DIGITAL TECHNOLOGIES FOR A SUSTAINABLE AGRIFOOD SYSTEM:

A STRATEGIC RESEARCH AND INNOVATION AGENDA.

ERA-NET ICT-AGRI 2 Strategic Research and Innovation Agenda

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LIST OF ABBREVIATIONS

AKIS - Agricultural knowledge and innovation systems

AI - Artificial Intelligence

BTC - Blockchain technologies

DSS - Decisions Support Systems

EDI - Electronic Data Interchange

EDIFACT - United Nations/Electronic Data Interchange for Administration, Commerce and Transport

ERP - Enterprise resource planning (software)

FMIS - Farm management information system

GACS - Global agricultural concept scheme

GDPR - General Data Protection Regulation

GNSS - Global navigation satellite systems

GPS - Global positioning system (US Government)

ICT - Information and Communications Technology

IOT - Internet of Things

LIDAR - Light Detection and Ranging (type of radar)

LOD - Linked Open Data

PA - Precision Agriculture

POS - Point of sale (terminal/software)

RFID - Radio-frequency identification

RTK - Real time kinematic satellite navigation

SDG - UN's sustainable development goals

UAV - Unmanned aerial vehicle (drone)

1 EXECUTIVE SUMMARY

ICT-AGRI is an ERA-NET (European Research Area - NETwork) aiming to help coordinating European research in ICT and robotics for the agriculture sector, and to develop a common Strategic Research and Innovation Agenda (SRIA) based on shared priorities. New technologies are rapidly emerging and revolutionising farming in the next decade. ICT-AGRI has been supporting the development and implementation of these new technologies for a competitive, sustainable and environmentally friendly agriculture since already 2009.

In December 2012, the ERA-NET ICT AGRI 1 published a Strategic Research Agenda (Lötscher et al., 2012) concerning the global challenges in agriculture. This report made proposals for addressing those challenges and discussed how ICT and robotics could contribute to their resolution or mitigation. The conclusion of this report defined the focus of calls for transnational European research projects in ICT and Agriculture, both within the ICTAGRI project as well as influencing other funders. In the five years since then, the use of new technologies in agriculture has grown immensely in significance and there is widespread expectation that we are on the cusp of a “digital revolution” in the agrifood sector[1] which is expected to revolutionise the primary sector, dissolve the boundaries between the agriculture and food systems, create new markets for data, as well as showing the importance of creating new global policies. In this Strategic Research and Innovation Agenda (SRIA), we have reviewed the major current and future challenges for sustainable agriculture (in Chapter 3) as well as the key goals. In view of changing awareness and political priorities we have extended our reach into the whole food system. Thus, we describe the state of the art and current trends in ICT and robotics (Chapter 4) for agriculture as well as the wider food system. The current and future challenges of ICT and robotics adoption in agrifood system are considered in Chapter 5. We conclude with a Vision for the integration of ICT in the agri-food sector that addresses the sustainability challenges of the present and near future.

[1] https://ec.europa.eu/programmes/horizon2020/en/news/digitising-agriculture-and-food-value-chains

2 INTRODUCTION

The first modern agricultural revolution arrived with the beginnings of the automation of agriculture during the 18th century. Since then, the primary sector has evolved first slowly, then more rapidly, with the introduction of many different innovative processes and technologies, especially after WWII with the “Green Revolution”. The relatively recent innovations in telecommunication and information technologies have led to a far more connected world, which is now affecting more and more the agricultural sector. In the 2000s, the terms “e-agriculture” or “ICT (Information and communication technologies)” were used for the first time in official documents concerning agriculture, and the potential of applying these new technologies in agriculture began to be recognised. Concurrently there has been a growing awareness of issues concerning sustainability and the agrifood sector, in terms of environmental, social and economic dimensions.

Under the 7th Framework Programme for Research, the European commission funded the ICT-AGRI 1 ERA-NET. The objective of an ERA-NET scheme is to develop and strengthen the European Research Area by facilitating practical initiatives to coordinate regional, national and European research programmes in specific fields. The overall goal of ICT-AGRI has been to strengthen European research within the diverse area of precision farming, to develop a common European research agenda concerning ICT and robotics in agriculture, and to follow up with calls based on funds from the participating countries' national research programmes. In 2012, ICT-AGRI 1 published a Strategic Research Agenda (Lötscher et al., 2012) which identified six main future challenges for agriculture: Global food security, sustainable resource management, energy consumption, food quality and safety, climate change and social aspects and demands. Key goals were outlined for meeting these challenges, such as reducing waste in the food chain, optimising fertiliser and pesticide use (see Fig. 1). As ICT-AGRI covered all type of agriculture, the goals were placed in the context of different sectors for both plant and animal production as well as the umbrella domain: overall farm management. Those sectors were used to define the subject of the subsequent ICT AGRI calls.

CHALLENGES	GOALS	STATE OF ART AND TRENDS IN ICT	CHALLENGES RELATED TO ITC AND ITS ADOPTION
Global food security	Increase productivity	More sensors and UAVs	Compatible software systems
Sustainable resource management	Reduce waste in the food chain	More robotics	Data ownership
Energy consumption	Optimize fertilizer and pesticide use	Network connectivity	Training of farmers
Food quality and safety	Optimize water management	Big Data	Directly usable
Climate change	Maintain soil quality	Open/FAIR data	Change of farmers' way of life
Social aspects and demands	Protect and promote biodiversity	Apps everywhere	Bandwidth
	Minimize air pollution	Farm to fork integration/standards	Change of business model
	Increase energy efficiency	Explosion of start-ups	Society's (consumers) support
	Ensure food quality and safety	Consolidation and market dominance	Financial investment
	Food traceability and information		
	Reduce greenhouse gas emissions		
	Increase animal welfare and health		
	Less tedious and hazardous work		

Figure 1: Challenges, goals, trends and challenges related to ICT and its adoption as identified by the ERA-Net ICT-AGRI 2 questionnaire, see chapter 5. Current and future challenges for ICT-AGRI adoption for more information.

Since the publication of the ICT-AGRI 1 SRA, new technologies in agriculture have made major advances, with increases in the number of sensors, applications and management systems. This "digital revolution" in the agrifood 7 sector[2] is envisaged in part as addressing the global environmental challenges and is expected to revolutionise the primary sector: data, especially big data, is expected to provide new revenue streams and the power of the different agriculture and food stakeholders will be rebalanced. All these changes will also bring new challenges, including the need for new policies and regulations concerning data ownership, and mechanisms to avoid the mechanisms to avoid the monopoly tendencies of information-based industries (Wu, 2010).

If digital agriculture is really to offer solutions to problems like the environmental impact of agricultural production, then one of the biggest challenges is the adoption of the technology. Even though adoption has been encouraged for many years (OECD, 2001), adoption is currently still low. For instance, only 63% of French farms were connected to the Internet in 2016[3], while 86% of the French household are connected[4], and only 30% of farms in Netherland use milking robots and this reduces to 2% for the USA. The use of new technologies will increase only if they provide clear value for farmers and other food producers, and if all stakeholders are able to adapt to these changes.

The present text, the ICT-AGRI 2's Strategic Research and Innovation Agenda (SRIA), is an overview of the current state of digital agriculture (and to a lesser extent the digital food system) providing both a roadmap and a set of signposts for the future development and funding of digital agriculture in the EU. It describes the current state of the art and trends in the agriculture and food systems, as well as defining the actual and future challenges that act as barriers to the further adoption of ICT and digital technologies by the sectors involved. This report aims to be the **reference** for the research and projects priorities for the next 10 years **to enable the use of new technologies for a competitive, sustainable and environmentally friendly food and agriculture systems.**

[2] https://ec.europa.eu/programmes/horizon2020/en/news/digitising-agriculture-and-food-value-chains

[3] https://www.slideshare.net/GENTILLEAU/etude-agrinautes-2016-70295422

[4] https://fr.statista.com/statistiques/509227/menage-francais-acces-internet/

3 CURRENT AND FUTURE CHALLENGES FOR A SUSTAINABLE GLOBAL FOOD AND AGRICULTURE SYSTEM

Between ICT-AGRIs first SRA, published in 2012 and this new one six years later, public awareness of the challenges faced by the agrifood sector has grown considerably, and there is a great deal more evidence to show how unsustainable current agricultural practices are.

The current global food and agriculture system has been widely recognised to be in crisis on a number of fronts. A large proportion of major global challenges including climate breakdown, population growth, environmental pollution, loss of biodiversity, deforestation and soil loss, obesity and malnutrition, and water conflicts can be linked partially or entirely to the current practices of the food and agriculture system. Many different organisations have produced reports in the last five to ten years identifying current or emerging existential challenges for humanity due to the agriculture sector. Examples include the following:

- The UK government's Foresight report (Government Office for Science, 2011) emphasised the conflicting pressures on the food system between feeding a growing population, predicted to exceed 9B[5], and the competition for global resources (land, water, energy) in the context of the imperative to adapt to climate change. Among other challenges, the report emphasised the need to maintain biodiversity and ecosystem services while feeding the world, as well as managing the food system to mitigate climate change.

- The FAO has produced many reports in this area. In 2017, its report on *The Future of Food and Agriculture (FAO, 2017)* noted that while agricultural productivity has tripled since 1960, much of the success has come at heavy cost to the natural environment, and emphasises the loss of half the world's forests, the depletion of groundwater and the erosion of biodiversity. It notes further the impact that deforestation and degradation of natural buffers has had not only in greenhouse gas emissions but also in enabling extreme weather events and other natural disasters. "High-input, resource-intensive farming systems, which have caused massive deforestation, water scarcities, soil depletion and high levels of greenhouse gas emissions, cannot deliver sustainable food and agricultural production." The report goes on to identify 10 challenges that need to be addressed in order to achieve a sustainable food and agriculture system which specifically meets the Sustainable Development Goals[6].

- The *US Government Global Food Security Strategy* report also identifies significant challenges to the global food security due to among other causes the impact of climate change and the stress it is placing on ecosystems, land, water, and natural resources, while emphasising the need for new tools to improve agricultural productivity and monitor natural resources (USGOV, 2016).

- The Barilla Foundation report, written by the Economist Intelligence Unit, on *Fixing Food* also notes the "unprecedented challenges" facing the world's food system including reducing the environmental damage caused by agriculture (emissions, ground pollution, deforestation) as well as addressing the scourge of food loss and food waste. They note the fact that the world is running out of cultivable land much of which is suffering from erosion and overuse. The agricultural sector has to reduce both deforestation as well as the development of non-food crops which drives much of this (EIU, 2016).

[5] Now predicted to reach 10B by 2050 (FAO, 2017)

[6] https://sustainabledevelopment.un.org/sdgs

- The IPES report *From Uniformity to Diversity* on the one hand notes the major achievements of the food system in the 20th century in crop productivity, food processing and distribution, and the decrease in the global percentage of people going hungry; and on the other hand notes that agriculture contributes up to 29% of global anthropogenic greenhouse gas, 70% of all water is consumed by the agricultural sector, as well as being responsible for nitrate, phosphorus, pesticide, soil sediment and pathogen pollution in soil and water. It further notes the global decline in pollinators due to the use of pesticides and habitat loss presenting a fundamental challenge to crop productivity. Like the FAO reported cited above, it attributes many of agriculture's problems and its impact to the "industrial agriculture" model with extensive use of fertilisers, pesticides and antibiotics (IPES-Food, 2016).

The intensity and urgency of these reports and analyses has grown over time. In 2018, a flurry of further reports along these lines emphasizes the urgency even more. Papers such as Steffen et al. (2018) in combination with the new IPCC report (IPCC, 2018) in October, 2018, have significantly increased awareness of the "anthropocene" and its wider impacts on the planet. The well-known investment manager, Jeremy Grantham, produced a revised version (Grantham, 2018) of a widely read report "The Race of our Lives" which has laid great emphasis on the impact of climate change on agriculture as being the key challenge facing humanity[7]. He is optimistic about the role of technology but considers it a "race" between environmental devastation due to climate change and the adoption of mitigating technologies. Of particular interest is Grantham's focus on soil erosion as having a dramatic effect of food production, and the likelihood that there are only 30-70 harvests left[8] (Erasmus 2017, Shah 2018). Springman et al. (2018) demonstrated that huge reductions in meat consumption (in excess of 90%) were needed to keep within the Paris Agreement targets of less than 2°C warming. This need to reduce meat and dairy is identified in many other reports (Poore & Nemecek, 2018; Searchinger et al., 2018) in large part because these sectors produce disproportionately more emissions.

It is obvious that climate change, loss of soil fertility, depletion of water and other resources, the vulnerable genetic basis of industrial monocultures with an expanding use of chemical agents are damaging world food security. Within the next decades, the world food system has to adapt quickly to the changing boundary conditions. These are widely accepted analyses of the situation, even if the path forward is open to discussion. This awareness is now one reason (among others) that after a long period of decreasing investment in agricultural research, recent years have seen a much stronger commitment from national and international stakeholders for research into agriculture and the means to make it more sustainable.

[7] A good visual summary is provided by Jeremy Leggett here: https://is.gd/9oLuaO

[8] http://www.fao.org/soils-2015/events/detail/en/c/338738/

3.1 SUSTAINABLE AGRICULTURE AND THE FOOD SYSTEM

What is a sustainable agriculture? As one of the most developed continents in the world Europe takes its responsibility and is aware of its leading position in pushing agriculture towards a more sustainable way of producing food and other natural commodities. In fact, sustainability is an intensively discussed term. The most detailed analysis of sustainable agriculture can be found in the IAASTD report (McIntyre, Herren, Wakhungu, & Watson, 2008) and more recently in the IPES report (IPES-Food, 2016). Neither of these reports addresses the role that ICT can play in a sustainable agricultural future largely because their focus was not on technological innovation.

In the following we stick to the simple and generally accepted concept encompassing the three pillars of economic, environmental and social affairs. A suitable definition for sustainable agriculture in this respect can be found on the webpage of the Sustainable Agriculture Initiative[9]:

Sustainable agriculture is the efficient production of safe, high quality agricultural products, in a way that protects and improves the natural environment, the social and economic conditions of farmers, their employees and local communities, and safeguards the health and welfare of all farmed species.

It is from this perspective that we will consider how ICT and related technologies may support a future for the agricultural sector that is above all environmentally sustainable but also can contribute to social and economic sustainability.

[9] http://www.saiplatform.org/sustainable-agriculture/definition

The above definition is, however, relatively narrow in its focus. In view of current scientific understanding and political developments[10], it is important to broaden the perspective beyond purely the production, processing and delivery of agricultural products. Political commitments such as the UN Sustainable Development Goals (SDGs) and the realisation that a great many of SDGs are linked to production, access and rights concerning food, as well interlinked with issues concerning human rights and justice, make a more **systemic perspective** important. Scientific research equally is pointing to a systems perspective which will take into account issues such as food loss and waste, human population diets, animal welfare, cultural values associated with food, rural employment and other related issues particularly from the perspective of food security (Benton, 2018; Challinor et al., 2018). Such a food system approach has also received backing for example from trade bodies such as FoodDrink Europe and the ETP “Food for Life” who in their recent publications recognise how much interconnected the different parts of the food system, society and environment are (ETP ‘Food for Life’, 2018). However, here the emphasis is much more on consumer engagement and the role of potentially active consumers rather than such issues as food waste or biodiversity. There is, nonetheless, considerable recognition of the potential of ICT in the development of new products, enabling consumer engagement, personalisation of food products and supply chains etc.

A closely related topic much promoted by the European Commission is the “Bioeconomy” defined as “"the production of renewable biological resources and the conversion of these resources and waste streams into value added products" (European Commission, 2012, 2018). This covers food, feed, bio-based products and bioenergy and naturally includes ways to address food waste. The EC’s approach to the bioeconomy is highly systemic integrating land and sea products, micro-organisms and energy production from waste. As the policy on the bio-based economy has developed there has been a growing awareness of the importance of ecological boundaries, addressing topics such as biodiversity loss and loss of soil quality (European Commission, 2018). Furthermore waste across the food system, at every step of the supply chain, is an issue that has attracted more and more attention, especially in the light of research such as Alexander et al. (2017) which demonstrated that food system losses are far higher than previously thought, possibly reaching 94% of harvested dry biomass.

[10] The EC is seeking a more integrative food systems perspective in its upcoming research plans reflecting the more integrative understanding that we are developing of agriculture and food’s impact on the environment and human health.

3.2 THE ROLE OF ICT IN SUPPORTING SUSTAINABLE AGRICULTURE

The use of ICT in agriculture is one of several promising means to manage the predicted increase in food demand while simultaneously supporting the creation of a more environmentally sustainable and also resilient manner of food production. Many reports have stressed that technological solutions must play a significant role to mitigate or at least substantially address these issues. This has important policy implications. Technologically this has meant, beyond obvious sources of innovations in agronomy and crop development, a whole range of technologies from mechanical engineering to information and computer systems. Some examples of such a position can be found in the following:

- The IMechE report on global food (IMechE, 2013) stressed the high waste levels in the food system (over 50% losses) in the context of ever growing pressures on land, energy and water, and argues that there is a significant role for technology in reducing waste both in emerging and developed countries.

- An FAO report notes the significance of relatively simple technologies like mobile phones resulting in innovations concerning "commodity and stock market price information and analysis, meteorological data collection, advisory services to farmers for agricultural extension, early warning" and thus argues that "rolethat ICT can play as an instrument of change is potentially transformative" (FAO, 2013).

- Similarly the World Bank sourcebook on the role of ICT in agriculture for smallholders provides many examples and case studies showing the significance of different types of ICT in increasing productivity, improving soil quality, reducing waste and many other use cases which impact both the economic and environmental sustainability of farmers around the globe (World Bank, 2017). Examples include weather forecasting reducing agricultural risk, monitoring livestock to prevent pasture damage, the use of RFID to prevent cattle disease, the use of satellite data in combination with irrigation systems, crop insurance especially index insurance, and field data collection tools for certified farmer groups.

- The role of ICT and digital agriculture for promotion of the Sustainable Development Goals has been much discussed and explored. Digital agriculture is considered to have great potential in helping to achieve the SDGs, and in the context of the UN's Global Compact has been identified as playing a key role: "Digital agriculture has the potential to make agriculture more productive, more consistent, and to use time and resources more efficiently" (UN Global Compact, 2016). Further examples from that report are shown in the figure below.

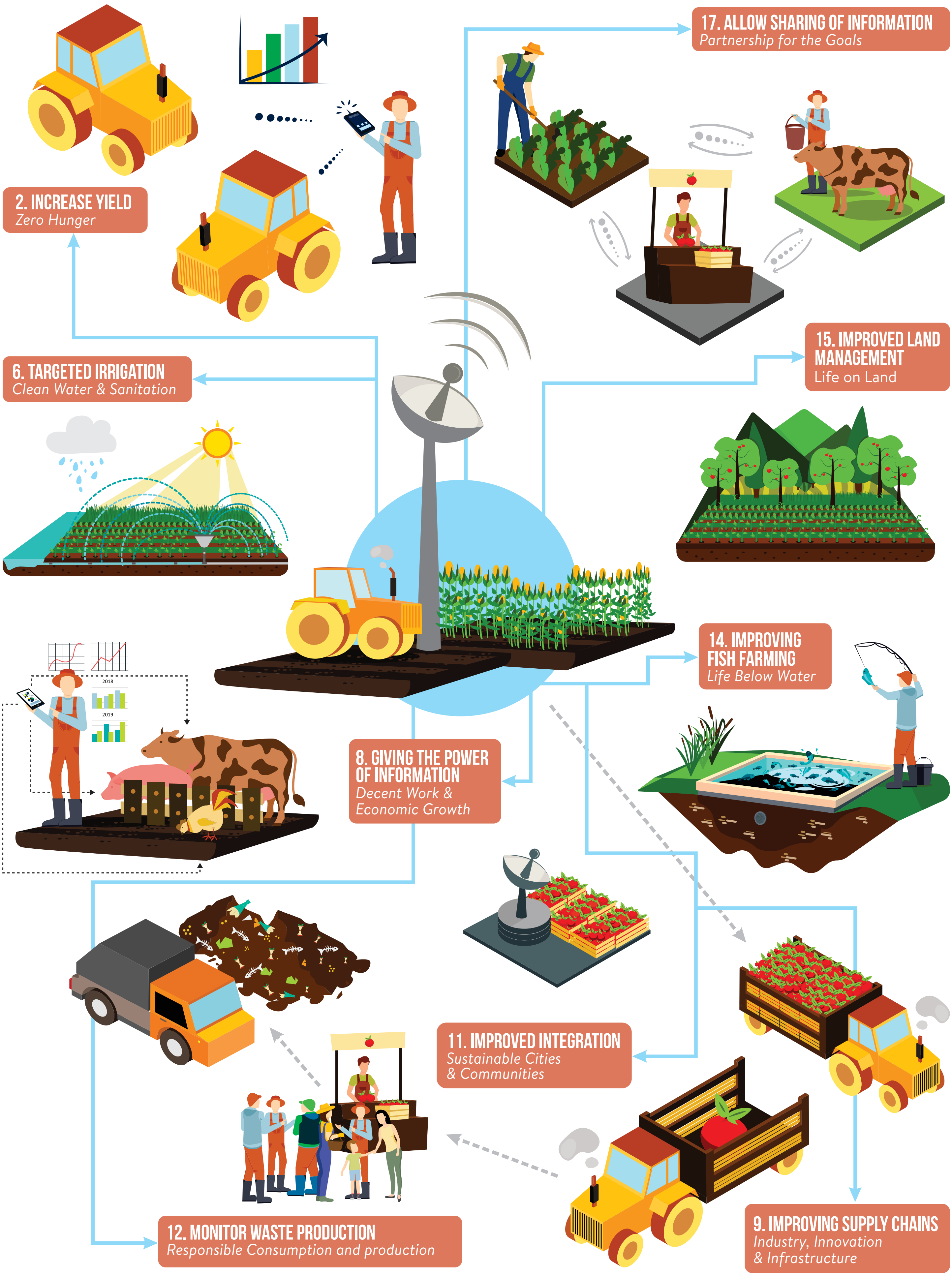


Figure 2: Examples of areas of application across a wide variety of sectors (UN Global Compact, 2016).

- Not only at a UN level but also internationally individual countries are committing themselves to using digital agriculture as means to address both the need for greater food production as well as a reduction of environmental impact. For example, India has established the "Mission India for Transforming Agriculture" initiative with this specific objective (Wani, Bergvinson, Raju, Gaur, & Varshney, 2016).

- A number of academic studies have similarly argued for the significant role of digital agriculture in enabling a sustainable future for agriculture. For example, (Walter, Finger, Huber, & Buchmann, 2017) argue that "ICT and data management can provide novel ways into a profitable, socially accepted agriculture that benefits the environment (e.g., soil, water, climate), species diversity, and farmers in developing and developed countries". Dinesh, Campbell, Bonilla-Findji, & Richards (2017) argue thatdigital agriculture is one of the ten best bet innovations for adaptation in agriculture. An analysis of using a variety of tools to assess the sustainability of farms has been undertaken by Evelin et al. (2016a, 2016b), and they emphasise "the importance of context specificity, user-friendliness, complexity of the tool, language use, and a match between value judgements of tool developers and farmers"

While there appears to be widespread agreement on the significance of digital agriculture or the use of ICT in agriculture to support more sustainable practices, there remain many challenges including demonstrating the added value (especially for smallholders) and encouraging adoption. The following chapter provides an overview of some of the current trends in the application of ICT in agrifood sector.

4 STATE OF ICT ART AND TRENDS IN THE EU AGRICULTURE AND FOOD SYSTEMS

The last 10 years have seen a rapid growth in the awareness, interest and investment in the application of ICT technologies to the agrifood sector. While visions of the application of technology to farming (i.e. precision agriculture) go back 30 years or more, the main areas of penetration of ICT has been in the retail sector (POS systems, ERP, data warehouses on customer transactions and loyalty cards (Felgate & Fearne, 2015; Verhoef et al., 2010)) and in the dairy sector with the widespread uptake[11] of dairy robots (Butler, Holloway, & Bear, 2012). In parallel there has been a growing awareness of the importance of data (of all sorts) mostly in the research arena to start with (Wolfert, Ge, Verdouw, & Bogaardt, 2017). The role of ICT has spread in the last 15 years -- in substantial part due to projects like ICT-AGRI, initially in experimental efforts but slowly spreading to commercial settings particularly in the widespread use of GPS to track or guide vehicles (on farms, in logistics), the growing use of remote and local sensors and the data theyproduce for farm management and food condition monitoring.

It must be stressed, from the outset, that there is great variability in the degree and range of uptake of ICT in the agrifood sector even in developed, wealthy countries. For example, in the UK, while supermarkets like Tesco pioneered the use of club card data to track and analyse shopper's habits and better target special offers (Felgate & Fearne, 2015; Rowley, 2005), until very recently the grain sector in the UK has been using paper based "passports" to record the quantity and quality of grain leaving a farm, the means of transport and the eventual arrival at a mill (AHDB, 2016). The variability applies not just between different parts of the food system but also geographically between different countries in the same sub-sector. Currently over 30% of Dutch dairy cows are milked by fully automated robots, while only 2% are in the US (Varinsky, 2017).

[11] Such statements concerning uptake and adoption in this report largely refer to Western Europe and sometime include North America.

4.1 SECTORS OF THE AGRIFOOD SYSTEM

Different sectors of the food and agriculture system have adopted ICT at different rates and focussed on different aspects of these technologies. Even if in a broad sense all ICT is interconnected, specific choices have been made to automate or use digital data differently in different contexts. In the **research and development** sector, there has been a growing awareness of the importance of data, as well as widespread interest in the potential of all sorts of technological (i.e. computer related) innovations. In this sector, we are concerned with the use made of ICT to facilitate development rather than the development of ICT solutions. Under the influence of other domains such as the Life Sciences, much effort has been put into the development of standards such as AGROVOC, a multilingual vocabulary largely used to annotate agrifood research (Rajbhandari & Keizer, 2012), such as for example in the AIMS/AGRIS database of agricultural publications. This has led more recently to attempts to unify major agricultural metadata vocabularies globally, the GACS initiative, in order to facilitate the markup and integration of academic data sets[12]. There has been a substantial growth in the development of crop modelling (Matthews, Rivington, Muhammed, Newton, & Hallett, 2013; Teixeira et al., 2017) which provide mathematical models of plant development and depend on considerable bodies of data for testing and validation. There is growing awareness that data sets in themselves have value leading the development of scientific outlets for such datasets as well as pressures upon scientist to annotate and publish their data for reuse by fellow researchers[13] (Grassini et al., 2015). Here the growth of the Open Data movement together with the more recent move towards FAIR data (Wilkinson et al., 2016) has led to strong guidelines or conditions on research grants that outputs including data sets should be openly available. A major factor for the crop modelling community has been the growing availability of remote observation (satellite) data extensively used to provide crop predictions (e.g. the EC's Copernicus and MARS project[14]). Another area of considerable development has been genetic and germplasm data banks with suitable annotations (for example the Genesys databank which supports crop biodiversity or the Integrated Breeding Platform[15]).

On farm, both arable farming and livestock farming have seen considerable developments in the actual (or potential) use of ICT. Precision agriculture has a history going back at least to the 1980s but has only become realisable in the last decade due to the reduction in the cost of hardware components, especially satellite guidance and sensors (Spyros Fountas, Aggelopoulou, & Gemtos, 2015; Mulla, 2013; Pedersen & Lind, 2017). There are three steps to precision agriculture[16]:

1. Collection of data with the maximum possible resolution concerning the farm plots which are managed.
2. Analysis of this data (often necessitating integration of multiple data sources) so as to plan a set of actions or treatments.
3. The actions or treatments are undertaken with great control and precisions (again dependent on sensors and measuring equipment).

[12] http://agrisemantics.org/gacs/

[13] http://library.wur.nl/ojs/index.php/ODJAR/index

[14] http://copernicus.eu/ and https://ec.europa.eu/jrc/en/mars

[15] https://www.genesys-pgr.org/welcome and https://www.integratedbreeding.net

[16] https://nifa.usda.gov/program/precision-geospatial-sensor-technologies-programs

Three areas of application of precision agriculture methods have developed: crop farming, horticulture (especially under glasshouses) and livestock farming. The poster child for precision agriculture has been the use of global navigation satellite navigation (e.g. GPS) for farm machinery control, initially mostly to ensure the most efficient path across fields but now tightly integrated with variable rate spraying and fertilisation, livestock movement monitoring, and other applications. The success of GPS based methods also depended on the availability of Light Detection and Ranging (LIDAR) measurements to provide detailed topography necessary for understanding soil development and soil water movement upon which successful crop management depends (Galzki, Birr, & Mulla, 2011). GPS has expanded immensely into guidance of seed drilling and fertilizer and pesticide application. Other sources of data include meteorological data (both historic and current), remote observation (via satellite sources such as Copernicus) and local observation using near or proximal sensors. The tailoring of meteorological data for specific farm services led to the creation of the first major "Big Data" company in the agrifood domain, Climate Corp., bought by Monsanto in 2011) which provides site specific weather prediction for a three-hour window (Specter, 2013). Remote observation has changed considerably with arrival of hyperspectral remote sensing, making possible the analysis of specific compounds and molecular interactions, crop stress and other crop characteristics. Sub-metre granularity also now makes remote sensing much more useful for precision farming (Mulla, 2013). The main disadvantage of satellite-based sensing is that cloud cover can reduce accuracy and utility in comparison to using UAVs. The use of drones or UAVs has taken off in the last five years with significant reductions in costs such that there are now "best buy" guides in some parts of the world[17].

Remote sensing applications in precision agriculture include measuring crop yield and biomass, crop nutrients, water stress, insect and plant diseases, moisture, clay content and salinity (Mulla, 2013). Integration with proximal sensors provides greater accuracy and a wider range of data (e.g. Ph values, detailed humidity data, specific pest infestation data). All these data sources feed either individual applications (apps; such as on a smartphone or tablet) or some form of integrated farm management information system (FMIS) which allows the farmer to manage their crops or livestock (S. Fountas et al., 2015; Kaloxylos et al., 2014). FMISs provide decision support systems based on simulation and optimization models for specific crops or livestock, but also cover many other farm operations. Apart from field operations management, commercial FMISs also include functionalities to handle financial and budgetary management, inventory and traceability functionalities, reporting, machinery management and human resources (S. Fountas et al., 2015). Obviously not all systems offer all such functionalities, although there are some integrating platforms that try to bring multiple services together (e.g. 365FarmNet[18]). The long terms vision of many researchers is for the integration of robots into farm management systems so as to achieve completely automated farming[19] (Pringle, 2017a).

[17] http://agrisemantics.org/gacs/

[18] http://library.wur.nl/ojs/index.php/ODJAR/index

[19] http://copernicus.eu/ and https://ec.europa.eu/jrc/en/mars

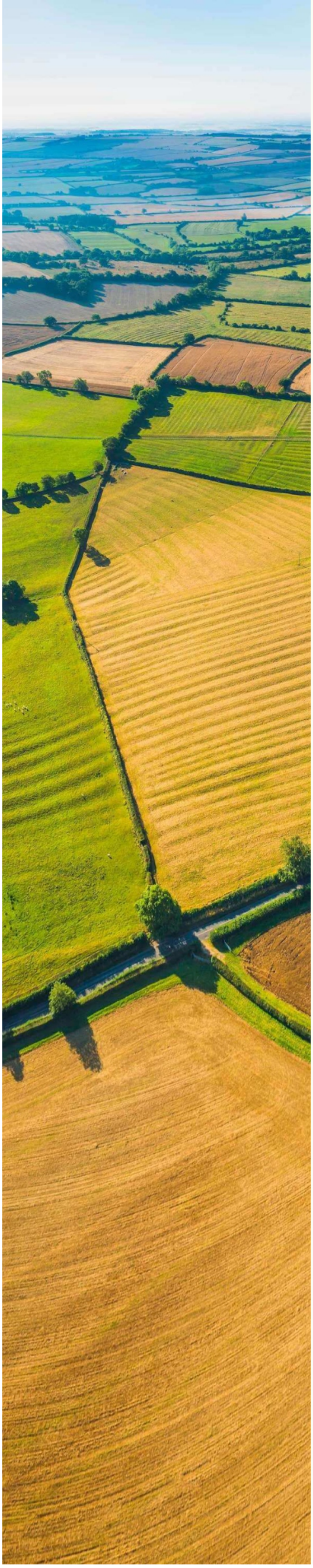
[20] https://www.genesys-pgr.org/welcome and https://www.integratedbreeding.net

[21] https://nifa.usda.gov/program/precision-geospatial-sensor-technologies-programs

The focus on the application of ICT in **food production and processing** has been on ever greater automation, the identification of food pathogens, and the need for ever better tracking and tracing. An example of automated horticultural packing can be found in the "Pick n Pack" project[20] which combines image recognition with delicate robotics to adaptively package different agricultural products into their appropriate packaging. This results in greater speed, greater hygiene and potentially lower overall costs. Identification of pathogens has largely been addressed by ever cheaper and more efficient testing tools, including more recently "lab on a chip" approaches (Kim, Park, Kim, & Cho, 2014; Sun et al., 2015). Such techniques are essential in view of the substantial challenges faced by the agrifood sector with regard to food integrity issues[21] and food crises. There is ongoing work, both commercial and academic, concerning the role of ICT in ensuring greater food integrity and enabling better, faster responses to food crises such as the 2011 E. Coli crisis or the 2013 Horsemeat crisis (Elliott, 2014). Food integrity is closely connected to food trading and transportation.

[20] https://www.genesys-pgr.org/welcome and https://www.integratedbreeding.net

[21] https://nifa.usda.gov/program/precision-geospatial-sensor-technologies-programs



In the **food trading and transportation sector**, including **supply chain management**, the development of ICT has been driven in part by reasons of traceability, but mostly in the expectation that greater optimisation would be possible. Food traceability as a set of regulations (cf. EU's General Food Law Regulation 178/2002) and related technologies implies that records have to be kept in order to trace food after some kind of incident. Much has been written about food traceability (Badia-Melis, Mishra, & Ruiz-García, 2015; Espiñeira & Santaclara, 2016; Scholten, Verdouw, Beulens, & van der Vorst, 2016) and while the need for traceability is motivated in part by issues of food integrity, traceability systems also enable to varying degrees the optimisation of the supply chain (van der Vorst, 2006). Core technologies used are standard industrial ERP systems (from vendors such as SAP, Oracle and Rubicon) frequently integrated with quality monitoring components from external third-party suppliers[22]. Barcodes and scanning equipment for barcodes on packaged goods are standard now across most of the agrifood supply chain. There is growing use of RFID chips (passive and active) although cost constraints have always impeded widespread adoption (Kemény & Ilie-Zudor, 2016). *Within* enterprises processing food, there is growing use of the GS1 EPCIS standard whereby aggregation (packaging) and transformation processes can be recorded in a standardised manner. Between enterprises, far greater use is made of simple identification barcodes (GTIN) (cf. data standards below). Some major food enterprises use EDI[23] but this is mostly limited to orders and invoices.

The ever-greater integration of logistics in the agrifood sector has resulted (for example) in the spread of reusable packaging (which flow from farm to retailer and back again) with current innovations exploring the use of integrated active RFID, sensors and GPS tracking so as to provide temperature and handling data for quality control. This is equally true of the cold chain (refrigerated and frozen food products such as meat and ice cream) where food losses due mishandling have remained a major challenge (Jedermann, Nicometo, Uysal, & Lang, 2014), and where continuous monitoring using IoT technologies may reduce temperature failures or at least making their identification much easier (Wang, He, Matetic, Jemric, & Zhang, 2017). However, our ability to share food quality monitoring data is hampered by lack of agreed data standards (cf. below) and corresponding business models as food travelling along the food chain is continually split and different sensors and monitoring equipment is used (Jedermann, Praeger, & Lang, 2017). More generally, Verdouw et al. (2016/5) suggest that food system sustainability can be dramatically enhanced through the revolutionary potential of the Internet of Things (IoT) due to potential of the technology for even better optimisation. For example, IoT based inventory

[22] For example, Muddy Boots https://en.muddyboots.com/

[23] EDIFACT (ISO standard 9735) and GS1-EDI (https://www.gs1.org/edi)

management of perishable produce could reduce costs and secure quality maintenance during post-harvest and thus reduce losses and waste (Riad, Elgammal, & Elzanfaly, 2018). Other research has tried to track the whole chain of an agricultural product including production, processing, warehousing, inspection, logistics and sales, and improve the effective transmission of traceability information (J. Zhang, Liu, Li, & Song, 2018). Several such proposals exist usually for a narrow vertical supply chain (e.g. coffee, cocoa, tuna), recently often claiming to use blockchain technology to share data[24] (cf. on blockchain technology below).

At the **retailer and consumer** end of the food system, as noted elsewhere ICT has long penetrated with the use of Point of Sale information systems based on scanning barcodes, the integration of such systems with ERP systems and automated (re-)ordering. Such developments go back more than a decade, so recent developments have focussed more on a) using self-service tills, b) the better use of data to target advertising and special offers usually via loyalty cards, and c) recent developments in e-commerce and a multitude of start-ups and applications bringing the consumer, the retailer or food producer into greater communication. Self-service tills have become ubiquitous in supermarkets across Europe and there has been growing satisfaction with this technology (Demirci Orel & Kara, 2014; Kallweit, Spreer, & Toporowski, 2014; NCR, 2014). The latest trend in this area is the proposal by Amazon[25] to develop a "grab and go" store which uses computer vision, sensor fusion, and deep learning to allow shoppers to merely grab their items and leave (Wingfield, 2016). Ever more sophisticated uses of data and machine learning is developing so as to target advertising, special offers and physical location of products more accurately. Of particular importance is the huge growth in the variety of data sources which now include apart from sales data, also loyalty card data, customer behaviour on retailer website data, customer's social graph, product locations, environmental data etc. (Bradlow, Gangwar, Kopalle, & Voleti, 2017). The ever-expanding use of personal data has raised significant privacy concerns (famously when the US retailer Target predicted a woman's pregnancy before she was aware (Duhigg, 2012)) and the application of the EC's GDPR will also impact the manner in which data is used here. There is widespread and growing concern regarding the pervasiveness of data collection in our societies and the intentional or accidental misuse of that data (Zuboff, 2015).

[24] Companies such as Provenance.org (https://www.provenance.org/) in the UK, Moyee Coffee (https://www.moyeecoffee.com/) in the Netherlands have made such proposals.

[25] https://www.amazon.com/b?node=16008589011

4.2 ICT AND DIGITISATION TECHNOLOGIES: HARDWARE

Satellite navigation (global navigation satellite systems - GNSS) as provided by the US GPS system and the EC's Galileo system are core technologies for the development of Precision Agriculture. In the US, GPS guidance systems on tractors have now reached over 80% penetration (Erickson & Lowenberg-DeBoer, 2017). The main developments here have been ever greater accuracy and ubiquity. While in the past systems such as RTK have been used to combine with GNSS so as to obtain high accuracy, current developments in autonomous cars and specialised chips are leading to cheap highly accurate navigation systems (Moore, 2017) which will lower the cost of using such systems in precision agriculture. GNSS are playing an increasing role in food logistics as well for the tracking of containers especially in the cold chain but also down to the returnable containers used in horticulture. For example. Maersk is tracking all cold chain containers on container ships using a combination of GPS and 3G and is capturing data about location, power status, temperature, humidity and ventilation (Sowinski, 2016). Current adoption levels of GNSS technology in farming are over 80% in the US but below 20% in the EC (EGSA, 2017; Fulton, 2015).

There are other significant uses of **satellites** in agriculture. Early uses of satellite imagery were for estimating how much land was being cultivated and differentiating between different crop types so as to enable predictions of crop yields ahead of harvest. One of the best known such services is the "Monitoring Agricultural Resources" (MARS) project[26] which has been estimating crop yields for the purposes of the EC's Common Agricultural Policy since the late 1980s, but also more generally helping establish estimates of global food security. Satellite imagery (using optical and radar images) has also been used for farm management (in close integration with GNSS) and before the advent of drones (cf. below) has been the primary source of data for precision agriculture. Satellite imaging radar (Synthetic-aperture radar) can be used to obtain crop growth and biomass estimates, and even soil moisture conditions, and it is unaffected by cloud cover, and this is now available through the EC's Sentinel system (McNairn et al., 2018; Merzouki, McNairn, Powers, & Friesen, 2017; Yang et al., 2015).

A major boost to the use of satellite imagery globally has been the EC funded Copernicus project[27] which provides a wide variety of remote sensing data to end users for free. For example, BASF is currently using Copernicus data to provide pesticide and fertiliser advice to farmers[28]. Apart from the use of satellite data to support precision agriculture, satellite data is also being used for the purposes of crop insurance (so called "index insurance") which eliminates the need for on the ground inspection of agricultural land (for example in the RIICE project using Copernicus satellite data)[29]. Another example is the Belgian company AVIA-GIS[30] which uses satellite images in combination with proximal sampling for tracking the spread of plant and animal diseases across the landscape.

[26] https://ec.europa.eu/jrc/en/mars

[27] http://www.copernicus.eu/

[28] https://www.basf.com/en/company/news-and-media/news-releases/2017/02/p-17-127.html

[29] https://www.asean-agrifood.org/projects/riice/

[30] https://www.avia-gis.com/

The major success story, in recent years, has been the use of **Unmanned Aerial Vehicles** (UAVs) or **drones** for agricultural purposes. This has been foretold as a major potential area for the application of ICT to agriculture (C. Zhang & Kovacs, 2012), and PWC's report from 2016 predicted that agricultural uses of drones would be the second largest market globally for that kind of technology (PWC, 2016). The combination of lightweight hyperspectral (NDVI) snapshot cameras which can calculate biomass and the fertilisation state of crops (Bareth et al., 2015; Li, Mistele, Hu, Chen, & Schmidhalter, 2014) together with ever more reliable and low cost unmanned aerial vehicles is transforming certain parts of agriculture. Drones are being used for to identify soil variations, pest and fungi infestations, healthy vs. diseased plants, and generally collect aerial imagery for precision farming decisions support. A key advantage of drones is that they fly below the cloud canopy and at a much lower altitude when compared to satellite images and data. And due to their low cost, data can be collected at will by the farmer. There is also much interest in the potential of drones for crop spraying because this enables zero ground compaction, spraying of tall plants, access to difficult terrain, and saves time and labour. One of the arguments in favour of drone technology is their ability to support environmentally sustainable agriculture, especially in reducing pesticide use and managing irrigation more effectively. One significant uncertainty has been the regulatory context for the use of drones both in the EC and the US (Freeman & Freeland, 2015). Until 2016, in the US, a pilot's licence was required but this has now been abandoned in favour of a "Remote Pilot Airman Certificate" allowing farmers to use drones as long as they keep "line of sight" with the drone, operate below 500m and under 25kg. In Europe, regulations differ by country with the UK (for example) allowing non-commercial flights similar to the US, while in the Netherlands drones must be inspected by regulators before being allowed to fly. Switzerland, China and Australia allow crop spraying with drones while most other jurisdictions do not as yet (Riley, 2017). It is important also to see data from UAVs as complementary to data from satellites and there is extensive work currently to integrate different data sources and evaluate the respective advantages (Matese et al., 2015; Murugan, Garg, Ahmed, & Singh, 2016; Pantazi, Moshou, Mouazen, & Alexandridis, 2015). In addition, the opportunity UAVs provide to collect thermal imaging data (as opposed to optical images) is providing new opportunities for analysis of crop performance (Khanal, Fulton, & Shearer, 2017).

The key challenge to the effective and widespread use of data from satellites, drones or even aeroplanes for the purposes of precision agriculture lies in the successful combination of the data with appropriate crop models and then the calibration of those model/data for the specific geographical region and its micro-climate. Crop models are often developed with indices based on satellite data that is not freely or commercially available, and furthermore do not follow necessarily standard representations[31].

[31] Assessment based on interview with a crop model and satellite data specialist.

Another area of significant development in digital agriculture is in **robotics**. Since labour has always remained a major cost factor in the agrifood sector, the expectation has been that robots would play a significant role in the future but until now the economics have not favoured such developments. The core robot developments have been in dairy robots, autonomous mechanical weeding, the application of fertilizers and the harvesting of crops. The most successful use of robots has been in "robotic milking parlours" (dominated by the milking parlour companies Delaval and Lely). Currently over 35,000 robots are in use but high capital costs and lower overall profits have made robotic milking have until now limited penetration globally[32] (Salfer, Endres, Lazarus, Minegishi, & Berning, n.d.). Approximately 2% of US dairy cows are milked by robots, while about 30% in the Netherlands are (Varinsky, 2017). Robots have been developed for crop harvesting including grapes, strawberries, barley, cucumbers and many other crops. A key challenge for robotic farming is navigation around fields although there is overlap with technology developed for autonomous driving, combining GNSS and vision technologies. The challenges are even greater in some regards as robots in farming need to manipulate their environment, planting, picking or spraying. For example, the EC funded RHEA project developed autonomous robots for chemical and physical weed management[33].

[32] There are over 23M dairy cows in the EC, and a milking-robots can milk approximately 70 cows so adoption is still very low.

[33] http://www.rhea-project.eu

Autonomous tractors using on board detection systems are able to kill a high percentage of weeds currently. An example of crop harvesting can be found in the H2020 project Sweeper[34] which has focussed on the development of robots for bell pepper harvesting and uses advanced colour and 3d imaging. The "hands free hectare" project at Harper-Adams University has succeeded in sowing and harvesting barley entirely automatically using robots and a combination of cameras, drones and GPS systems[35] (Pringle, 2017b). The project has plans to grow wheat in another cropping season. The use of robots in greenhouses is somewhat simpler that in open fields due to the more controlled environment (Al-Beeshi, Al-Mesbah, Al-Dosari, & El-Abd, 2015). (Asefpour Vakilian & Massah, 2017) showed how to use a greenhouse robot to significantly decrease the use of nitrogen for example. The Belgian company Octinion[36] has developed a strawberry picking robot with a picking speed comparable to a human and which can pick only the perfectly ripe fruit. The importance of robots for achieving environmentally sustainable agriculture is emphasised by Deepfield Robotics[37], a company expecting to "Sustainably increase agricultural production whilst minimising environmental impact" focussing on weed management. It should be noted that agriculture has been identified as a key application area by the EC's Strategic Research Agenda in robotics (SPARC, 2014). However, current adoption of robotic solutions is still relatively limited above all due to cost of capital investments.

Proximal sensors or land-based sensors are a key technology in agricultural robotics and precision agriculture more broadly (Bogue, 2017). The major revolution in recent years has not only been the variety of measurements that can be taken but also the significant reduction in the cost of manufacture and the consequent greater availability of these technologies, although most business analysts still judge them too high (Fisher, 2015). Furthermore, the integration of proximal sensors with wireless sensor networks has made precision agriculture much more practicable in a variety of contexts such as horticulture and greenhouse crops (Ojha, Misra, & Raghuwanshi, 2015). Proximal sensors include the following types (based on Schriber, 2018): a) location sensors (using GPS and RTK) (Marucci, Colantoni, Zambon, & Egidi, 2017; Odolinski & Teunissen, 2017); b) optical sensors to measure soil properties such as soil reflectance, water deprivation and nitrogen shortages in plants, etc.(Kweon, Lund, & Maxton, 2013; Peteinatos, Korsaeth, Berge, & Gerhards, 2016) ; c) electrochemical sensors for soil properties such as pH and nitrogen values (Adamchuk, Hummel, & Morgan, 2004; Joly et al., 2017); d) mechanical sensors to measure properties such as soil compaction (Hemmat & Adamchuk, 2008; Naderi-Boldaji, Weisskopf, Stettler, & Keller, 2016); e) dielectric sensors to measure soil moisture and soil composition (Kapilaratne & Lu, 2017) ; f) airflow sensors measuring other soil properties ; g) movement and temperature sensors usually for dairy or livestock (Borchers, Chang, Tsai, Wadsworth, & Bewley, 2016; Rutten, Velthuis, Steeneveld, & Hogeveen, 2013; van Eerdenburg et al., 2017). In addition, one should mention on field weather stations measuring temperature, humidity, and air pressure (Mesas-Carrascosa, Verdú Santano, Meroño, Sánchez de la Orden, & García-Ferrer, 2015). Proximal sensors measure a variety of parameters including: (in the soil) moisture/humidity, pH value, salinity, compaction, (on plant) plant colour (NDVI), (on animal) movement, temperature, etc. The measurements from the sensors have to be integrated for the purpose of any decision support service. It must be noted that one of the biggest challenges here is difficulty in integrating data from different sensors due to the absence of industry wide accepted standards. In principle, the decision service would thus enable the planning of (for example) a fertilisation or spraying plan for an arable field, a decision to irrigate or harvest (in a horticulture or greenhouse context), a treatment plan for sick animals (in a livestock scenario).

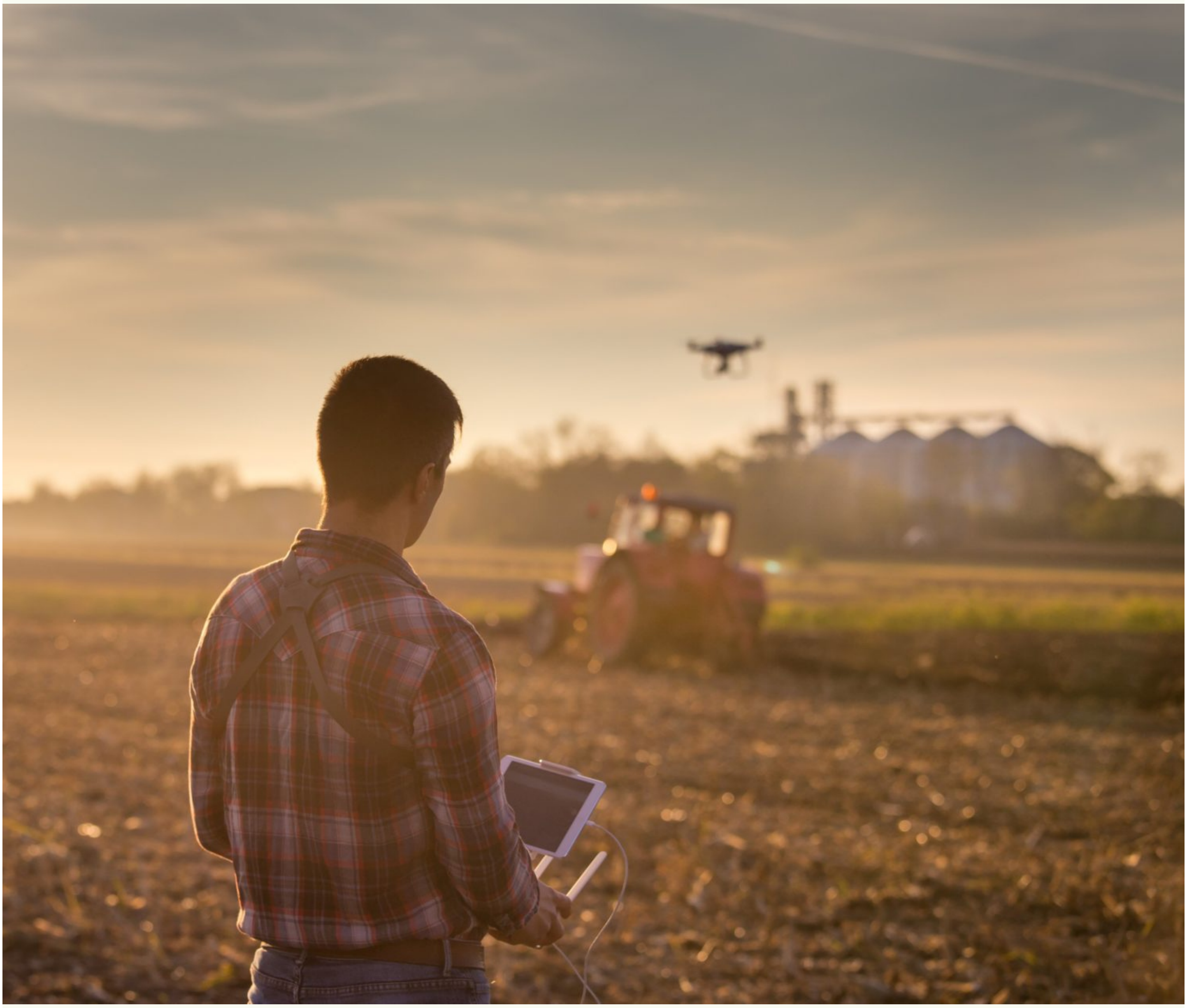
[34] http://www.sweeper-robot.eu/

[35] http://www.handsfreehectare.com/

[36] http://octinion.com

[37] https://www.deepfield-robotics.com/

Radio-frequency Identification (RFID) is a technology that enables data exchange through small devices called tags. These devices do not have a battery; instead, they are powered remotely (through an external reader that wishes to communicate with them), allowing tags to be cheap, lightweight and easily disposable (Ilie-Zudor, Kemény, van Blommestein, Monostori, & van der Meulen, 2011). In the context of agrifood, RFID tags are used in a similar way as barcodes in the sense that they enable product traceability (Dabbene, Gay, & Tortia, 2016; Kemény & Ilie-Zudor, 2016). It should be noted that while RFID tags offer substantial advantages over conventional barcodes, the technology has often been found too expensive for the food-supply chain (Aung & Chang, 2014). Kemeny and Ilie-Zudor (2016) note that in spite of costs having dropped significantly the use of RFID "remains an issue for products with low profit margin and low per-unit value, e.g. fresh vegetables." This has led to the use of both barcodes and RFIDs in parallel. In precision farming, there is significant use of RFID tags for livestock management (Anu, Deepika, & Gladance, 2015; Trevarthen & Michael, 2008). Recent research on the use of RFID in warehouses indicates that temperature and food composition also present a challenge to the use of RFID for tracking and tracing (Barge et al., 2019).



Internet of Things (IoT) for agriculture and the food system: A natural outgrowth of the technical developments in hardware for precision agriculture (or smart farming) has been the ever-greater network integration of these different types of hardware. At a local level, this can be seen in considerable research and innovation in the development of **wireless sensor networks** (Ferentinos, Katsoulas, Tzounis, Bartzanas, & Kittas, 2017; Ojha et al., 2015) which enable the networking of collections of sensors so as to feed some form of farm management system (cf. below). From this it has been natural to extend the "internet of Things" vision (originally mostly conceived largely in a "smart cities" context) to and Internet of Things for agriculture and even the whole food system (integrating from farm to fork, i.e. bringing mobility and logistics into the picture) (AIOTI WG06, 2015; Verdouw, Wolfert, & Tekinerdogan, 2016). This direction of activity has been much support by the EC's investment particularly in the Large-Scale Pilot in IoT for smart farming[38]. Data can also be collected by an integration of smartphones and IoT devices as demonstrated in Alfian et al. (2017) where a real-time monitoring system based on integrating smartphone-based sensors, a big data platform, and data mining to identify perishable food in the supply chain. The challenge for many of these approaches for the supply chain is a dependence on centralised data sharing which is not welcome due to business confidentiality issues (Brewster & Seepers, 2018).

[38] https://www.iof2020.eu/

4.3 ICT AND DIGITISATION TECHNOLOGIES: SOFTWARE AND SERVICES

Farm Management Information Systems (FMIS) are software tools for the collection of data on the farm and the processing of that data in order enable decision making (Sørensen et al., 2010; S. Fountas et al., 2015; Tsiropoulos, Carli, Pignatti, & Fountas, 2017). This has been an area of considerable growth in recent years. There are different types of systems for crop management, livestock and dairy management and greenhouse management. Greenhouse and dairy systems are more mature and have greater uptake than in other areas of agriculture. FMIS cover such aspects as field operations management and herd management, inventory, finance, sales reporting (e.g. for certification), best practices including yield estimation, site-specific functionalities, machinery management and human resources management (ibid.). There are many commercial offerings in this area, and even more for herd management and dairy farms. An indication of the vitality of the sector is than in the survey of Fountas et al. (2015), 161 systems across Europe and North America were identified excluding dairy and greenhouse systems. Nonetheless, there are many challenges in this area particularly to do with the lack of interoperability of data: "in European farming ... most data and information sources are fragmented, dispersed, difficult, and time-consuming to use" (ibid.). Furthermore, uptake is still limited as the majority of farms in the EU are too small to justify the cost of the investment in such technology. Finally, Fountas et al. note that the integration of crop models (widely used in research) has not yet occurred to a large extent in FMIS. A key vision for future farm management information systems is the concept of customised FMIS's, where farmers and other users build their systems based on dedicated applications ("smart-apps") targeting the specific needs of the farm and production systems. The basic idea is to establish a cloud-based Farm Management System integrating data from sensors and actuators together with a range of services needed for the farm management. Farmers will interact with this system and activate different kinds of applications/decision support systems (Kaloxylos et al. 2014).

Usually tightly integrated into the FMIS are **decisions support systems or tools,** though these can be found as independent services, or form part of logistics or supply chain management systems (cf. Taechatanasat and Armstrong (2014) for a brief survey). Purely for the agriculture sector, Rose *et al*. (2016) identified nearly 400 such tools (nearly all either online or smartphone apps) with indications that many more were being prepared for release to the community. This paper noted that nearly 50% of UK farmers in their sample were using such tools in one form or another. There are many companies across Europe offering a variety of decisions support tools, covering different stages in the agrifood production and delivery process. Typical examples include ITK[39] (from France) which seeks to "optimize the yield and quality of [farmers'] crops, and reduce risks on their farm, while preserving the environment through better management of inputs (irrigation, fertilizer, phytosanitary products)" or SmartVineyard[40] from Hungary whose software enables vineyard disease predictions and decisions support. Many such products are integrated into FMIS handling a wider range of farm management processes[41]. There are several challenges in this area that are limiting its success. First is the interoperability of relevant data (e.g. from sensors and other instruments) thus leading to complete platforms being sold rather than component services that are interoperable. Second is the challenge of tailoring a DST to the local characteristics of a farm including its microclimate and terroire. Third, there are important issues of context that need consideration as Evans et al. (2017) note "IT solutions must account for dynamic and context-bound situations, individual decision-making style, and the degree of trust needed for a solution to play the

[39] https://ec.europa.eu/jrc/en/mars

[40] http://www.copernicus.eu/

[41] https://www.basf.com/en/company/news-and-media/news-releases/2017/02/p-17-127.html

desired role in decision-making." In the wider food system, decision support tools are also expanding. For example, complex optimisation modelling for the fresh food supply chain are proposed by Dellino et al. (2018), enabling food demand forecasting and order planning. Optimisation models are proposed by many authors for supply chain management (e.g. (Esteso, Alemany, & Ortiz, 2018; Soto-Silva, González-Araya, Oliva-Fernández, & Plà-Aragonés, 2017; Tavakkoli Moghaddam, Javadi, & Hadji Molana, 2018)). However, such optimisation approaches depend on full monitoring of the chain, especially the cold chain, and the ability to collect data and integrate it.

Farm management systems and decision support tools depend on data to function and thus we should consider the variety of new initiatives concerning data and sources of data. The **Open Data** movement arose in the 2000s partly driven by a desire for greater transparency concerning government activities, and partly out of the expectation that data made freely available would lead to economic and social benefits. There has been a flowering of open data availability across the world supported by such organisations as the Open Data Institute and the Open Knowledge Foundation. Much of the initial “open” data was either government data sets or academic data (publications and research data sets). There has been particular interest in the open availability of agricultural data (or data useful for the agrifood sector) and this was given a further boost by the G-8 leaders commitment to the New Alliance for Food Security and Nutrition (2012) which led to the creation of the Global Open Data for Agriculture and Nutrition[42] initiative (GODAN). This has supported the widespread development and uptake of open data for agrifood purposes, with many success stories being told of apps and tools being built to support farmers both in developed and developing countries[43]. The free availability of the Copernicus data from the EC follows fully in this paradigm. Recently there are signs of interest from commercial organisations to make data open and available (e.g. the Syngenta Good Growth plan data set). The availability and accessibility of open data is largely dependent on appropriate standards being followed both to describe the data sets and to annotate the data.

Linked Data is a technology stack that arose out of the semantic web (Bizer, Heath, & Berners-Lee, 2009) and the Open Data movement. The fundamental idea is that data is represented in the form of RDF triples and use common identifiers with reference to specific ontologies. By using common identifiers, data can be interlinked, and queries performed across distributed data sets. Much of the work in linked data focussed on "Linked Open Data" (LOD) which was driven in large part by the need to integrate heterogeneous data sources in Life Science research and the desire to construct Open Data which could be reusable for a variety of purposes (Heath & Bizer, 2011). The Linked Data paradigm has been much promoted for government data as well (Wood, 2011) including agricultural data sets, and for the agrifood domain mostly with regard to agricultural research data (Pesce, Geser, Caracciolo, Keizer, & L'Abate, 2013; for example, Pesce, Maru, Archer, Malapela, & Keizer, 2015). There is also recent work on using formal ontologies about products with Protected Designations of Origin (PDO) specifications to publish Linked Data about government policy concerning those products (Peroni, Lodi, Asprino, Gangemi, & Presutti, 2016). The Netherlands provides a good example of Linked Open Data focussing on geodata with a SPARQL endpoint[44].

[42] http://www.godan.info/

[43] http://www.godan.info/resources/success-stories

[44] https://data.pdok.nl/

While **Big Data** is more of buzzword than a specific technology, the increasing availability of very large quantities of data, of considerable heterogeneity, and at ever increasing speeds of update have given rise to considerable discussion as to its impact on the agrifood sector. Food and agriculture are quintessential "big data" domains, and areas such as food retail have had a long history of CRM focussed data analytics dealing with very large-scale data warehouses providing extensive opportunities for business intelligence based on the data collected from customers (Bradlow et al., 2017; Ngai, Xiu, & Chau, 2009). Although some authors view "big data" as playing a significant role in agriculture (Wolfert et al., 2017) as this does not form a basic technological category, it is unsurprising to see a move by companies toward the use of the term "**AI**" instead (with the intended meaning of "**machine learning**" or "deep learning"), which at the time of writing (late 2018) has become the latest buzzword. The interest in "Big Data" has provoked wider discussion of the ethics and governance models around data, especially as there are inevitable imbalances of power between large corporations and individual farmers (Carbonell, 2016). This has led to a number of initiatives to protect the farmer or at least clarify contractual relationships include the Digital Charter in Switzerland[45], and the "Code of conduct on agricultural data sharing" developed by COPA-COGECA in collaboration with a range of industry representatives (Copa-Cogeca et al., 2018).

[45] https://agridigital.ch/fr/charte/

Data standards are essential for any information system where data is intended to be shared between different organisations or participants and as such are central to the development of ICT in the agrifood sector (Scholten et al., 2016). A basic distinction can be made between syntactic standards (typically in XML) and semantic standards (such as ontologies); and between messaging and ontological standards see (Brewster, 2017). The food and agriculture sector have a surfeit of standards but a relative lack of consistent uptake and adoption across participants. In the **agronomic research** area, the major standards include AGROVOC (used largely for the annotation of academic publications), the GACS top level standard (concept scheme)[46], and more recently the US originating FOODON (Dooley et al., 2018). AGROVOC was developed by the FAO and is maintained by a network of institutes around the world (Rajbhandari & Keizer, 2012), and has now been partially mapped onto the US National Agricultural Library of the USDA and the CABI thesaurus in the form of the GACS ontology which has mapped and integrated the top 15,000 concepts[47]. FOODON integrates a number of existing ontologies but its focus is again on research and clinical data although its ambition is to provide a mechanism for data integration across the food system. A wide variety of ontologies, mostly for research purposes are catalogued in the Agrisemantics Catalogue of Data Standards[48]. A major challenge for **digital agriculture** has been the lack of integration between different farm machinery manufacturers and the consequent difficulty of obtaining an integrated view of a farm. Most major manufacturers (such as John Deere, Kverneland, Laval, etc.) have provide apps and web interfaces to the data collected from a farm rather than use existing standards to enable data integration directly between farm machinery and the FMIS. This is gradually changing with the ever-wider adoption and extension of the relevant standards. These include the AEF[49] supported ISOBUS-XML for farm machinery, the AgGateway[50] supported ADAPT standard for FMISs, and the livestock and dairy standard from ICAR[51]. Most of these are XML based but gradually moving towards more semantic approaches. In the supply chain, EDIFACT is widely used in Europe according to a number of sources[52] and supermarkets have been ever more insistent that their suppliers are EDI capable. Another important standard is the GS1 EPCIS standard[53] which is intended to "enable disparate applications to create and share visibility event data, both within and across enterprises". In practice "visibility" means the ability to track and trace objects (including all food products) along the supply chain.

[46] https://agrisemantics.org/GACS/

[47] http://agrisemantics.org/gacs/

[48] https://vest.agrisemantics.org/

[49] https://www.aef-online.org/

[50] http://www.aggateway.org/

[51] https://www.icar.org/

[52] http://www.edibasics.co.uk/edi-resources/document-standards/

[53] http://www.gs1.org/epcis

While **social media** is an established technology in many areas of business and human activity, its growing importance in the food and agriculture sector is worth mentioning. Twitter and Facebook have proven to be of immense significance for farmers as a means to communicate while they are working on the field, on the tractor. Communication occurs between farmers and there are cases of advice being provided by farmers located on different sides of the globe; and also communication with other participants in the food system especially consumers who are usually unaware of the nature and challenges of food production. An example of the latter is "Farmer of the Week" in different countries[54] where a farmer takes over a persistent Twitter account for a week and reports on all their daily activities. Twitter also plays a significant role in some countries with weekly "AgChat" or "AgriChat" sessions[55] (e.g. on Thursday evening) enabling different members of the food system to have a conversation on a topical issue of the day. At the retailer end of the system, social media is mostly used for promotions and for customer relation management e.g. when customers complain about products (Ramanathan, Subramanian, & Parrott, 2017; Stevens, Aarts, Termeer, & Dewulf, 2016). There is some limited use of social media at a type of human sensor to track food crises or integrity issues (Johnston, 2017). YouTube has also an important role, with the creations of channel by farmers[56] but also for farmers, such as the FIBLFilm which is a channel of a research institute giving advice or making documentary regarding organic agriculture[57].

A**pps on smartphones** are playing an ever-greater role at various stages of the food system. Many of the decision support tools mentioned above used by farmers or traders are delivered as smartphone apps. For **consumers** apps are playing an important role both in providing access to information (for example the app of OpenFoodFacts[58] using crowd-sourced open data on food composition), helping with cooking advice, nutrition information, and interestingly waste reduction. Vogels et al. (2018) published a report on ICT tools for food management and waste prevention at the consumer level. The authors list a number of informative apps (to help reducing food waste in the storage phase), reminder apps (concerning the expiry date of a food product), food sharing apps (both consumer to consumer and retail to consumer), apps coordinating food surplus for charity, planning apps, recipe apps (for food waste) as well as apps released by supermarkets as service for their customers. These types of apps form part of a wider movement of personal nutrition tracking apps (often coming from Silicon Valley) such as *MyFitnessPal* where the key objective is weight loss or general health. Overconsumption of food is, of course, now being seen as a food system issue affecting total waste (Alexander et al., 2017).

There are many **other technologies** that are important to the future development of ICT in agrifood. Here we mention **Blockchain technologies** (BCT) (or distributed ledger technologies) because they have received a lot of attention in the past since 2014. BCT is seen as providing opportunities to disrupt traditional products and services due to features such as removing the need for a trusted third party, the permanence of the Blockchain record, the distributed, decentralised nature of blockchains and the ability to run small programs (otherwise known as smart contracts). Several authors and start-ups have proposed that this technology may play an important role in the agrifood system. Provenance.org, a UK start-up have proposed to use this for tracking and tracing (Steiner & Baker, 2015) based on the Ethereum blockchain.

[54] http://farmersoftheuk.org/

[55] http://agchat.org/ and http://www.agrichatuk.org/

[56] Ex. https://www.youtube.com/user/onelonleyfarmer and https://www.youtube.com/user/FarmersWeeklyVideo

[57] https://www.youtube.com/user/FiBLFilm

[58] https://world.openfoodfacts.org/ provides open data on over 700k food products.

In a very similar manner, Versetti and Meyer (2017) of Foodblockchain.xyz (now rebranded as Ambrosius[59]) propose to solve all tracking and tracing problems by recording transactions on the Ethereum blockchain. Weston and Nolet (2016) identify three areas in agriculture where BCT could be used: provenance and radical transparency; mobile payments, credits, and decreased transaction fees; and real-time management of supply chain transactions and financing. With respect to provenance and transparency, they argue that "The value of blockchain here is its ability to make the supply chain entirely transparent and rich with immutable provenance data from farm to table". Walmart is currently running experiments to use this technology for tracking and tracing in the pork sector in China, in collaboration with IBM and based on the Hyperledger Fabric technology, a response greater pressure to improve food integrity in the Chinese market (del Castillo, 2016; Higgins, 2017). A start-up has proposed to certify the authenticity of Italian wine on a blockchain (Tomasicchio, 2017). Agriledger are using BCT to provide an immutable register for supply chain finance and transactions for farmers in Kenya and New Guinea[60].

[59] https://ambrosus.com/

[60] http://www.agriledger.com and http://agunity.com/

Currently BCT has a number of limitations which put these ambitions into questions. Transaction throughput on blockchains like Ethereum are currently about 20 per second which is far too slow for most practical applications. Most proposals involve using hashes of data and placing those on the blockchain in which case the only utility of BCT is in showing that transaction x at time t has not been changed at a later date. Using hashes makes search in a blockchain data set impossible and thus there is no real "radical transparency." Much effort is being expended currently to scale up BCT so that it can handle real life data transactions and the applicability of the technology to the food system depends on this succeeding (Croman et al., 2016; cf. for example McConaghy et al., 2016; Vukolić, 2015). Another challenge is squaring the circle between total transparency across the supply chain provided by blockchain technology and the need to protect business confidentiality and even personal privacy.

4.4 EUROPEAN RESEARCH INITIATIVES

The Wider Funding Landscape for Digital Agriculture.

Investment in the application of ICT to the food and agriculture sector has been transformed in the past 15 years. While there were some projects related to what we would now call "digital agriculture" or "smart farming" under the EC's FP6 programme, we would argue that the ICT-AGRI project has been very influential in making ICT a topic of interest in the EC's FP7 and H2020 research programmes. Beyond the many different individual projects of relevance, here we will mention some of the major programmes and projects:

- Towards the end of FP7, the EC decided to fund the Future Internet Public Private Initiative with approximately €500M to support the development of "future internet" capabilities. Unusually, it was decided to dedicate funding to agrifood as a potential domain of application and this led to the funding of two major projects totalling over €35M of funding in the 2011-2015 period (Smartagrifood, FiSpace[61]).

- One of the characteristics of late FP7 funding and the H2020 programme has been a turn towards extensive support for SME, often in the form of dedicated instruments (calls) and "accelerator" projects centred around cascading funding. There have been a number of these in the ICT for agrifood space including Smartagrifood2, Finish Accelerator, and Fractals projects[62].

While historically DG Agri has not had as its focus ICT developments for agriculture, this has gradually changed with a significant shift in funding especially in the H2020 framework programme towards supporting the use of ICT in agrifood as well as the wider ecosystem necessary. This has been evident in the collaborative funding within H2020 by DG Agri and DG Connect/DG Research of the IoT large scale pilot in smart farming with over €30M funding (IOF2020 project)[63].

Current major funded projects related to the digitisation of the food system including agriculture include:

- IOF2020 (Internet of Food and Farm 2020), a four year €34M Horizon 2020 project (2017-2020) focussing on the role of IoT in the agrifood system. Building around 21 pilots, it is developing a wide range of demonstrator showing the applicability of IoT devices and data for different agricultural sectors (covering Arable, Dairy, Fruits, Vegetables and Meat verticals) and parts of the agrifood supply chain.

[61] https://agrisemantics.org/GACS/

[62] http://agrisemantics.org/gacs/

[63] https://vest.agrisemantics.org/

[64] https://www.aef-online.org/

[65] http://www.aggateway.org/

- DataBio[64], a three year €16M project (2017-2019) focussing on the use of "big data" in raw material production across the bioeconomy including agriculture, forestry and marine resources. A big data platform will be deployed across a number of pilots across agriculture, forestry and fishery/aquaculture.

- SmartAgriHubs[65], a four year €22M Horizon 2020 project (2018-2022) focussing on accelerating the digital transformation of the European agri-food sector by addressing the need for a wider ecosystem of expertise and opportunity integrating technology and business support.

- EIT Food[66] - this is EIT KIC focussing on food. As a partnership with industry the EC, through the European Institute of Technology will provide €400M, with private industry providing a further €1.2B over seven years. There are several objectives including address low consumer trust, enabling individuals to make informed personal nutrition choices, developing a digital food supply network, enhancing sustainability, provide 'food system' skills for 1000s of students, entrepreneurs and professionals, catalyse food entrepreneurship.

The national funding landscape has also changes substantially in the last ten years. For example, in the UK after a long period of little or no investment in precision agriculture and related technologies, the UK government announced in 2013 £160M investment in "agritech". This investment included the creation of centres of excellence, namely Agrimetrics for agricultural data (in 2015), and the Agricultural Engineering Precision Innovation Centre (Agri-EPI) (in 2016)[67]. In France, in 2015, the ministry of agriculture published a national action plans AgricultureInnovation 2025[68], which included 12 proposed projects, i.e. 45 actions[69] for the development of new technologies in agriculture. One of these consecutive actions was the launch of a chair of digital agriculture AgroTIC in national agriculture school SupAgro in Montpellier in 2016. In the same year a "Institut de Convergence Agriculture Numérique" (#Digitag) was funded at Irstea, Montpellier to integrate precision farming and data driven agriculture in France[70], being part of the above-mentioned action plan. Similarly, in Switzerland in 2017, the theme of digitalization and new technologies

[65] http://www.aggateway.org/

[66] https://www.icar.org/

[67] https://www.agrimetrics.co.uk/ and https://www.agri-epicentre.com/

[68] 30 projets - Ministère de l'Agriculture

[69] Some actions resulting from the report: https://www.digitag-challenge.fr/, https://www.vegepolys.eu/,
http://www.treize-articles.com/content/blog/imagine-agri-la-data-agriœle-sur-les-r%C3%A9seaux-sociaux-0,
https://www.arvalisinstitutduvegetal.fr/agriculture-connectee-arvalis-lance-le-projet-digifermes-en-partenariat-avec-l-idele-l-itb-et-terres-inovia-@/view-1171-arvstatiques.html.

[70] http://www.hdigitag.fr/fr/dossier-presse-inauguration/

in agriculture has been defined as a priority with the "digital Switzerland" strategie[71]. On a policy level, a digital charter describing the good practice was recently establish after a collaborative work[72], and the data sharing platform Barto was created[73]. Even Greece in spite of its economic difficulties has announced national investments in the "digital development of the agricultural sector" of over €33M in 2018[74]. There have been parallel initiatives in many other European countries, reflecting a global upsurge of interest in this area. Globally there have been major commitments and investments in the US and in China, from organisation such as the Gates Foundation, and development funding agencies such as USAid and DFID as well.

ICT-AGRI Project Mapping

This section provides overview of national and EU level initiatives to support the development and implementation of ICT in agriculture. A framework for categorising initiatives by their means and targets for supporting digitisation in agriculture is suggested. The framework could be used for estimating the volume of support in different initiative categories and ultimately for measuring the impacts of different initiative categories. This is however beyond the scope of the current report apart from some examples. The funding and collaboration initiatives will be discussed in the following categories of means and targets:

1. Agricultural research
2. Technological research and development
3. Bottom-up projects reflecting end-user needs
4. Coordination of European players / stakeholders
5. Support to private enterprises, especially start-ups and SMEs
6. Support to farmers

ICT-AGRI performed in 2016 a mapping of projects within ICT and robotics in agriculture. The mapping was made manually by the ICT-AGRI partners as a simulation of an automated collection of project data from funding agencies. The underlying idea is that meta-data on grants given by national as well international funders could be a valuable source of information. The mapping resulted in information about 530 projects, which is largely complete concerning EU funded projects while the completeness on national projects vary greatly from country to country. The overall goal of the funding of these projects is to promote, in a broad sense, digitisation in agriculture and food, but the means to obtain this goal and the targets of the initiatives are different.

[71] https://agridigital.ch/

[72] https://www.blw.admin.ch/blw/fr/home/politik/digitalisierung.html

[73] https://www.barto.ch/home-fr.html

[74] http://www.voria.gr/article/nikos-pappas-i-kivernisi-ependii-stin-effii-georgia

1. Agricultural research (Impact by enlarging and improving the agricultural knowledge base)

Agricultural research related to digitisation is mainly focussing on the decision rules required in Decision Support Systems (DSS). Scientifically based decision rules are required for the realisation of the potential benefits of data from emerging new sensors. There are therefore two stages in agricultural research related to digitisation:

- Achievement of the agricultural knowledge in the traditional format of publication in scientific journals.

- Transformation of agricultural knowledge in journal format into machine-readable decision rules covering the complete value room of the sensor data.

Examples of this kind of work can be found in DSS for crop protection based on weather data, which have been done over the last 30 years. For newer types of sensor data, the agricultural research may be less advanced. Constructors of DSS based on new sensor data will often leave it to the user to define the decision rules. Agricultural research related to digitisation is often combined with technological research and development.

2. Technological research and development (Impact by enlarging and improving the technological knowledge base)

Technological research and development is a diverse area, the main areas being measuring (sensors), data import and storage, user interaction, and data export to automated machines. R&D is not specific for agriculture, except for some sensors, and most of the work in this area with an agricultural stamp is about application of technology in agricultural context. Most of the work in this area is within Internet of Things (IoT).

3. Bottom-up projects reflecting end-user needs (Impact by increasing the relevance of ICT solutions)

In H2020 there is an attempt to make EU projects more effective by involving all parties in the agricultural and food ecosystem especially the end-users. This approach, termed the "multi-actor" approach was initially trialed in the agriculture and forestry projects from 2014[75], and has now spread across H2020 project work programmes. Many calls, especially in agriculture, include the statement ""Proposals should fall under the concept of multiactor approach." This way of constructing research collaborations has been supported by the EIP-AGRI initiative, the European Innovation Partnership for Agricultural Productivity and Sustainability. This partnership between the EU Member States and the EC also supports "Operational Groups.", which are multi-actor innovative projects funded under the national or regional Rural Development Programmes. Some institutes such as the ETHZ from Switzerland created some methods and tool kit to better understand and involve the end-users[76].

4. Coordination of European players/stakeholders (Impact by improving the awareness of ICT solutions, business models, etc.)

Coordination projects attempt to bring players together and to collect and publish information on a specific area. Standardisation needs coordination to achieve impact on an international level. The EIP-AGRI network connects Operational Groups with relevant H2020 multi-actor projects and projects funded by other means. A series of workshops and seminars dealing with digitising agriculture have been organised, and their results are presented on the EIP-AGRI website, together with links to other relevant projects and materials[77].

5. Support to private enterprises, especially start-ups and SMEs (Impact by stimulating the supply of ICT solutions)

The idea is to stimulate the providers of ICT to the agri-food system with access to technology and direct economic support to front runners. This often focusing on start-ups and SMEs. An example on EU level is the Future Internet Public-Private Partnership, which developed easy access to advanced Internet technology (FIWARE) and supported about 100 SMEs and start-ups in three accelerator projects within agriculture and food. Business development is also very popular in national programs, usually not exclusive on but open for agriculture and food.

[75] http://ec.europa.eu/programmes/horizon2020/en/news/interactive-innovation-motion-multi-actor-projects-and-thematic-networks-under-horizon-2020

[76] https://naturalsciences.ch/topics/co-producing_knowledge?_ga=2.204520660.531601301.1504727849-1132012580.1500019512

[77] https://ec.europa.eu/eip/agriculture/en/digitising-agriculture

6. Support to farmers (Impact by direct motivation of farmers)

On the EU level the Common Agricultural Policy (CAP)[78] and at the national level subsidies to investments in new technologies. The implementation of the CAP and national regulations has led to public investments in ICT infrastructure and data (e.g. data about field boundaries, crops, cattle movements, etc.) which are made available for other purposes. There is a growing number of ICT applications based on Open Data coming from regulations. Farm investments in Precision Farming could be rewarded with less restrictive nitrogen fertilisation regulation. In Denmark, farmers can be allowed a higher nitrogen fertilisation if they implement a certified environment protection instrument, for example to lead field drainage through a mini wet area. Work is in progress to certify Precision Farming as an environment protection instrument.

Volume of support initiatives in impact categories

The ICT-AGRI mapping of projects within ICT and robotics in agriculture is used as a source for estimating the volume of support initiatives in impact categories. This gives only rough estimates as the data are not perfect for the purpose. The projects were not tagged with impact category (outlined above) when the data were entered into the database. The categorisation is done on the funding agency level, which is a manageable task. Coordination projects are however identified on the project level (only EU projects, we assume there are few such projects at a national level). Volume is estimated by number of projects although there is a large variation in project budget. The data structure includes project budgets, but this information is missing in many cases. It was not possible to distinguish between Agricultural R&D, Technological R&D and Bottom-up projects. Support to farmers is not applicable for projects.

The results are shown in Table 1. The distribution of projects on R&D versus support to enterprises is inverse in national and EU projects. However about 120 of the EU support projects were in three Future Internet accelerator projects with quite small grants and short duration. If these are taken out of the comparison, the distributions are quite similar. EU R&D projects tend to become very large and probably much larger than national R&D projects.

[78] https://ec.europa.eu/agriculture/cap-overview_en

PROJECT SIZE	NATIONAL PROJECTS	EU PROJECTS
Agricultural R&D	156	63
Tech R&D		
Bottom-up		
Coordination		10
Support to enterprises	49	159
Support to farmers	n/a	n/a

In principle estimation of impact is more straightforward for support projects, because a good indicator is the business success of the supported enterprises, which can be obtained from the enterprises. Also impact from technological support can be estimated, for example by application of FIWARE technologies. However, in practice it is hard to obtain accurate figures to determine how successful the EC and national support has been in creating an ecosystem of digital agrifood enterprises, just as it is quite difficult to identify which technological developments have had the most uptake in digital agrifood. Anecdotal evidence suggests that the combination of FP7 and H2020 funding has helped to kick-start a revolution in the creation of many digital agrifood enterprises around Europe. Furthermore, substantial impact has derived from the availability of Open Data such as from Copernicus. Initiatives such as FIWARE have not resulted in the expected level of uptake and have instead provided indirect seed funding for start-ups

Impact from R&D projects on digitisation in agriculture is not easy to estimate. There seems not to be a common European route from R&D to applications as for example a high production of open source and free software within the agricultural area. For example, it is not well known how producers of DSS obtain the required decision rules. It is most likely that decision rules spread locally from research institutes to ICT providers. Also, the developers of DSS systems invest time and effort in reading the academic literature on crop models or vulnerability to pests to support the software design. The utilisation of agricultural R&D for digitisation in agriculture may appear to be inefficient but this largely due to a history of under investment in digital agriculture as well as limited disposable capital for investment in new technologies until now.

5 CURRENT AND FUTURE CHALLENGES FOR ICT-AGRI

For ICT-AGRI, the adoption of new technologies is a significant challenge. Although ICT and robotics as technologies have developed immensely in the last two decades (as described in Section 4), adoption is still very low both in EU and globally[79]. Several organisations, such as the OECD and UN Global Compact are currently concerned with this aspect. In order to provide a basic assessment of the current challenges, and because these issues concern all stakeholders, the ICT-AGRI project conducted a questionnaire based survey. The Network Management team and the Expert Advisory Group of ICT-AGRI defined a list of current and future (i.e. in the next 10 years) challenges that ICT in Agrifood (such as GNSS in precision agriculture) will face in getting adopted the EU agriculture and food systems. A questionnaire of 15 questions taking less than 5 minutes was developed. The aim of this questionnaire was to present the challenges identified by ICT-AGRI, and quantify the importance of these challenges, as well as asking for other possible challenges. The questionnaire was disseminated to all ICT-AGRI stakeholders and during ICT AGRI events in 2017 (sometimes discussed during a workshop). 248 individuals from diverse backgrounds participated (see Figure 1) in the online questionnaire, and around 60 individuals during the workshops. As can be seen from Figure 2, all the challenges covered in this SRIA were defined as challenging (from moderately to extremely) and all proposed challenges were covered in the ICT-AGRI list.

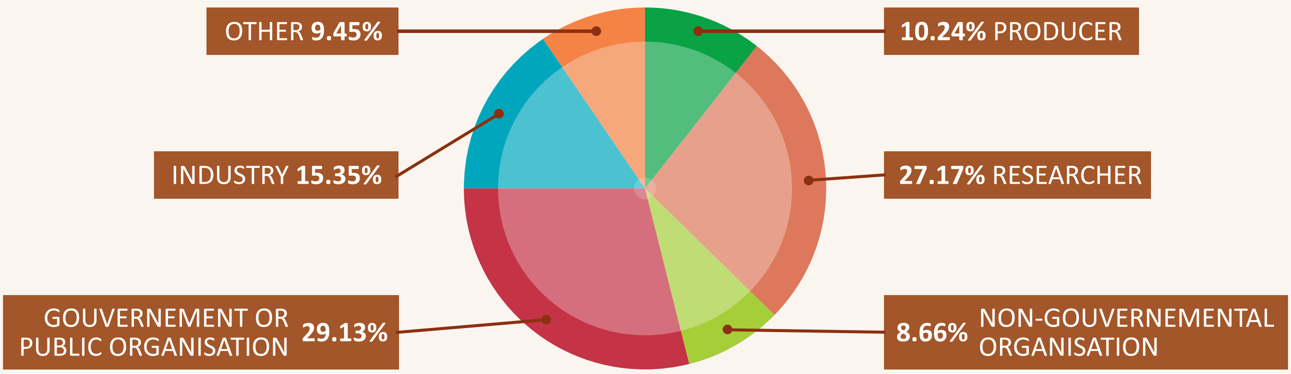


Figure 1

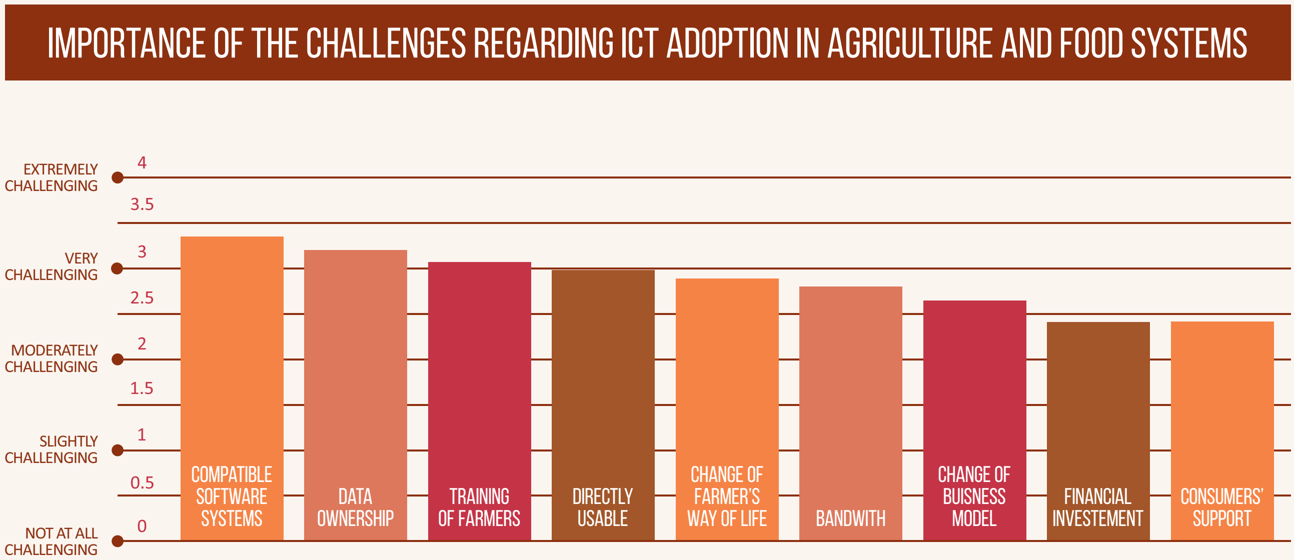


Figure 2

[79] We cited above the example of milking robots with a 30% penetration in the Netherlands and 2% in the US. Milking robots are the most widely used example of technology in precision farming apart from GPS/GNSS which is currently used by over 70% of farms in the US (Fulton, 2015).

5.1 ECONOMIC CHALLENGES

As a result of the development of the Digital Single Market, some authors have suggested that Big Data among other technological developments will cause major shifts in roles and power relations among different players in current food supply chain networks (Wolfert et al., 2017). The landscape of stakeholders exhibits a complex dynamic between farmers, cooperatives, tech companies, venture capitalists and often small startups and new entrants, with much of the dynamic centring around the production, access and use of data. At the same time, there are many public institutions that are publishing open data (cf. discussion in Section 4), on condition that the privacy of individual citizens including farmers be guaranteed. The future of Smart Farming will develop somewhere on a continuum between 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. The further development of data and application infrastructures (platforms and standards) and their institutional support will play a crucial role in the battle between a number of possible scenarios. One of the most important areas of development will be the manner in which new business models develop for the agrifood sector especially farmers.

What is the challenge?

Numerous articles, reports and reviews emphasize the importance of digitalization in the Agrifood sector. In the final report of the EIP-AGRI Focus Group on Precision Farming, the group clearly states that "*new business models for data management are needed; sharing and open-data sources should be developed to bring Precision Farming to the next level. The recognition of data ownership is crucial. Portals that can facilitate the exchange of data are a prerequisite*" (EIP-AGRI, 2015). With the introduction of precision farming in agriculture, the sector is evolving into a more service-**oriented environment with 'knowledge' being exchanged via a variety of management support** systems. Machines are no longer only relieving farmers of hard labour, they also tend to collaborate with other devices and progressively take over the decision process within daily operations. Data has been described as the 'new oil' as a metaphor for the value it represents across industrial sectors including agriculture. Interconnectivity (IoT networks, 5G, etc.) will be the new pipeline grid to transfer this oil. New service-oriented business models are needed in order to translate data into knowledge to feed today's machines with yesterday's findings. The ultimate goal is to have real time feedback loops with instant decisions based on computer algorithms. To make that work, multiple stakeholders are involved, **and their roles vary from data provider to data agent to data processor to data validator. van't Spijker** (2014) describes five Business Model Patterns to leverage the value of data in organizations:

1. Basic Data Sales.

Companies create data in their primary process, package this data into a feed and sell it in a single transaction or a subscription. For example: Farmobile[80] (Kansas, US) claims that "*one farmer earned $17,952 for his Electronic Field Records in 2016*". As long as a farmer is already a subscriber to their data products, there is a relatively straightforward process for signing up and in theory you earn $1/acre. The farmer can subscribe to various different products starting from $750/year. Homologa[81] is another example which collects MRL data from around the world and organises and processes that data for sale to farmers and cooperatives.

[80] https://www.farmobile.com/

[81] http://www.homologa-new.com

2. Product Innovation.

Companies create new products or services based on the data they generate in their primary process. Typical examples are the agricultural machine manufacturers like Amazone[82], Claas, Krone, Horsch, John Deere and CNH which add services such as predictive maintenance, adaptive driving based on soil conditions or GNSS based applications for precision steering due to the data they collect from their machines.

3. Commodity Swap.

Commodity providers offering their original products (e.g. agriculture machinery) at a discount or even for free (unlikely in this sector) but charge for extra services provided in combination with the commodity products. The German initiative 365FarmNet[83] presents itself as an association of companies for farmers and partners. Founded in 2013, it promotes a holistic data-for-data approach and entered the market with the aim of supporting farmers in all aspects of farm management. So far, it's free of charge and the approach seems to stand somewhere between product innovation and commodity swap.

4. Value Chain Integration.

Two companies exchanging (usually sensitive business) data to integrate parts of their value chains in order to save money or optimize business performance. In 2017, Cargill announced Dairy Enteligen™ demonstrating their ambition "to collect data and combine this disparate information from multiple software programs on one comprehensive platform". It allows Cargill advisors and customers to make precise decisions on feed and farm management practices. This model seems to act as a value chain integrator of the farmer's data.

[82] http://www.amazone.net

[83] https://www.365farmnet.com/en/

5. Value Net Creation.

Multiple companies sharing the same customer exchange data in a 'value network' with the aim to provide unrivalled service to the customer. In the Netherlands, SmartDairyFarming[84] developed a digital highway for farm-generated data (Vonder, van der Waaij, Harmsma, & Donker, 2015). Stock management at herd level is not accurate enough to enable optimal attention for individual animals. Sensors, index figures and decision-making models can help farmers establish the precise needs of individual cows and make the right choices. With the farmer's consent, a data hub is used as a platform to release this data for a variety of applications.

What business models are needed for the future?

Data driven applications in Smart Farming are closely connected to the socio-economic challenges to be addressed. The opportunity to extract value goes beyond primary production; it is influencing the entire food supply chain. Data correlations are being used to provide predictive insights in farming operations, drive real-time operational decisions, and redesign business processes for potentially game-changing business models. Five important axes could be considered in order to capture the future data business models in smart farming:

Axis 1: Access.

Is the basic approach open for every stakeholder to join or closed in a membership only? John Deere have spent $305 million to buy a robotics company, called Blue River Technology (Pringle, 2017b). This startup makes agricultural robots capable of identifying weeds and other unwanted plants and dosing them with high-precision sprays of herbicide. Albeit a good decision for John Deere, the acquired knowledge of Blue River Technology is no longer available for other manufacturers on the market as it is locked in the service data silo of its new owner. In parallel, Open Source efforts have emerged on a worldwide scale even in agriculture (Young, 2016)[85]. Unfortunately, there are as yet too few agronomic service-oriented companies operating independently in order to create sufficient momentum in the Open Source community for a sustainable data ecosystem.

Axis 2: Data source.

Does the source rely on individual (raw, nominative) data which will fall under the General Data Protection Ruling or is data provided by a processor which already anonymized, cleansed, processed and/or aggregated data making it GDPR-proof? In agriculture, there is not necessarily a clear line between a farmer's business data and data related to him or her as a person. As of May 2018, GDPR might pose a problem tackled in axis 4: who's the owner of the data? If data can be extracted directly from the farm, some parts can be considered to be personal as the origin of the information is still connected to personal data of the farmer. In this case, it will be difficult to bring it to open platforms before thorough processing. Therefore, the farmers' cooperative COPA-COGECA and associations of machine manufacturers such as CEMA have produced 'codes of conducts' in order to achieve compliance with GDPR[86].

[84] https://smartdairyfarming.nl/en/

[85] http://farmos.org/ and http://opensourceecology.org/

[86] Reference to be added.

Axis 3: Data chain.

If we consider the total value/process chain as being 'from farm to fork', do data sets capture parts of the process chain (e.g. only between 2 stakeholders) or does it cover all stakeholders (the whole supply chain or supply web)? Fragmented data sets are both a technical limitation and a reflection of economic choices. Opportunities exist in more than one dimension: horizontal integration will focus on joining more data sources for one specific item (data layers) whereas vertical integration will try to connect the total journey of the item (data chains). Irrespective of whether the data platform is open or closed, fully integrated data sets covering the whole process chain will be more valuable for a bigger number of stakeholders. They will offer more intelligence to decision support systems to fine tune certain actions - including the possible impact of those actions up and down the chain - in order to maximize the farm's efficiency and profitability. and a reflection of economic choices. Opportunities exist in more than one dimension: horizontal integration will focus on joining more data sources for one specific item (data layers) whereas vertical integration will try to connect the total journey of the item (data chains). Irrespective of whether the data platform is open or closed, fully integrated data sets covering the whole process chain will be more valuable for a bigger number of stakeholders. They will offer more intelligence to decision support systems to fine tune certain actions - including the possible impact of those actions up and down the chain - in order to maximize the farm's efficiency and profitability.

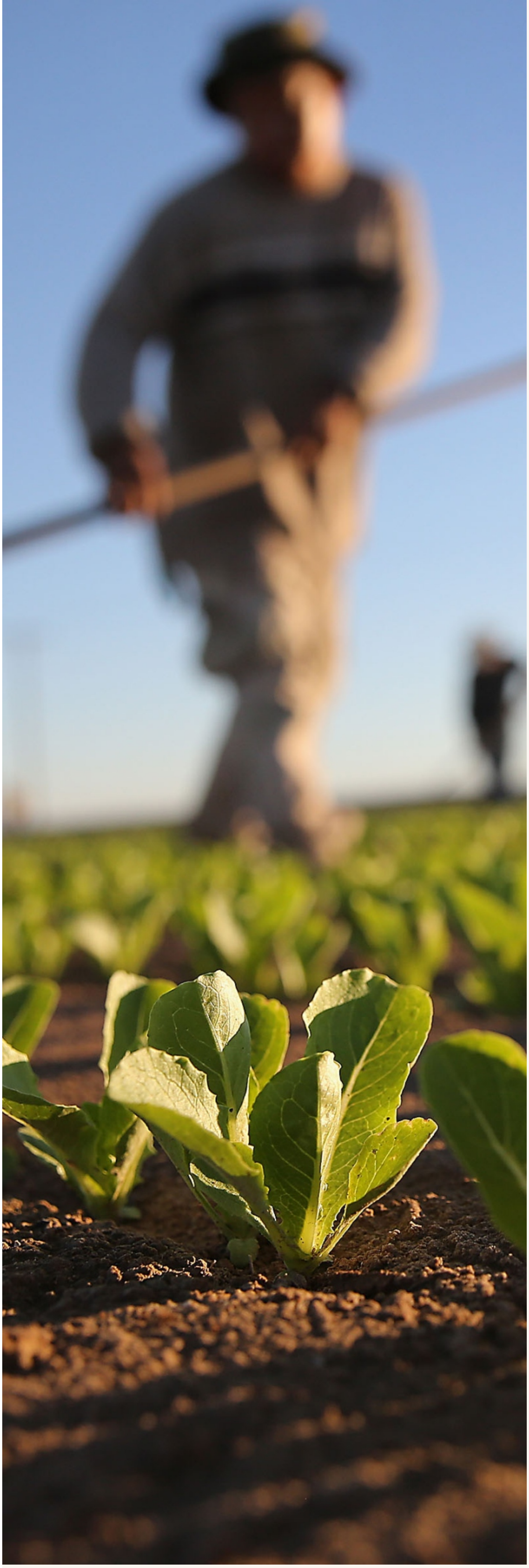
The farmer's adoption process of data-driven decision tools, however, might work better when taking smaller steps. In a more 'show and tell' situation, fragmented data sets might make it easier for the farmer to understand what was done, the way it was processed and how the decision support system formed its recommendation. In this way, trust can be built for the farmer to compare his or her experience (if not gut feeling) with the outcome of a support system based on data.

Axis 4: Ownership.

Who's in the driver's seat, is the individual farmer the data owner or another party (supplier, processor, cooperative)? For example, the Dutch economic press puts much attention on precision agriculture technology and data ownership. In 2017, the Dutch financial newspaper 'Het Financieele Dagblad' published a series of articles with headlines such as "*the farmer has the data, but others are making money using it*" or "*Who profits from the farmer's data*?" addressing the ownership question[87]. The GDPR redefines the rules of the game for 'personal' data processing but leaves a substantial grey zone between strictly personal and strictly business data coming from the farm (or any other data source for that matter). Looking at the business opportunity, a farmer's individual data is worth very little if it cannot be correlated with other, related data sets in an ecosystem. However, most of the smart geo-apps, software tools and connected devices depend heavily upon data from many farmers in order to provide services, and those who gather the data will profit. Only large datasets, gathered over time and over as many sources as possible will lead toward accurate agronomic decisions that are relevant for a paying customer. This evolution is going on in many other sectors such as smart cities with traffic control, parking management and crowd monitoring; social media with sentiment analytics, manufacturing with predictive maintenance; logistic planning with parcel delivery routings, and it will not be different for agriculture[88]. In this new relationship, farmers, suppliers, distributors, cooperatives and food processors will need each other regardless of which party will claim the ownership of the extracted intelligence. In fact, only open, integrated eco-systems where every stakeholder appreciates the input of all others, might become sustainable enough to be called a real and working '*business model*'.

[87] https://fd.nl/economie-politiek/1208103/wie-profiteert-van-de-data-van-de-boer

[88] The caveat to this statement is that decision support based on generic data and crop models need to be calibrated to the specific micro-climates depending on the geographic location of farms.



Axis 5: Value.

Is the 'currency' to exchange value rather focused on money or knowledge? Ideally, a business model should strive for value to be created and redistributed in a well-balanced way for all stakeholders in the game. Even when all parties have access to the same data ecosystem, there will be a substantial difference on how they monetize their activities seen their core businesses are different too. They will tap into other layers of the same data pool and transform it into a service in accordance with their own portfolio and expertise. Some parties will transform data into knowledge and others, with no direct return opportunities, will be compensated for making their data accessible. Friction might occur when too many parties develop similar services for comparable customers. Intrinsic competition is bound to re-introduce data silos. Anyway, sustainable trust will be the key in order to make the business model valuable over time.Although several initiatives have started to develop data platforms, the critical success factors for sustainable business models remain under debate. The majority of the existing models will play out along the 5 axes mentioned above. It is uncertain which models will have a smooth adoption and which will be disruptive for or forced upon farmers.

What is mostly lacking are collaborative initiatives in public-private partnerships where real ecosystems are nurtured by farmers', suppliers', controllers', processors', retailers', health providers' and even consumers' data collected and provided over an open value exchange infrastructure supported by all stakeholders in the grid. Tailor-formed 'consortia by objective' may be needed to develop new strategies by opening relevant data silos and unleash the real power of (big) data in multi-source correlation exercises. Performing farm management systems including decision support mechanisms and feedback loops has the potential to tackle the Industry 4.0 challenges of integrated data value chains from farm to fork.

5.2 LIMITATION AND CONSEQUENCES OF ICT

Here we briefly consider the various inherent limitations of ICT systems which may act as barriers to adoption and/or provide unintended consequences for farmers and stakeholders in general in the agrifood system. A key inspiration here is the vision that precision agriculture could (or should) achieve the same or even greater level of knowledge and understanding of the characteristics of a farm as traditional farms used to have (for example before WWII)[89]. In one possible scenario, there will eventually be extensive instrumentation of the farm and food system, with widespread use of crop models feeding prediction and decision support systems in combination with data captured from a variety of sources feeding farmers, advisors and other actors. Here we highlight various limitations and potential problems with such a highly instrumented approach to the agrifood system:

- **Security:** Historically a very large number of computer systems have been shown to be insecure and data breaches being regular occurrences[90] (Lord, 2018), often leading to the release of personal and sensitive information. The GDPR is raising stakes here as data breaches will be very expensive mistakes in future but this may also act as a significant break on enthusiasm for sharing data across the agrifood system. Architectures will need to be designed where personal (or personally identifiable) data from farmers do not leave farmers own data stores and only aggregated or pseudonymised data is shared with other actors[91]. The argument can be made that food and farming data is of relatively low interest to illegal hackers due to its relatively low value (hard to use farm data for extortion). Nonetheless the occurrence of such data breaches could make the sharing of data or any business models around data more difficult to realise.

- **Absence of Compatibility and Lock In:** There is a strong tendency for ICT companies to promote systems which engender lock-in to their system and oblige the end user only to use one system. This has been attempted with varying degrees of success since the inception of the computer age. Unless there is a coherent and continuous focus on compatibility between systems (standards, interoperability, and data ownership), farmers and other actors will easily become locked into different systems and this will stifle innovation apart from provoking strong resistance to adoption. Another form of this can be found in the new hi-tech tractors which depend on software systems to function. There is growing resistance in the US to tractors that cannot be fixed except by the company sending out a special technician botha great expense and after a long wait. Farmers are getting bootlegged software from the Ukraine to be able to fix their tractors themselves (Koebler, 2017).

- **Potential for monopoly and centralisation:** Wu has shown how nearly all information technologies since the invention of the telegraph (telephone, radio, television, internet etc.) have tended to go through an early exuberant phase leading to a gradual consolidation resulting in a monopoly of just one or very few providers. This is due to the economies of scale that information technologies allow and also importantly the network effect (Wu, 2010). The digitisation of the agrifood sector exposes it to exactly those dangers that Wu identified. There already much opposition to the consolidation that is occurring in farm input companies (a current spate of mergers is reducing seed and input companies to only four global players) (Moldenhauer & Hirtz, 31. October 2017) and it is widely recognised that both Amazon and Google have eyes for the food and agriculture sector (Bhattarai, 2017).

[89] https://www.farmobile.com/
[90] http://www.homologa-new.com
[91] http://www.amazone.net

Monopoly and centralisation are likely to have detrimental effects on crop diversity and increase the industrial (un-sustainable) approaches in agriculture. Strong regulation is needed to protect small scale agriculture in the face of digitisation of the sector.

- **Smart farming vs. smart cities - the dangers of high modernism:** Smart farming is term frequently used to indicate the next step beyond precision agriculture. There are strong echoes of the concept of "smart cities" in "smart farming" and then there has been significant criticism of smart cities from technical, creative and democratic perspectives (Greenfield, 2013). One of the key challenges identified by Greenfield with smart cities is overspecification i.e. the belief that the designer can anticipate all the uses and applications for which systems can be used in advance. This intimately related to high modernist ideals of order and organisation being imposed on modern cities (especially by Le Corbusier). For ICT to be effective in agriculture and the food system, it must retain fluidity and adaptability, remain aware of the huge variety of ecosystems, micro-climates, crop variety and soil types across any environment it is deployed and not expect or impose a "one size fits all" set of assumptions.

- **Overdependence and deskilling:** Currently farmers are forced to pay attention to their fields, their crops and the environment in which they operate. There is strong tendency for users of ICT systems to trust the system rather than their own senses and this often leads to problematic outcomes. One issue to consider carefully is how to avoid eventual dependence of farmers on fundamentally brittle software systems which may or may not be sufficiently well designed to adapt to changing weather, climate and other conditions. Furthermore, in this process there is strong likelihood of deskilling certain types of farmers as expertise is transferred from the individual to the software system. It is unclear at this stage what the consequences will be and whether this will be an unmitigated positive result.

Our intention here is merely to highlight certain issues that are worthy both of further academic research but also need to be considered as we proceed with the further digitisation of the agrifood system. These are issues which need to be raised in such fora as the EIP-AGRI or other venues for the sector to develop coherent strategies and to mitigate any unpleasant consequences.

5.3 POLICY ADAPTATION

Having reached the middle of its mandate, the European Commission has published the mid-term review of its Digital Single Market strategy on May 10, 2017. It takes stock of the progress made, calls on co-legislators to swiftly act on all proposals already presented, and outlines further actions on online platforms, data economy and cybersecurity. Since May 2015, the European Commission has delivered 35 legislative proposals and policy initiatives as announced in its Digital Single Market strategy. The focus is now on obtaining political agreement with the European Parliament and the Council on all proposals, above all the updated EU telecoms rules which will boost investments in high-speed and quality networks, which are critical for the full deployment of the digital economy and society. (European Commission, 2017)

In order for the "Digital Single Market" strategy to succeed in some sectors a variety of policy and regulatory adjustments will need to be made. One example of such an action has been the institution of the GDPR regulation which both affects agriculture directly but also significantly impacts the business models of certain participants in the food system. Here we point to just three such areas where further work needs to be undertaken. There will surely be many more.

- **Broadband access:** There are still significant geographical regions where network access is inadequate for many precision farming tasks (Michalopoulos, 2017). 4G coverage is very poor in many rural areas, and while WLAN (LoRA and SigFox) provide alternatives both are low bandwidth solutions which cannot help with transmission and processing of complex NDVI images (for example). Regulatory or policy support in this area is crucial if network access is not to become a barrier for the adoption of digital agriculture. While there have been efforts in this area, current results are highly uneven across Europe.

- **UAV Regulation:** As we noted in section 4.2, there is considerable variety in regulations concerning the use of UAVs/drones for agricultural purposes, for example in some places allowing crop spraying and in others not. This is a good example, where more uniform regulation in a nascent industry would allow greater uptake and cross border development.

- **Data ownership and control:** As noted above in Section 4.3, data ownership is becoming an important issue. The GDPR is having a major effect in perceptions and (hopefully) practices concerning data ownership and control. However, if data is not to become another occasion for farmers to lose added value from the system, there will need to be coherent regulation that protects the farmer from data aggregators or protects them from giving away the data too easily (as individuals have done until now to Facebook). As noted above, Copa-Cogeca and other industry actors have provided a "Code of Conduct" concerning data sharing in agriculture sector (Copa-Cogeca et al., 2018) largely focussing on the contractual arrangements. However, at the EIP AGRI workshop on data sharing in 2017, there was a distinct preference for the EC to regulate this area (EIP-AGRI, 2017). With regard to the wider food system, a major area of challenge is food integrity (food adulteration, fraud), and here data sharing has been identified as a major requirement but stakeholders would prefer a third party organisation (even in preference to a food safety organisation) to have access to data and provide analyses (Minnens, Sioen, van de Brug, Luijckx, & Verbeke, 2018).

5.4 FARMERS AND THE SOCIAL DIMENSION

ICT tools and associated technologies such as Internet of Things (IOT) and Big Data need to be considered as valuable tools in striving for more sustainable agriculture and food systems (El Bilali & Allahyari 2018). In line with this digital revolution, the practice of farming and food production is expected to change dramatically in the coming years and decades. As such, we have to question what the impacts will be for the farmer and the farming community as a whole. The digital revolution will transform the way farms are managed and operate. However, adoption of promising digital technologies is slow. Too often, ICT tools are built to develop impressive solutions for issues at stake without taking into account social aspects and demands from the start. In this section, we try to summarise the issues at stake.

First, end-users need to see the value of the ICT in addressing their demands. Using such technologies is very promising for a variety of end-users. Primarily, it is expected that farmers will increasingly be making their decisions based on feedback from data coming from the farm, utilizing targeted and precise information and knowledge that has been generated in real-time and in a local-specific context (Wolfert et al., 2017). They will be able to save time and achieve greater efficiency in their day to day routine. Furthermore, consumers are becoming more concerned about the environmental impact, food safety and nutritional aspects of food related to health and well-being (Tong, Hong, & JingHua, 2015, Perry 2017).

Second, next to the technical issues, major governance issues arise for big data applications. For example, achieving agreements on responsibilities and liabilities becomes challenging for business processes (Wolfert et al., 2017). When data is gathered at the level of the farm and accumulated at the supra farm level (chain, sector or industry), extra value does arise. However, together with this extra value, a lot of questions related to ownership and data governance arise which need to be addressed. "How to ensure privacy and security?" is one of the biggest challenges (Lesser, 2014). Mainly in the USA, a growing number of initiatives address or ease privacy and security concerns, e.g. the Big Data Coalition (Haire, 2014), and AgGateway (AgGateway, 2017). Closely related to this is the question of how the extra value will be distributed across the actors involved.

Third, demographics and the profile of the current "EU farmer" are most probably a major reason for the lack of adoption of IT and IoT technologies in the agricultural sector. Family farms are by far the most common type of farm in the European Union (EU), encompassing a wide range of agricultural holdings: from small, semi-subsistence farms with only family workers and farms which have to rely on other gainful activities for a diversified source of income, through to much larger, more productive farms which nevertheless maintain family management (Eurostat, 2016a). Furthermore, current farmers are mostly not digital natives. The fact that a high proportion of farms with only family workers are managed by persons aged 65 or over (32.3 %), or by persons aged 55–64 (24.7 %) is most striking (Eurostat, 2016a). Nevertheless, the profile of the farmer can be very diverse and is ranging from young alternative farmers, to traditional mostly aged farmers and the more innovative or technical profiles. Furthermore, we want to mention other human barriers for adopting IT and IoT technologies often occurring within the agricultural community. Farmers tend to distrust what they cannot see (the issue of trusting the tool) and mainly follow their peers (the subjective norm). Next to the human barriers, the geographic remoteness of many farms, especially in eastern European countries is a major technical barrier for adopting new technologies. The trend is changing, however, and more farmers are getting connected today, especially the younger generation that will drive the industry in decades to come.

Need for action:

In this section, we present a partial list of possible actions that can address aforementioned issues at stake. They are focused on increasing adoption rates of ICT tools and IoT technologies.

First, a multi-actor approach is of great importance to support a better interaction between tool developers and end-users in ICT. There are 3 major reasons for implementing a participatory approach with multiple stakeholders: 1) the cognitive argument (they know a lot), 2) the normative argument (they need to decide and make choices) and 3) the instrumental argument (the need for creating ownership). Using this approach, tool developers should be able to address the following questions:

1) what is the right level of end-user (farmer, advisor, company, policy, ...) for the problem to be solved?
2) what is the right end goal for the tool from the start, based on needs of the selected end-user?
3) what is the right knowledge and what choices do we have to make?

Second, issues concerning governance and ethics needs to be addressed thoroughly. Building and guaranteeing trust with farmers should be a starting point in developing applications (van 't Spijker, 2014). New organizational linkages and modes of collaboration need to be formed in the agri-food chain (Sonka, 2015). It needs to become a common practice to sign data exchange agreements on ownership in order to control data flows between farmers and agriculture technology providers. Such agreements need to address questions such as: How can farmers make use of the application? 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?

Third, knowledge transfer has in the past been conceptualized as a rather linear process. New research-based knowledge is passed to farmers on in the form of advice and recommendations in order to finetune the way they farm and manage their enterprises. However, a changing context with respect to extension, markets and challenges has initiated a more complex system of knowledge exchange. Rather than a linear model of innovation, this is now envisaged as a set of networks, in which innovation is 'co-produced' through interactions between all stakeholders in the food chain, called an AKIS - Agricultural Knowledge and Innovation System (EU SCAR, 2012) . Research on the adoption and diffusion of innovations has consistently confirmed that one of farmers' most commonly cited sources of information and ideas is other farmers (Rogers, 2003). Farmers and small scale foresters tend to be most influenced by proof of successful farming methods by their peers (Hamunen et al., 2015; Kilpatrick & Johns, 2003; Schneider, Fry, Ledermann, & Rist, 2009). In industrialized countries, however, this collaborative learning has become increasingly marginalized. Industrialized agriculture has drawn more individual farmers into supply chains where they often act more as competitors, in order to achieve a low-cost strategy. This has contributed to a weakened collective culture that cannot sustain such learning through dialogue in many industrialized countries (Bell, 2004). Therefore, educating farmers on the topic of ICT tools and IoT technologies, peer-to-peer knowledge exchange within a context of AKIS and supporting collaborative, cooperative structures for farmers is essential for ICT innovations to succeed in this area.

Overall significant further research is needed to understand the barriers to adoption and whether the ICT solutions on offer actually address the needs of farmers in a manner that adds value or benefits them. Comparisons with technology adoption in other sectors may be especially insightful.

5.5 THE ROLE OF CONSUMERS AND FOOD CERTIFICATION

In the past 20 years, consumers have embraced the digital revolution. This is due to the fact that digitisation of markets replaces the "middlemen" or gatekeepers to products and services, allowing the customers and suppliers to interact more seamlessly, increasing choice and reducing prices. The phenomenal growth of platforms such as Kayak, TripAdvisor or AirBnB has increases choice while eliminating many gatekeeper roles. It seems self-evident, but it is important to be aware that digitisation of markets is driven by technology. According to the 2017 report of the International Telecommunications Union (ITU - the United Nations specialized agency for ICT), in developed countries 81% of individuals use the internet and the same metric for developing countries is 41%. Similarly, there are almost 100 mobile broadband subscriptions/100 inhabitants in developed countries and almost 50 such subscriptions/100 inhabitants in developing countries (ITU, 2017). This availability of technology on the consumer side has created huge opportunities for online businesses. While some of the revolution in markets has happened organically, companies now understand that market disruption is the best way to secure market-share. As Anurag Harsh wrote in his analysis of the digital revolution "If you can't dominate a market, you change its dynamics........because consumers have so much digital technology at their disposal and are constantly connected, innovating on those axes is the fastest way to disrupt an industry" (Harsh, 2016).

The digitisation of the agri-food sector offers huge potential benefits to the consumer. Eurostat figures show that the percentage of total household expenditure on food and non-alcoholic beverages has held steady at approximately 12% since 2005 (Eurostat, 2016b)[92]. With an increasing world population and an expected 76 % rise in the global appetite for meat and animal products by 2050, unless there is a significant increase in production efficiency, this is likely to rise significantly. The application of precision technologies to the agri-food system offers the opportunity to increase efficiency and thereby keep the price of food at reasonable levels. Consumers are increasingly concerned about animal welfare and a variety of environmental issues including water quality, biodiversity and climate change. Precision agriculture brings potential for the improved management of animal health and welfare, reduced inputs (water, fertiliser and pesticides) and more precise management of natural resources such as soil, all of which can help to allay consumer concerns. The collection and analysis of data across the food chain offers the possibility that consumers will be able to access data on provenance, environmental impact and animal welfare at the point of purchase. The question remains to what extent consumers will be willing to pay a premium for this information, and to what extent the retailers will absorb this in order to add value to their offering. Current growth projections for the organic food sector (16% compound annual growth rate from 2015 – 2020) (TechsciResearch, 2015) indicate that there is a market for premium food products which promise a more ethical production system and health benefits.

Consumers' main interaction with the food system is through the retailer. As with the travel market, there may be major disruption in this market in the coming years. Already, most large supermarket chains have started to offer online shopping and same-day delivery of food and groceries. Amazon, the world's third largest retailer (Gensler, 2017) has now entered the food market and is likely to aim to disrupt the existing market in order to gain significant market share. It is also likely that the internet will offer possibilities for new marketplaces, directly connecting small artisan producers to consumers. Online shopping offers the possibility for retailers to use data analytics to propose products that the consumer may seek, based on their previous buying habits and on the purchases of similar customers. All of this brings the opportunity to save time.

The retail market is already dominated by a relatively small number of large companies. This concentration of power creates a natural tension between primary producers, suppliers and retailers. A move to online shopping may drive or facilitate further consolidation in this marketplace, thereby reducing competition in the long run and further increasing the power of a small number of retail companies (cf. notes on potential for monopolies above). While new information technologies often provide opportunities for new entrants initially, subsequently network effects and control of data is likely to enable monopolistic behaviour (Wu 2010). The other major concern for consumers will be privacy. Data collection and usage can bring advantages in terms of online retailers being able to show customers products that they may wish to purchase, but it also allows the retailer to collect a lot of information on individual customers. So far, the public has shown itself to be willing to give this data in return for free services (Facebook, Google) or improved retail experience and choice (Amazon), but as data collection becomes more ubiquitous and data analytics become more powerful, it may lead to unease amongst consumers.

[92] Note that there is considerable variation between countries and also between different socio-economic groups.

One of the important vectors of interaction between consumers and food producers has been through certification. There are many kinds of certifications for food products, many of which such as GlobalGAP, most consumers are unaware of even if they act as guarantors of quality. Publicly visible certification such as Organic, FairTrade, MSC and others provide a means for consumers to know more about the food product, and to influence the market through their buying habits. The use of information provided either through certificates or more indirectly through social media has been termed informational governance and depends on a considerable degree of transparency and trust. The growth of the quantity of information here may endanger the capability of consumers to absorb this information and thus engage with the food system effectively, for example in making more sustainable buying choices (Ge & Brewster, 2016). The latter challenge may lead to opportunities for new arbiters of consumer choice and decisions.

6 A VISION FOR AN ICT ENABLED SUSTAINABLE AGRIFOOD SYSTEM

Up until this point, the ICT-AGRI ERA-NET, and other funding in the area of precision farming, has focused on projects related to food production at the farm level. However, suppliers, processors, retailers and consumers have also a huge influence on the production systems. Also, as noted in Section 2, there has been a growing scientific and political shift towards treating the agrifood system as an integrated whole rather than a set of disjunct parts. The potential gains that exist from the automated ICT-based collection and analysis of data and the implementation of precision technologies can only be fully realised when the whole agri-food system and its dynamics and responsiveness is dealt with as a whole. This allows for feedback and learning mechanisms whereby preferences of consumers and processors can influence the practices of primary producers which can in turn influence the products developed by agriculture suppliers (e.g., seed companies). It also facilitates feed-forward mechanisms where information from the farm - which gives an indication of the likely production processes, quantity, quality and composition of primary products - can influence the short and medium term plans of processors, thereby minimising waste, maximising the efficiency of the system, including optimisation of the supply chain in terms of energy, waste and overall sustainability, while facilitating the production of higher value end-products. In addition, information on the provenance of food and the emissions associated with different foodstuffs should empower consumers. Data analysis across the whole system has the potential to lead to a significant reduction in inputs and emissions which should contribute to the reduction of the environmental footprint of the sector. The barriers which prevent adoption of new technologies by producers and others in the food chain can also be considered. The integrated systems perspective described will assist with this by facilitating the development of entirely new business models, whereby actors in the system other than primary producers may be willing to bear (some of) the cost of new technology in exchange for the downstream benefits of its adoption. The much-promoted idea of using a multi-actor approach to projects, both large and small, will also be important to ensure that developed technologies will be taken up by actors across the agri-food system.

Key priorities to make this vision a reality can be described as follows:

1. Trust and transparency. Usually interpreted purely from a consumer perspective but this applies at every stage and part of the food system, from farmers' interactions with ag tech companies, from food inspections and food companies to consumer confidence in the quality and social acceptability of the food they receive. ICT has an important role here in data collection, data sharing, data analysis as well as providing means and methods for communication of mechanisms the whole system uses to all stakeholders. Data security (cf. below) is essential as well to ensure the trust and confidence of participants.

2. Data collaboration. Data sharing, standardisation of data infrastructure, enabling the use and reuse of data while respecting data ownership (including the acknowledgement that farmers own their own data) and individual or business confidentiality are major areas for future work. This applies both at a technical level (developing new solutions) and at social/ behavioural level by ensuring actors both adopt technologies and also behaviours (including institutions i.e. contracts and collaborations) that enable ethical, respectful and sustainable collaborations. Work in this area needs to include farmers, companies, researchers and governments (opening up public data for free) to ensure the relevant infrastructure and software tools are available. The role of government (both national and supra-national) should not be forgotten in ensuring regulatory environment that fosters data collaborations and appropriate institutions.

3. Support for ICT research in agrifood, and technology transfer. Compared to sectors like the life sciences, research in the agrifood sector ranging from seeds and inputs, through farming methods, food production, transportation, logistics, retailing, as well as nutrition and environmental interactions is a poor cousin. The brief list of projects in section 4.4 demonstrates that research funding is an order of magnitude less than other industry sectors. Even greater efforts need to be made for an integration of research with innovation and adoption so that developments and breakthroughs are not lost.

4. Data and cybersecurity. The repeated loss of data to cyberattacks and the conflicting needs of data aggregation with the loss of security create a fundamental challenge for data driven innovation in the food system. The push for greater integration and collaboration around data will fail unless cyber security is made a top priority in research, innovation and societal change.

5. Collaboration and communication between consumers and food growers and producers. Public awareness and engagement with the food system depends on the education of the public, and above all communication between farmers and consumers. This can be mediated or facilitated using ICT and needs further reinforcement.

6. Training the next generation. This refers to training and education in ICT for all stakeholders in the food system, but also education and training concerning the social, legal and environmental consequences and context of technological innovations. This means that researchers and stakeholders can better respond to the societal and environmental issues faced by the food and agriculture system.

All these priorities need to be approached from the perspective that the food system must face the realities of **climate breakdown**, of the immense impact agriculture has on the environment, and the need to rapidly adapt agricultural practices in such a context. Agriculture, food production, and the whole food system are not separate disconnected activities from the rest of human activity, they need to be seen as fundamental, central and treated with the corresponding importance. **Humanity's survival depends on a transformation of the food system -- ICT will play a central role in achieving this ambition.**

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