derived by it are not GMOs (Sprink et al., 2016), that these should be treated as no different in kind from those derived from non-gene editing techniques (Cardi, 2016), and that its regulation should be product-based and not process-based (Zimny et al., 2019; Eriksson et al., 2020; for a critique of this binary, see Kuzma, 2016). Arguments in support of deregulation include the claim that crops produced by gene editing techniques have the potential to contribute to global food security challenges as well as to produce nutritional benefits, that these crops are in principle no less safe than conventionally bred crops, that especially crops that contain no foreign DNA present fewer ethical issues, that Europe should not be left behind as other nations and regions power ahead in research and commercialization, and that the reduced costs of a deregulated market will enable smaller breeding companies to enter the market, thus dissipating the monopolistic structure of the current agrifood sector (amongst many, see European Academies Science Advisory Council, 2013, 2015, 2017, 2018, 2020). In Europe, this has generated considerable polemic and a clear impasse between two opposing camps of actors, each with entrenched and apparently incommensurate positions (Macnaghten and Habets, 2020), and with little evidence of social or institutional learning (Rayner, 2004). Despite lobbying from plant breeding companies, and largely to their surprise, in 2018 the European Court of Justice ruled that gene editing did indeed fall under the GMO Directive (Court of the Justice of the European Union, 2018). Responding to the judgment, however, the European Commission commissioned a study that reported in a manner strongly in favor of a deregulatory approach, questioning whether current GMO regulations were "fit for purpose" and whether new policy instruments were needed to make the legislation better equipped to enable gene-edited crops to contribute to a "sustainable" food system (European Commission, 2021).

Because the policy debate on gene editing in Europe has converged on plants, with an active plant sector that lobbies for soft or no regulations to serve its interests, it is less clear how the livestock sector and (animal) scientists anticipate the future of gene editing in livestock breeding and research. On the one hand, gene editing technology promises radical transformation in livestock breeding programs, ranging from the breeding of hornless cows, pigs resistant to the PRRS virus, cows that are tolerant to heat, and chickens resistant to avian flu, none of which can easily be achieved with conventional breeding techniques (Nuffield Council on Bioethics, 2016; COGEM, 2018). On the other hand, given the importance of animals in society (DeMello, 2012), the high levels of importance attached to animal welfare across Europe (Eurobarometer, 2016), as well as the cultural importance of food and meat (Murcott, 1982), gene-edited livestock could very well reignite the policy and societal debate. By not addressing the underlying questions and concerns of society, and of scientists and of breeding company representatives in policymaking, there remains considerable potential for future controversy in gene-edited livestock akin to the controversy pertaining to GM crops and foods in the late 1990s. For this reason, it is important to identify and scrutinize how livestock breeding companies and agricultural scientists, as key actors in the development of the technology, envision the future of gene editing in livestock breeding.

The structure of our article is as follows. In this section, we have argued that a dominant policy imaginary around gene editing in plants has been constructed by plant breeding organizations in Europe; we note, however, that no such narrative is visible in livestock, despite research occurring in this area. In Section 2, we explicate an approach that examines the narratives about gene editing of animals that are being developed within livestock breeding companies and agricultural science, using the

1. Concerns about what GM crops and foods are, how they interfere with people's well-being, and how they transform social relations raise matters that transcend risk–benefit considerations to include questions about political economy, naturalness, hubris, and telos (Macnaghten, 2004; Macnaghten and Carro-Ripalda, 2015). At the same time, there has been an ongoing and as yet unresolved debate in the scientific community on the presence of actual risks to biodiversity and human health arising from wide releases of GM crops, especially on whether these have been properly assessed.

2. It is beyond the scope of this article to address whether gene editing is likely to generate new risk dynamics of a kind not recognized in current regulation. Heinemann et al. (2021) have argued convincingly that the biochemical imaginaries that underpin extant regulatory practices and cultures rely on a narrow conception of risk—as actual or potential biological harm—that downplay the potential scalable outcomes of their use.

idea of sociotechnical imaginaries as a lens for this analysis. In Section 3, we set out our methodology, and in Section 4, we describe our findings, articulating three interrelated yet relatively distinct imaginaries about the future of genome editing in livestock that appear to be circulating within breeding companies and animal science. In Section 5, using the framework of responsible innovation, we conclude by exploring the implications of these imaginaries for the governance of gene editing in livestock and for new directions of research.

2. Gene editing in livestock and the sociotechnical imaginary

It remains unclear how livestock breeding companies and agricultural scientists envision the future of gene editing in animal breeding. How do scientists and breeding company representatives imagine the future of gene editing in livestock?[3] Can their views and visions be analyzed in the form of coherent and relatively discrete imaginaries? If so, what are the assumptions, values, and commitments that underlie these imaginaries? What makes these imaginaries desirable or plausible? Which gene editing applications are of interest in these imaginaries, and why? And how does this compare and contrast with the debate on gene editing in plants?

These questions raise a conceptual as well as a methodological challenge. Conceptually, we need analytical categories that can help illuminate how the future of gene editing is imagined in livestock breeding and research. Since gene editing in livestock is still at an early stage of development—as is clear from the diverse range of potential gene editing applications currently being researched (Ruan et al., 2017)—we need to attend to the research commitments and purposes of the technology and to how they are being configured in practice. Since the applications of the technology in livestock currently exist only in terms of imaginings, expectations, and visions (Borup et al., 2006), we can follow these immaterial qualities, which activate and legitimate the activities of companies, scientists, and policymakers, and which are used to mobilize resources, set research agendas, and develop the technology (Konrad et al., 2017). To operationalize research, we draw on and elaborate the concept of the sociotechnical imaginary,[4] defined by Jasanoff (2015) as "collectively held, institutionally stabilised, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology" (p. 3).

The sociotechnical imaginary concept was first developed by Jasanoff and Kim (2009) to compare nation-states' approaches to the development and regulation of civil nuclear development programs in the United States and South Korea. The focus on nation-states and nation-specific imaginaries was later extended to "expanding scales of governance" ranging from "communities to nation states to the planet" (Jasanoff, 2015, p. 15). Jasanoff (2015) further developed three conditions for a sociotechnical imaginary: (1) they are collectively held by groups of respondents, (2) different imaginaries can coexist or support each other, and (3) they are normative and material simultaneously. While endorsing these conditions, we add two elaborations that accommodate the in-the-making attributes of an emerging technology whose imaginaries are not (yet fully) institutionally stabilised and that make the concept more useful for understanding the kinds of micro-scalar science and technology developments we are tracing.

While the concept of the sociotechnical imaginary has thus far been used in policy and politics with a focus on how imaginaries shape technological development, this concept has rarely been expressed the other way around: in terms of how imaginaries can change through the interaction with a technology and its applications. In this rebalancing, the focus of the sociotechnical imaginary shifts from an analysis of sociopolitical factors shaping the reception of emerging technologies to a broader focus on material practices (Verran, 1998; Barad, 2003, 2007). This "performative" approach closely resembles Verran's (1998) argument that imaginaries are located in the practices that constitute them, that are enacted and that enact in the "everyday messing around with mucky, obdurate stuff, . . . [as well as] in conversations and texts" (p. 252). Our focus on practices and what these do materially and discursively leads to a focus on the microlevel practices performed in the present and to practices anticipated in the future. In this way, we recognize that imaginaries in gene editing not only exert tangible effects over how material livestock systems work but that material breeding practices in turn are shaping futures envisioned for the technology. Our second elaboration lies in attending to the situated and "more-than-human" dimensions in anticipatory practices (Groves, 2017). Specifically, if we are to understand how and why certain futures become a matter of concern, and others not, we need to attend not only to the (social) expectations of the technology but also to how the technology constrains action and forms of life (Brown and Michael, 2003; Borup et al., 2006; Groves, 2017), as well as to the potentially transformative implications of

3. For the purpose of this article, we are restricting discussion of gene editing to terrestrial and not aquatic livestock.

4. In this section, we define what a sociotechnical imaginary is and how we have used it to analyze gene editing in livestock. However, we have not elaborated how the sociotechnical imaginary concept differs from other analytical concepts, such as discourse or narrative. For us, although all three concepts belong to a mode of analysis pertaining to the level of culture rather than that of the individual (i.e., that they all pertain to entities that are collectively held across groups and that are drawn upon by actors in everyday practice and talk), key differences include the following: (a) a discourse or narrative is about analyzing discursive practices (talk or text) as an entity that could very well exist separately from the biophysical world, whereas in an imaginary, both discursive *and* material practices are analyzed (in which the link between both is central; see also Janasoff 2015); (2) an imaginary provides space for an active role for the biophysical (nonhuman) world, whereas this is not explicitly the case for a discourse or narrative.

Sociotechnical imaginary
"collectively held, situated and imagined forms of life and order reflected in current and prospective practices performed through, and supportive of, modes of scientific and technological innovation".

Collectively held
An imaginary is identified only when its constituent elements come forward in and across a spectrum of interviews conducted.

Situated
The situatedness of an imaginary requires of the analyst to attend to the spatial, temporal and cultural dimensions of its constituent practices.

Forms of life and order
Forms of life and order refers to the co-production of social (human) and biophysical (nonhuman) entities, and to their potentially transformative implications for reshaping social and political relations.

Figure 1. Glossary box: Our definition of "sociotechnical imaginary." DOI: https://doi.org/10.1525/elementa.2020.00073.f1

the technologies for reshaping social and political relations (Winner, 1989).

In this article, we attend to materiality by investigating the interplay between social and biophysical characteristics of gene editing technologies and how these raise questions about governance, applications, and public acceptance. We look at which technologies are being invested in, why and where, and to the underlying assumptions and values attached to how the technology works. We attend to spatial and temporal situatedness by paying attention to (European) public concerns about gene editing technology, as well as to broader concerns about governing the technology for livestock. For these purposes, we redefine sociotechnical imaginaries in **Figure 1**.

3. Methodology

For the research, we employed a qualitative methodology, with the first author conducting 26 semi-structured interviews following standard qualitative research norms and procedures (Silverman, 2009). Interviews were undertaken with 20 livestock breeding company representatives of the Breed4Food Consortium,[5] and 6 academic agricultural scientists (animal scientists, plant scientists, and microbiologists) currently working with gene editing at a Dutch university. Each academic was chosen for their expertise and for the level of their engagement in technical, commercial, policy, and societal debates on gene editing, while all breeding company representatives held a strategic role in decisions about gene editing in their company, either as a scientific advisor or as a decision-maker. The four breeding companies involved in the consortium serve a substantial part of the global market in livestock breeding, and for this reason, the dominant imaginaries circulating in these companies are important for the future direction of gene editing in livestock (and vice versa).

The open-ended questions in the interviews revolved around the following: What is gene editing? What are the differences/commonalities with classical breeding? How do respondents see the future of gene editing in livestock? What role do respondents see the technology playing in their breeding programs or for the university? What are their concerns and hopes for gene editing in livestock? What are plausible future scenarios? Are these desirable? What are the downsides, limits, and uncertainties surrounding the technology? What is a worst-case scenario? What is cutting-edge research? What position does the Netherlands/Europe play in research and development? What would a future look like in which edited livestock is embedded in (Dutch/European) society? What does responsible research and innovation look like? Are there alternatives? What is the informant's view on governance? How do they view the current policy debate in the Netherlands, in Europe, internationally? For the purposes of the research, the future referred to a 10- to 20-year period from 2019, a time span chosen in line with what livestock breeding companies use in the preparation of future breeding lines. With a few exceptions, all interviews were audiotaped, transcribed, and coded. Both authors regularly reflected on the codes, and together they identified important themes in the transcripts, which led to the imaginaries identified below. Each of the imaginaries were held by both scientists and breeding company representatives. Often a response would fit into more than one imaginary, so the imaginaries are not used to categorize respondents but to categorize their narratives.

4. Research findings: Three sociotechnical imaginaries

From a coding analysis of the interview data, we distilled three sociotechnical imaginaries, each of which appears to be circulating within breeding companies and agricultural

5. Breed4Food is a consortium established by Wageningen University & Research Center and four international animal breeding companies: CRV (cattle), Hendrix Genetics (turkeys, layers, pigs, aquaculture, and traditional poultry), Topigs Norsvin (pigs), and Cobb Europe (broilers). Breed4Food has the ambition to be the world-leading center for research and innovation in livestock genetics (Breed4Food, 2021).

Table 1. Underlying assumptions of sociotechnical imaginaries. DOI: https://doi.org/10.1525/elementa.2020.00073.t1

Assumptions	Cautiously Exploring	Move Fast	Move Out
Regulatory landscape	Unclear what laws and regulations will look like in the future	Laws and regulations on gene editing will be permissive and light-handed.	Laws and regulations on gene editing will remain strict in the Netherlands and Europe.
Social assumptions	Unclear how citizens or the value chain will respond to edited livestock	Citizens and value chain actors will accept gene editing of livestock once they are properly informed.	Citizens and the value chain will reject gene-edited livestock in the Netherlands and Europe.
Technological trajectory	Unclear whether or not gene editing of livestock is technologically possible or economically feasible leading the technology to develop slowly	Gene editing of livestock is technologically possible, economically feasible, and will develop quickly.	Gene editing of livestock is technologically possible, economically feasible, and will develop quickly.
Biological assumptions	Unclear whether and how livestock can be reduced simply to their genetic code as they are part of poorly understood complex biophysical systems	Livestock can in principle be reduced to their genetic code, uncertainties can be resolved through research, and interventions using gene editing can be assumed to function as planned.	Livestock can in principle be reduced to their genetic code, uncertainties can be resolved through research, and interventions using gene editing can be assumed to function as planned.
Situated in place and time	Unclear where gene editing will be practiced and to what extent, and in which countries the technology and its products will be available	Gene editing of livestock will be practiced worldwide, and gene edited products will become widely available.	Gene editing of livestock will be practiced outside of the Netherlands and Europe with research and commercialization pursued elsewhere.

science communities in the Netherlands and which narrate the future of genome editing in livestock in specific ways. We name these *Cautiously Exploring*, *Move Fast*, and *Move Out*. Underlying these three imaginaries are five assumptions that we present in **Table 1**. In the following subsections, we describe these imaginaries in turn and illustrate how our elaboration of the sociotechnical imaginary concept enables us to focus inquiry on the kinds of futures that are being imagined, on the material and discursive practices through which these are enacted, and on how each is situated in time and place. After discussing each imaginary, we reflect on how each could lead to plausible industry, researcher, government, or consumer/citizen effects. Interestingly, in the articulation of these imaginaries, there was no clear difference between breeding company representatives and academic agricultural scientists.

4.1. Cautiously exploring

Cautiously Exploring was a dominant imaginary for our respondents and one that was routinely and collectively held. The imaginary is rooted in uncertainty, indecision, ambivalence, and hesitation, with gene editing of livestock neither embraced nor rejected. The uncertainties surrounding the technology are diverse, ranging from uncertainty and ambivalence about the technology, its economic feasibility, what the regulatory landscape will look like, and whether or not the public and the value chain will accept it—all of which are seen as in need of cautious exploration before commitments are made (see **Table 1**). Alice, a breeding company representative, shows clearly her reservations about the use of gene editing techniques in their breeding program any time soon:

> *I just think it's still a very unknown area and . . . I think most breeding companies will agree that finding those targets [to edit] is our first challenge. And that's a really difficult thing to do . . . It's a really expensive technology just to you know throw a bunch of stuff at it and see what works . . . I don't think . . . the development of this is going to be very fast. I think there will be a couple of quick wins out there . . . I just think it's going to be a bit of a long road and we have to be patient with it. I don't think we can give up on it, because it's a very powerful technology.*

From this quote, it is clear that knowing what to edit with gene editing is one of the questions that is difficult to answer, in particular because it is still unclear which genes are responsible for which traits and, as the respondent has discussed earlier, how they affect or interact with other genes. It remains unclear in this imaginary what the purpose of gene editing in livestock is or will be. Due to these biological uncertainties, the need to use the technology at all in breeding programs become a question that needs to be addressed. For David, another breeding company representative, it is debatable whether there will be a future for gene editing technology in livestock at all:

> *We're not terribly in favor of it, because we think that there are other alternatives with which you can realize what you want. At the same time there is always competition. So, if it starts to be an accepted technology then we have to seriously consider*

whether we want to follow the trend or not . . . Normal quantitative selection is incremental, it's bit by bit by bit. And it [gene editing] can be a sudden change. It's not a gradual more fuel-efficient car but it's a new model . . . : And so suddenly the cattle without horns yeah, it's a different different animal. And then a pig which cannot get sick because of the PRRS that they edit, it's a different product. It's not that it's gradually less sensitive for the disease. And then in 20 years it's kind of insensitive. No. From from one year to the other that there could be animals on the market which are resistant against an important disease. Or double muscling in animals, it's a simple gene somewhere.

Both Alice and David see an uncertain future for gene editing in livestock breeding programs because it is not clear what to edit, because alternatives are preferred if available, and because it is not clear whether the technology will be accepted in society. However, the potential for the technology to deliver so-called game-changing applications makes it worth investigating—such as "an animal resistant to an important disease"—not least to lose competitive advantage. The deployment of the *Cautiously Exploring* imaginary has generated material effects. First, driven by the recognition of multiple uncertainties and potential sensitivities from consumers and the value chain, several breeding companies have organized informal discussions to explore what diverse stakeholders in the value chain think about the technology as a precondition for developing the technology. This point is made clear by Chris, a breeding company representative:

And . . . at this moment I'm not willing to do it [gene editing] because we first want to have the right discussion with ourselves and our stakeholders on . . . Is this the right technology for us? Do we want to do it? Do we understand fully enough the consequences of the technology perspective from an animal welfare perspective and from a societal perspective? And . . . because it's such a powerful technology you have to be very certain . . . that you are not doing something where you cannot oversee the consequences.

The second material effect derived from the imaginary concerns provenance; both the companies and the university have chosen thus far to restrict research on gene editing to the study of livestock genes and their function, as reflected in the following quote from Donald, an animal scientist:

I see it [gene editing] mostly as a very powerful new tool for research. To really . . . make [molecular] changes and to really understand . . . what the effect is, and by doing that, [to] better understand biology and [the] functions of cells and animals.

The focus on researching the function of genes is valuable for companies to use in current breeding programs to help decide which genetic traits to select for. This has led to a close and ongoing collaboration between the university and the breeding companies to use the technology as a research tool, even when the use of the technology does not result in actual edited livestock in breeding programs. Alongside the use of gene editing to understand the function of livestock genes, the technology is used to edit genes of which the function is already known to learn more about the technology and its possibilities, particularly in application domains of disease resistance and animal welfare. In particular, since disease resistance is genetically very complex, alternatives to gene editing in the form of conventional breeding techniques are rarely available. For now, simple single-edit applications that could become game changers are of key interest for the breeding companies because these are potentially economically viable. However, the breeding companies and universities are cautious about this type of research, reflected in the modest levels of investment compared to other domains of research in breeding programs, such as genetic sequencing.

Many respondents expressed concerns about the biophysical effects of the technology, and the potentially negative effects gene editing could have for livestock, for the environment and for people. This concern is captured poignantly by Martin, a breeding company representative, discussing what it is that concerns him about the potential (mis)use of the technology.

As far as we know it today it [gene editing] can be a powerful tool. And you know with every powerful tool it can also be abused or misused. [Is that a serious concern?] Yeah. For me personally it is. As an organization we did not touch upon that topic in the world of discussion yet. [What kind of abuse or misuse would . . . be possible?] Well . . . if you are focused on improving certain traits or even introducing totally new traits into a species without really testing out what are the side effects. Like I said we can . . . create animals or even humans of which we do not know in the long run . . . what the impact will be. Maybe we are creating the foundation for a totally new devastating disease, because we've changed the genetics of of a human or an animal. We need to be careful, like with any new technology we need to be careful.

Interestingly, for Martin, this kind of deliberation had yet to enter into the formal discussion space of the organization, suggesting a latency of concern and a potential disruption between such sentiments and the more techno-optimistic ethos and culture of breeding companies driven by the imperative to use science to "improve" animals. It is unclear from the data what underpins these concerns and the extent to which they are driven by general sentiments toward animals or by examples of edited livestock proving to be more complex than anticipated. An

example of the latter is the case of Recombinetics' gene-edited hornless cattle which—despite company arguments to the U.S. Food and Drugs Agency [FDA] that its gene-edited cows should be "generally recognized as safe" and with no off target effects, a designation which would have allowed the animals to enter the food supply without much oversight—produced edited animals trialed in Brazil in 2019 that were subsequently found to contain an additional and unintended stretch of bacterial DNA that included a gene conferring antibiotic resistance (Regalado, 2019[6]). This apprehension with unintended and potentially far-reaching consequences also concerns Fiona, another breeding company representative, when she imagines the possible effects of a future for livestock with gene-edited immune systems:

> *If we start to gene edit aspects of the immune system . . . What are the long-term consequences of that? Viruses and bacteria are highly adaptable . . . If these bacteria change or those viruses change, will they find other ways of causing a more virulent virus or bacteria that would come in and destroy herds . . . [V]iruses may adapt completely. Or . . . it could be an opportunity for other viruses to come in through different mechanisms . . . So, we would have to go ahead and gene edit against that.*

For such reasons, many respondents expressed a preference to wait and cautiously explore before moving forward with the technology in their breeding programs. Hence, also the calls of respondents "to be patient," and that it will be "a long road." An important assumption about the materiality of the technology in the *Cautiously Exploring* imaginary is that livestock cannot be reduced simplistically to their genetic code since it is understood that livestock and the connections with their environment and "messmates" (Haraway, 2008, p. 19) are complex and situated in social and biophysical systems (see also Shah, 2018). The extracts of conversation above suggest that for many respondents, simple genetic reductionism cannot be assumed as a reliable epistemological foundation for the use of gene editing in livestock precisely because it overlooks the interaction between genetic, epigenetic, and environmental factors in producing phenotypes, the complexity of the causal interactions, and the relational interdependence of genomic components (Kitcher, 2001). Associated with the potentially negative long-term effects of gene editing in livestock are a host of technical problems such as off-target effects, low success rates of the technology, mosaicism, and genetic lag in edited livestock.[7] To provide a countermeasure against these technological downsides, and against the possibility of unforeseen long-term effects of gene editing in livestock, parallel unedited breeding lines are seen by scientists and breeding company representatives as a necessary precaution. A further argument for maintaining parallel breeding lines is that of choice, that consumers should have the right to choose between edited or unedited livestock products, alongside the distinct possibility that organic meat certification criteria may not permit the use of edited meat. However, the costs of extra breeding lines are substantial and could make edited livestock economically less feasible. For these reasons, the economic gains of gene editing applications in livestock would in all probability have to be "game-changing" to be economically feasible.

The use of the *Cautiously Exploring* imaginary by breeding company representatives and scientists is situated in a European and Dutch context. According to many respondents, the ruling of the European Court of Justice to place gene editing under the GMO Directive shows that caution is required when thinking about the development of the technology, supplemented by concerns that the technology is not ready to be applied in livestock breeding programs due to technological uncertainties and the potential unforeseen long-term effects of using it. Faced by such circumstances, the strict regulations currently in place are seen as reflecting a commonplace view that (European) society is not ready for this technology. The underlying assumption is that European regulations reflect European public views, and that if society is not ready, then the technology should not be used in breeding programs. Since this imaginary is neither clearly in favor of using gene editing in livestock nor rejecting it completely, there is little pressure from breeding companies or from animal scientists to change current Dutch or European regulations. A final issue underpinning the cautiousness of breeding company representatives and scientists lies in a shared fear of reputation damage for the breeding companies if the technology is applied too quickly, and of how this could lead to public controversy and to the public, NGOs, and value chains banning or boycotting gene-edited livestock products. For example, Brian, an animal scientist, stated that:

> *It would be a shame if . . . the livestock sector, which we [have] had already so many affairs . . . in the past. It would be a shame if the sector, because of this, would [be seen] even more in a negative light. And as a result, that the consumption of animal products would decrease even more . . . I'm thinking more in terms of image.*

Brian no doubt is attentive to the history of controversy that has engulfed the livestock sector in Europe in recent decades, ranging from food scares of salmonella in eggs to the contamination of feedstuff with dioxins, from welfare concerns with factory farming to the threat of Bovine Spongiform Encephalopathy, commonly known as mad

6. Unfortunately, this controversy surfaced only in August 2019 when the majority of interviews had been completed and thus was not a topic in the interview discussions.

7. Genetic lag in edited livestock is when many genetic traits are selected and improved simultaneously in regular breeding programs. If it takes a year to improve one trait with gene editing, the other traits of the edited animal are lagging behind compared to unedited animals in regular breeding programs.

cow disease, spreading to humans. To avoid such eventualities, time, care, and foresight are needed to explore whether the technology is technically possible, whether possible long-term negative effects have been examined in advance, and under what conditions, if any, the public, the value chain, and the regulatory landscape might accept, permit, and perhaps even embrace the technology in livestock applications. These stringent conditions mean that for those holding this imaginary, it is possible that the technology may not be used at all. To summarize, the assumptions underpinning this imaginary are that breeding companies will wait and explore what happens in other sectors and with their competitors before going ahead with the technology in their breeding programs; that in the meantime, companies and universities will collaborate on research on the basic functions of livestock genes; that companies will engage with and listen to stakeholders in the value chain; and that strict modes of governance and regulation will be respected and upheld.

4.2. Move Fast

The *Move Fast* imaginary was held by respondents who fully embrace the prospect of gene editing in livestock, and who frame the most pressing challenge as that of how to get the technology ready, deregulated, and onto the market as soon as possible. This imaginary closely resembles the dominant promissory policy imaginary on gene editing in plants as outlined earlier, as well reflecting 30 years of agroindustry and establishment plant science views on GMOs. However, in the livestock sector, this proved to be a marginal imaginary and was held by only a few respondents in roles that were far removed from downstream applications. As set out in **Table 1**, the underlying assumptions in the imaginary are that gene editing in livestock is technologically possible, economically feasible, socially acceptable, endorsed by the value chain, and governed by light-touch or product-based regulation and soft law. A starting point for this imaginary lies in the growing demand for livestock products worldwide, and in particular in countries of the Global South. For example, Thomas, a breeding company representative, sees a bright future for gene editing in livestock:

> *I think that gene editing . . . is the answer to feeding 9 billion people. It is the answer to care for our planet. It is the answer to care for our animals. And it is the answer to actually all the challenges that we are facing. And if we don't embrace this, we cannot live up to the demands from society . . . And if we cannot keep up with this technology race, we will be out of business.*

Thomas clearly argues the need to fully embrace the technology, emboldened by his belief that the technology will solve *all* of our global food security challenges. A familiar line of argument is brought forward here: that we are morally obliged to invest in emerging technologies and that this, in turn, will lead to untrammeled economic, environmental, and societal progress (Jasanoff, 2003; Macnaghten, 2020). For those expressing the imaginary, the technological feasibility and efficacy of using gene editing in livestock is accepted and remains unchallenged, and the main challenge is a technical one: how to scale up the technology in breeding lines to ensure that desirable edits can spread quickly into the breeding population. Current and prospective practices that would help operationalize the imaginary include investment in the breeding infrastructure to prepare it for gene editing, and the integration of gene editing with other new reproductive technologies, such as embryo technology, cloning technology, and semen sexing. These technologies are also currently explored in the natural sciences and have been proposed as the next step to integrate gene editing into livestock breeding programs (McFarlane et al., 2019; Menchaca et al., 2020). Thomas discusses the need to scale up the technology as follows:

> *From a kind of a political economical point of view [Europe] missed out on the information technology side. [Scaling up the gene editing technology in livestock breeding] is our chance [for] Europe to get a grip on the technology and on the use of the technology in a proprietary way. Proprietary means that you have a patent. But then we need money. So . . . I would not spend a penny on developing the technology that we are now discussing . . . , because you can buy it. It's a commodity . . . But then when you have it then other companies will tell you how to upscale it and who is going to do that? There is no upscaling technology yet.*

In this quote, Thomas imagines a role for breeding companies based in Europe to be at the forefront of applying gene editing in breeding programs through investment and the acquisition of patents. However, such investment is costly, and for these reasons, further market consolidation in the livestock breeding sector will be inevitable. George, another breeding company representative, explained that breeding companies will

> *focus on keeping . . . knowhow and IP within the companies. And so there will be an increasing trend towards big companies [through ongoing] consolidation . . . [And] companies [will] try . . . to protect their knowhow, file patents and compete based on their IP portfolio.*

Underpinning this imaginary are assumptions about the material properties of the technology, about what it is, and how it works. One of its key epistemological assumptions is a broad-based belief shaped by genetic determinism, "the view that all life processes can be causally reduced to the function of genes" (Shah, 2018, p. 2). For this imaginary, livestock can in principle be reduced to their genotype, and through the application of gene editing their DNA can be edited to "improve" welfare and product quality, "increase" disease resistance and yields, and "lower" greenhouse gas emissions, with genotype changes leading directly to improvements in phenotype.

Utilizing this imaginary, and in the belief that further research will iron out uncertainties and clarify causal relationships, it becomes desirable to use gene editing in livestock across a wide range of applications since these are presumed as likely to be beneficial for livestock, for humans and the planet at large. This is clearly different from the *Cautiously Exploring* imaginary, in which concerns are raised about the material properties of the technology itself, as well as the desirability of future applications. Alongside its economic, solutionist, and genetic determinist tropes, this imaginary also configures a particular role for the public. The *Move Fast* imaginary is situated in a European context, in which the concerns of citizens are seen as important. Public acceptability will be assured, the argument goes, once the public is provided with clear and robust science-based information about the benefits of the technology and its application in livestock.[8] For these reasons, as the microbiologist Joe states below, the need for scientists to inform the public is an important responsibility:

> *We should explain to the public what we are doing and that we believe in the possibilities of CRISPR to contribute to a better society. And that's our responsibility. So, since we believe in that and since we are kind of convinced that CRISPR can make a difference there, we work very hard . . . to make it even more accurate if needed and [even more] faster and more efficient.*

For those using this imaginary, there is the oft-cited claim that the concerns of European citizens about GM technologies, and also Europe's (over)stringent animal welfare standards and expectations, are the luxurious concerns of the North and should not be used to impede sorely needed livestock biotechnology development in the Global South—where breeders do not have the luxury of relying on alternative and typically more expensive nonediting technologies for meeting consumer animal protein needs (although of course, in Global South countries, the "alternative" for traditional farmers is in fact very low cost; most animals do it for free). As Hank, a breeding company representative, claims, not embracing the technology in Europe means that Europeans are denying poor countries the opportunities of gene editing:

> *Well . . . they need that protein to decrease mortality but also to decrease the level of poverty that they are experiencing today. So, we can from a very luxurious position, we can deny other continents . . . their consumption [of] animal protein.*

Underlying this line of argument is the assumption that there is no plausible alternative to the use of gene editing technology in livestock and that it is an ethical imperative to permit the widespread use of the technology to help solve some of the grand societal challenges of our time. To summarize, the assumptions underpinning the imaginary are that breeding companies will refocus their efforts on scaling up the technology, that governments and consumers/citizens will be convinced of the economic and societal usefulness of the technology, that regulations will be softened or abandoned to enable edited livestock and products to enter swiftly onto the marketplace, and that this may lead potentially to the very disappearance of nonedited livestock products from the market in the medium term.

4.3. Move Out

The *Move Out* imaginary was collectively held by many respondents, sketching an inevitable future in which gene editing will arrive anyhow, regardless of the decision-making and lobbying powers of the consortium of breeding companies and universities. The main storyline is that while Europe needs to stay involved with the technology—in research and development and in livestock applications, not least to make sure that their high standards for animal welfare and health are taken into account—the reality is that the technology and its livestock applications will be developed elsewhere for purposes and under conditions that Europeans may not approve of. Underlying this imaginary is the assumption that gene editing in livestock is economically viable, technologically possible (see **Table 1**), and superior to regular breeding techniques. This imaginary is concerned mainly with questions of dependency and control and about the distribution of economic benefits. In this imaginary, Europe locks herself out of gene editing research and development due to a lack of societal acceptance and widespread distrust in the value chain, ensuring that the strict regulatory regime for the technology is maintained. This is clearly stated by Joe, a microbiologist:

> *Well, my worst nightmare is that the European Court of Justice does not change its opinion. So that would be really bad and not for me personally but for biotechnology in Europe . . . It's really a big risk if we don't change this whole view of regulation . . . So, if you don't take action then we will be fully dependent on everything that happens in the United States and in Japan . . . Now that would be really a shame if that would happen.*

Inevitably, those who hold the *Move Out* imaginary envision that scientists and breeding companies will leave Europe for countries where rules and regulations are less stringent. Evidence to support this viewpoint include current and prospective levels of investment in livestock gene editing by China and the United States compared to Europe (for a recent example of one such non-European collaboration, see Genus, 2019). Several respondents mentioned that technology development is being actively

8. This is in line with research on UK institutional responses to public concerns on fracking, with similar assumptions of public deficits that would be remedied through the one-way communication of authoritative knowledge by expert scientists to skeptical publics (see Williams and Macnaghten, 2019).

embraced and promoted in these countries, whereas in Europe the technology is under strict regulations, which limits innovation. Another effect for respondents holding this imaginary is that breeding companies will increasingly undertake their research on gene editing applications in livestock abroad and mainly in the United States. Many breeding companies already invest in large breeding stations outside Europe, raising the prospects of moving their headquarters outside Europe altogether. Adopting this imaginary would lead not only breeding companies to leave Europe but possibly animal scientists too, including those who depend on animal experimentation for their work. If animal experimentation regulations become even stricter, or when animal experimentation is not allowed at all, animal scientists will move abroad. This emerged as a big concern for Sarah, an animal scientist, when asked what would happen if animal experimentation is not permitted in the Netherlands at all:

> *Oh sure, it will go to China and to the U.S. To every country where there is not such a strict regulation. Then you achieve exactly the opposite of what you want. You remove animal experimentation from a very civilized country like the Netherlands where we know we would do it [in the most ethically sound way for animals] . . . I'm not saying that in all those countries I mentioned is necessarily done wrong, but I certainly know that the rules are much much less strict.*

Working through this imaginary, respondents envision that breeding companies and scientists would leave Europe and the Netherlands, leaving Europe behind, both as a research leader and as a major contributor to the solving of grand societal challenges. In addition, the materiality of the technology raises a further challenge for breeding companies. If Europe were not to permit, or were to enforce prohibitive regulation on edited livestock and livestock products, this could create enforcement problems. Respondents pointed to the difficulty, even impossibility, of detecting edited livestock or livestock products given that genetic marks are challenging to find when same-species cisgenesis is used (even though companies may be encouraged to add markers to gene-edited animals for their own intellectual property (IP) purposes or in response to regulatory requirements). For those holding the *Move Out* imaginary, this would mean that if livestock breeding companies remain in Europe producing only unedited animals, then how would they know whether imported animals or animal products (or semen or embryos) are edited or not? The main concern would be how to maintain a level playing field between edited and unedited livestock and livestock products, as described below by Sam, a breeding company representative:

> *So, a level playing field is easily said. Oh, we [can] stop products that are gene edited . . . People [say] that you can stop it, but if they don't tell you [livestock is edited] there's no way you can find [it] . . . . You can determine if it just got that genetic characteristic. But then, . . . if you really make a legal case out of it . . . Well can you prove that this could not occur through natural mutation? You could only say that it's highly unlikely . . . Yeah. But it's not the same as it cannot be done. So, it's not proven beyond doubt that this needs to be the result of gene editing. So that's why I'm not optimistic on that level playing field.*

The assumption in the *Move Out* imaginary is that it will be impossible for Europe, with conventionally bred livestock, to compete against countries with edited livestock because edited livestock will be superior in quality and price compared to regularly bred livestock. The *Move Out* imaginary is situated in a European context, in which citizens are concerned about animal health, animal welfare (Eurobarometer, 2016), and animal experimentation (Röcklinsberg et al., 2017), reflected in strict EU policies on GM and gene editing, and in legislation on animal experimentation. In this imaginary, the physical situatedness of breeding companies and scientists in Europe is a key factor in shaping concerns raised by breeding company representatives and scientists because they anticipate the technology to be developed by countries and scientists with less stringent ethical norms and values. To summarize, the development and commercialization of the technology outside Europe raises a set of political and societal problems and uncertainties reflected in this imaginary: that livestock will be edited under conditions that are socially and ethically unacceptable for Dutch and European society, that expertise about breeding and gene editing will leave the Netherlands and the EU, and that it will be impossible to distinguish between an edited or an unedited animal or livestock product, leading to unfair competition and a lack of consumer choice.

5. Discussion and conclusions

In our analysis, we explored how livestock breeding companies and agricultural scientists envision the future of gene editing in livestock breeding in a Dutch-led international consortium that has the ambition to be "the world-leading center for research and innovation in livestock genetics" (Breed4Food, 2021). We identified three interlocking sociotechnical imaginaries, all collectively held by key respondents and with differential effects in how they structure economic, social, political, regulatory, and technical relations. One of these we named *Cautiously Exploring*, which we found to be dominant in respondents' conversation. This imaginary was rooted in uncertainty, indecision, ambivalence, and hesitation, with gene editing of livestock neither being embraced nor rejected. Another was *Move Fast*, a marginal imaginary for our respondents, but one that fully embraced the technology in livestock and that framed the challenge as to how to get the technology ready, deregulated, and onto the market as soon as possible. The third was *Move Out*, another prominent imaginary that sketched an inevitable future for gene editing in livestock, but one that would take place largely

outside the Netherlands and Europe. Although each of the imaginaries has a degree of coherence, stability, and separation, they nevertheless can be deployed at the same time and by the same respondent, even in circumstances when they clash, interfere, and obstruct (Mol, 2002). At the same time, each imaginary is situated in an ongoing policy and economic debate shaped by a 2018 European Court of Justice ruling that gene-edited products are subject to the same stringent regulations as other GMOs. In this final section, we reflect on what these findings mean for governance and for research.

5.1. Implications for governance

This particular study took place within a larger research project—the *Just Editing* project—aimed at understanding the conditions, if any, under which gene editing in livestock could be aligned with societal values. To operationalize this research question, the AIRR responsible innovation framework was deployed, aimed at anticipating (A) the future effects of gene editing in livestock, through inclusive (I) deliberation with a broad range of stakeholders, that fosters reflexivity (R) about background assumptions, and that responds (R) to concerns, interests, and values of diverse stakeholders. On the one hand, it is clear that our analysis of sociotechnical imaginaries most clearly contributes to the anticipation dimension of responsible innovation given that the focus of the paper is to understand what are known, contingent, likely, plausible, and possible effects and how such imaginaries help to stabilize visions and enroll resources. Yet it is also clear that each of the imaginaries frame the other dimensions, limiting or enabling the capacities for certain kinds of reflexivity and responsiveness and prioritizing only certain kinds of inclusion.[9] For instance, the *Cautiously Exploring* imaginary is quite tentative, opening up space for engagement and listening with stakeholders, for acknowledging uncertainty, and for developing more reflexive and "listening" cultures as a precondition for responses on the actual use of the technology in livestock breeding programs. *Move Fast* (and to a lesser extent *Move Out*) configures the dimensions in other ways, prioritizing inclusion solely in the form of one-way information provision, configuring stakeholders as users to be persuaded of the benefits of gene editing in livestock, and of the need for changing regulation and public opinion so that the Netherlands and Europe are not left behind. Such underlying beliefs further mitigate against reflexive cultures given the a priori belief in the technical and economic viability and superiority of the technology. They promote responses only insofar as responses endorse and advance the technology and its use in livestock breeding.

An important characteristic in the *Cautiously Exploring* imaginary lies in how uncertainty—that is, the distinction between the known and unknown (technological, societal, and regulatory)—is configured at the level of ontology and how it differs from assumptions of "genetic determinism" that are more prominent in underpinning and shaping the *Move Fast* and *Move Out* imaginaries. These differences are important because they configure the kinds of research that are seen as necessary to advance the technology. For the *Move Fast* and *Move Out* imaginaries, the epistemological questions that are presumed to be answerable by natural science and economics and that lie at the forefront of the research endeavor include the following: Can we make the technology more precise, more accurate, and more reliable? Can we make it faster, cheaper, and more efficient? Can we undertake research to iron out current uncertainties concerning the causal links between livestock genotype and phenotype? To answer such questions necessitates the funding of research in the pursuit of quantitative answers. However, such approaches are not constituted to be able to answer the ontological, ethical, and sociopolitical questions that emerge from the *Cautiously Exploring* imaginary and that have been posed by animal scientists and livestock breeders in our research: What might it mean to interfere in livestock immune systems? How might it potentially change viruses and bacteria? What could be the long-term (environmental, health, animal welfare) effects of these interferences in livestock DNA? Will society accept to live with and consume edited livestock products? These questions cannot be answered by natural science and quantitative methodologies alone but require transdisciplinary research involving wider and continuous engagement of diverse stakeholders. This is necessary if we are to prevent an overrepresentation of a particular epistemological frame and a subsequent narrow constitution of the public issues surrounding gene editing in livestock policymaking—a configuration that has historically been the case in the dominant promissory policy frame for plants (Macnaghten and Habets, 2020). In particular, if we recognize that knowledge and imaginaries are necessarily partial, this requires that stakeholders—including agricultural scientists—exercise humility, avoid easy judgment, and learn to hesitate.

This has important implications for the governance of gene editing in livestock. We have shown that the gene editing debate is broader than a fact-finding mission in which the outstanding questions, concerns, consequences, and uncertainties of gene editing in livestock can be adequately resolved through the conduct of more research. Instead, if perfect knowledge is inevitably asymptotic, uncertainty, ignorance, and indeterminacy are always present. This means that a simple reliance on the promissory policy imaginary in plants, or in our case the imaginary *Move Fast*, is too solutionist and reductionist in its assumptions to fruitfully think through the far-reaching complexities of governing gene editing in livestock. As Jasanoff (2007) proposes, "[w]e need disciplined methods to accommodate the partiality of scientific knowledge and to act under irredeemable uncertainty . . . [that] compel us to reflect on the sources of ambiguity, indeterminacy and complexity. Humility instructs us to think harder about how to reframe problems so that their ethical dimensions are brought to light, which new facts to seek and when to resist asking science for clarification" (p. 33). This call for

9. We are grateful to Rob Smith for this insight, who gracefully reviewed this paper for *Elementa*.

humility is a call for breeding companies and policymakers to reengage with the moral foundations for action in the face of inevitable scientific uncertainty. This is clear from the dominant *Cautiously Exploring* imaginary, in which respondents are cautious about the purpose and necessity of using the technology, in which the uncertainties and unknowns that accompany gene editing in livestock are at the forefront of thinking about the future of gene editing in livestock, and which creates an unusual opening for greater reflexivity, given the larger trends of the gene editing arena.

Alongside an appeal for humility, we need to take time to bring different imaginaries together and to open them up to each other by investigating their underlying assumptions. This requires us to include other imaginaries beyond the fairly narrow terrain of breeding companies and agricultural scientists to include the views and perspectives of a broad range of users with an interest in the future of livestock. For this, we need open conversations about the implied futures of emerging technologies associated with different sociotechnical imaginaries, and that includes the choice to say no (Montenegro de Wit, 2020). Explicating the multiple imaginaries of gene editing livestock enables us to work through the challenges and concerns about the technology, to question underlying norms and values, and to open up political space for counter-norms (see Hinchliffe et al., 2017, for a related argument), which are likely to be very different from merely technological, economic, and scientific matters of concern. This also requires the analyst to embrace and take seriously multiple imaginaries and knowledges in order to keep them open to diverse and perhaps valuable alternative approaches to gene editing of livestock and to emphasize the need to bring these together in the political arena.

Developing accounts of a plurality of sociotechnical imaginaries can be an important tool because these provide alternatives to the currently dominant envisioned role of plant scientists and economists in policymaking and, importantly, the wider *political* arena of gene editing technology. Instead, as we found, the practitioners of gene editing technology in livestock have very different imaginaries of the future, in which concerns and questions arise that cannot be answered by natural science or economics alone. These imaginaries are currently underrepresented in the early constitution of the political and policy arena that surrounds the gene editing of livestock, adding value and perspective to concerns and questions about the technology and how it should be governed. For these reasons, imaginaries of livestock gene editing deserve a greater place within the political realm of gene editing, where decisions about rules and regulations are made that directly affect practitioners, breeding companies, scientists, and society at large (English et al., 1992; Enticott, 2014; Lavau, 2017). In order to take practitioners seriously in the political realm, we need to find ways to slow down and to hesitate, to remain open to other imaginaries of gene editing in livestock, and to connect with entities of diverse kinds "as matters that are not simply vital for life but key for a re-constituted politics of living" (Hinchliffe et al., 2017, p. 20).

5.2. Implications for research

It has been argued that the sociotechnical imaginary concept is insufficiently sociological (Konrad et al., 2017). While Jasanoff and Kim (2009) used the concept to explain how policies have developed in the light of different national imaginations that differentially shaped the development and regulation of nuclear power in the United States and Korea, such a conceptualization imposes a rigidity that is not necessarily warranted and that leaves other kinds of questions relatively unaddressed. How do sociotechnical imaginaries come about? How are they clustered? When are certain imaginaries getting stronger and others weaker, and for what reasons? How are imaginaries sustained and challenged? What is the role of interests, waiting games, and competition?[10]

In our research, we found three sociotechnical imaginaries at play in a particular place and at a particular time. The finding that the dominant sociotechnical imaginary of gene editing in livestock appears to be different from the promissory policy imaginary of gene editing in plants was a key finding and one that warrants scrutiny and further research. First, the global reach of the breeding companies and the university involved in this research ensures that their imaginaries will help shape the global livestock market and research and development. Follow-up research would need to explore how imaginaries fold into the future, including analysis on how they are shaped, contested, clustered, negotiated, and fought over. Moreover, our focus on dominant Dutch and European imaginaries means that we have excluded the imaginaries of U.S., Chinese, and other non-Western scientists and breeding companies, which could very well shape the technology development very differently. And, in addition, there is the need to examine other imaginaries of stakeholders with an interest in the future of livestock, which includes among others pastoralists, agroecological livestock farmers, and breeders who rely on indigenous and organic breeding practices. The pluriverse is wide, and part of what makes the imaginary powerful is what it occludes; at the same time it imagines some future, it forecloses upon others.[11]

Second, public and regulatory acceptance is considered very important by many respondents, but actual public concerns about the technology are not investigated to find out whether or not gene editing in livestock is desirable for society and, if so, under what conditions. This can be approached through upstream engagement methodologies as articulated in the responsible innovation literature (Stilgoe et al., 2013; Macnaghten, 2021). Similarly, we have not interviewed policymakers about how they anticipate the future of gene editing in livestock and how it should be governed. The main reason for this is that policymakers in the Netherlands in 2019–2020 did not have animal biotechnology in their portfolio. For this reason, no policymaker agreed to be interviewed about gene editing in

10. We are grateful to Harro van Lente for this point.

11. We are grateful to Maywa Montenegro de Wit for this (and many other) helpful points.

livestock, not least because there was no sensed need to configure a policy imaginary at this stage.

Third, the purpose of livestock gene editing applications represented as that of producing "better" animals, with "improved" animal welfare and "increased" disease resistance, that contribute a vital role to play in "solving" the global food challenge, have been framed as inherently positive and beneficial for livestock by agricultural scientists and breeding companies across all three imaginaries. However, this positive framing is contested by nongovernmental organizations such as Friends of the Earth and Greenpeace, who question the desirability and plausibility of gene editing and their contribution in developing just and equitable responses to today's grand societal challenges. As a recent report states: "[m]any emerging applications of these genetic engineering technologies could result in further entrenching the intensive animal farming model, rather than generating true solutions to the serious animal welfare, public health and environmental problems it creates" (Friends of the Earth, 2019, p. 27). This is another imaginary that requires further research, including its prevalence and uptake in wider stakeholder and public groups.

Fourth, while we have made the theoretical claim that just as sociotechnical imaginaries shape the development of gene editing in livestock so too can livestock editing technologies and applications feed back into each of the imaginaries, we have provided little empirical evidence to support this claim. Arguably, it is mostly too soon in the animal gene editing domain to observe the "reverse" influence from applications, although some evidence of such influence can be seen in upstream investments in the R&D pipeline. One example where this reverse influence is demonstrated lies in the current and prospective investments in livestock gene editing by China and the United States compared to Europe, where material investments in gene editing technologies (if not yet livestock products/applications) are feeding back to shape the *Move Out* imaginary. Future research is needed to observe the "reverse" influence, such as whether early experiments and applications in animal editing are feeding back to inform future visions. One could imagine, for example, that the failed Recombinetics' initiative on gene-edited hornless cattle trialed in Brazil may (yet) have a formative influence in stabilizing the *Cautiously Exploring* imaginary.

Fifth, while our research points to the need to find ways to slow down to work through the challenges and concerns about livestock gene editing, we have not identified the challenges of putting this into practice, whether in breeding companies or in universities. In organizational terms, practices of "slowing down" can be viewed as part of a governance process aimed at the organizational institutionalization of responsible innovation (Owen et al., 2021). Drawing on insights from organizational theory, we can delineate institutional dynamics on how such change takes place. More specifically, research would need to attend to the forces and counterforces of slowing down, the institutional logics that influence and configure behaviors and practices, the analysis of norms and incumbent logics, of rewards and incentive regimes, of external expectations and of modes and models of institutional entrepreneurship.

Finally, from the interviews, it remains unclear why the dominant imaginary in gene editing of livestock is so different from the dominant promissory policy imaginary of gene editing in plants. One explanation is that plants and animals are very different, that animals fulfill a symbolic alongside a utilitarian role in society (DeMello, 2012), that animal health and welfare are highly valued, that there exists a long historical arc of European concerns about animal food safety, and that these factors in unison create a high ethical sensitivity to animals. For example, discarding millions of livestock animals is ethically controversial (e.g., in livestock disease outbreaks), whereas discarding millions of diseased plants is not (Kallhoff et al., 2018). A second explanation is that the livestock sector is aware of its bad reputation (e.g., as evidenced in controversies about antibiotics use, and major disease outbreaks), that partially in response it has developed a conservative culture (particularly marked in the Netherlands and arguably in Europe more broadly), that practices have developed where prototypically it is the environment that adapts to the animal (rather than with plants where it tends to be vice versa), and where the industry is particularly careful to avoid or fuel future controversy. In the Netherlands, in particular, this corresponds to a so-called polder model where policymakers, industry, and NGOs routinely deliberate and negotiate in a national style of governance that aims to develop consensual responses (Van Dijck and Van Saarloos (2017). Third, while the plant sector has a history of successfully developing GM crops for commercialization, including a few that are currently grown in Europe, the livestock sector does not have a history of bringing GM livestock to market. Therefore, the questions that gene editing technology poses a range of new questions to the livestock sector remain less developed than in the plant sector (although it is not clear at all the extent to which lessons have been learned within the plant sector, see Macnaghten and Habets, 2020). Finally, the caution about gene editing in livestock could be a response to the major controversies that occurred when GM crops arrived in Europe, fearing a similar response and polemic. These differences all require further research.

Data accessibility statement

Interview audio and transcripts are archived and stored under password protection on the W-Drive of Wageningen University & Research.

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