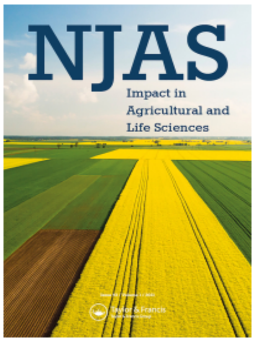

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Digital twins in agri-food : Societal and ethical themes and questions for further research

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ABSTRACT
Digital Twins are computational representations of both living and non-living entities and processes, which can be used to analyse and simulate interventions in these entities and processes. When developing Digital Twins, it is important to anticipate on the societal, ethical and safety impacts they may have. Since in the agri-food domain Digital Twins are still in its infancy, it is possible to include societal values from the beginning onwards, during the research and development process. In this paper, we present four themes (i.e. resources, representations, actions and implementations) to organise the anticipation of and reflection on potential impacts of Digital Twins in the agri-food domain. Using insights from the smart farming literature, we assess for each theme which issues and questions require further research and attention, in order to develop an agenda for responsible research and innovation on Digital Twins.

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KEYWORDS Responsible research and innovation (RRI); agri-food; digital twin; societal and ethical challenges

1. Introduction

A Digital Twin integrates various technological developments, such as Internet of Things, Artificial Intelligence, machine learning and software analytics, to develop a digital representation of a real-world living or non-living physical entity (Boschert and Rosen, 2016; Bruynseels, Santoni, van den Hoven, J. 2018; Jones, Snider, Nassehi, Yon, Hicks 2020; Saddik, 2018). Although there is no generally accepted definition of Digital Twins, descriptions generally bring forward two characteristics: first, their continuous connection between the physical (real-life) object and the corresponding virtual counterpart (the twin) due to the availability of real-time data about the physical object, and second, their capacity to not just

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represent the current state of the physical original but also simulate and predict future states based on past data on how different developments in the real-world interact (Verdouw and Kruize, 2017; Wright and Davidson, 2020).

Digital Twins have been developed for a variety of contexts and purposes. In various industrial sectors, twins are being used to provide information on how to optimize the operation and maintenance of objects (such as vehicles or aircrafts), systems and/or manufacturing processes (Glaessgen and Stargel, 2012; Tuegel, Ingraffea, Eason, Spottswood 2011). In healthcare, Digital Twins link various types of information of a particular patient and therewith allow to combine them to make a treatment plan, which is "personalized" or tailored' to that patient (Gambhir, Ge, Vermesh, Spitler 2018). In the agri-food domain, however, the development of Digital Twins is still in its infancy (Alves et al. 2019; Jones, Snider, Nassehi, Yon, Hicks 2020; Verdouw and Kruize, 2017). Here, Digital Twins serve to represent real-world entities and processes, which is supposed to enhance knowledge and facilitate decision-making about farming and the management of a supply chain, or the use of natural resources (Verboven, Defraeye, Datta, Nicolai 2020). An illustration of an application is a Digital Twin of mango fruit, whose development is followed through the transcontinental supply chain in order to offer better understanding where and why the fruit loses quality (Defraeye et al. 2019).

The aim of Digital Twins to provide knowledge that is to inform decision-making of farmers or other actors in the agri-food sector resembles the purpose of other so-called "smart farming technologies". Like these other digital farming technologies, such as farm management systems, drones, or robots and AI systems, Digital Twins are expected to influence human action and interaction in the agri-food sector, and they will likely also have wider societal or ethical impacts. In this paper, we are interested to explore the societal and ethical questions that Digital Twins raise, and we want to know whether Digital Twins raise any particular questions that are new or different from the questions already explored in the literature about digital or "smart" farming. Based on these questions, we will set an agenda for social science and ethics research into Digital Twins intended for the agri-food sector. More specifically, we are interested in approaching Digital Twins from a Responsible Research and Innovation (RRI) approach, which generally seeks involvement early on in the research and innovation process, which allows to take societal and ethical aspects into account during development. The research agenda that we aim for is therefore an agenda for RRI research.

In the following, we will first explain the basics of RRI and then we will present our ordering of the societal and ethical issues around Digital Twins in agri-food under four themes: (1) *resources*, which labels issues around collecting, selecting, combining and using data; (2) *representations*, which refers to concerns around how knowledge is created in and with Digital Twins; (3) *actions*, for issues that have to do with the use of this knowledge to inform decision-making; and (4) *implementations*, which is about issues related to the implications of Digital Twins in particular contexts of use. In the final section of the paper, we use these four themes to sketch key questions for future RRI research on Digital Twins in agri-food.

2. Background: Responsible Research and Innovation (RRI)

Digital Twins are expected to bring along various societal and ethical challenges. RRI offers a specific way to approach these questions and stands for research, which contains various characteristic activities. It fosters an open, multi-stakeholder collaboration between researchers and/or innovators and societal stakeholders, such as citizens, policy makers, businesses or NGOs (Owen et al. 2013; Von Schomberg 2013). These stakeholders discuss the question of how science and technology should be shaped in the best possible way to not only contribute to solving today's problems but also create a world that will be desirable and safe for future generations. This means that the focus not only is on achieving outcomes from research and innovation that are socially and economically desired as well as ethically and legally acceptable but also implies that the *process* of research and innovation should be desirable for society (Von Schomberg 2013).

RRI starts from the supposition that the "human factor" is an important element in research and innovation, as technology is taken to be an enduring world shaping force with profound impacts on human (social) lives. It is for this reason that stakeholders and sometimes even society at large should have a say in where science and technology go. A variety of approaches to RRI are available (Blok 2019). Some authors include more and some less elements, but they all contribute to a common goal, which is to broaden and enrich the perspectives of the makers of technological innovation (including scientists, technicians, businesses, and sometimes policy makers) to help them make decisions that are responsive to considerations about its societal and ethical aspects. This demands, at the very least, the four components of RRI (Macnaghten 2016): to *anticipate* (or engage in an informed imagination of) the intended and unintended consequences of technological innovations and to *include* stakeholders and members of the wider public in a *reflection* about the desirability of these effects. The purpose of these endeavours is to make research and innovation more *responsive* to societal values and wishes and realize technological innovation that is desirable and widely used in society and which contributes to enhancing human capacities to realize a life that they consider worth living.

Because the development of Digital Twins for agri-food is still in an early stage, it is possible to include societal values and wishes in the process of research and development on the technology. It is therefore the right timing for RRI research into Digital Twins. Hence, in this paper, we will identify the societal and ethical issues that Digital Twins in agri-food raise and develop a research agenda for such RRI research. First, however, we will explain our methodological approach.

3. Mapping the challenges around digital twin: Methodological approach

Our approach for identifying a RRI research agenda for Digital Twins had two components: first, we explored literature on digital farming to develop a thematic approach to map issues around Digital Twins in agri-food. Second, we discussed with our research team whether and to what extent the social and ethical challenges identified in the digital farming literature are relevant for two examples of Digital Twins for agri-food.

3.1. Developing the thematic approach

As there is no literature on societal and ethical issues of Digital Twins for agri-food, we turned to literature on the societal and ethical aspects of digital farming to develop our overarching thematic approach. Our reason for doing this is that we regard Digital Twins as a recent member of the family of digital farming technology. Just like other digital farm management systems, Digital Twins aim to support farm management decisions by means of data-based knowledge collected on multiple farms and in various situations. To organise the identification of issues and questions, we used and updated an earlier review article on ethics of smart farming of Van Der Burg et al. (2019), which distinguishes different core themes in the literature. This review covered a broad selection of scholarly and "grey" literature, published in a variety of disciplines, including social and political sciences, information technology and law. Because such a broad perspective was adopted, we think the review article offered a good starting point, which we updated (see appendix 1 for details), to distinguish the socio-ethical questions that can function as a guide for RRI research into a new digital farming technology; Digital Twins.

The review article identified three main themes in the literature on digital farming: 1) data ownership, accessibility, sharing, and control; 2) distribution of power; and 3) impact on human life and society. Due the "family resemblance" of Digital Twins with digital farming technologies, these general themes are also relevant in the context of Digital Twins. At the same time, we realise that "digital" or "smart" farming is an umbrella term, which stands for a large variety of technologies that may each raise slightly different questions. Digital Twins also have their own distinctive characteristics, which raise (partly) different issues than other digital farming technologies.

If we consider characteristics of Digital Twins, we can distinguish four aspects: Digital Twins (1) require existing and/or newly collected data, (2) process this data to offer representations of a dynamic development or process in the real world, and (3) these outputs are used to inform the choices for actions and interactions of human actors, in (4) specific (farming/growing) contexts. We therefore adapted the themes from the review to cover these aspects and arrived at the four themes of *resources, representations, actions*, and *implementations*. The first theme covers issues around the data ("resources") that Digital Twins collect and use and encompasses the questions around data ownership, accessibility, sharing and control in the digital farming literature. The second theme ("representations") covers issues around whether, how and what knowledge is created in and with Digital Twins. Such epistemic issues have so far received much less attention in the literature on societal or ethical aspects of digital farming, but the ambition of Digital Twins to accurately represent current and future states of living entities and systems means these types of issues warrant our attention. The third theme ("actions") has clear connections with digital farming literature that discusses impacts on human life, as it has to do with the question of how the output of the Digital Twin steers or informs actions and decisions. Finally, while deployment of Digital Twins in agri-food is still scarce, the literature on digital farming can be of help in anticipating intended and unintended societal and environmental impacts in particular context of use ("implementations"). Obviously, the four themes are intertwined: the particular selection of data to include in a Digital Twin influences the type of representation it offers of the real world, which in turn shapes the actions that can be conducted with a Digital Twin, making the Digital Twin's outcomes more beneficial for certain contexts of use than others. The organisation of our reflection into four themes therefore does not imply that each theme deals with entirely separate concerns; often a focus on one of them will immediately raise questions about the others as well.

3.2. Identifying socio-ethical questions and issues

The insights from the literature were discussed with the entire research team in relation to two examples of Digital Twin prototypes that were developed as part of a research programme at a Dutch University. This programme runs from 2019 to 2022 and includes research and development of three Digital Twins, two of which focus on agri-food and on which our attention focuses here.

The first Digital Twin project aims to represent the development of a tomato crop in a greenhouse. This twin consist of a 3D simulation model that is fed in real-time with sensor information from a real greenhouse. In this way, interactions between the tomato crop, environmental factors and crop management are represented in the Digital Twin. The Digital Twin can be used not only to keep track of the current of affairs in the greenhouse but also to make predictions about the development of the crop based on past data. This can inform decision-making of growers about the real crop, such as about the effect of the temperature in the greenhouse on the growth of the crop, or about the use of inputs such as fertilizers and their effects, or what is the right time to harvest and for what yield to prepare.

The second project develops a Digital Twin that displays the existing nitrogen cycle on an arable and/or dairy farm. The Digital Twin combines different models, real-time sensor data, weather data, and farm-level data. This Digital Twin can not only be used to show current emissions but also allows to anticipate the effects of interventions that aim to reduce nitrogen emissions. The Digital Twin allows to create different scenarios, which can be compared to optimise the nitrogen cycle of a farming system. The Digital Twin will include a dashboard for farmers via which they can receive information and advice about their actions, which aims to empower them to make more informed decisions about whether and how nitrogen emissions can be reduced.

To identify relevant socio-ethical challenges, the insights from the digital farming literature were discussed in iterative rounds in our team, exchanging ideas about whether and how the issues and questions are relevant for the examples of Digital Twins and formulating new issues and questions, until consensus was reached. After finishing our own overview, we presented the result to the wider community of Digital Twin experts and invited them to comment on our findings, after which we finalised them. Below, we discuss the questions and issues that we identified for each of the four themes.

4. Results

4.1. Resources

The resources on which Digital Twins rely are either data sets, which are already collected or they may include data sets that are specifically generated with the purpose of developing the twin. In any case, Digital Twins can typically be regarded as an effort to manage data that are "big". Big can be defined in terms of electronic size, the number of entries or the amount of individuals, events or phenomena represented by the data. While data sets may occupy a large electronic space, they are primarily called "big" because it is difficult to open them and make them available in a way that is meaningful for agri-businesses, research or policy making. Making a Digital Twin is supposed to help contribute to this meaning-making activity. It is for this reason that Digital Twins raise questions about what data sets are generated or chosen as input for the twin, which data sets are combined, and how they are made available to generate new knowledge or considerations about actions. On the level of data themselves, this already raises some topics to consider.

A first topic concerns the devices and technologies through which data is captured. In the case of digital farming technologies, these technologies may include remote or aerial sensing through satellites or drones, sensing technologies that are located on or in the ground, or sensors embedded in farming equipment. Ethical issues may arise when data capturing technologies are used on or in animals, for example, issues around animal welfare and the way they connect to data-based choices about breeding that may change the nature of animals (Bos and Munnichs, 2016; Bos, Bovenkerk, Feindt, Van Dam 2018; Holloway, Morris, Gilna, Gibbs 2011). But considering our examples of the Digital Twin of a tomato crop and the twin of the nitrogen cycle, welfare of living beings does not seem to play an important role when data are collected, except perhaps when measurements to monitor nitrogen levels are made close to cattle in barns.

A second group of issues circle around the choice of data to collect and/or (re-) use in the Digital Twin. For digital farming technologies in general, but also for our two examples of Digital Twins, these data can include (a selection of) data about:

- Inputs needed and used, such as fertilizer and nutrients of the soil or crop, humidity and water-use, animal feed, energy (light, warmth).
- Location of plant, cattle or human beings; diversity, number and movement of wild animals across a natural area; movement/behaviour of human beings.
- Health of plants, animals or human beings, their behaviour, what they eat, amount of medication/pesticides used, genomics, fertility of human beings/animals.
- Productivity of animals/plants, aspects (such as sugars) that effect taste of plants, fruits, dairy, meats.
- Production and financial records of farms on a yearly basis.
- Environmental data about pollution (such as CO2, nitrogen), changes in biodiversity, climate change and geodata from sensors, satellites and drones.
- Amount, location and output (productivity; waste) of people in a natural area, or of employees on a farm.

Collecting these data and combining them could lead to a wealth of opportunities for the development of new knowledge and action. But exactly what knowledge will be generated or which options for action will result depends largely on the choices that are made in the selection of data to collect or re-use, and the ways in which the data are combined (Dourish and Gómez Cruz, 2018; Kuch, Kearnes, Gulson 2020; Ossewaarde 2019). The first questions raised about Digital Twins are therefore pertaining to the societal effects of these choices: What goals do we want to serve with science, innovation and policy making? What data sets do we need to serve these goals? And how do gaps in the availability of big data about certain topics influence the eventual choice of goals?

The choice of data sets could raise a variety of issues. These may be related to the quality of the data as such, thus raising questions about the validation of the methods with which the data have been obtained, or the ways in which these methods are being applied. It may also relate to the completeness of the data: in case of gaps, there is a risk that the outcomes of the Digital Twin (knowledge or suggested actions) are not well informed, which may lead to safety issues. Incompleteness of data can also lead to questions about the metadata. How large should a set of metadata be to offer sufficient information; and how should we deal with (meta)data that are open to multiple interpretations? Coming to an agreement about what data should be selected, how much data is required, and what are appropriate ways to collect, process, store and interpret them. is important because the knowledge and decision making that Digital Twins are to enable may have unintended consequences for the health, safety and integrity of living beings in the environment.

Apart from these questions about data quality and completeness, there are also questions concerning the content of the data chosen as a basis for the Digital Twin. This will influence the knowledge about the real object that the twin provides the selection of users it is intended for and the decisions that it invites these users to make (Bronson and Knezevic, 2016; Fleming, Jakku, Lim-Camacho, Taylor, Thorburn 2018; Holloway, Morris, Gilna, Gibbs 2011; Kshetri 2014). Our example of the Digital Twin of tomato crops, for example, could focus on data monitoring the growth of the plant to anticipate yield focusing on size and amount of tomatoes on each plant, but it could also focus on improving the taste of the growing tomatoes. These two focuses of the twin will demand collecting a different selection of data.

Digital farming technologies, including Digital Twins, can also raise questions about privacy (Sykuta 2016). Private data are first and foremost data that tell something about the health, movements and behaviour of human beings, which can be linked to the identity of a particular person. Farm data about crops, soil, animals, inputs used, yield or emissions, which cannot be directly linked to the identity of specific people, are generally considered "non-personal", yet farmers sometimes feel their privacy is being breached when these data are shared. The level of control over this information that farmers used to have is shifting, which may raise privacy questions for them and consequently lead to a reinterpretation of what is considered "private" data. Who is entitled to control the selection (frequency and level of precision) of information that is shared with Digital Twin technology, such as the one monitoring the growth of tomatoes or the one providing insight into nitrogen emissions? Should it be farmers, when it is information about their business that they should be in charge of? Is there also a right to know on the part of the consumers or policy makers to have access to (some parts of the) information, as far as public interests are concerned? How should individual and collective interests be balanced with regard to data access and data use?

Data ownership, transparency, who should have access to or control over information (and on what grounds) and who is to benefit from information, are ethical issues that have been raised about digital farming in general and that are also relevant in relation to Digital Twins (Ryan 2020; Van Der Burg, Wiseman, Krkeljas 2020b; Wiseman, Sanderson, Zhang, Jakku 2019; Rasmussen et al. 2016;

Tzounis, Katsoulas, Bartzanas, Kittas 2017; Schoitsch, 2017; Lokers, Knapen, Janssen, van Randen, Jansen 2016; Eastwood, Klerkx, Ayre, Dela Rue 2019). The re-use of existing data is an important concern that is related to ownership issues. As data that a Digital Twin uses may have been collected in the past for other purposes than the creation of the Digital Twin, questions may be raised about who is entitled to control this re-use of existing data sets, and who may consequently benefit from the creation of this new instrument: the Digital Twin (Isabelle M. Carbonell, 2016; Carolan 2017; Jakku et al. 2019; Jouanjean, Casalini, Wiseman, Gray 2020; Van Der Burg et al. 2020a; Wiseman and Sanderson, 2019)(Carbonell, 2016; Carolan 2017; Jakku et al. 2019; Jouanjean, Casalini, Wiseman, Gray 2020; Van Der Burg et al. 2020a; Wiseman, Sanderson, Robb 2018; Wiseman and Sanderson, 2019). What care is due to the agri-businesses on whose business data are originally collected, and how should that care be offered? Should they be asked for their informed consent to the use and re-use of data stemming from their business? How feasible is it to ask for a truly informed consent for every re-use, especially if we are considering large data sets that may stem from a multitude of businesses active in the agri-food sector?

4.2. Representations

Like other precision farming technologies, Digital Twins are supposed to provide more knowledge to inform action. This may raise questions regarding to ways in which Digital Twins mediate our knowledge-relationships with the world. A lot of authors suspect, for example, that digital farming will change people's perception of climate change, as changes in for example, temperature or crop level are quantified and monitored over time and therefore become available and accessible for people to understand (Carolan 2017; Poppe 2016; Poppe, Bogaardt, Van Der Wal 2016). Furthermore, it is mentioned that digital farming technologies mediate how people "see" or engage with the world around them, such as how they look at (and interact with) their cattle (Bos, Bovenkerk, Feindt, Van Dam 2018; Driessen and Heutinck, 2015; Holloway 2007). It is anticipated that when there are digital technologies available to look at animal welfare, for example, there will be less interaction between human beings and animals which could lead to a different (and some would say: lesser) perception of animal welfare.

Similar questions might be raised about Digital Twins. But in the case of Digital Twins, we might question the type of knowledge they provide about the world, but also how they "represent" the real object or process that they are twinning. For example, should we consider Digital Twins of tomatoes as "representations" of real tomatoes? How representative is the twin – what aspects does it represent? – and how do we distinguish between "good" and "bad" Digital Twin representations of tomatoes? The developers of Digital Twins make decisions about what the twin is to represent, and what aspects it should minimally cover, but it is not always transparent how they take these decisions and what vision of "good" and "bad" twins figures in the background of their choices. What aspects of the world do Digital Twins enhance and make visible about tomatoes growing in a greenhouse, and which ones disappear from sight? What conceptions of "good" and "bad" shape the twin? These are questions that deserve more attention when Digital Twins start to play a larger role in the management of farm practices.

Related to this is the question what (parts of) the real world the Digital Twin is representing and who has been involved in defining the "issues" that the Digital Twin should help to tackle. Considering the Digital Twin representing the nitrogen cycle, for example, it may be questioned who asked for the twin, and whose interests it is serving. Are decisions about what the twin should represent made solely by the developers of the Digital Twin (e.g. the scientists), which means it is their ideas, values, and assumptions about the issue that are included, or does a larger group of stakeholders have a say in that? And do the "big data" on which Digital Twins are based introduce a bias by themselves, given that they do not represent everything (e.g. the entire animal population or the full range of possible scenario's), and they may likely lack or have insufficient data on small farms or rare phenomena?

Apart from representations of the present world, Digital Twins are also supposed to offer predictions of the future world. However, Digital Twins that extrapolate knowledge based on data from the past into the future may also fail to take into account relevant changes that may come about in environmental conditions, social and economic behaviour, market structures, laws and institutions or governments. Such changes may undermine the relevance of the future that is represented by the Digital Twin. For example, data of the past may fail to predict disruptive events like the credit crisis in 2008, or environmental disasters such as excessive rain that causes floods, or extremely hot and dry summers. One of the questions to raise about a Digital Twin's representation of the future is whether it always offers a reliable picture of the future. While the Digital Twin is said to represent reality, reality may change faster than it is able to anticipate, given that it is based on data from the past.

Like many digital farming technologies, Digital Twins are meant to support the realisation of societal goals (Lajoie-O'Malley, Bronson, Van Der Burg, Klerkx 2020) such as the realisation of economic, environmental and social sustainability (Barrett and Rose, 2020; Rose, Wheeler, Winter, Lobley, Chivers 2021). If the Digital Twin represents the future, based on data about the past, there is a possibility that the future represented by the Digital Twin will provide a repetition of that past and cover up various possibilities to realise sustainability goals. Furthermore, given the extensive discussion about the meaning and content of the term "sustainability", the question may be asked what or whose interpretation of "sustainability" a Digital Twin is to represent and what interpretations therewith disappear from sight that also deserve attention. Or we might ask and debate whether it is right or justified that the representation of "sustainability" offered by the Digital Twin should guide human action.

4.3. Actions

The two themes that were discussed so far (*resources* and *representations*) address challenges around the collection, combinations and use of data to make representations of the present and future world. This representation is supposed to provide knowledge about reality, which is support for decision making; it should be *actionable* knowledge. The development of Digital Twins therefore also gives rise to questions related to the desirability and acceptability of the actions that they afford, recommend or even take themselves.

In the digital farming literature, the impacts of digital technologies on the actions and decisions of farmers are discussed with regards to the autonomy of farmers, and the ways in which smart farming changes their daily work and routine (inter)actions. Decisions related to animal welfare, how much pesticides to spray and where, when to seed, to harvest, or how much fertilizer or water are needed (and where) to optimize growth are all examples of decisions that digital farming technologies help to make (Driessen and Heutinck, 2015; Fountas, Wulfsohn, Blackmore, Jacobsen, Pedersen 2006; Leonard et al. 2017; Leone 2017; Lokers, Knapen, Janssen, van Randen, Jansen 2016). With the use of Digital Twins, farmers' interactions with living entities (animals, crops) may be replaced by interactions with its digital representation. As Digital Twins can represent actual states of objects and processes at the farm through (near) real-time data collection, they enable farmers to monitor these objects and processes remotely instead of via direct observation. But Digital Twins can also predict possible future problems and simulate the effects of specific interventions. This combination of real-time representation and prediction means that a Digital Twin transforms moments of intervention: it changes farmers' decision-making, for example, regarding actions taken to avoid certain anticipated undesired outcomes from materialising. In the hypothetical case of a Digital Twin of a cow, the twin could diagnose a cow with a disease and generate predictions of how the health of a cow will evolve in two different scenarios, for example, one in which the cow receives a specific type of medication and one in which she does not receive this medication. These scenarios could include the effect on the health of the animal, the duration of the disease, the costs of the medication versus the effects of providing it on the production level of the cow and -in the end- the revenues of the farm. Such predictive abilities of Digital Twins may result in decisions being taken at an earlier stage, taking into account various variables at the same time. This possibility, however, raises a number of questions. On what information is the twin based and to what extent does this apply to this particular cow? If the information about prevention, diagnosis and treatment-effects are based on average herd statistics how does it relate to a particular animal? And how do measurements relate to animals in particular environments? For example, it has been shown that cows have different bodily temperature and level of activity depending on the temperature of their environment. Such variations are important background information to assessments of animals as being “ diseased” or “ healthy”, as well as to estimate the time until their recovery and the associated costs (Hahn 1999; Mallard et al. 2020). Furthermore, the increasing move towards preventive medicine (in people and in animals) has also raised questions about overtreatment including on whether and how it can be avoided (Esserman, Thompson, Reid 2013; Wegwarth and Gigerenzer, 2013).

Another set of questions relates to the degree of influence of Digital Twins over human decision-making and action. The promise of Digital Twins is that they support or enhance the agency of human actors, i.e. that they allow their users to take better-informed decisions. Depending on their particular design, Digital Twins can be used for monitoring and prediction of current and future states, but they can also prescribe or suggest certain actions, or (in the case of AI) even (automatically) intervene in its physical counterpart (Verdouw and Kruize, 2017). Verdouw and Kruize (2017) provide an example of “prescriptive” Digital Twins, which recommend certain actions, but leaves human actors freedom to reflect and decide which one they will carry out; and “autonomous” Digital Twins which intervene in the physical object they are “twinning” by themselves without human interference. In the example of Digital Twins that prescribe actions for human users, what raises questions is how the Digital Twin “communicates” and makes transparent its workings and the underlying processes leading to a certain recommended action. In this respect, the design of the user-interface via which the output of the Digital Twin is displayed is important. While some user interfaces may make the steps and processes that lead to a certain recommended decision open for users to inspect, and possibly disagree with, other interfaces may close them off. Also, the recommended decision may be communicated in different ways, e.g. as a probabilistic result, which shows that there is a degree of uncertainty or in a more binary way (yes/no), suggesting certainty about the recommended decision. If Digital Twins lack transparency and their workings are not open for scrutiny by its users, they risk becoming opaque systems (Introna 2005), or black-boxes (Pasquale 2015). Such issues link to current debates about responsible Artificial Intelligence (Dignum 2019) and the ethics of algorithms (Mittelstadt, Allo, Taddeo, Wachter, Floridi 2016) inquiring into whether designers of these technologies should foster accountability and traceability, meaning that systems should be able to explain and justify their actions and decisions.

Autonomous Digital Twins that include automatically executed interventions in the physical entities to our knowledge do not exist yet. A hypothetical case is a Digital Twin that is linked to its physical twin by smart devices or machines that can intervene in the physical twin. For example, if a Digital Twin of a tomato plant has a connection to a robot, the Digital Twin can diagnose the disease of the plant and prescribe the optimal intervention, which is then communicated to a robot that will subsequently go to the plant to spray the instructed amount of pesticides. In this example, there is no human involved in the diagnosis of the problem and in the intervention. This raises questions, including ethical ones, about the type of decisions and actions that should be delegated to Digital Twins and the digital systems (such as robots) around them, and what role human actors should (continue to) play.

The delegation of decisions and actions to Digital Twins thus raises a range of questions related to the changing character of decision-making and interventions. Decisions that used to be taken by human actors based on past knowledge, skills, experiences, routines, preferences, or values are now taken (or influenced) by the Digital Twins, which have their own values and optimization aims designed into them. This may be done intentionally or unintentionally, for example, a Digital Twin may act on preconceptions of appropriate size, taste and number of tomatoes a plant should produce and reject plants for breeding that don't, whereas these views are not shared by everyone. This also raises questions about the degree of autonomy of a Digital Twin and responsibility for consequences. Who or what is responsible (and liable) for the actions and interventions supported or taken by the Digital Twin? If these actions have harmful consequences, who is responsible for the eventual damage and can be held accountable? Digital twins, their designers and end-users may all be (partly) responsible, depending on the design of the Digital Twin. But it is unclear who should carry what degree of responsibility (and who should pay) and whether and how it would be possible to share responsibility for the same consequences (Basu, Omotubora, Beeson, Fox 2020; Ryan 2020; Van Est, Gerritsen, Kool 2017).

Moreover, questions may be asked about who the stakeholders are who are affected by Digital Twins, as responsibilities for addressing issues such as the sustainability of food production and consumption may be (re)distributed as an effect of the deployment of Digital Twin. For a Digital Twin that is used to support making farms more environmentally sustainable, for example, stakeholders also include agricultural suppliers, consumers, policy-makers, food industry actors, retailers, etcetera. The responsibilities that they have with regard to the sustainability of food production and consumption may shift as a result of the use of Digital Twins. For example, the Digital Twin representing the nitrogen cycle is aimed at supporting sustainable farm management through the minimalization of nitrogen emissions. With this tool, farmers are made (partly) responsible for optimizing the nitrogen cycle, while the role of other actors in perpetuating the problem of farms burdening the environment, such as consumers and retailers demanding low-priced dairy products which reduces the space for investments for a farmer to move towards more environmentally friendly production, is left out of scope.

Examples such as these show that Digital Twins raise all types of questions about actions, as well as where it puts the onus of responsibility for them. Therefore, it is important to look critically at how a Digital Twin does this. What is the current distribution of responsibility for a particular problem (without the use of a Digital Twin) and how may this change when the Digital Twin is introduced? What are the ethical and political questions that it raises? And what legal consequences does it have in the case of accountability for accidents? Or how do stakeholders view these shifts in responsibility? All of these questions deserve careful research and reflection.

4.4. Implementations

Development of Digital Twins for agri-food is in an early stage of development, and real-world implementation is (to our knowledge) not anticipated soon. Nevertheless, questions may be asked about potential intended and unintended effects it may have if it would be deployed in particular social and environmental contexts, which allows to prevent and mitigate potential undesirable or negative effects.

Based on insights from the smart farming literature, a fundamental question to start with is what the value of a Digital Twin is and for whom this value is created (Barrett and Rose, 2020; Bronson 2018; Bronson and Knezevic, 2016; Chavez Posada 2014; De Beer 2016; Eastwood, Klerkx, Ayre, Dela Rue 2019; Ferris and Rahman, 2016; Fleming, Jakku, Lim-Camacho, Taylor, Thorburn 2018; Lajoie-O'Malley, Bronson, Van Der Burg, Klerkx 2020; Lioutas and Charatsari, 2020; Mark 2019; Maru et al. 2018; Mooney, Clément, Jacobs 2017; Rose, Wheeler, Winter, Lobley, Chivers 2021). If it leverages available data sets, as was discussed earlier, Digital Twins may strengthen aspects of agri-food systems about which a lot of data are available (such as large farms rather than smaller ones; or food safety and quality, rather than environmental performance). It is questionable, however, if these are also the areas where the contribution of Digital Twins is most needed or valued from a societal perspective. It may therefore be important to explore the needs of various types of end users and other stakeholders ahead of time, in order to first develop a well thought-through vision of where and how Digital Twins can make a contribution that stakeholders truly consider an improvement.

Related to the issue of data availability is the broader question about who the Digital Twin "privileges" and what societal development it strengthens (Barrett and Rose, 2020; Bronson 2019; Carbonell, 2016; Carolan 2017, 2018; Rose, Wheeler, Winter, Lobley, Chivers 2021; OMalley et al., 2020; Fleming, Jakku, Lim-Camacho, Taylor, Thorburn 2021; Ehlers et al., 2021). As the optimization aim implied in a Digital Twin may be geared towards certain types of processes and users, they may also benefit some types of farms rather than others. For example, the use of indoor sensors in a barn for measurement of temperature and (nitrogen) emissions to provide the real-time data needed for a Digital Twin of a dairy farm may be less useful for farming paradigms in which cows spend a lot of time outdoors. This relates to broader discussions about how values and choices in the design of digital tools and systems have implications for who can profit from it. For digital agriculture, for example, developers may have quite narrow values regarding what good farming is, which has been shown to lead to design choices and data selection choices that privilege large-scale farmers over smaller ones, or focussing more on quantity of a uniform product (such as tomatoes) rather than aiming at values that pertain to diversity and quality (Bronson 2019).

There is also the question how Digital Twins affect the nature and experience of everyday practices, for example, the practice of farming or policy making around agriculture, land use, nature and the environment. The use of Digital Twins may affect the knowledge, skills and (risk) behaviour needed to manage a farm and it can impact on the type of jobs opening up in the agri-food sector as well as in other sectors where they will be used (AWTI 2015; Frey and Osborne, 2017; Pekkeriet and Splinter, 2020; Van Est and Kool, 2015). Moreover, if farmers and policy-makers will become more reliant on Digital Twins to make decisions, this will create new dependencies on the technology itself as well as on the providers of these systems and the people who offer services connected to the use of Digital Twins. What role will these new actors take, and what effect will their influence have on the wider trend of technology companies entering and reshaping fields such as farming, natural resource management, and nature conservation?

Besides this, the implementation of Digital Twins can have diverse socio-economic effects. For example, if the costs of developing and using Digital Twins are high, or if they are very difficult to use, not everyone will have access to them (Van Der Burg et al. 2020a). Access to the technology may thus result in competitive advantage (or disappearance of it) for certain users. In addition, the implementation of Digital Twins may shift power relations among actors in the agri-food chain, depending on who uses the Digital Twin and who has access to the data and knowledge produced with Digital Twins. In the digital farming literature, it has been argued that when data about production processes is made transparent to consumers, this could enable consumers to make better-informed choices to buy (or boycott) particular products and services (Kshetri 2014; Leone 2017; Ratten 2018; Witterhold 2018; Żakowska-Biemans and Tekień, 2017). In that way consumers exercise influence over the choices that farmers and growers make with regards to their production practices. Similarly, Digital Twins could improve consumers insight into the environmental performance of farms and greenhouses if this data becomes accessible to them. Digital Twins could also become part of public or private governance arrangements to monitor and verify environmental performance of farms and businesses. For example, a Digital Twin that monitors nitrogen levels on farms could in theory be used by government actors to assess adherence to environmental regulations. Such potential implementations of Digital Twins as governance tools may increase the capabilities of farmers and growers to sustainable manage their businesses, but at the same time also broaden the possibilities for other actors to exercising control over farmers, or to impose new requirements on them, or even publicly penalize them based on data.

For Digital Twins in the agri-food domain, we also need to take into account the intended and unintended consequences of Digital Twins for the environment, including ecosystems, plants, and animals. Digital Twins can help humans to acquire more knowledge about current and future states of the environment and support practical decision-making to reduce emissions (such as nitrogen emissions), pollution, and other environmental risks. This may open up new possibilities to foster more sustainable production and consumption in the agri-food domain. The Digital Twin of the tomato crop, for example, seeks to optimise the balance between energy use of the greenhouse and crop yield, while the Digital Twin of the nitrogen cycle on an entire farm seeks to reduce nitrogen while maintaining or even increasing farm yield. While environmental aims are thus central to the envisioned workings of these twins, a narrow focus of Digital Twin approaches on improving efficiency of existing systems and processes may also result in a rather one-sided conceptualisation of sustainability as eco-efficiency, at the expense of other approaches, such as the downsizing of farms or moving consumers towards a more sober lifestyle.

Questions about the implementation of Digital Twins may also include questions about business and environmental risk and safety. Can Digital Twins be trusted to have taken into account all relevant safety aspects? And what about the reliability of Digital Twins over time: risks may arise from limited investments in maintenance of the underlying digital systems and keeping related understanding, knowledge and expertise up to date. If the system is not updated, well maintained, in terms of (balanced) available data sets as well as the latest scientific insights, and the knowledge it provides thus deepened, this may have consequences for safety, such as over spraying of pesticides on tomatoes, or inefficient recommendations about how to lower nitrogen levels.

Finally, while all of these issues for consideration are quite general, it should be stressed that anticipating societal and ethical concerns around the implementation of Digital Twins requires a case-by-case approach. Digital Twins in agri-food are anticipated for diverse applications (arable farming, horticulture, livestock, supply chains, nature conservation) and may land in very different use-contexts (e.g. geographically, culturally and socially). Examining who or what will be affected in these contexts and how requires awareness of the characteristics of these specific use-contexts and the (anticipated) effects on the range of stakeholders in and around it. These stakeholders need to be engaged in the process of the development of the Digital Twins, in order to be able to tailor the twin to their values and realise an acceptable and valued twin. For Digital Twins of which the physical object is a living entity or system, however, also non-human entities such as animals, plants, and ecosystems may be affected by the intended and unintended positive and negative effects of Digital Twins. Questions of responsibility with regards to implementation need to include these non-human entities, even if they cannot be engaged as conversation partners, such as other stakeholders who are able to defend their standpoint (Ryan and van der Burg, 2021). Questions around implementation of Digital Twins include therefore human and non-human stakeholders.

5. Conclusion

In this article, we approached Digital Twins as members of the various and expanding family of digital farming technologies. The societal and ethical questions that these twins raise are in many ways similar to the questions that other digital farming technologies can raise. What stands out most for Digital Twins, is perhaps only their capacity to represent: as they are "twinning" actual dynamically evolving processes and organisms in the real world, users might forget that they are looking at a man-made construct which is based on choices around what data sets to use and to combine to create a picture of what is happening. As the technology itself does not transparently reveal these choices, this could make it easier to substitute the real for the twin, which would leave a lot of the complexity of the real-world entities and processes out of scope.

Beside the more specific questions around representation, however, we do not see that Digital Twins will raise fundamentally different societal and ethical questions, than other smart farming technologies do. Table A1 provides an overview of the key issues and questions per theme. This overview of issues can be used as an agenda for research in Responsible Research and Innovation (RRI) about Digital Twins for agri-food. As noted in the beginning of this article, RRI strives to include reflection about (anticipated) societal and ethical aspects of innovation during its research and development in order to contribute to realizing products that will be valued and widely used. The questions in Table 1 support the set-up of RRI research. The key questions under resources and representations invite Digital Twin developers to develop a critical attitude towards the selection and use of data sets that shape the twin. This helps to anticipate the possibilities and constraints of the representation that the twin offers of reality and the effects this will have on the knowledge that is derived from twins. The key questions under the themes of actions and implementations invite Digital Twins developers, RRI researchers and societal stakeholders to critically reflect on questions of responsibility in relation to actions driven by Digital Twins and to anticipate and reflect on the wider societal and environmental effects of such actions. This includes considerations about the maintenance of the Digital Twin in terms of quality and representation, the socio-economic context it is intended for, the way it affects current power structures, everyday experiences and routines.

These themes thereby offer rather general questions to think about in RRI research related to Digital Twins. They provide just a starting point, to facilitate reflection and considerations, which can be elaborated further in the coming years. For now, this "menu" of themes and questions provided in Table 1 at least shows the relevance of coupling RRI research to the

Table 1. Themes and questions for RRI research on Digital Twins (DT)

Themes	Resources	Representations	Actions	Implementations
Focus	Issues around data	Epistemic issues	Issues around DT-driven actions	Issues around societal impact
Socio-ethical challenges	Privacy; consent; transparency; data quality (incl. validation of methods for data generation, completeness and accuracy); data security; data protection	Biases in representation of current and future states of affairs; transformative effects on how people understand and relate to animals, and to ecosystems	Normative effects on physical twin; Automation; User autonomy; (re) distributions of responsibility; accountability and liability;	Socio-economic inequalities; animal welfare, environmental benefits and risks; impact on everyday life
Key questions				
Questions about power and control	Who is in charge of the data? How is access to, control over, and (re) use of data arranged? What power (im-) balances are anticipated, related to acces and use of data? How are these being mitigated?	What/whose knowledge is enhanced with the help of the DT? Who considers this knowledge valuable and why? What/Whose futures does the DT represent? What effect does this representation have on some people's control over reality/ the future as opposed to other's?	The DT influences actions of people. How does it do that? How much room does it leave for the autonomy of the user? Does it merely inform his or her decision? Does it nudge or paternalistically steer towards certain outcomes? Who gets to say what the user should do with this DT? And who is responsible/liable for the outcomes of DT inspired interventions?	The DT is implemented in some contexts and not in others. Who does it give more power in these contexts? And who is less empowered? Are there also people excluded from the benefits that DTs offer?
Questions about societal consequences	What are the (anticipated) societal consequences of the selection and combination of datasets as input for DTs?	What are the (anticipated) societal consequences of the ways in which this DT represents (present or future) reality?	What are the (anticipated) societal consequences of the transformed actions that the DT brings about?	What societal impacts does the DT have? How will animals, plants, people, and ecosystems be affected by the DT?

(*Continued*)

Table 1. (Continued).

Themes	Resources	Representations	Actions	Implementations
Questions about decisions that underlie the DT	How are decisions made about the selection and combination of datasets for DTs? Are there (tacit) selection criteria at play?	How are decisions made about what (aspects of) reality or the future the DT will represent? Are there elements that receive less attention or disappear from view?	Does the DT transform interventions in its physical counterpart? If so, how do the resulting (new) data sets feed back into the DT, is there a related decision step? How are interventions selected? How is it decided what needs to be transformed?	How are decisions made about where and how to implement the DT? (And where not?)
Questions about inclusiveness	What stakeholders are involved in discussions and decisions around data governance and their use for DTs?	What stakeholders are involved in decisions about what elements of (future) reality to represent in the DT?	What stakeholders are involved in deciding what interventions deserve attention and how they need to be made?	What stakeholders are involved in deciding where and how to implement the DT and how to assess its performance?
Questions about morality, including moral changes and altering ethical debates	Does the selection and combination of these datasets for the DT alter the meaning or application of present moral concepts? Does it raise (new) ethical issues? (such as, for example related to privacy, security/safety or data ownership?) Does it influence/ change present ethical debates?a	How do DTs effect what we consider to be 'knowledge' about reality? Does the knowledge that the DT provides also raise ethical issues? Does it influence/change present morality or raise new ethical debates?	What/whose interests are served with these changed interventions? What/whose values play a role in these interventions? Do these interventions raise ethical issues? Do they change present ethical debates?	What are the benefits and harms associated with the use of DTs? What moral values and norms are associated with it? How is the performance of the DT evaluated according to this understanding of benefits/harms, values and norms? Are there alternative ways available to look at it?

development of Digital Twins, as RRI invites to reflect on choices that the developers of these twins make and to involve stakeholders to get their input about crucial development decisions. RRI starts from the supposition that there is no pre-given set of criteria or principles that Digital Twins will have to satisfy: the stakeholders themselves should determine what is acceptable or desirable for them. It is the task of RRI researchers to enhance and broaden their reflection by offering information that answers the descriptive questions such as the ones noted in Table 1.

There has been a discussion whether RRI should be carried out parallel to technical research, or fully integrated into the Digital Twin development, but given (financial) size and impact of average Digital Twin products, and the relevance of the RRI themes for the development and success of Digital Twins, it seems that integration does provide better options for public acceptance, positive results and long-term success (Flipse, van der Sanden, Osseweijer 2013; Van Gorp and van der Molen, 2011). Such a multidisciplinary collaboration demands effort on both sides. From developers, it demands to explain their work and make crucial choices a topic for reflection and discussion with RRI researchers that may bring in unfamiliar perspectives; for RRI researchers, it demands effort to think along with the developers and make their work, which can be broad and explorative, relevant for concrete developmental choices. It can mean, sometimes, slowing the development process down to be able to consider the societal, including safety, aspects of the twin more in depth, but it can also have a surplus value as the RRI researcher may bring in content for reflection about the societal function of the twin that can enrich the reflection of developers and enhance their creativity.

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Appendix 1

The list of themes and questions mentioned in this review was updated by using the same research terms as were use in the initial review and the same databases (web of Science, LexisNexis and Google Scholar), but focusing on the publications published after 2019. We used search terms such as “smart”, “digital” or “precision” and “farming” (or “agriculture”) in combination with “ethics”; and we used “big data” in combination with “farming” (or agriculture) and “ethics”. We used “big data” because most (but not all) technologies that are part of smart farming deal with data.

The title and abstract of the articles found were reviewed in order to determine the relevance of the article. Inclusion was based on whether or not the article concerned smart farming and contained a reflection on, or discussion about, social or moral values. In Table 1, an overview can be found of the themes characterized in this review. This table offers an updated version of the table provided on page 3 in Van Der Burg et al. (2019), focusing just on the peer reviewed articles and reports.

Table A1. Themes in the literature about smart farming.

Theme	Questions	Type of sources on which we based this theme
Data ownership, accessibility, sharing and control	How are data understood by different people? What are advantages/disadvantages of different (for ex. individual or relational) perspectives to farm data? Who owns the data? What starting points do current laws provide to think about data ownership? Should different ownership rights be ascribed to different partners in the network? Do ownership rights help to protect the interests of (all) partners in the network? What are advantages/disadvantages of speaking about ownership in relation to data? What does "open access" to data mean? What are advantages/disadvantages of open access to different stakeholders? What are advantages/disadvantages of open access to the realization of societal goals or private company goals related to smart farming? Does it make sense to speak about openness in terms of "degrees"? What data should be open or shared with whom? What is the meaning of fairness/equity in relation to data sharing? In what ways do partners/stakeholders become vulnerable because of the sharing of data? Who has responsibility to care for these vulnerabilities? And how can they be protected? What does trust in data sharing require?	20 peer reviewed articles (Bronson and Knezevic, 2016; Carbonell, 2016; Carolan 2017, Carolan 2018; Eastwood, Klerkx, Ayre, Dela Rue 2019; Fleming, Jakku, Lim-Camacho, Taylor, Thorburn 2018; Jakku et al. 2019; Jouanjean, Casalini, Wiseman, Gray 2020; Kamilaris, Kartakoullis, Prenafeta-Boldú 2017; Kshetri 2014; Kuch, Kearnes, Gulson 2020; Lokers, Knapen, Janssen, van Randen, Jansen 2016; Ryan 2020; Rasmussen 2016; Sykuta 2016; Schoitsch 2017; Tzounis, Katsoulas, Bartzanas, Kittas 2017; Van Der Burg, Wiseman, Krkeljas 2020b; Wiseman, Sanderson, Zhang, Jakku 2019; Wiseman and Sanderson 2019) 5 reports (De Beer 2016; Kritikos 2017; Maru et al. 2018; Poppe, Bogaardt, Van Der Wal 2016; Van Der Burg et al. 2020a)

(*Continued*)

Table A1. (Continued).

Theme	Questions	Type of sources on which we based this theme
Distribution of power	What shifts in the distribution of power are expected to take place as an effect of smart farming? What are advantages and disadvantages of different power-distributions in the network in relation to (a) the realization of the goals of smart farming, (b) the distribution of burdens of benefits amongst partners within the network, (c) the sustainability of farms, and (d) the autonomy of farmers and consumers (e) the meaning of values such as fairness, justice, just distribution, transparency and trust? Who should be involved in reflection about the goals of smart farming? How should disagreement about goals be dealt with?	19 Peer reviewed articles (Barrett and Rose, 2020; Bronson 2019; Bronson and Knezevic, 2016; Carbonell, 2016; Carolan 2018, Carolan 2017; Eastwood, Klerkx, Ayre, Dela Rue 2019; Fleming, Jakku, Lim-Camacho, Taylor, Thorburn 2018; Jakku et al. 2019; Kamilaris, Kartakoullis, Prenafeta-Boldú 2017; Kshetri 2014; Lajoie-O'Malley, Bronson, Van Der Burg, Klerkx 2020; Leone 2017; Ryan 2020; Ryan and van der Burg, 2021; Rose, Wheeler, Winter, Lobley, Chivers 2021; Sykuta 2016; Van Der Burg, Wiseman, Krkeljas 2020b; Wolfert, Bogaardt, Ge, Soma, Verdouw 2016) 6 reports: (Chavez Posada 2014; De Beer 2016; Ferris and Rahman, 2016; Maru et al. 2018; Mooney, Clément, Jacobs 2017; Van Der Burg et al. 2020a)
Impacts on (human/ animal) life on farms	What are private company goals served with smart farming? How should these goals be understood and valued? Does smart farming actually succeed to bring them about? How does smart farming change the daily work, routines (inter)action, experience, choices and deliberation of smart farmers? Are (all) these changes desirable? For whom/what are they desirable? (How) Can undesirable impacts be avoided? What are the gains and losses associated with smart farming for farms and other companies collaborating in the value-chain? And how should their desirability be weighed?	7 peer reviewed articles (Blok 2019; Carolan 2015; Isabelle M. Carbonell 2016; Driessen and Heutinck, 2015; Holloway, Morris, Gilna, Gibbs 2011/Holloway 2007; Kshetri 2014) 4 reports (Bos and Munnichs, 2016; De Beer 2016; Kritikos 2017; Poppe 2016)
Impacts on society	Smart farming is expected to foster societal goals such as to diminish the environmental impact of farming and to improve food security. How should these goals be understood and valued? Does smart farming actually succeed to bring the desirable goals about? What trade-offs need to be made between different goals that digital farming can serve in society, such as economic, environmental societal/ cultural goals? What should visions of the societal future with digital farming look like? What are the impacts of digitalisation on agricultural policy? And what impacts should it have?	4 peer reviewed articles (Barrett and Rose, 2020; Lajoie-O'Malley, Bronson, Van Der Burg, Klerkx 2020; Rose, Wheeler, Winter, Lobley, Chivers 2021; Van Der Burg et al. 2020a) 4 Reports: (Kritikos 2017; Pekkeriet and Splinter, 2020; Poppe 2016; Van Der Burg et al. 2020a)