Review

Big Data in Smart Farming – A review

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ABSTRACT

Smart Farming is a development that emphasizes the use of information and communication technology in the cyber-physical farm management cycle. New technologies such as the Internet of Things and Cloud Computing are expected to leverage this development and introduce more robots and artificial intelligence in farming. This is encompassed by the phenomenon of Big Data, massive volumes of data with a wide variety that can be captured, analysed and used for decision-making. This review aims to gain insight into the state-of-the-art of Big Data applications in Smart Farming and identify the related socio-economic challenges to be addressed. Following a structured approach, a conceptual framework for analysis was developed that can also be used for future studies on this topic. The review shows that the scope of Big Data applications in Smart Farming goes beyond primary production; it is influencing the entire food supply chain. Big data are being used to provide predictive insights in farming operations, drive real-time operational decisions, and redesign business processes for game-changing business models. Several authors therefore suggest that Big Data will cause major shifts in roles and power relations among different players in current food supply chain networks. The landscape of stakeholders exhibits an interesting game between powerful tech companies, venture capitalists and often small start-ups and new entrants. At the same time there are several public institutions that publish open data, under the condition that the privacy of persons must be guaranteed. The future of Smart Farming may unravel in a continuum of two extreme scenarios: 1) closed, proprietary systems in which the farmer is part of a highly integrated food supply chain or 2) open, collaborative systems in which the farmer and every other stakeholder in the chain network is flexible in choosing business partners as well for the technology as for the food production side. The further development of data and application infrastructures (platforms and standards) and their institutional embedment will play a crucial role in the battle between these scenarios. From a socio-economic perspective, the authors propose to give research priority to organizational issues concerning governance issues and suitable business models for data sharing in different supply chain scenarios.

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1. Introduction

As smart machines and sensors crop up on farms and farm data grow in quantity and scope, farming processes will become increasingly data-driven and data-enabled. Rapid developments in the Internet of Things and Cloud Computing are propelling the phenomenon of what is called Smart Farming (Sundmaeker et al., 2016). While Precision Agriculture is just taking in-field variability into account, Smart Farming goes beyond that by basing management tasks not only on location but also on data, enhanced by context- and situation awareness, triggered by real-time events (Wolfert et al., 2014). Real-time assisting reconfiguration features are required to carry out agile actions, especially in cases of suddenly changed operational conditions or other circumstances (e.g. weather or disease alert). These features typically include intelligent assistance in implementation, maintenance and use of the technology. Fig. 1 summarizes the concept of Smart Farming along the management cycle as a cyber-physical system, which means that smart devices - connected to the Internet - are controlling the farm system. Smart devices extend conventional tools (e.g. rain gauge, tractor, notebook) by adding autonomous context-awareness by all kind of sensors, built-in intelligence, capable to execute autonomous actions or doing this remotely. In this picture it is already suggested that robots can play an important role in control, but it can be expected that the role of humans in analysis and planning is increasingly assisted by machines so that the cyber-physical cycle becomes almost autonomous. Humans will always be involved in the whole process but increasingly at a much higher intelligence level, leaving most operational activities to machines.
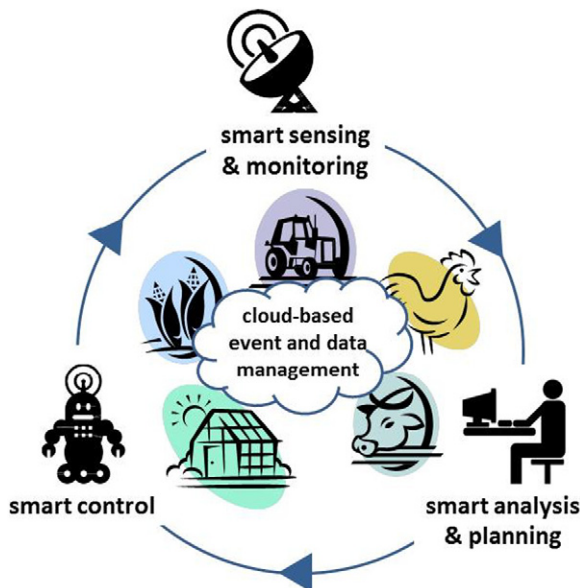

Fig. 1. The cyber-physical management cycle of Smart Farming enhanced by cloud-based event and data management (Wolfert et al., 2014).

Big Data technologies are playing an essential, reciprocal role in this development: machines are equipped with all kind of sensors that measure data in their environment that is used for the machines' behaviour. This varies from relatively simple feedback mechanisms (e.g. a thermostat regulating temperature) to deep learning algorithms (e.g. to implement the right crop protection strategy). This is leveraged by combining with other, external Big Data sources such as weather or market data or benchmarks with other farms. Due to rapid developments in this area, a unifying definition of Big Data is difficult to give, but generally it is a term for data sets that are so large or complex that traditional data processing applications are inadequate (Wikipedia, 2016). Big data requires a set of techniques and technologies with new forms of integration to reveal insights from datasets that are diverse, complex, and of a massive scale (Hashem et al., 2015). Big Data represents the information assets characterized by such a high volume, velocity and variety to require specific technology and analytical methods for its transformation into value (De Mauro et al., 2016). The Data FAIRport initiative emphasizes the more operational dimension of Big Data by providing the FAIR principle meaning that data should be Findable, Accessible, Interoperable and Reusable (Data FAIRport, 2014). This also implies the importance of meta-data i.e. 'data about the data' (e.g. time, location, standards used, etc.).

Both Big Data and Smart Farming are relatively new concepts, so it is expected that knowledge about their applications and their implications for research and development is not widely spread. Some authors refer to the advent of Big Data and related technology as another technology hype that may fail to materialize, others consider Big Data applications may have passed the 'peak of inflated expectations' in Gartner's Hype Cycle (Fenn and LeHong, 2011; Needle, 2015). This review aims to provide insight into the state-of-the-art of Big Data applications in relation to Smart Farming and to identify the most important research and development challenges to be addressed in the future. In reviewing the literature, attention is paid to both technical and socio-economic aspects. However, technology is changing rapidly in this area and a state-of-the-art of that will probably be outdated soon after this paper is published. Therefore the analysis primarily focuses on the socio-economic impact Big Data will have on farm management and the whole network around it because it is expected that this will have a longer-lasting effect. From that perspective the research questions to be addressed in this review are:

1. What role does Big Data play in Smart Farming?
2. What stakeholders are involved and how are they organized?
3. What are the expected changes that are caused by Big Data developments?
4. [illegible] challenges need to be addressed in relation to the previous questions?

The latter question can be considered as a research agenda for the future.

To answer these questions and to structure the review process, a conceptual framework for analysis has been developed, which is expected to be useful also for future analyses of developments in Big Data and Smart Farming. In the remainder of this paper the

methodology for reviewing the literature (Section 2) and the framework will be described (Section 3). Then the main results from the analysis will be presented in Section 4. Section 5 concludes the review and provides recommendations for further research and actions.

2. Methodology

To address the research questions as outlined in the Introduction, we surveyed literature between January 2010 and March 2015. The choice of the review period was a practical one and took into consideration the fact that Big Data is a rather recent phenomenon; it was not expected that there would be any reference before 2010. Beside the period of publication, we used two inclusion criteria for the literature search: 1) full article publication; 2) relevance to the research question. Two exclusion criteria were used: 1) articles published in languages other than English or Chinese; 2) articles focussing solely on technological design. The literature survey followed a systematic approach. This was done in three steps. In the first step we searched two major bibliographical databases, Web of Science and Scopus, using all combinations of two groups of keywords of which the first group addresses Big Data (i.e. Big Data, data-driven innovation, data-driven value creation, internet of things, IoT) and the second group refers to farming (i.e. agriculture, farming, food, agri-food, precision agriculture). The two databases were chosen because of their wide coverage of relevant literature and advanced bibliometric features such as suggesting related literature or citations. From these two databases 613 peer-reviewed articles were retrieved. These were scanned for relevance by identifying passages that were addressing the research questions. In screening the literature, we first used the search function to locate the paragraphs containing the key words and then read the text to see whether they can be related to the research questions. The screening was done by four researchers, with each of them judging about 150 articles and sharing their findings with the others through the reference management software EndNote X7. As a result, 20 were considered most relevant and 94 relevant. The remaining articles were considered not relevant as they only tangentially touch upon Big Data or agriculture and therefore excluded from further reading and analysis. We found the number of relevant peer-reviewed literature not very high which can be explained because Big Data and Smart Farming are relatively new concepts. Especially the applications are rapidly evolving and expected not to be taken into account in peer-reviewed articles which are usually lagging behind. Therefore we decided to also include grey literature into our review. For that purpose we have used Google Scholar and the search engine LexisNexis for reports, magazines, blogs, and other web-items in English. This has resulted in 3 reports, 225 magazine articles, 319 blogs and 19 items on twitter. Each of the 319 blogs was evaluated on relevance based on its title and sentences containing the search terms. Also possible duplications were removed. The result was a short list containing 29 blogs that were evaluated by further reading. As a result, 9 blogs have been considered as presenting relevant information for our framework. Each of the 225 magazine articles was similarly evaluated on their relevance based on its title and sentences containing the search terms. After removing duplicates, the result is a short list of 25 articles. We then read these 25 articles through for further evaluation. Consequently 9 articles have been considered as containing relevant information for further analysis.

In the second step, we read the selected literature in detail to extract the information relevant to our research questions. Additional literature that had not been identified in the first step was retrieved in this step as well if they were referred to by the 'most relevant' literature. This 'snow-ball' approach has resulted in 11 additional articles and web-items from which relevant information was extracted as well. In the third step, the extracted information was analysed and synthesized following the conceptual framework as described in Section 3.

3. Conceptual framework

For this review a conceptual framework was developed to provide a systematic classification of issues and concepts for the analysis of Big Data applications in Smart Farming from a socio-economic perspective. A major complexity of such applications is that they require collaboration between many different stakeholders having different roles in the data value chain. For this reason, the framework draws upon literature on chain network management and data-driven strategies. Chain networks are considered to be composed of the actors which vertically and horizontally work together to add value to customers (Christopher, 2005; Lazzarini et al., 2001; Omta et al., 2001). An important foundation of chain networks is the concept 'value chain', which is a system of interlinked processes, each adding value to the product of service (Porter, 1985). In big data applications, the value chain refers to the sequence of activities from data capture to decision making and data marketing (Chen et al., 2014; Miller and Mork, 2013).

The often-cited conceptual framework of Lambert and Cooper (2000) on network management comprises three closely interrelated elements: the network structure, the business processes, and the management components. The network structure consists of the member firms and the links between these firms. Business processes are the activities that produce a specific output of value to the customer. The management components are the managerial variables by which the business processes are integrated and managed across the network. The network management component is further divided into a technology and organization component.

For our purpose the framework was tailored to networks for Big Data applications in Smart Farming as presented in Fig. 2.

In this framework, the business processes (lower layer) focus on the generation and use of Big Data in the management of farming processes. For this reason, we subdivided this part into the data chain, the farm management and the farm processes. The data chain interacts with farm processes and farm management processes through various decision making processes in which information plays an important role. The stakeholder network (middle layer) comprises all stakeholders that are involved in these processes, not only users of Big Data but also companies that are specialized in data management and regulatory and policy actors. Finally, the network management layer typifies the organizational and technological structures in the network that facilitate coordination and management of the processes that are performed by the actors in the stakeholder network layer. The technology component of network management (upper layer) focuses on the information infrastructure that supports the data chain. The organizational component focuses on the governance and business model of the data chain. Finally, several factors can be identified as key drivers for the
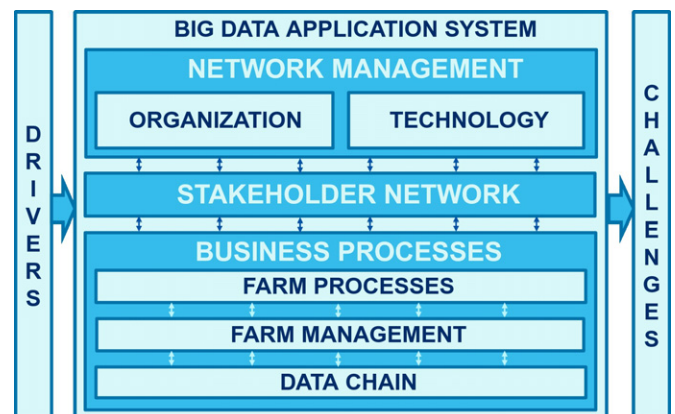
Fig. 2. Conceptual framework for the literature analysis (Adapted from Lambert and Cooper (2000)).

development of Big Data in Smart Farming and as a result challenges can be derived from this development.

The next subsections provide a more detailed description of each subcomponent of the business processes layer and network management layer of the framework.

3.1. Farm processes

A business process is a set of logically related tasks performed to achieve a defined business outcome (Davenport and Short, 1990). Business processes can be subdivided into primary and supporting business processes (Davenport, 1993; Porter, 1985). *Primary Business Processes* are those involved in the creation of the product, its marketing and delivery to the buyer (Porter, 1985). *Supporting Business Processes* facilitate the development, deployment and maintenance of resources required in primary processes. The business processes of farming significantly differ between different types of production, e.g. livestock farming, arable farming and greenhouse cultivation. A common feature is that agricultural production is depending on natural conditions, such as climate (day length and temperature), soil, pests, diseases and weather (Nuthall, 2011).

3.2. Farm management

Management or control processes ensure that the business process objectives are achieved, even if disturbances occur. The basic idea of control is the introduction of a controller that measures system behaviour and corrects if measurements are not compliant with system objectives. Basically, this implies that they must have a feedback loop in which a norm, sensor, discriminator, decision maker, and effector are present (Beer, 1981; in 't Veld, 2002). As a consequence, the basic management functions are (Verdouw et al., 2015) (see also Fig. 1):

- *Sensing and monitoring*: measurement of the actual performance of the farm processes. This can be done manually by a human observer or automated by using sensing technologies such as sensors or satellites. In addition, external data can be acquired to complement direct observations.
- *Analysis and decision making*: compares measurements with the norms that specify the desired performance (system objectives concerning e.g. quantity, quality and lead time aspects), signals deviations and decides on the appropriate intervention to remove the signalled disturbances.
- *Intervention*: plans and implements the chosen intervention to correct the farm processes' performance.

3.3. Data chain

The data chain refers to the sequence of activities from data capture to decision making and data marketing (Chen et al., 2014; Miller and Mork, 2013). It includes all activities that are needed to manage data for farm management. Fig. 3 illustrates the main steps in this chain.

Being an integral part of business processes, the data chain consists necessarily of a technical layer that captures raw data and converts it into information and a business layer that makes decisions and derives value from provided data services and business intelligence. The two layers can be interwoven in each stage and together they form the basis of what has come to be known as the 'data value chain' (Dumbill, 2014) (Table 1).

3.4. Network management organization

The network management organization deals with the behaviour of the stakeholders and how it can be influenced to accomplish the business process objectives. For the uptake and further development of Big Data applications, two interdependent aspects are considered relevant: governance and business model. Governance involves the formal and informal arrangements that govern cooperation within the stakeholder network. Important arrangements for the management of big data include agreements on data availability, data quality, access to data, security, responsibility, liability, data ownership, privacy and distribution of costs. Three basic forms of network governance can be distinguished (Lazzarini et al., 2001): managerial discretion, standardization and mutual adjustment. These forms correspond with the three forms of network governance presented by Provan and Kenis (2008): lead organization-governed network, network administrative organization, and shared participant-governed network. The choice of a particular network governance structure aims at mitigating all forms of contractual hazards found between the different contracting parties in such a way that transaction costs are minimized (Williamson, 1996). When studying hybrid forms of organization such as supply chain networks, two main dimensions should be identified: the allocation of decision rights, i.e., who has the authority to take strategic decisions within the supply chain network, and the inter-organizational mechanisms aiming at rewarding desirable behaviour and preventing undesirable behaviour (risk and rewarding mechanisms).

Despite agreement on the importance of business model to an organization's success, the concept is still fuzzy and vague, and there is little consensus regarding its compositional facets. Osterwalder (2004) defines business model as "… a conceptual tool that contains a set of elements and their relationships and allows *expressing a company's logic of earning money*". It is a description of the value a company offers to one or several segments of customers and the architecture of the firm and its network of partners for creating, marketing and delivering this value and relationship capital, in order to generate profitable and sustainable revenue streams." This definition reflects a so-called firm-centric view of business model. Another view on business model is the network-centric business model which builds upon value network theories (Al-Debei and Avison, 2010). The value network theories consider both financial and non-financial value of business transactions and exchanges. Both views are relevant to the network management of Big Data applications.

3.5. Network management technology

The network management technology includes all computers, networks, peripherals, systems software, application packages (application software), procedures, technical, information and communication
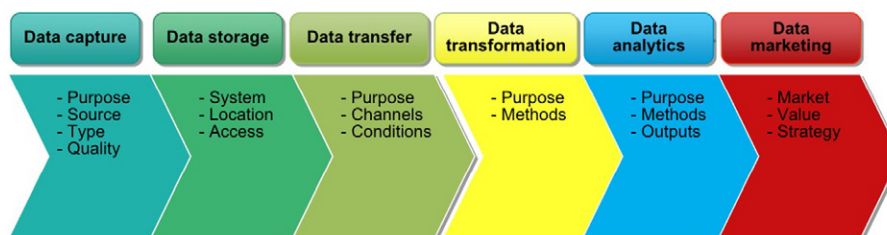
Fig. 3. The data chain of Big Data applications, based on Chen et al. (2014).

Table 1
Key stages of the data chain on technical and business layer.

Layer of data chain	Stages of a data chain			
	Raw material	Processing	Transport	Marketing
Technical	Data generation and capture	Data janitorial work, Data transformation Data analytics	Data transfer	Data transfer Data analytics
Business	Data discovery Data warehousing	Interpreting data, Connecting data to decision (Obtaining business information and insight)	Information share and data integration	Data-driven services

standards (reference information models and coding and message standards) etc., that are used and necessary for adequate data management in the inter-organizational control of farming processes (van der Vorst et al., 2005). Components to be mentioned here encompass:

- Data resources stored in shared databases and a shared understanding of its content (shared data model of the database).
- Information systems and services that allow us to use and maintain these databases. An information system is used to process information necessary to perform useful activities using activities, facilities, methods and procedures.
- The whole set of formalised coding and message standards (both technically and content-wise) with associated procedures for use, connected to shared databases, which are necessary to allow seamless and error-free automated communication between business partners in a food supply chain network.
- The necessary technical infrastructure. None of the above can work if we don't have the connected set of computers (workstations of individual associates or people employed by or interested in the network and the database, communication and application servers and all associated peripherals) that will allow for its usage.

In conclusion, this framework now provides a coherent set of elements to describe and analyse the developments of Big Data in Smart Farming. The results are provided in the next section.

4. Results

4.1. Drivers for Big Data in Smart Farming

There has been a significant trend to consider the application of Big Data techniques and methods to agriculture as a major opportunity for application of the technology stack, for investment and for the realisation of additional value within the agri-food sector (Noyes, 2014; Sun et al., 2013b; Yang, 2014). Big data applications in farming are not strictly about primary production, but play a major role in improving the efficiency of the entire supply chain and alleviating food security concerns (Chen et al., 2014; Esmeijer et al., 2015; Gilpin, 2015a). Currently, big data applications discussed in the literature are taking place primarily in Europe and North America (Faulkner and Cebul, 2014). Considering the growing attention and keen interest shown in the literature, however, the number of applications is expected to grow rapidly in other countries like China (Li et al., 2014; Liu et al., 2012). Big data is the focus of in-depth, advanced, game-changing business analytics, at a scale and speed that the old approach of copying and cleansing all of it into a data warehouse is no longer appropriate (Devlin, 2012). Opportunities for Big Data applications in agriculture include benchmarking, sensor deployment and analytics, predictive modelling, and using better models to manage crop failure risk and to boost feed efficiency in livestock production (Faulkner and Cebul, 2014; Lesser, 2014). In conclusion, Big Data is to provide predictive insights to future outcomes of farming (predictive yield model, predictive feed intake model, etc.), drive real-time operational decisions, and reinvent business processes for faster, innovative action and game-changing business models (Devlin, 2012). Decision-making in the future will be a complex mix

of human and computer factors (Anonymous, 2014b). Big data is expected to cause changes to both the scope and the organization of farming (Poppe et al., 2015). While there are doubts whether farmers' knowledge is about to be replaced by algorithms, Big Data applications are likely to change the way farms are operated and managed (Drucker, 2014). Key areas of change are real-time forecasting, tracking of physical items, and reinventing business processes (Devlin, 2012). Wider uptake of Big Data is likely to change both farm structures and the wider food chain in unexplored ways as what happened with the wider adoption of tractor and the introduction of pesticides in the 1950s.

As with many technological innovations changes by Big Data applications in Smart Farming are driven by push-pull mechanisms. Pull, because there is a need for new technology to achieve certain goals. Push, because new technology enables people or organizations to achieve higher or new goals. This will be elaborated in the next subsections.

4.1.1. Pull factors

From a business perspective, farmers are seeking ways to improve profitability and efficiency by on the one hand looking for ways to reduce their costs and on the other hand obtaining better prices for their product. Therefore they need to take better, more optimal decisions and improve management control. While in the past advisory services were based on general knowledge that once was derived from research experiments, there is an increasing need for information and knowledge that is generated on-farm in its local-specific context. It is expected that Big Data technologies help to achieve these goals in a better way (Poppe et al., 2015; Sonka, 2015). A specific circumstance for farming is the influence of the weather and especially its volatility. Local-specific weather and climate data can help decision-making a lot (Lesser, 2014). A general driver can be the relief of paper work because of all kind of regulations in agri-food production (Poppe et al., 2015).

From a public perspective global food security is often mentioned as a main driver for further technological advancements (Gilpin, 2015b; Lesser, 2014; Poppe et al., 2015). Besides, consumers are becoming more concerned about food safety and nutritional aspects of food related to health and well-being (Tong et al., 2015). In relation to that, Tong et al. (2015) mention the need for early warning systems instead of many ex-post analyses that are currently being done on historical data.

4.1.2. Push factors

A general future development is the Internet of Things (IoT) in which all kinds of devices – smart objects – are connected and interact with each other through local and global, often wireless network infrastructures (Porter and Heppelmann, 2014). Precision agriculture can be considered as an exponent of this development and is often mentioned as an important driver for Big Data (Lesser, 2014; Poppe et al., 2015). This is expected to lead to radical changes in farm management because of access to explicit information and decision-making capabilities that were previously not possible, either technically or economically (Sonka, 2014). As a consequence, there is a rise of many ag-tech companies that pushes this data-driven development further (Lesser, 2014).

Wireless data transfer technology also permits farmers to access their individual data from anywhere – whether they are at the farmhouse or meeting with buyers in Chicago – enabling them to make

informed decisions about crop yield, harvesting, and how best to get their product to market (Faulkner and Cebul, 2014).

Table 2 provides an overview and summarizes the push and pull factors that drive the development of Big Data and Smart Farming.

4.2. Business processes

4.2.1. Farm processes

Agricultural Big Data are known to be highly heterogeneous (Ishii, 2014; Li et al., 2014). The heterogeneity of data concerns for example the subject of the data collected (i.e., what is the data about) and the ways in which data are generated. Data collected from the field or the farm include information on planting, spraying, materials, yields, in-season imagery, soil types, weather, and other practices. There are in general three categories of data generation (Devlin, 2012; UNECE, 2013): (i) process-mediated (PM), (ii) machine-generated (MG) and (iii) human-sourced (HS).

PM data, or the traditional business data, result from agricultural processes that record and monitor business events of interest, such as purchasing inputs, feeding, seeding, applying fertilizer, taking an order, etc. PM data are usually highly structured and include transactions, reference tables and relationships, as well as the metadata that define their context. Traditional business data are the vast majority of what IT managed and processed, in both operational and business information systems, usually structured and stored in relational database systems.

MG data are derived from the vast increasing number of sensors and smart machines used to measure and record farming processes; this development is currently boosted by what is called the Internet of Things (IoT). MG data range from simple sensor records to complex computer logs and are typically well-structured. As sensors proliferate and data

Table 2
Summary of push and pull factors that drive the development of Big Data and Smart Farming.

Push factors	Pull factors
• **General technological developments**	• **Business drivers**
- Internet of Things and data-driven technologies	- Efficiency increase by lower cost price or better market price
- Precision Agriculture	- Improved management control and decision-making
- Rise of ag-tech companies	- Better local-specific management support
• **Sophisticated technology**	- Better cope with legislation and paper work
- Global Navigation Satellite Systems	- Deal with volatility in weather conditions
- Satellite imaging	
- Advanced (remote) sensing	
- Robots	• **Public drivers**
- Unmanned Aerial Vehicles (UAVs)	- Food and nutrition security
	- Food safety
• **Data generation and storage**	- Sustainability
- Process-, machine- and human--generated	
- Interpretation of unstructured data	• **General need for more and better information**
- Advanced data analytics	
• **Digital connectivity**	
- Increased availability to ag practitioners	
- Computational power increase	
• **Innovation possibilities**	
- Open farm management systems with specific apps	
- Remote/computer-aided advise and decisions	
- Regionally pooled data for scientific research and advise	
- On-line farmer shops	

volumes grow, it is becoming an increasingly important component of the farming information stored and processed. Its well-structured nature is suitable for computer processing, but its size and speed is beyond traditional approaches. For Smart Farming, the potential of unmanned aerial vehicles (UAVs) has been well-recognized (Faulkner and Cebul, 2014; Holmes, 2014). Drones with infrared cameras, GPS technology, are transforming agriculture with their support for better decision making, risk management (Anonymous, 2014c). In livestock farming, smart dairy farms are replacing labour with robots in activities like feeding cows, cleaning the barn, and milking the cows (Grobart, 2012). On arable farms, precision technology is increasingly used for managing information about each plant in the field (Vogt, 2013). With these new technologies data is not in traditional tables only, but can also appear in other formats like sounds or images (Sonka, 2015). In the meantime several advanced data analysis techniques have been developed that trigger the use of data in images or other formats (Lesser, 2014; Noyes, 2014).

HM data is the record of human experiences, previously recorded in books and works of art, and later in photographs, audio and video. Human-sourced information is now almost entirely digitized and stored everywhere from personal computers to social networks. HM data are usually loosely structured and often ungoverned. In the context of Big Data and Smart Farming, human-sourced data have rarely been discussed except in relation to the marketing aspects (Verhoosel et al., 2016). Limited capacity with regard to the collection of relevant social media data and semantic integration of these data from a diversity of sources is considered to be a major challenge (Bennett, 2015).

Table 3 provides an overview of current Big Data applications in relation to different elements of Smart Farming in key farming sectors.

From the business perspective, the main data products along the Big Data value chain are (predictive) analytics that provide decision support to business processes at various levels. The use or analysis of sensor data or similar data must somehow fit into existing or reinvented business processes. Integration of data from a variety of sources, both traditional and new, with multiple tools, is the first prerequisite.

4.2.2. Farm management

As Big Data observers point out: big or small, Big Data is still data (Devlin, 2012). It must be managed and analysed to extract its full value. Developments in wireless networks, IoT, and cloud computing are essentially only means to obtain data and generate Big Data. The ultimate use of Big Data is to obtain the information or intelligence embodied or enabled by Big Data. Agricultural Big Data will have no real value without Big Data analytics (Sun et al., 2013b). To obtain Big Data analytics, data from different sources need to be integrated into 'lagoons of data'. In this process, data quality issues are likely to arise due to errors and duplications in data. As shown in Fig. 4, a series of operations on the raw data may be necessary to ensure the quality of data.

Since the advent of large-scale data collections or warehouses, the so-called data rich, information poor (DRIP) problems have been pervasive. The DRIP conundrum has been mitigated by the Big Data approach which has unleashed information in a manner that can support informed - yet, not necessarily defensible or valid - decisions or choices. Thus, by somewhat overcoming data quality issues with data quantity, data access restrictions with on-demand cloud computing, causative analysis with correlative data analytics, and model-driven with evidence-driven applications (Tien, 2013).

Big data on its own can offer 'a-ha' insights, but it can only reliably deliver long-term business advantage when fully integrated with traditional data management and governance processes (Devlin, 2012). Big Data processing depends on traditional, process-mediated data and metadata to create the context and consistency needed for full, meaningful use. The results of Big Data processing must be fed back into traditional business processes to enable change and evolution of the business.

Table 3
Examples of Big Data applications/aspects in different Smart Farming processes (cf. Fig. 1).

Cycle of Smart Farming	Arable	Livestock	Horticulture	Fishery
Smart sensing and monitoring	Robotics and sensors (Faulkner and Cebul, 2014)	Biometric sensing, GPS tracking (Sonka, 2014)	Robotics and sensors (temperature, humidity, CO_2, etc.), greenhouse computers (Sun et al., 2013a)	Automated Identification Systems (AIS) (Natale et al., 2015)
Smart analysis and planning	Seeding, Planting, Soil typing, Crop health, yield modelling (Noyes, 2014)	Breeding, monitoring (Cole et al., 2012)	Lighting, energy management (Li and Wang, 2014)	Surveillance, monitoring (Yan et al., 2013)
Smart control	Precision farming (Sun et al., 2013b)	Milk robots (Grobart, 2012)	Climate control, Precision control (Luo et al., 2012)	Surveillance, monitoring (Yan et al., 2013)
Big Data in the cloud	Weather/climate data, Yield data, Soil types, Market information, agricultural census data (Chen et al., 2014)	Livestock movements (Faulkner and Cebul, 2014; Wamba and Wicks, 2010)	Weather/climate, market information, social media (Verdouw et al., 2013)	Market data (Yan et al., 2013) Satellite data, (European Space Agency, 2016)

4.2.3. Data chain

As often discussed in the literature, a wide range of issues need to be addressed for big data applications. Both technical and governance issues can arise in different stages of the data chain, where governance challenges become increasingly dominant at the later stages of the data chain. Table 4 summarizes the state-of-the-art features of Big Data applications in Smart Farming and the key issues corresponding to each stage of the Big Data chain that were found in literature. At the initial stages, technical issues concerning data formats, hardware, and information standards may influence the availability of big data for further analysis. At the later stages, governance issues such as achieving agreements on responsibilities and liabilities become more challenging for business processes.

4.3. Stakeholder network

In view of the technical changes brought forth by Big Data and Smart Farming, we seek to understand the stakeholder network around the farm. The literature suggests major shifts in roles and power relations among different players in existing agri-food chains. We observed the changing roles of old and new software suppliers in relation to Big Data and farming and emerging landscape of data-driven initiatives with prominent role of big tech and data companies like Google and IBM. In Fig. 5, the current landscape of data-driven initiatives is visualized.

The stakeholder networks exhibits a high degree of dynamics with new players taking over the roles played by other players and the incumbents assuming new roles in relation to agricultural Big Data. As opportunities for Big Data have surfaced in the agribusiness sector, big agriculture companies such as Monsanto and John Deere have spent hundreds of millions of dollars on technologies that use detailed data on soil type, seed variety, and weather to help farmers cut costs and increase yields (Faulkner and Cebul, 2014). Other players include various accelerators, incubators, venture capital firms, and corporate venture funds (Monsanto, DuPont, Syngenta, Bayer, DOW etc.) (Lane, 2015).

Monsanto has been pushing big-data analytics across all its business lines, from climate prediction to genetic engineering. It is trying to persuade more farmers to adopt its cloud services. Monsanto says farmers benefit most when they allow the company to analyse their data - along with that of other farmers - to help them find the best solutions for each patch of land (Guild, 2014).

While corporates are very much engaged with Big Data and agriculture, start-ups are at the heart of action, providing solutions across the value chain, from infrastructure and sensors all the way down to software that manages the many streams of data from across the farm. As the ag-tech space heats up, an increasing number of small tech start-ups are launching products giving their bigger counterparts a run for their money. In the USA, start-ups like FarmLogs (Guild, 2014), FarmLink (Hardy, 2014) and 640 Labs challenge agribusiness giants like Monsanto, Deere, DuPont Pioneer (Plume, 2014). One observes a swarm of data-service start-ups such as FarmBot (an integrated open-source precision agriculture system) and Climate Corporation. Their products are powered by many of the same data sources, particularly those that are freely available such as from weather services and Google Maps. They can also access data gathered by farm machines and transferred wirelessly to the cloud. Traditional agri-IT firms such as NEC and Dacom are active with a precision farming trial in Romania using environmental sensors and Big Data analytics software to maximize yields (NEC, 2014).

Venture capital firms are now keen on investing in agriculture technology companies such as Blue River Technology, a business focusing on

Fig. 4. The flowchart of intelligent processing of agricultural Big Data. (Source: Li et al., 2014)

Table 4
State of the art of Big Data applications in Smart Farming and key issues.

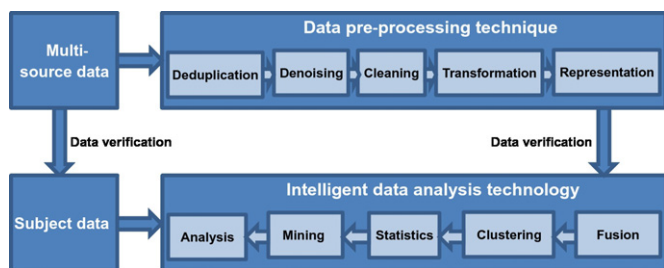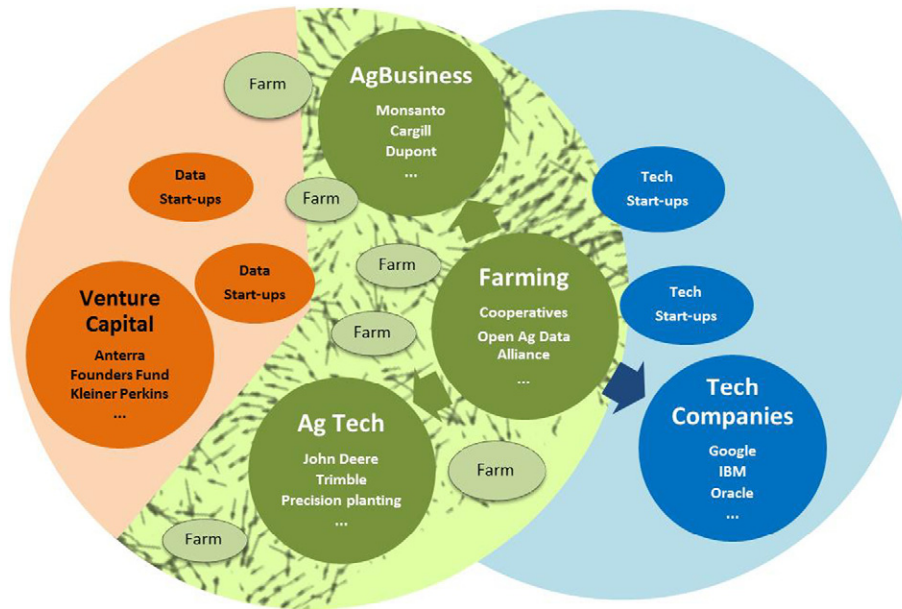| Stages of the data chain	State of the art	Key issues
Data capture	Sensors, Open data, data captured by UAVs (Faulkner and Cebul, 2014) Biometric sensing, Genotype information (Cole et al., 2012) Reciprocal data (Van 't Spijker, 2014)	Availability, quality, formats (Tien, 2013)
Data storage	Cloud-based platform, Hadoop Distributed File System (HDFS), hybrid storage systems, cloud-based data warehouse (Zong et al., 2014)	Quick and safe access to data, costs (Zong et al., 2014)
Data transfer	Wireless, cloud-based platform (Karim et al., 2014; Zhu et al., 2012), Linked Open Data (Ritaban et al., 2014)	Safety, agreements on responsibilities and liabilities (Haire, 2014)
Data transformation	Machine learning algorithms, normalize, visualize, anonymize (Ishii, 2014; Van Rijmenam, 2015)	Heterogeneity of data sources, automation of data cleansing and preparation (Li et al., 2014)
Data analytics	Yield models, Planting instructions, Benchmarking, Decision ontologies, Cognitive computing (Van Rijmenam, 2015)	Semantic heterogeneity, real-time analytics, scalability (Li et al., 2014; Semantic Community, 2015)
Data marketing	Data visualization (Van 't Spijker, 2014)	Ownership, privacy, new business models (Orts and Spigonardo, 2014)

Fig. 5. The landscape of the Big Data network with business players.

the use of computer vision and robotics in agriculture (Royse, 2014). The new players to Smart Farming are tech companies that were traditionally not active in agriculture. For example, Japanese technology firms such as Fujitsu are helping farmers with their cloud based farming systems (Anonymous, 2014c). Fujitsu collects data (rainfall, humidity, soil temperatures) from a network of cameras and sensors across the country to help farmers in Japan better manage its crops and expenses (Carlson, 2012). Data processing specialists are likely to become partners of producers as Big Data delivers on its promise to fundamentally change the competitiveness of producers.

Beside business players such as corporates and start-ups, there are many public institutions (e.g., universities, USDA, the American Farm Bureau Federation, GODAN) that are actively influencing Big Data applications in farming through their advocacy on open data and data-driven innovation or their emphasis on governance issues concerning data ownership and privacy issues. Well-known examples are the Big Data Coalition, Open Agriculture Data Alliance (OADA) and AgGateway. Public institutions like the USDA, for example, want to harness the power of agricultural data points created by connected farming equipment, drones, and even satellites to enable precision agriculture for policy objectives like food security and sustainability. Precision farming is considered to be the "holy grail" because it is the means by which the food supply and demand imbalance will be solved. To achieve that precision, farmers need a lot of data to inform their planting strategies. That is why USDA is investing in big, open data projects. It is expected that open data and Big Data will be combined together to provide farmers and consumers just the right kind of information to make the best decisions (Semantic Community, 2015).

4.4. Network management

4.4.1. Organization

Data ownership is an important issue in discussions on the governance of agricultural Big Data generated by smart machinery such as tractors from John Deere (Burrus, 2014). In particular, value and ownership of precision agricultural data have received much attention in business media (Haire, 2014). It has become a common practice to sign Big Data agreements on ownership and control data between farmers and agriculture technology providers (Anonymous, 2014a). Such agreements address questions such as: How can farmers make use of Big

Data? Where does the data come from? How much data can we collect? Where is it stored? How do we make use of it? Who owns this data? Which companies are involved in data processing?

There is also a growing number of initiatives to address or ease privacy and security concerns. For example, the Big Data Coalition, a coalition of major farm organizations and agricultural technology providers in the USA, has set principles on data ownership, data collection, notice, third-party access and use, transparency and consistency, choice, portability, data availability, market speculation, liability and security safeguards (Haire, 2014). And AgGateway, a non-profit organization with more than 200 member companies in the USA, have drawn a white paper that presents ways to incorporate data privacy and standards (AgGateway, 2014). It provides users of farm data and their customers with issues to consider when establishing policies, procedures, and agreements on using that data instead of setting principles and privacy norms.

The 'Ownership Principle' of the Big Data Coalition states that "We believe farmers own information generated on their farming operations. However, it is the responsibility of the farmer to agree upon data use and sharing with the other stakeholders (...)." While having concerns about data ownership, farmers also see how much companies are investing in Big Data. In 2013, Monsanto paid nearly 1 billion US dollars to acquire The Climate Corporation, and more industry consolidation is expected. Farmers want to make sure they reap the profits from Big Data, too. Such change of thinking may lead to new business models that allow shared harvesting of value from data.

Big data applications in Smart Farming will potentially raise many power-related issues (Orts and Spigonardo, 2014). There might be companies emerging that gain much power because they get all the data. In the agri-food chain these could be input suppliers or commodity traders, leading to a further power shift in market positions (Lesser, 2014). This power shift can also lead to potential abuses of data e.g. by the GMO lobby or agricultural commodity markets or manipulation of companies (Noyes, 2014). Initially, these threats might not be obvious because for many applications small start-up companies with hardly any power are involved. However, it is a common business practice that these are acquired by bigger companies if they are successful and in this way the data still gets concentrated in the hands of one big player (Lesser, 2014). Gilpin (2015b), for example, concluded that Big Data is both a huge opportunity as a potential threat for farmers.

4.4.2. Technology

To make Big Data applications for Smart Farming work, an appropriate technological infrastructure is essential. Although we could not find much information about used infrastructures in literature it can be expected that the applications from the AgTech and AgBusiness companies in Fig. 5 are based on their existing infrastructure that is usually supplied by large software vendors. This has resulted in several proprietary platforms such as AGCO's AgCommand, John Deere's FarmSight or Monsanto's FieldScripts. Initially these platforms were quite closed and difficult to connect to by other third parties. However, they increasingly realize to be part of a system of systems (Porter and Heppelmann, 2014) resulting in more open platforms in which data is accessible through open Application Programming Interfaces (APIs). The tech- and data start-ups mainly rely on open standards (e.g. ISOBUS) through which they are able to combine different datasets. Moreover, Farmobile recently introduced a piece of hardware, the passive uplink communicator (PUC), which captures all machine data into a database that can be transmitted wirelessly (Young, 2016).

In North America, several initiatives are undertaken to open up data transfer between several platforms and devices. The ISOBlue project facilitates data acquisition through the development of and open-source hardware platform and software libraries to forward ISOBUS messages to the cloud and develop applications for Android smartphones (Layton et al., 2014). The Open Ag Toolkit (OpenATK) endeavours to provide a specialized Farm Management Information System incorporating low-cost, widely available mobile computing technologies, internet-based cloud storage services, and user-centred design principles (Welte et al., 2013). One of the internet-based cloud storage services that is candidate in the OpenATK is Trello, which is also advocated by Ault et al. (2013). They emphasize the capability to share data records easily between several workers within the farm or stakeholders outside the farm and the guarantee of long-term ownership of farmer's data.

In Europe, much work to realize an open infrastructure for data exchange and collaboration was done within the Future Internet programme. The focus of this programme was to realize a set of Generic Enablers (GEs) for e.g. cloud hosting, data and context management services, IoT services, security and Big Data Analysis which are common to all Future Internet applications for all kind of different sectors, called FIWARE (Wolfert et al., 2014). The SmartAgriFood proposed a conceptual architecture for Future Internet applications for the agri-food domain based on these FIWARE GEs (Kaloxylos et al., 2012; Kaloxylos et al., 2014). The FIspace project implemented this architecture into a real platform for business collaboration which is visualized in Fig. 6 (Barmpounakis et al., 2015; Wolfert et al., 2014).

FIspace uses FIWARE Generic Enablers (GEs) but has two particular extensions for business collaboration: the App Store and the Real-Time B2B collaboration core. These key components are connected with several other modules to enable system integration (e.g. with IoT), to ensure Security, Privacy and Trust in business collaboration and an Operating Environment and Software Development Kit to support an 'ecosystem' in which Apps for the FIspace store can be developed. The FIspace platform will be approachable through various type of front-ends (e.g. web or smartphone), but also direct M2M communication is possible.

Because all mentioned open platforms are result from recent projects, their challenge is still how they could be broadly adopted. For the FIspace platform, a first attempt was made in the FIWARE accelerator programme[1] in which several hundreds of start-ups were funded to develop apps and services and also received business support. Some of them were already successful in receiving further funding from private investors, but it is too early to determine the final success rate of this programme.

4.5. Challenges

The challenges for Big Data and Smart Farming found in literature can be broadly classified into technical and organizational ones of which the latter category is considered the most important (Orts and Spigonardo, 2014; Sonka, 2015). Moreover, most technical challenges will be solved if enough business opportunities for Big Data in Smart Farming can be created, so there needs to be a clear return on investment (Lesser, 2014). On the revenue side, there is a challenge to make solutions affordable for farmers, especially for those in developing countries (Kshetri, 2014). If there will be more users of Big Data applications it will lead in its turn to more valuable data, often referred to as the *reciprocal value* of Big Data (Van 't Spijker, 2014). This is a very important feature that needs to be carefully implemented in companies' strategies. On the costs side, the challenge is to automate data acquisition in such a way that there are virtually no costs (Sonka, 2015). Because on-farm data will generally remain in the hands of individual companies, investments are needed in a common pool infrastructure to transfer and integrate data and finally make applications out of it. Poppe et al. (2015) refer to this as Agricultural Business Collaboration and Data Exchange Facilities (ABCDEFs). An important question concerning these ABCDEFs is if these will be closed, proprietary systems such as currently Monsanto's FieldScripts or if these will be more open as proposed by e.g. the OpenATK or the FIspace platform. Finally, another business-related challenge of Big Data is how the potential of information across food systems can be utilized (Sonka, 2015).

One of the biggest challenges of Big Data governance is probably how to ensure privacy and security (Lesser, 2014; Orts and Spigonardo, 2014; Sonka, 2014; Van 't Spijker, 2014). Currently this is sometimes inhibiting developments when data are in silos, guarded by employees or companies because of this issue. They are afraid that data fall into the wrong hands (e.g. of competitors) (Gilpin, 2015b). Hence privileged access to Big Data and building trust with farmers should be a starting point in developing applications (Van 't Spijker, 2014). Therefore new organizational linkages and modes of collaboration need to be formed in the agri-food chain (Sonka, 2014). In other words, it means the ability to quickly access the correct data sources to evaluate key performance/core processes and outcome indicators in building successful growth strategies (Yang, 2014).

All aforementioned challenges make that the current amounts of farm data is currently underutilized (Bennett, 2015). Another problem is that the availability and quality of the data is often poor and needs to be ensured before you can make use of it (Lesser, 2014; Orts and Spigonardo, 2014). A lack of integration is also reported as an important problem (Yang, 2014). Anonymization of data, so that it cannot be traced back to individual companies can also be a problem sometimes (Orts and Spigonardo, 2014). There are also attempts to include more open, governmental data (cf. the GODAN initiative), but a problem can be that the underlying systems were never designed for that or they contain many inconsistent, incompatible data (Orts and Spigonardo, 2014).

5. Conclusions and recommendations

In this paper a literature review on Big Data applications in Smart Farming was conducted. In Section 2 it was concluded that currently there are not many references in peer-reviewed scientific journals. Therefore, a reliable, quantitative analysis was not possible. Furthermore, findings from grey literature may lack scientific rigor as can be expected from peer-reviewed journal articles. However, as articles from grey literature are publicly available, they can be seen as being subject to public scrutiny and therefore reasonably reliable. As such, we consider that the knowledge base was enriched by articles from grey literature. Besides, much effort was put into developing a framework for analysis that can be used for future reviews with a more quantitative approach.

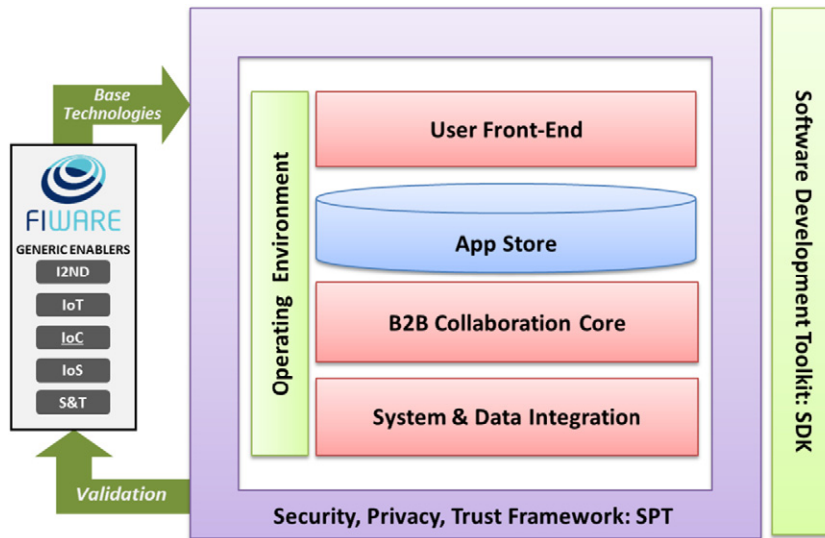[1] https://www.fiware.org/fiware-accelerator-programme/.

Fig. 6. A high-level picture of the FIspace architecture based on FIWARE GEs. Further explanation in text.

Based on the findings in this paper several conclusions can be drawn on the state-of-the-art of Big Data applications in Smart Farming. First of all, Big Data in Smart Farming is still in an early development stage. This is based on the fact there are only limited scientific publications available on this topic and much information had to be derived from 'grey literature'. The applications discussed are mainly from Europe and Northern America, with a growing number of applications expected from other countries as well. Considering the scope of the review, no geographic analysis was performed in this study. Further conclusions, drawn as answers to the research questions we formulated in the Introduction, are elaborated below.

What role does Big Data play in Smart Farming?

Big Data is changing the scope and organization of farming through a pull-push mechanism. Global issues such as food security and safety, sustainability and as a result efficiency improvement are tried to be addressed by Big Data applications. These issues make that the scope of Big Data applications extends far beyond farming alone, but covers the entire supply chain. The Internet of Things development, wirelessly connecting all kind of objects and devices in farming and the supply chain, is producing many new data that are real-time accessible. This applies to all stages in the cyber-physical management cycle (Fig. 1). Operations and transactions are most important sources of process-mediated data. Sensors and robots producing also non-traditional data such as images and videos provide many machine-generated data. Social media is an important source for human-sourced data. These big amounts of data provide access to explicit information and decision-making capabilities at a level that was not possible before. Analytics is key success factor to create value out of these data. Many new and innovative start-up companies are eager to sell and deploy all kind of applications to farmers of which the most important ones are related to sensor deployment, benchmarking, predictive modelling and risk management.

What stakeholders are involved and how are they organized?

Referring to Fig. 5, there are first of all the traditional players in agriculture such as input suppliers and technology suppliers for which there is a clear move towards Big Data as their most important business model. Most of them are pushing their own platforms and solutions to farmers, which are often proprietary and rather closed environments although a tendency towards more openness is observed. This is stimulated by farmers - organized in cooperatives or coalitions - that are concerned about data privacy and security and also want to create value with their own data or at least want to benefit from Big Data solutions. Beside the traditional players we see that Big Data is also attracting many new entrants which are often start-ups supported by either large private investors or large ICT or non-agricultural tech companies. Also public institutions aim to open up public data that can be combined with private data.

These developments raise issues around data ownership, value of data and privacy and security. The architecture and infrastructure of Big Data solutions are also significantly determining how stakeholder networks are organized. On the one hand there is a tendency towards closed, proprietary systems and on the other hand towards more open systems based on open source, standards and interfaces. Further development of Big Data applications may therefore likely result in two extremes of supply chain scenarios: one with further integration of the supply chain in which farmers become franchisers; another in which farmers are empowered by Big Data and open collaboration and can easily switch between suppliers, share data with government and participate in short supply chains rather than integrated long supply chains. In reality, the situation will be a continuum between these two extremes differentiated by crop, commodity, market structure, etc.

What are the expected changes that are caused by Big Data developments?

From this review it can be concluded that Big Data will cause major changes in scope and organization of Smart Farming. Business analytics at a scale and speed that was never seen before will be a real game changer, continuously reinventing new business models. Referring to Fig. 1, it can be expected that farm management and operations will drastically change by access to real-time data, real-time forecasting and tracking of physical items and in combination with IoT developments in further automation and autonomous operation of the farm. Taking also the previous research question into account, it is already visible that Big Data will also cause major shifts in power relationships between the different players in the Big Data farming stakeholder network. The current development stage does however not reveal yet towards which main scenario Smart Farming will be developed.

What challenges need to be addressed in relation to the previous questions?

A long list of key issues was already provided in Table 4, but the most important ones are

- *Data-ownership* and related *privacy* and *security* issues – these issues have to be properly addressed, but when this is applied too strictly it can also slow down innovations;
- *Data quality* – which has always been a key issue in farm management information systems, but is more challenging with big, real-time data;

- *Intelligent processing* and *analytics* – for Big Data this is also more challenging because of the large amount of often unstructured, heterogeneous data which requires a smart interplay between skilled data scientists and domain experts;
- *Sustainable integration* of Big Data sources – integration of many different data sources is challenging but because this is crucial for your business model this has to be done in a sustainable manner;
- *Business models* that are attractive enough for solution providers but that also enable a fair share between the different stakeholders;
- *Openness of platforms* that will accelerate solution development and innovation in general but also empower farmers in their position in supply chains.

The framework for analysis was developed from a chain network perspective with specific attention to network management between the stakeholders that are involved. In future research it could also be valuable to look at this subject from a wider innovation perspective (Busse et al., 2015; Klerkx et al., 2010; Lamprinopoulou et al., 2014). The same holds for ethical aspects of an innovation such as Big Data that could be addressed in future research (Carolan, 2016; Driessen and Heutinck, 2015; Wigboldus et al., 2016).

The promise of Big Data in agriculture is alluring, but the challenges above have to be addressed for increased uptake of Big Data applications. Although there are certainly technical issues to be resolved we recommend to focus first on the governance issues that were identified and design suitable business models because these are currently the most inhibiting factors.

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