The Significance and Ethics of Digital Livestock Farming

Suresh Neethirajan

Farmworx Research Institute, Van der Waals Straat, 6705 Wageningen, The Netherlands; sneethir@gmail.com

Abstract: The emergence of precision and digital livestock farming presents an opportunity for sustainable animal farming practices that enhance animal welfare and health. However, this transformation of modern animal farming through digital technology has several implications for the technological, social, economic, and environmental aspects of farming. It is crucial to analyze the ethical considerations associated with the digitalization of modern animal farming, particularly in the context of human–animal relationships and potential objectification. This analysis can help develop frameworks for improving animal welfare and promoting sustainability in animal farming. One of the primary ethical concerns of digital livestock farming is the potential for a digital divide between farmers who have access to advanced technologies and those who do not. This could lead to a disparity in animal welfare and health outcomes for different groups of animals. Additionally, the use of artificial intelligence in digital livestock farming may lead to a loss of personal connection between farmers and animals, which could impact the animal's well-being. Another ethical concern of digital livestock farming is the potential for the objectification of animals as mere data points. The use of sensors and other monitoring technologies can provide valuable data on animal health and behavior, but it is important to remember that animals are sentient beings with complex emotional and social needs. The use of digital technologies should not lead to neglect of animal welfare or a lack of human responsibility toward animals. Furthermore, social context becomes essential while integrating technologies in livestock farming to overcome ethics. By considering the cultural and societal norms of different communities, we can ensure that the use of digital technologies does not undermine these values. To address these ethical challenges, the development of standards and codes of conduct for the adoption and implementation of digital livestock farming tools and platforms can help ensure that animal welfare and sustainability are prioritized. This can help alleviate the privacy concerns of stakeholders and improve sustainability in animal farming practices. Additionally, the use of virtual and augmented reality technologies can provide a way to enhance human–animal interactions and provide more personalized care to animals, further promoting animal welfare.

Keywords: precision livestock farming; digital livestock farming; smart farming; societal impacts; data ownership; open access; sustainability; animal ethics; digital divide; digital agriculture

1. Introduction

The increasing demand for animal products has led to significant changes in animal farming practices, with a shift toward more intensive and industrialized methods of animal production. As a result, animal welfare and sustainability have become important concerns for consumers, policymakers, and stakeholders in the animal agriculture industry. This has led to the development of new technologies and farming practices, such as precision and digital livestock farming, which offer potential benefits for animal welfare and sustainability.

Technologies can be considered a double-edged sword—something that is clearly exemplified in livestock farming. For instance, deepfake technologies have been drawing attention lately. Such technologies are used mostly in malicious applications, but they can also be integrated with virtual reality to enhance animal welfare. To illustrate, suppose that a calf is suffering emotionally owing to the absence of a mother that has been sent for

slaughter. The technologies in question can be harnessed to create a digital simulation of the mother cow that may provide comfort to the calf and enhance its emotional well-being [1].

Indeed, there are problems that are presently considered unsolvable in the livestock farming sector but that can, in fact, be solved or might become solvable using digitization approaches, which make possible innovations such as the following:

- Transitioning from subjective judgments to objective methods of measurement;
- Moving from one-dimensional to multidimensional approaches in solving problems from a holistic standpoint;
- Becoming able to solve problems by moving from a coarse-grained to a fine-grained level of analysis in order to understand, design and develop solutions;
- Moving away from reactive to predictive approaches.

Two such digitized approaches in livestock farming are precision livestock farming and digital livestock farming, the latter of which has emerged from the former. Precision livestock farming and digital livestock farming are two examples of digitized approaches that offer benefits such as real-time monitoring, predictive analytics, and automated decision-making. The integration of digital technologies into animal farming practices raises several ethical concerns, particularly with regard to human–animal relationships and objectification. There is a need to analyze the ethical considerations associated with digital livestock farming and develop frameworks for improving animal welfare and sustainability.

The research question that inspired this opinion review is, "What are the ethical considerations associated with digital livestock farming, and how can they be addressed to improve animal welfare and sustainability?" The review aims to provide a critical analysis of the ethical challenges of digital livestock farming technologies and their potential impact on animal welfare and sustainability. It also offers recommendations for ethical considerations, including the development of standards and codes of conduct for the adoption and implementation of digital livestock farming tools and platforms. The review is intended to inform policymakers, animal agriculture industry stakeholders, and consumers about the potential benefits and ethical challenges of digital livestock farming and to encourage discussion and action to promote animal welfare and sustainability in animal farming practices.

2. Precision Livestock Farming, Digital Livestock Farming and Smart Livestock Farming

To begin, let us explore the core notions that shall occupy the stakeholders, namely precision livestock farming, digital livestock farming and, in addition smart livestock farming.

Precision livestock farming (PLF) terminology has been used for over 10 years. PLF may be defined as "the management of livestock production using the principles and technology of process engineering" [2]. Its purpose is to "improve the efficiency of production while increasing animal and human welfare, via applying advanced information and communication technologies (ICT), targeted resource use and precise control of the production process" [3].

More recently, PLF has been defined as farm management based on continuous automatic real-time monitoring and control of production/reproduction, animal health and welfare, and the environmental impact of livestock production [4–6]. However, as we shall see presently, this is a definition that reflects the ways in which PLF has been moving toward digital livestock farming since it emphasizes real-time monitoring and control, something that has been characteristic of the digital farming transformation. Accordingly, the previous definition offered above is more appropriate for our purposes of observing the distinction between precision livestock farming and digital livestock farming.

Despite the recent prevalence of PLF, we are now slowly moving from PLF to digital livestock farming (DLF) and, relatedly, smart farming (SF). DLF may be defined as digital agriculture or farming, applied specifically to livestock farming. Digital agriculture, in turn, is defined as follows [7]:

We define digital agriculture as the use of elaborate and detailed digital information in guiding decisions along the agri-food value chain. This includes the use of high-volume, variable source data ("big data") that creates critical insights, modeling, actionable analytics and automation for precision livestock farming. Importantly, it is not restricted to farm animal production alone but also can span all or part of the value chain; the transformational aspect of digitization offers a bridge between the consumer and animal caretaker or the farmer.

There is a marked difference in precision and accuracy with respect to each type of farming. PLF is mostly an incremental way of finding solutions, while DLF features a higher degree of integration and encompasses sustainability [8] and predictive possibilities that account for time-scale phenomena [9]. The primary focus of PLF is on post-data collected measurements for supporting decision-making and directing farming practices. By contrast, DLF is about real-time and predictive capabilities, which are made possible by self-learning artificial intelligence algorithms [10]. Digitalization is about creating actionable intelligence via data and creating meaningful value for all of the stakeholders in livestock farming, all while ensuring the well-being of animals.

Thus, DLF incorporates and integrates precision and smart animal farming concepts. Additionally, the emphasis of DLF is not anymore on precision, which was already achieved at the stage of PLF. Instead, now that precision has been achieved, the emphasis is on the integration of precise data into digital systems. Thus, we see that DLF goes beyond PLF.

One useful way of thinking about PLF is in terms of a multi-layered structure. First, we may speak in terms of input systems, such as wearable devices, sensors, recording equipment, etc. These input devices generate data, which constitutes the second layer. On the third layer, we find data management and storage. This is followed by a further layer which includes processing, interpretation and, finally, feedback.

To clarify, however, one should bear in mind that, in certain specific cases, some digital animal farming technologies can be considered more as an incremental acquisition of understanding through observation. An example of this would be mobile, on-farm real-time detection tools that measure the health of farm animals in the form of data for commercial use and to address animal caretaker concerns.

There are some useful points of contrast that can be appealed to in order to elaborate on the differences between PLF and DLF:

In a conventional system such as precision livestock farming (PLF), sensors (wearable and minimally invasive or non-invasive) and video monitoring technologies collect animal measurements and send this data to a computer [11]. Algorithms process this data and create insights or enable farmers to make decisions. This data can be compared to a target value or a model, for example, in monitoring temperature. If the temperature is between two given values, it is within an acceptable range, but if it falls outside that range, there is something amiss that may require some decision-making. The underlying condition behind the anomalous temperature could be variations or fluctuating hormonal levels inside an animal. Here, the interaction between various physiological parameters has to be considered and evaluated. Thus, conventional PLF basically collects data based on health- or welfare-indicating parameters after the occurrence of an event. By contrast, with digital animal farming, we have the capability to move from reactive to predictive measurements; even before disease onset, the data analysis can tell when it will occur [10,12].

It is also important to point out that the transition from PLF to DLF can be analyzed under a two-stage approach. The initial stage is characterized by an emphasis on digitalization. The second stage, in turn, involves a more precise distinction between digital livestock farming and smart livestock farming (SLF), where both of these can be regarded as successors to PLF. Smart farming is a development that focuses on the usage of information and communication technology (ICT) in the cyber-physical livestock farm management cycle [13]. Now, many of the ethical and social implications of both farming systems will be the same. However, SLF also has specific implications of its own. Some work needs to be

done to give more weight to SLF compared to DLF in discussions of new trends in farming. Another important question to explore here is whether SLF complements DLF.

Digital and/or precision livestock farming is an emerging area of research, and the technologies are currently being developed rapidly without much consideration of the implications of ethics in relation to the animals and the bonding with the animal caretakers and other social elements. There is a need for understanding the elements of ethics from the social context and from the animals' individual needs perspective.

3. The Ethics of DLF

Ethics is a crucial dimension of analysis to consider when discussing DLF [14]. In this regard, there are multiple issues to bear in mind, which bring to the fore the ethical complexities created by DLF. Here, we discuss several of those issues.

3.1. Animal Contentment

Animal contentment is closely associated with productivity. As one may say, "A happy cow is a productive cow" [15]. It is the fundamental responsibility of farmers and farming industries to ensure that animals live fully in their short life span (such as by exhibiting natural behavior, demonstrating playfulness and enjoying a quality of life). DLF incorporates this concern in the development of solutions since it can be used to promote animal welfare [16]. Of course, sometimes society can be considered venal, as the main focus is on maximizing profits and efficiency, not on animal welfare. As researchers, however, we know that it is not sustainable to consider profit alone as a goal in livestock farming, and DLF serves as a powerful tool in this ethical pursuit. Here are some ways in which DLF can help achieve this goal:

Precision management: DLF can provide real-time data on animal health, behavior, and performance. This information can be used to identify potential health problems or changes in behavior that may indicate stress, pain, or discomfort. With this information, farmers can intervene early to prevent or treat health issues, resulting in better animal welfare and productivity.

Environmental monitoring: DLF can also provide real-time data on environmental conditions, such as temperature, humidity, and air quality, which can affect animal health and welfare. By monitoring these factors, farmers can make adjustments to improve animal comfort and reduce the risk of disease.

Efficient resource management: DLF can help farmers manage resources more efficiently, including feed, water, and energy. By optimizing the use of these resources, farmers can reduce waste and minimize environmental impact while also improving profitability.

Traceability and transparency: DLF can provide a detailed record of each animal's life cycle, including its origin, breeding, feed, and medication history. This information can be used to ensure the safety and quality of animal products and to provide consumers with transparency about where their food comes from and how it was produced. In addition, transparency in the use of DLF and the sharing of data with consumers would increase accountability and drive positive change in the industry.

Animal Welfare: To ensure animal welfare in DLF, it is important to prioritize the use of digital tools that facilitate real-time monitoring and early detection of animal health issues. This would allow for timely interventions and treatment, minimizing animal suffering. DLF can certainly help farmers optimize animal welfare, reduce environmental impact, and improve profitability. However, it is important to remember that DLF is a tool, and it should be used in conjunction with other ethical and sustainable farming practices to achieve the best possible outcomes for animals, the environment, and society as a whole.

3.2. Disruption and Critical Analysis

DLF has the potential to be disruptive in management [17]. Now, being disruptive does not necessarily mean that technology is negative. For example, by alleviating physiological uncertainty in animals differently from how it was intended to be alleviated, predictive

digital farming tools can be self-fulfilling and provide their own raison d'être. Nonetheless, normative questions and a constant reflection on reality are necessary for developing solutions via DLF. We should learn from our mistakes, for example, even when poorly supported predictions end up being true. That is, we do not learn from mistakes if we cannot recognize mistakes as such. Proper use of digital technology has to consider and look at ways to realize and take stock of our mistakes and learn from them.

To avoid the self-fulfilling prophecies of predictive digital farming tools and the misuse of technology, it is essential to subject all digital tools to rigorous ethical scrutiny before they are deployed. This should involve a multidisciplinary approach that includes experts in animal welfare, ethics, and data privacy. The use of ethical principles such as the precautionary principle and the principle of non-maleficence could help to guide decision-making.

3.3. Digital Divide and Obsolescence

"Digital divide" is another concept that we have to consider in connection to ethics [18,19]. Not everyone is capable of using DLF technologies. The digital divide between educated and not technically savvy users will lead to a technological rift. Animals' inability to access digital tools in farms may lead to detrimental isolation from social interactions and may affect the nature and quality of interactions between farm animals and caretakers. A related issue is that of obsolescence. It has been estimated that engineering knowledge becomes obsolete, on average, every 5.2 years [20]. Technology obsolescence is also a prevalent issue. This may deepen the technological divide between those who are able to keep up with the pace of technological change and those who are not.

To address the digital divide in the livestock farming industry, stakeholders should prioritize providing access to digital tools and training for all farmers. This could involve the development of user-friendly digital tools and training programs that cater to individuals with varying levels of technical proficiency. To mitigate obsolescence, the development of digital tools should be agile and adaptable, with regular updates and support provided to users.

3.4. Social Considerations

A further crucial issue to consider is the social dimension of DLF. Of particular note here is the question of social attachment. Some groups with a more individualistic approach may see social attachment as less beneficial and perhaps even as a burden. Nonetheless, a concern for well-being in relation to technology should take into account that users and farm animals are diverse and be inclusive [21]. How to fight digital discrimination in technological adoption and build inclusion should be considered part of the development of digital tools for livestock farming. This can be done by integrating values into the design of those tools. Indeed, technology is not just an artifact, it is a tool, and it can also be an institution and an intermediary. Design is part, as well, of social, political, and moral values, which may lead to some fundamental challenges that involve resolving potential ethical conflicts.

To ensure social inclusion in DLF, it is important to involve all stakeholders in the design and deployment of digital tools. This would enable the integration of diverse perspectives and values and could help to mitigate digital discrimination. Additionally, the use of participatory design approaches could help to ensure that digital tools are developed with the needs and preferences of all users in mind.

3.5. Greenhouse Gas Emissions

Digital-tool design and deployment in modern animal farming should also consider the individual carbon footprint associated with animals, processes and facilities, as well as other greenhouse emissions like methane. Greenhouse emissions are of peak importance in considering the environmental implications of farming. This is a particularly clear example, among many others, of how digital farming requires analyzing whether the digital tools

deployed improve society in addition to enhancing food productivity. Doing so should consider various platforms and applications of those tools and the context in which they are being applied. DLF offers various ways of monitoring and perhaps reducing emissions, both methane [22,23]. To reduce greenhouse gas emissions in DLF, stakeholders should prioritize the use of digital tools that help to minimize the carbon footprint of livestock farming. This could involve the use of precision feeding systems that reduce feed waste and associated methane emissions, as well as the use of renewable energy sources to power digital tools and other farm processes.

3.6. Artificial Intelligence and Public Policy

The uptake of artificial intelligence-enabled digital tools for livestock farming via public–private partnerships and arrangements is becoming a main policy tool. The public sector is not very approachable for citizens when considering AI algorithms, which therefore become black boxes, raising questions of transparency [24]. Relating this issue to freedom of information, we may note that proprietary information is completely different and varies between the public and private sectors. The public sector emphasizes transparency, legitimacy and shared benefit for all, while the private sector focuses on efficiency and profitability.

With that being said, we should bear in mind that, as is often the case, "The medium is the message". Digital tools can be perceived in both a favorable and less favorable light. It is important to consider how to create avenues so that digital tools shape our ideas about modern animal farming in a responsible manner.

To ensure transparency and ethical use of AI in DLF, it is essential to involve all stakeholders in the development of public policy around the use of AI in the industry. This could involve the establishment of independent bodies that oversee the use of AI in livestock farming, ensuring that AI systems are transparent, explainable, and accountable. Additionally, public–private partnerships should prioritize shared benefits and the interests of all stakeholders, including farmers, consumers, and animals.

3.7. Human–Animal Relationships

The gap between the farm animal's and the farmer's intellect can possibly be bridged using the magic of visualization platforms (Figure 1) via digital technologies. Due to the complexity of the vocalization of farm animals and the verbal depth and breadth involved, visualization tools can offer avenues for better clarity of understanding [25–27]. This can lead to a more humane form of farming, which is of vital importance, given that alienation and dehumanization are some of the chief current concerns around farming. Additionally, healthy human–animal relationships are central to farming productivity [28]. The integration of digital technologies in livestock farming challenges traditional human–animal relationships by changing the way humans interact with animals. With real-time monitoring, automated decision-making, and predictive analytics, the role of the farmer shifts from that of a caretaker to that of a supervisor, with less direct involvement in animal care. This raises questions about the value of human–animal relationships and whether the use of digital technologies leads to the objectification of animals.

Moreover, digital technologies can lead to the reduction of human–animal interaction, which can impact animal welfare negatively. For instance, if animals are housed in automated facilities, they may not receive the necessary physical contact and socialization required for their well-being, leading to decreased welfare. Therefore, it is important to ensure that the use of digital technologies does not compromise human–animal relationships and that animals continue to receive proper care and socialization.

3.8. Privacy and Data Protection

The integration of digital technologies in livestock farming requires the collection, storage, and analysis of large amounts of data. This data includes sensitive information such as animal health, behavior, and genetics, which could be used to infer private information

about the farmers and the farm's business operations. Moreover, if this data falls into the wrong hands, it could lead to issues such as cyber-attacks, fraud, or theft, compromising the privacy and safety of farmers and animals.
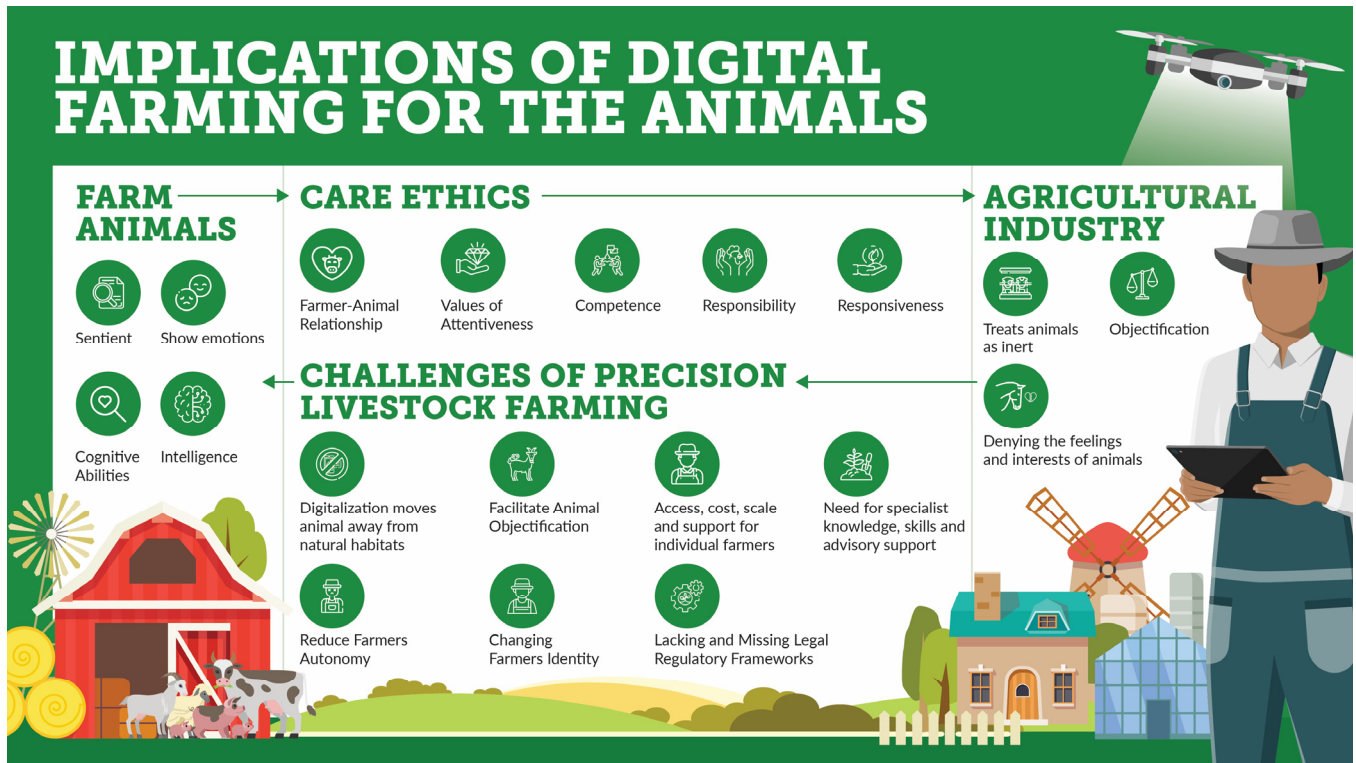

Figure 1. Implications of digital livestock farming for the animals.

Therefore, it is essential to have adequate data protection and security measures in place to ensure that data is not misused or exploited. This includes secure storage, data anonymization, and secure data transfer protocols. Farmers must be transparent about data collection and usage and obtain informed consent from stakeholders before collecting data.

3.9. Bias and Discrimination

Digital technologies in livestock farming rely on algorithms to analyze data and make decisions. However, these algorithms may have inherent biases, leading to discrimination and unfair treatment of animals. For instance, algorithms may not consider the diversity of animal breeds or account for individual differences in behavior, leading to inaccurate predictions or decisions.

Therefore, it is essential to ensure that algorithms used in digital livestock farming are fair, transparent, and unbiased. This includes regular testing, validation, and audit of the algorithms to prevent unintended discrimination or biases. The development of ethical standards and guidelines for algorithm development and use is also essential to prevent potential discrimination and ensure fairness.

3.10. Environmental Impact

Digital livestock farming has the potential to improve environmental sustainability by reducing waste, optimizing resource use, and minimizing the environmental impact of livestock production. However, the use of digital technologies in animal farming can also lead to increased energy consumption, e-waste, and carbon emissions from the production, maintenance, and disposal of digital devices and infrastructure.

Therefore, it is crucial to consider the environmental impact of digital livestock farming and adopt sustainable practices to mitigate its negative effects. This includes using

renewable energy sources, recycling and disposing of electronic waste appropriately, and reducing unnecessary energy consumption.

3.11. Creating New Values

Current values do not suffice to solve the ethical conundrums of DLF, which calls for the creation of new values. For example, consider the issue of how digital tools bring about value changes. Farmers can conceptualize digital tools differently based on the context in which they are applied. They may see them as tools that extend their agency or as an imposition [29]. It is important, therefore, to engage in careful deliberations to interpret the significance of technology adoption among farmers as it unfolds. This may lead to the creation of new values and perspectives that provide solutions to current problems.

Ethical issues surrounding DLF require a multidisciplinary approach that integrates diverse perspectives and values. By involving all stakeholders in the development and deployment of digital tools, we can ensure that DLF promotes animal welfare, reduces environmental impact, and meets the needs of all users.

3.12. The Prospect of Monopolies

Another possible concern is that a single multinational company may take control of the digital technology market for agriculture, creating a monopoly—something that would harm the freedom of small-scale farmers [30]. This could be a real danger because a monopoly would have the power to determine all sorts of crucial factors, such as the inner workings of programs, digital environments and algorithms, assumptions, modeling techniques, etc., thereby compromising objectivity. Furthermore, there needs to be accountability with respect to algorithms and modeling, something that monopolies threaten. For example, a model may prioritize the achievement of certain breeding goals at the expense of animal well-being. This calls for a proper balancing of values that requires inclusive solutions and scrutiny.

The issue described here becomes more pressing, considering how a priority for farmers clearly is to have access to economical systems that integrate many different parameters and assumptions into their models. This is due to the fact that margins are very low in the farming sector. Hence, livestock farming scientists have a responsibility to balance a wide range of variables that go into modeling, a process requiring oversight and openness.

3.13. A Civic Approach

When technologies are being developed for livestock farming, a true civic approach to science is needed that allows us to incorporate viewpoints from the public at large, farmers and ethicists [19]. We cannot predict the future; rather, we are making it, so we must all partake in it as members of civil society. Of course, we hope that whatever emerges from new technologies such as DLF will be positive, but the results cannot be fully predicted at the beginning of the whole enterprise. If ethicists are involved in the very beginning of such new research, they could provide some valuable foresight on the consequences of technological development. This is the case even when technologies are developed with good intentions since, to emphasize, the issue is that of unexpected consequences. Accordingly, at the earliest stage, during the technology's development, ethics have to be considered and integrated into the design and planning processes.

3.14. Social Issues

In relation to issues pertaining to the social dimension of DLF, we should mention how digital animal farming tools can be adopted and how their development proceeds, depending on how we think about them. A broader social perspective of technological development is essential (Table 1). One example is the DeLaval brushes and other comfort technologies available in dairy farms. There is evidence suggesting that such technologies enhance cow productivity [31]. However, we may go beyond that issue and focus on

the social significance of the technologies. What does it mean in terms of societal trends when such devices are developed for the comfort of animals in ways analogous to human luxuries? Is this simply a matter of pursuing productivity?

Table 1. Overview of the Ethical implications of Digital Livestock Farming per level.

Level	Potential Improvements	Concerns and Knowledge Gaps
Animal	▪ Automatic and continuous sampling of objective parameters to improve health and welfare; ▪ Potential for increased autonomy, such as choosing when to be milked.	▪ This could lead to increased objectification of animals, being just another part of the system and through digitalization of the habitat; ▪ Decreases human–animal interactions; ▪ Accuracy, reliability, and efficiency of the machinery needs to be validated; ▪ Algorithms and target values must be carefully considered to take into account individual differences; ▪ A holistic, multi-modal approach has to be taken to assess each platform per species, e.g., through a bioethical analysis.
Farmer	▪ Limits repetitive, time- and labor-consuming tasks done by the farmer; ▪ Increases productivity while minimizing environmental impact leading to potentially more income after initial investment; ▪ Automatic and constant monitoring of the entire farm, even remotely.	▪ Need for a new specialist, digital skills and advisory support; ▪ Reduces farmer's autonomy as they depend more on technology; ▪ Changes the job and will lead to job losses; ▪ Interpretation of complex systems can increase mental workload; ▪ Lack of trust between farmers and tech companies; ▪ Lack of a framework regarding data ownership, usage, storage and misuse.
Society and the Planet	▪ Addresses the increasing customer demand for better animal welfare; ▪ Decreases farm animal and human health issues by reducing disease and the need for antibiotics; ▪ It can aid in reducing pollution, emissions of greenhouse gases and energy consumption.	▪ Provides more transparency toward the customer due to increased traceability; ▪ Lack of public acceptance, but society is also relatively unaware of the advantages and disadvantages of PLF; ▪ Other attitudes are still unknown, such as those of veterinarians and stakeholders; ▪ The added value of PLF has not been quantified yet, and there is a need for Life Cycle Assessment.

3.15. The Limits of Biology and the Case of Dead-On-Arrival

Digital technologies enable the development of phenotyping and breeding of pigs that will have good heart conditions despite their body weight. Digital technologies can be used to derive digital biomarkers and use such biomarkers to select desirable heart traits through breeding in pigs. Digital biomarkers are digital measurements of phenotypes that are categorized according to the intended use of the collected data [32]. Biomarkers may allow for selective breeding since they facilitate the observation of phenotypes that are partly determined by genes that can be selected.

A related issue is that of heat stress. Pigs may often die during transportation from commercial farmers to slaughterhouses due to heat stress [33]. One possible way to stop this may be to use biomarkers in order to constantly monitor pigs and take preventative or palliative measures, if necessary, to reduce the incidence of dead-on-arrival cases. Another possibility is to use the data from biomarkers to breed more heat-resistant pigs. This is of particular importance given how global warming is expected to affect livestock well-being, which calls for a search for ways to adapt [34].

Similarly, digital biomarkers may provide a solution in the realm of antibiotic-related challenges. Often, farmers are unable to identify diseases in livestock before they arise due to limited capacities for phenotype observation and analysis. This means that farmers are often forced to apply antibiotics to livestock, which may have a negative effect on sales since consumers may be reluctant to consume meat from animals that have received

antibiotics. One solution to this would be to use biomarkers in order to identify diseases preventively and avoid the need to apply antibiotics as a curative measure.

A further example that highlights the potential uses of digital biomarkers concerns so-called "exploding chickens" or broiler chickens—that is, chickens that are raised to reach their maximum weight as early as possible for commercial purposes. Broiler chickens raise significant concerns about animal welfare. One common issue that affects the well-being of those chickens is respiratory problems. Biomarking can help identify such issues in order to potentially address them since certain respiratory diseases are correlated with detectable abnormal sounds in broiler chickens [35].

Relatedly, the use of biomarkers for selective breeding can lead to potential conflicts between the constant drive to push the boundaries of biological limits and ethical qualms. One may see this in the case of broiler chickens. Apart from the problems arising from their living conditions and the physiological consequences of forcing chickens to grow so quickly, we may identify a certain unease that arises from the idea of engineering life in order to attain the limits of what is possible in terms of productivity. This may lead to concerns that life is being excessively commoditized and reduced to a mere asset whose productivity must be maximized without any regard for what is natural or for the integrity of farm animals.

Inevitably, this leads to a conundrum that can only be solved through a delicate balancing act. Livestock productivity is of paramount importance in order to secure consumer demands, guarantee profitability and guarantee global food security [36]. It is no longer possible to raise animals according to traditional methods that used to require animals to grow for extensive periods of time before being ready for consumption. The demands of productivity must, therefore, be reconciled with animal welfare concerns about the implications of the "race to the limit" in extracting economic value from livestock. One possible solution may be to develop a framework that will allow us to determine how much is too much optimization, making sure to leave some room for farm animals to enjoy some minimal levels of quality of life and something approaching, to the extent possible, a completely natural life cycle.

3.16. Ethical Approaches

The ethical dimension of DLF can be explored by looking at four strategies (Figure 2) in understanding the impact of DLF and the way that it accounts for animal well-being.

Strategy 1: Sorry. If the animal becomes ill, we cannot help it, and we cannot cure it. The only option is for it to be culled. An example is diagnosing a seriously ill animal, such as a pig, as being antibiotic resistant. Most of the time, the animal, or the particular group of pigs that it belongs to, is culled, as it would not be economical for the farmer to treat them and also to avoid the possibility of contagion by other animal units within the farm. "Sorry" may be considered the least ethical strategy, as it involves the culling of animals that are deemed too costly to treat or too contagious to keep alive. While culling may be necessary in some cases, it is important to ensure that it is done in a humane and respectful manner and that alternatives to culling are explored where possible.

This solution involves culling animals that cannot be helped or cured when they become ill. While this approach may be necessary in some cases, it can raise ethical concerns if animals are being culled unnecessarily or if the reasons for culling are based purely on economic considerations rather than animal welfare. One way to address this issue is to improve disease prevention measures through the use of digital tools and monitoring systems, such as real-time monitoring of animal health and behavior. By identifying and addressing potential health issues early on, farmers can reduce the need for culling and improve overall animal welfare.
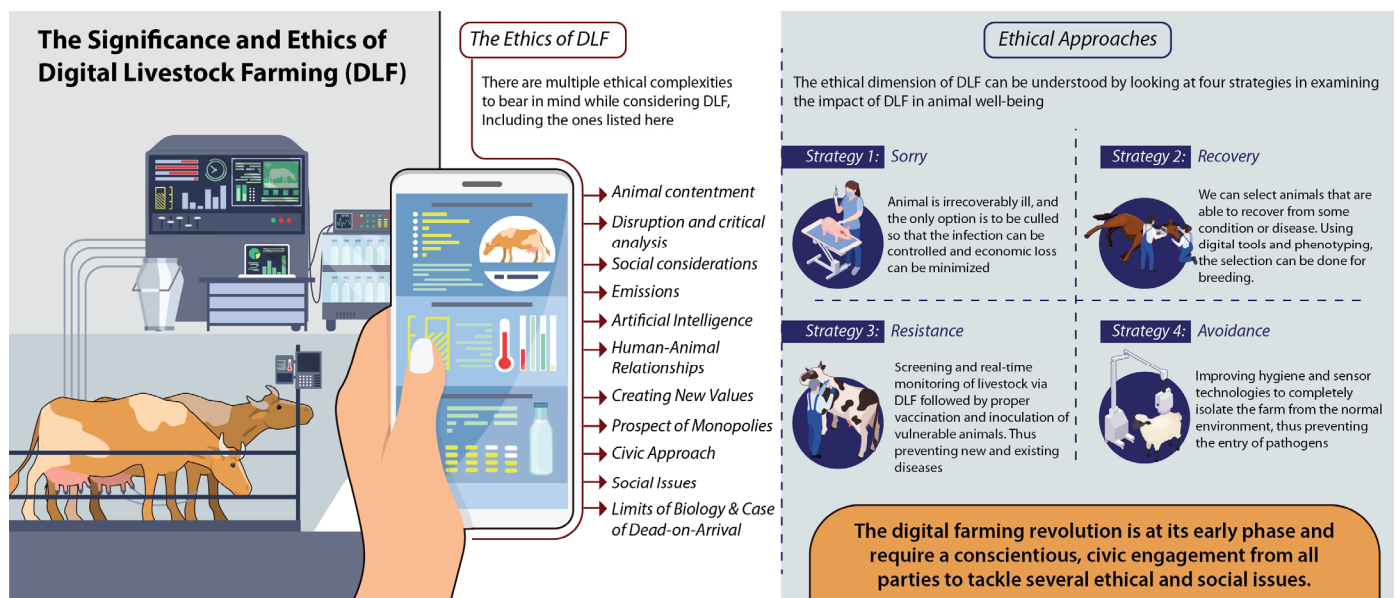
Figure 2. Roadmap to the digital transformation of modern livestock farming while integrating social and ethical awareness. Four strategies for the exploration of the ethical dimensions of digital livestock farming.

Strategy 2: Recovery. Farmers hope that the animal can recover. Here, we can select animals that are able to recover from some condition or disease. "Recovery" is a more optimistic strategy that focuses on breeding animals that are more resilient to disease and better able to recover from illness. This strategy emphasizes the importance of selecting desirable traits and genetics and may involve the use of digital phenotyping to identify animals that are better able to recover from certain conditions.

This solution involves selecting animals that are able to recover from certain conditions or diseases using digital phenotyping and breeding. By selecting desirable traits, such as good heart health or heat resistance, farmers can breed healthier animals and reduce the risk of disease or mortality. However, this approach can raise concerns about the ethical implications of genetic modification and selective breeding. It is important to consider the potential risks and benefits of these practices and ensure that animals are not subjected to unnecessary harm or suffering in the process.

Strategy 3: Resistance. This strategy emphasizes the importance of proactive measures to prevent illness and disease rather than simply reacting to outbreaks as they occur. DLF can be used to screen for potential diseases and to monitor animals in real-time, allowing farmers to intervene early and prevent the spread of disease.

This solution involves using inoculations or other forms of protection to prevent illness in animals, as well as screening and real-time monitoring using digital platforms to identify and prevent diseases. This approach can be effective in reducing disease and mortality rates, but it can also raise ethical concerns about the use of antibiotics and other treatments that may have negative effects on animal health or the environment. It is important to balance the benefits of disease prevention with the potential risks and ensure that animals are not being subjected to unnecessary harm or suffering.

Strategy 4: Avoidance. Here, the farm animal is not concerned with the system. By manipulating the environment, disease-causing pathogens are prevented from entering, thereby protecting the animal. In this way, the animal may be shielded from becoming ill, such as by improving hygiene or by sensor technologies that block certain factors and players in the environment. Rather than making the animal fit for the environment, by using digital tools, we adapt the environment to the needs of the animal. "Avoidance" is a strategy that focuses on adapting the environment to meet the needs of the animal. This strategy emphasizes the importance of providing a healthy and hygienic environment for animals

and may involve the use of sensor technologies to monitor and control environmental factors that can affect animal well-being.

This solution involves manipulating the environment to prevent disease-causing pathogens from entering, using digital tools such as sensor technologies and improved hygiene practices. This approach can be effective in reducing disease and mortality rates, but it can also raise ethical concerns about the impact of these interventions on animal behavior and well-being. It is important to ensure that animals are not being subjected to unnecessary stress or discomfort as a result of these interventions and that their natural behaviors and needs are being respected.

The key to addressing ethical problems in digital livestock farming is to balance the need for productivity and profitability with the need to ensure that animals are being treated humanely and that their welfare is being prioritized. By using a combination of these four solutions, and carefully considering the potential risks and benefits of each approach, it is possible to develop more ethical and sustainable practices in digital livestock farming.

4. Technological Change and Innovation

Aspects of DLF having to do with technological change and innovation shall be discussed. There are currently some interesting novel tools and developments happening worldwide under the DLF umbrella. However, we are at the tip of the iceberg, or at best, we have just started scratching the surface. DLF will be here for at least a couple of decades, with many significant developments still lying ahead of us.

4.1. Market Growth

Generally speaking, based on market research analysis, we can say that the precision agriculture market is projected to reach US $52.3 billion by 2030 at an annual growth rate of 10.67% [37]. This is a large number, but it includes both the crop and livestock farming sectors. Focusing on livestock, veterinary animals and farm animals alone, growth would be around US $19.37 billion by 2030 [38]. The whole DLF market can be categorized into multiple segments (animal monitoring technologies, animal biotechnologies, sensors/wearables, data (without the hardware component), etc.). We have to look carefully at what context the technologies are being applied in while considering these numbers. Obviously, North America will be the dominant player in the DLF area, followed by Europe, while the core and seminal R&D work will be led by EU countries.

4.2. Adoption

Based on surveys done by research groups, we can confidently say that farmers are more than willing, and indeed happy, to embrace DLF technologies, as it helps them to cut time in farm management and provides convenience, such as remote management and predictive capabilities [39]. Nonetheless, there are some reservations in farmers' minds. One of the major concerns we hear from them is the narrow profit margins and questions about who "owns" the data collected via these tools [40].

When mobile phones were introduced 30 years ago, they were very heavy, large brick-like objects. People had concerns about their potential to cause job loss, cancer, brain damage, and many other issues. And yet, everyone now lives with a mobile phone for multiple hours a day. Despite this, not much has resulted in terms of disruption regarding health (generally speaking). The common public has adapted, embraced and learned to live with mobile phone technologies. Extrapolating on this, we may perhaps conclude that digital livestock farming technology will not necessarily lead to bad outcomes down the road.

4.3. Changes in Worker Profiles

We live in a new world, a digital world. This is a new situation where it is not enough merely to regard farmers as laborers who may have extensive experience with phenotyping and may immediately detect issues affecting livestock, together with a pertinent solution.

Rather, we must go beyond this paradigm of experience-based competency that may be overly reliant on subjectivity. Digitization can introduce a supplemental element of objectivity in this respect. This will also reduce the work burden on farmers, who will profit from the ability of digital technologies and platforms to assist in decision-making and animal management. If something breaks, the system will try to fix it on its own, but with the intervention and approval of the human expert or the farmer, creating a dual and complementary system. This may also lead to a new professional class of "digital experts" who may fix things akin to how a plumber or electrician may do so when a farmer is not able to resolve an issue on their own.

With respect to more specific developments in DLF, below are a couple of noteworthy developments that are influencing each other:

4.4. Digital Twins

A digital twin can be defined as "a virtual representation of a physical asset enabled through data and simulators for real-time prediction, optimization, monitoring, controlling, and improved decision-making" [41]. In this way, the physical animal may be seen as the source of the data for its virtual twin.

In the past, farming was entirely based on monitoring physical animals, but now we may also use their digital twins as proxies that can be used to monitor them without physical contact or direct observation. For example, this could replace the need for blood samples, visually measuring and observing the animals instead and integrating the sampled data into their virtual twins. This represents a gradual shift of balance, in which the "virtual animal" becomes increasingly important and influences the physical animal, as the former can be used to make predictions about the latter.

4.5. Artificial Intelligence

Artificial intelligence can automate the development of analytical models via algorithms that basically "learn" from data. The algorithms are then able to update the models continuously and instantaneously, paving the path for real-time predictions. This offering of real-time modeling and periodical predictions makes AI powerful. However, the models are restricted to forecasting the effects of data that is similar to that obtained in the past. AI-enabled models tend to produce inaccurate results upon extrapolation beyond observed bounds.

Biased data or missing data in modeling, with or without an AI-based and data-driven method, can provide flawed models while exploring the future based only on the past. The over-dependence on data-driven models for decision-making based on past lessons and past experiences in modern animal farming is risky and makes the model fragile. This can be a major shortcoming during pandemics or other major incidents in animal farming. Data-driven models can indeed be worse when developing simulations or prediction platforms if they are exposed to previously unseen events. However, AI algorithms can overcome this hurdle by enabling the prediction of situations and incidents that have never occurred before by running hypothetical scenarios outside of conventional bounds. This can be done via enhanced theory and causal hypotheses about the farming system by taking a systematic approach, thoroughly understanding the processes involved, and implementing high-fidelity methodologies.

Generative adversarial networks and self-learning approaches come in handy to enable accurate predictions about various states/phases of livestock farming activity, which can then match the predicted output by simulated trajectories. Even a huge volume of "outside-the-known-parameter" data can be generated via simulation to train the model to such an extent that it becomes able to provide critical insights regarding unknown future events [10].

To be able to create sensible predictions, AI-enabled simulations have to precisely reflect the processes involved in the systems to which they are being applied. In terms of hybrid modeling (consider a gray box model), mixing various modeling paradigms

is possible via AI approaches, which allows the animal scientist to create a "bouquet" (combining multiple flowers from various plants) or a "cocktail" into a powerful platform.

Agent-based simulation models can account for deviations from optimization, environmental exploitation, or lapses of rationality. The AI models can then predict how the system can reconfigure itself via "adaptation" in the context of animal farming. This specific capability of AI will allow animal farming to stay ahead of human responses and interventions. Methods and technologies to build very powerful simulations are available already. The trend now is not to rely merely on collecting data from the real world but to venture into a "metaverse" or "virtual world" and create and develop various "what-if scenarios", converting the virtual digital world into trillions of terabytes of data at a meager cost.

Resource optimization can be taken to the maximum level via digital/smart farming approaches. There is a remote possibility of "desire discrepancy" due to digitalization, which may influence the next generation of consumers to refrain from eating artificially "selected" meat in the future. For example, it is known that consumers are often reluctant to adopt new technology-based food, in great measure, on how the technology is presented [42]. Due to an evolving consciousness caused by digitalization among the Gen Z and Gen Alpha cohorts, the emphasis on the transparency of meat production would matter in making choices about food. However, these are issues that seem eminently addressable by finding approaches to engage productively with consumer attitudes.

5. Responsible Research and Innovation

Responsible Research and Innovation (RRI) is an approach to innovation that seeks to integrate ethical, social, and environmental considerations [43] into the research and innovation process. It aims to ensure that the development and use of new technologies align with the values and needs of society.

Digital livestock farming is an innovative way of managing livestock that uses digital technologies such as big data, sensors, and the Internet of Things (IoT) to improve efficiency and productivity. The use of sensors and big data enables farmers to collect and analyze data on various aspects of animal health, behavior, and performance, helping them to make informed decisions about the management of their animals.

Farmers' perceptions play a crucial role [44] in the adoption of innovation in agriculture. Policymakers and researchers need to understand farmers' views and concerns in order to develop policies and technologies that are acceptable and useful to farmers. This requires engaging with farmers and involving them in the innovation process. By understanding farmers' views and involving them in the innovation process, we can ensure that the benefits of these technologies are shared equitably and that the livestock industry becomes more sustainable and resilient.

In a digitally focused era, RRI places emphasis on engaging stakeholders such as farmers, animal caretakers, researchers, veterinarians, animal scientists and policymakers in the design and implementation of research activities in a bid to ensure that the Digital Livestock Farming technologies are ethical, safe, and beneficial to society.

5.1. Ethics, Law, and Governance

From an ethical standpoint, digital livestock farming raises issues of animal rights and welfare, as well as data privacy and security. From a legal perspective, the use of digital tools for livestock management is subject to existing legislation, as well as new laws such as GDPR. Finally, from a governance perspective, there is a need to ensure that digital livestock farming is regulated in a way that is fair and effective.

5.2. Digital & Precision Livestock Big Data

One of the key aspects of digital livestock farming is the generation of large amounts of data. This data can be used to gain insights into livestock behavior, health, and performance. It can also be used to develop digital & precision livestock farming systems, which employ

data-driven decision-making to optimize animal husbandry and production. Big data refers to the massive amounts of data generated by various sources, including sensors and IoT devices. The ethical dimensions of digital livestock farming and the use of big data include privacy concerns, data ownership, and the potential for unequal access to these technologies. It is important to ensure that the benefits of these technologies are shared equitably and that farmers have control over the data they generate. The use of big data in digital & precision livestock farming raises important ethical and legal considerations, namely, the protection of data privacy, data security, and transparency. Furthermore, there is a need to ensure that data-driven decision-making is fair and equitable and that any decisions made with the use of big data do not discriminate against certain groups.

In order for digital livestock farming to revolutionize the way farmers raise and manage animals and for this to happen responsibly and ethically, it is important to consider the ethical, legal and governance challenges associated with this type of farming. The use of big data in precision livestock farming must be carefully regulated.

5.3. Micro-Innovations

Micro-innovations refer to small improvements or adaptations [45] made to existing technologies or the development of new ones. In the context of digital livestock farming, these innovations can include the use of sensors, big data, and artificial intelligence (AI) to optimize the management of livestock and improve the sustainability of animal agriculture. The ethical and social implications of digital livestock farming are significant and need to be considered in order to ensure the responsible and sustainable development of these technologies. For example, privacy concerns and data ownership issues need to be addressed to ensure that farmers retain control over the data they generate and that their rights and interests are protected.

Responsible technological innovation is crucial in ensuring that the benefits of digital livestock farming are realized while avoiding any unintended consequences that might negatively impact the resilience [46] of the livestock industry. The role of technology as a mediator of resilience-enhancing social behavior should not be underestimated, as it can help animal farmers to adopt more sustainable practices and overcome uncertainties and challenges they face.

Micro-innovations in digital livestock farming have the potential to improve the efficiency and sustainability of animal agriculture, but it is important to approach these innovations responsibly and with consideration for the ethical and social implications involved. By taking a responsible and holistic approach to technological innovation, we can ensure that the benefits of these technologies are shared equitably and that the livestock industry becomes more resilient and sustainable.

6. Summary

The ethics of digital livestock farming is an emerging field that focuses on the ethical implications of using digital technologies in animal agriculture. As the use of digital technologies in agriculture continues to grow, there are several key areas where future research in the ethics of digital livestock farming is likely to focus:

Animal welfare: One of the most important ethical considerations in digital livestock farming is the impact of digital technologies on animal welfare. Future research is likely to focus on developing and implementing digital technologies that can improve animal welfare, such as sensors and other monitoring devices that can detect signs of distress or illness in animals and trigger appropriate interventions.

Data privacy and ownership: Another key ethical concern in digital livestock farming is the collection, storage, and use of data generated by digital technologies. Future research will need to address issues of data privacy and ownership to ensure that farmers and other stakeholders have control over the data generated by these technologies and that it is used in an ethical and responsible manner.

Environmental sustainability: Digital livestock farming has the potential to improve the environmental sustainability of animal agriculture by reducing waste, improving efficiency, and decreasing the environmental impact of livestock production. Future research will need to explore the environmental benefits and costs of different digital technologies and their impact on the overall sustainability of animal agriculture.

Labor and social justice: Digital livestock farming is likely to have a significant impact on the labor market in agriculture, and there are concerns about the impact of these technologies on farmworkers and their communities. Future research will need to address issues of labor and social justice in the context of digital livestock farming, including the potential for automation to displace human workers and the need to ensure fair labor practices and working conditions.

Ethical governance: Finally, future research in the ethics of digital livestock farming will need to address issues of ethical governance, including the development of standards and guidelines for the responsible use of digital technologies in animal agriculture and the establishment of regulatory frameworks that can ensure that these technologies are used in an ethical and responsible manner.

To achieve a more ethical approach to DLF, there needs to be a shift in the goals and values of livestock farming, moving beyond profit as the sole objective. The use of DLF can aid in this ethical pursuit by providing tools and techniques to improve animal welfare, reduce environmental impacts, and promote sustainable practices.

Research on the ethical implications of DLF is a growing field, and many organizations and researchers are actively engaged in studying the impact of DLF on animal welfare, environmental sustainability, and ethical considerations. For example, organizations such as the World Wildlife Fund, the Humane Society, and Compassion in World Farming are actively involved in researching and advocating for ethical practices in livestock farming, including the use of DLF.

Furthermore, academic research in fields such as animal science, agricultural engineering, and computer science is also exploring the potential benefits and ethical implications of DLF. For instance, researchers are exploring the use of digital biomarkers to monitor animal health and welfare, the use of precision feeding systems to reduce feed waste and improve nutrient utilization, and the use of predictive analytics to improve herd management and reduce environmental impacts.

Achieving ethical DLF requires a multidisciplinary approach involving collaboration between stakeholders such as farmers, researchers, industry organizations, and animal welfare advocates. It also requires a commitment to ongoing research and evaluation of the impact of DLF on animal welfare, environmental sustainability, and ethical considerations to ensure that technological advancements are used in a responsible and sustainable manner.

The digital farming revolution is just beginning, and it calls for a conscientious civic engagement of all the parties involved, including farmers, scientists, ethicists, and consumers. In this way, DLF is a prime example of the complex interconnections that make us all co-actors in the construction of a common future.

References

1. Neethirajan, S. Is Seeing Still Believing? Leveraging Deepfake Technology for Livestock Farming. *Front. Vet. Sci.* **2021**, *8*, 740253. [CrossRef] [PubMed]
2. Wathes, C.M.; Kristensen, H.H.; Aerts, J.-M.; Berckmans, D. Is precision livestock farming an engineer's daydream or nightmare, an animal's friend or foe, and a farmer's panacea or pitfall? *Comput. Electron. Agric.* **2008**, *64*, 2–10. [CrossRef]
3. Banhazi, T.; Lehr, H.; Black, J.; Crabtree, H.; Schofield, P.; Tscharke, M.; Berckmans, D. Precision Livestock Farming: An international review of scientific and commercial aspects. *Int. J. Agric. Biol. Eng.* **2012**, *5*, 1–9.
4. Berckmans, D. Precision livestock farming technologies for welfare management in intensive livestock systems. *Rev. Sci. Tech. L'oie* **2014**, *33*, 189–196. [CrossRef] [PubMed]
5. Berckmans, D. General introduction to precision livestock farming. *Anim. Front.* **2017**, *7*, 6–11. [CrossRef]
6. Aquilani, C.; Confessore, A.; Bozzi, R.; Sirtori, F.; Pugliese, C. Review: Precision Livestock Farming technologies in pasture-based livestock systems. *Animal* **2021**, *16*, 100429. [CrossRef] [PubMed]
7. Shepherd, M.; Turner, J.A.; Small, B.; Wheeler, D. Priorities for science to overcome hurdles thwarting the full promise of the 'digital agriculture' revolution. *J. Sci. Food Agric.* **2020**, *100*, 5083–5092. [CrossRef]
8. Basso, B.; Antle, J. Digital agriculture to design sustainable agricultural systems. *Nat. Sustain.* **2020**, *3*, 254–256. [CrossRef]
9. Ozdogan, B.; Gacar, A.; Aktas, H. Digital Agriculture Practices in The Context of Agriculture 4.0. *J. Econ. Financ. Account.* **2017**, *4*, 186–193. [CrossRef]
10. Morota, G.; Ventura, R.V.; Silva, F.F.; Koyama, M.; Fernando, S.C. Big data analytics and precision animal agriculture symposium: Machine learning and data mining advance predictive big data analysis in precision animal agriculture. *J. Anim. Sci.* **2018**, *96*, 1540–1550. [CrossRef]
11. Ivanov, S.; Bhargava, K.; Donnelly, W. Precision Farming: Sensor Analytics. *IEEE Intell. Syst.* **2015**, *30*, 76–80. [CrossRef]
12. Koltes, J.E.; Cole, J.B.; Clemmens, R.; Dilger, R.N.; Kramer, L.M.; Lunney, J.K.; McCue, M.E.; McKay, S.D.; Mateescu, R.G.; Murdoch, B.M.; et al. A Vision for Development and Utilization of High-Throughput Phenotyping and Big Data Analytics in Livestock. *Front. Genet.* **2019**, *10*, 1197. [CrossRef] [PubMed]
13. Wolfert, S.; Ge, L.; Verdouw, C.; Bogaardt, M.-J. Big Data in Smart Farming—A Review. *Agric. Syst.* **2017**, *153*, 69–80. [CrossRef]
14. Van der Burg, S.; Bogaardt, M.-J.; Sjaak, W. Ethics of smart farming: Current questions and directions for responsible innovation towards the future. *NJAS—Wagening. J. Life Sci.* **2019**, *90–91*, 100289. [CrossRef]
15. Llonch, P.; Mainau, E.; Ipharraguerre, I.R.; Bargo, F.; Tedó, G.; Blanch, M.; Manteca, X. Chicken or the Egg: The Reciprocal Association Between Feeding Behavior and Animal Welfare and Their Impact on Productivity in Dairy Cows. *Front. Veter- Sci.* **2018**, *5*, 305. [CrossRef]
16. Schillings, J.; Bennett, R.; Rose, D.C. Exploring the Potential of Precision Livestock Farming Technologies to Help Address Farm Animal Welfare. *Front. Anim. Sci.* **2021**, *2*, 1–17. [CrossRef]
17. Yadav, S.; Kaushik, A.; Sharma, M.; Sharma, S. Disruptive Technologies in Smart Farming: An Expanded View with Sentiment Analysis. *Agriengineering* **2022**, *4*, 424–460. [CrossRef]
18. Rotz, S.; Duncan, E.; Small, M.; Botschner, J.; Dara, R.; Mosby, I.; Reed, M.; Fraser, E.D.G. The Politics of Digital Agricultural Technologies: A Preliminary Review. *Sociol. Rural.* **2019**, *59*, 203–229. [CrossRef]
19. Rotz, S.; Gravely, E.; Mosby, I.; Duncan, E.; Finnis, E.; Horgan, M.; LeBlanc, J.; Martin, R.; Neufeld, H.T.; Nixon, A.; et al. Automated pastures and the digital divide: How agricultural technologies are shaping labour and rural communities. *J. Rural. Stud.* **2019**, *68*, 112–122. [CrossRef]
20. Ignatova, E. Professional Standard as an Incentive for the Development of Polytechnic Education. *Adv. Econ. Bus. Manag. Res.* **2020**, *128*, 1833–1837. [CrossRef]
21. Hackfort, S. Patterns of Inequalities in Digital Agriculture: A Systematic Literature Review. *Sustainability* **2021**, *13*, 12345. [CrossRef]
22. Muñoz-Tamayo, R.; Agudelo, J.F.R.; Dewhurst, R.J.; Miller, G.; Vernon, T.; Kettle, H. A parsimonious software sensor for estimating the individual dynamic pattern of methane emissions from cattle. *Animal* **2019**, *13*, 1180–1187. [CrossRef] [PubMed]
23. Ma, S.; Li, J.; Wei, W. The carbon emission reduction effect of digital agriculture in China. *Environ. Sci. Pollut. Res.* **2022**, *29*, 1–18. [CrossRef]
24. Wischmeyer, T. Artificial Intelligence and Transparency: Opening the Black Box. *Regul. Artif. Intell.* **2019**, 75–101. [CrossRef]
25. Du, X.; Lao, F.; Teng, G. A Sound Source Localisation Analytical Method for Monitoring the Abnormal Night Vocalisations of Poultry. *Sensors* **2018**, *18*, 2906. [CrossRef]
26. Du, X.; Carpentier, L.; Teng, G.; Liu, M.; Wang, C.; Norton, T. Assessment of Laying Hens' Thermal Comfort Using Sound Technology. *Sensors* **2020**, *20*, 473. [CrossRef] [PubMed]
27. Friel, M.; Kunc, H.P.; Griffin, K.; Asher, L.; Collins, L.M. Positive and negative contexts predict duration of pig vocalisations. *Sci. Rep.* **2019**, *9*, 1–7. [CrossRef]
28. Mota-Rojas, D.; Broom, D.M.; Orihuela, A.; Velarde, A.; Napolitano, F.; Alonso-Spilsbury, M. Effects of human-animal relationship on animal productivity and welfare. *J. Anim. Behav. Biometeorol.* **2020**, *8*, 196–205. [CrossRef]
29. Wang, Y.-N.; Jin, L.; Mao, H. Farmer Cooperatives' Intention to Adopt Agricultural Information Technology—Mediating Effects of Attitude. *Inf. Syst. Front.* **2019**, *21*, 565–580. [CrossRef]

30. Syukta, M. Big Data in Agriculture: Property Rights, Privacy and Competition in Ag Data Services. *Int. Food Agribus. Manag. Rev.* **2016**, *19*, 57–74.
31. Keeling, L.; De Oliveira, D.; Rustas, B.-O. *Precision Dairy Farming Use of Mechanical Rotating Brushes in Dairy Cows—A Potential Proxy for Performance and Welfare?* Wageningen Academic Publishers: Leeuwarden, The Netherlands, 2016; pp. 343–347.
32. Neethirajan, S.; Kemp, B. Digital Phenotyping in Livestock Farming. *Animals* **2021**, *11*, 2009. [CrossRef] [PubMed]
33. Averós, X.; Knowles, T.G.; Brown, S.N.; Warriss, P.D.; Gosálvez, L.F. Factors affecting the mortality of weaned piglets during commercial transport between farms. *Vet. Rec.* **2010**, *167*, 815–819. [CrossRef] [PubMed]
34. Bernabucci, U. Climate change: Impact on livestock and how can we adapt. *Anim. Front.* **2019**, *9*, 3–5. [CrossRef] [PubMed]
35. Liu, L.; Li, B.; Zhao, R.; Yao, W.; Shen, M.; Yang, J. A Novel Method for Broiler Abnormal Sound Detection Using WMFCC and HMM. *J. Sens.* **2020**, *2020*, 2985478. [CrossRef]
36. Baldi, A.; Gottardo, D. Livestock production to feed the planet. Animal Protein: A Forecast of Global Demand Over the Next Years. *Relations* **2017**, *5*, 65–71. [CrossRef]
37. Precedence Research. *Digital Agriculture Market, s.l.: Precedence Research*; Precedence: Ottawa, ON, Canada, 2020.
38. Grand View Research. *Livestock Monitoring Market Size Worth $19.37 Billion by 2030, s.l.: Grand View Research*; Grand View Research: San Francisco, CA, USA, 2020.
39. Blasch, J.; van der Kroon, B.; van Beukering, P.; Munster, R.; Fabiani, S.; Nino, P.; Vanino, S. Farmer preferences for adopting precision farming technologies: A case study from Italy. *Eur. Rev. Agric. Econ.* **2020**, *49*, 33–81. [CrossRef]
40. Papst, F.; Saukh, O.; Römer, K.; Grandl, F.; Jakovljevic, I.; Steininger, F.; Mayerhofer, M.; Duda, J.; Egger-Danner, C. Embracing Opportunities of Livestock Big Data Integration with Privacy Constraints. In Proceedings of the 9th International Conference on the Internet of Things, Bilbao, Spain, 22–25 October 2019; Volume 27, pp. 1–4. [CrossRef]
41. Rasheed, A.; San, O.; Kvamsdal, A.T. *Digital Twin: Values, Challenges and Enablers*; IEEE Access: New York City, NY, USA, 2020; Volume 8, pp. 21980–22012. [CrossRef]
42. Siegrist, M.; Hartmann, C. Consumer acceptance of novel food technologies. *Nat. Food* **2020**, *1*, 343–350. [CrossRef]
43. Burget, M.; Bardone, E.; Pedaste, M. Definitions and conceptual dimensions of responsible research and innovation: A literature review. *Sci. Eng. Ethics* **2017**, *23*, 1–19. [CrossRef]
44. Vecchio, Y.; Di Pasquale, J.; Del Giudice, T.; Pauselli, G.; Masi, M.; Adinolfi, F. Precision farming: What do Italian farmers really think? An application of the Q methodology. *Agric. Syst.* **2022**, *201*, 103466. [CrossRef]
45. Charatsari, C.; Lioutas, E.D.; De Rosa, M.; Vecchio, Y. Technological Innovation and Agrifood Systems Resilience: The Potential and Perils of Three Different Strategies. *Front. Sustain. Food Syst.* **2022**, *6*, 872706. [CrossRef]
46. Owen, R.; Macnaghten, P.; Stilgoe, J. *Responsible Research and Innovation: From Science in Society to Science for Society, with Society*; Routledge Taylor and Francis Group: New York, NY, USA, 2017; pp. 117–126. [CrossRef]