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The Digitisation of Agriculture: a Survey of Research Activities on Smart Farming

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ABSTRACT

The impulse towards a larger introduction of Information and Communication Technology (ICT) in the agricultural field is currently experiencing its momentum, as digitisation has large potentialities to provide benefits for both producers and consumers; on the other hand, pushing technological solutions into a rural context encounters several challenges. In this work, we provide a survey of the most recent research activities, in the form of both research projects and scientific literature, with the objective of showing the already achieved results, the current investigations, and the still open challenges, both technical and non technical. We mainly focus on the EU territory, identifying threats and concerns, and then looking at existing and upcoming solutions to overcome those barriers.

1. Introduction

Smart Farming (SF) refers to the application of ICT to agriculture. Data collected and analysed through ICT techniques support efficient production processes [1], thus motivating scientists, practitioners, private and public companies to work towards the goal of developing and encouraging the use of innovative technologies to support farmers on the ground. According to the European Union (EU), the most relevant technologies and techniques to be fully exploited are the satellite imagery, the use of agricultural robots, a larger use of sensor nodes to collect data, and the potentialities of Unmanned Aerial Vehicles (UAVs) for aerial imagery and actuation. Those indications are contained into the declaration of cooperation on *A smart and sustainable digital future for European agriculture and rural areas*[1] signed on April 2019 by 24 EU countries.

According to the aforementioned declaration, the first obstacle towards a full implementation of SF in rural areas is the lack of connectivity, i.e., *digital divide*. The advent of 5G is promising to improve such a situation in rural and low-income areas [2], but scattered coverage must be still taken into account, as highlighted in recent surveys in the EU territory [3]. Rural areas remain challenging, not being covered by any Next Generation Access network: up to 53% at the end of 2017 in EU [3]. Putting this issue aside, a plethora of initiatives can be identified towards the objective of the digitisation of agriculture. As an exemplary case, *Smart AKIS*, an EU-funded thematic network promoted by the *Agricultural European Innovation Partnership* (EIP-AGRI) established in 2016, aims to close the gap between scientific knowledge and practitioners, in order to promote concrete solutions to be implemented. A solution can be defined as anything that makes the farming practice more controlled and accurate through ICT, reducing both the costs and the environmental impact, while also increasing the production. SF has the potential to also improve work safety, contributing to the sustainability of agriculture [1], but its socio-economic implications are debated [4].

In this innovative approach of farm management, a key component is the use of hardware and software technologies, like the deploying of sensor nodes, control systems, robotics, satellites for imagery and positioning, data storage and analysis, advisory systems, and terrestrial and aerial drones. However, the aim of SF should not be *just* in industrializing agriculture, but in making the whole process more efficient, sustainable, and of high quality, while respecting farmers' needs.

SF dates back to the middle of the 80's, but it has been practiced commercially only since the 90's [5]. However, many farmers are still skeptical about the actual advantages it can offer. This can be explained by considering the profit and the direct benefits for the farm. In fact, it is not straightforward to identify those [6], for instance when considering

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[1] available here: https://ec.europa.eu/digital-single-market/en/news/eu-member-states-join-forces-digitalisation-european-agriculture-and-rural-areas.

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Capital Expenditures (CAPEX) and Operating Expenditures (OPEX) for software, machinery, and data. Farmers generally tend to identify SF as a set of tools that benefits only large holdings, both in crop and livestock production. This is linked to the perception of high costs and complexity of the involved technologies. What is lacking from this image is the possibility that innovative technologies might not be only large-scale and thus costly, but rather also *slow and precise, plus small and cheap* [7].

Nowadays, SF is rapidly taking advantage of recent technological advancements for improving agricultural practices [8], further than business models for lowering adoption costs. For instance, rental programs for farming equipment, like *Trringo* in India, make possible farm mechanization processes with affordable costs for farmers, also providing support services. Such an initiative can be categorised as *cooperative farming*, potentially increasing the penetration of SF in low-income areas. *Karnott*, a French company, is pushing both web services and hardware solutions to transform legacy equipment into SF-ready one. Karnott sells a control unit to be installed on agricultural machines, offering several services through a battery-powered device, collecting and exchanging real-time data, as well as geolocation. Then, collected data can be exploited through on-line services, like those provided by *api-agro*, a secure platform to share data. Available data can be accessed and fed to different management systems, thus offering a valuable repository for farms. *Taranis* offers a platform using aerial and satellite imagery joint with Artificial Intelligence (AI) techniques to provide a Decision Support System (DSS) for Precision Farming (PF) applications. *AgriOpenData* provides a DSS as well, exploiting blockchain, UAVs, and adding support services on top of it. When considering fully autonomous solutions, *Iron Ox* offers a complete robotic solution to grow plants, from seeds to harvest, with a hydroponic system able to strongly reduce the water consumption. At last, traceability is experiencing a revolution thanks to digital ledgers. Even if it cannot be considered immediately within the umbrella of SF, still the origin and the quality of agricultural products remains a central issue. *Carrefour*, a French multinational retailer, is betting on blockchain as a solution to provide trustable data to consumers and intermediate actors. Blockchain is used by *Hectare Agritech* in a farm trading platform as well, highlighting how innovative paradigms can be adapted to different use cases in the agricultural field.

The aim of this work is to survey both research initiatives and scientific literature on the topic of SF, looking at recent technologies and techniques being used or being actively pushed for adoption. In addition, we discuss still open challenges hampering such an objective. The rest of this work is structured as follows: Section 2 surveys research and innovation projects covering SF activities in the EU territory, then the scope of the survey is enlarged by taking into account the state of the art in the scientific literature. Section 3 discusses the open challenges at today, considering both technical and non-technical factors. Finally, Section 4 draws the conclusions and opens to future directions.

2. State of the art

This section provides two main contributions. The first one is in Section 2.1, surveying relevant research projects recently funded by the EU in the field of SF; the aim is to highlight the increasing attention towards those activities, and then to identify the involved technologies. Table 1 provides an overview of surveyed R&I projects. Furthermore, Fig. 1 depicts relevant agricultural operations as faced by the described research projects, and the technological solutions exploited in the latter ones. The second contribution is in Section 2.2, surveying the scientific works that propose solutions for the implementation of SF. Table 2 provides an overview of surveyed literature, then a keyword analysis is proposed in Fig. 2.

2.1. EU research projects

In last years, the EU has been actively undertaking R&I activities laying the ground for the digitisation of agriculture by exploiting data-

Table 1

The most relevant EU-funded R&I projects towards increasing digitisation in the farming sector. The second part of the table is related to dissemination, engagement activities, and thematic networks. *Marketplaces* are here intended as virtual places where existing solutions can be publicly browsed. More details on each project are available on the EU CORDIS portal (https://cordis.europa.eu), searching for the grant agreement ID, or alternatively on the website.

project/initiative (EU grant agr. ID/website)	start date ended (yes/no)	goal(s)	cloud/ edge computing	data services and information systems	sensing		unmanned vehicles		data analysis		software platforms
					terrestrial	aerospace	aerial	terrestrial	big data	machine learning	
Mistrale (641606)	January 2015 (y)	Water Use				X					web-based
Sweeper (644313)	February 2015 (y)	Harvesting Robot			X			X			
Flourish (644227)	March 2015 (y)	Crop Monitoring	X		X		X	X		X	multi-platform
Auditor (687367)	January 2016 (y)	Satellite Imagery				X					
Apollo (687412)	May 2016 (y)	Crop Monitoring Water Use Engagement				X					web-based/mobile
AgriCloud P2 (720176)	May 2016 (y)	Crop Monitoring	X	X	X						
RUC-APS (691249)	October 2016 (n)	Management Optimisation	X	X							
Sensagri (730074)	November 2016 (n)	Crop Monitoring			X	X		X			
IoF2020 (731884)	January 2017 (n)	Crop Monitoring Livestock Farming Dairy Monitoring	X	X	X		X	X	X		multi-platform
DataBio (732064)	January 2017 (n)	Crop Monitoring Forestry Fishery	X		X	X			X	X	web-based
Agroradar (761481)	February 2017 (y)	Satellite Imagery				X					

(*continued on next page*)

Table 1 (*continued*)

project/initiative (EU grant agr. ID/website)	start date ended (yes/no)	goal(s)	cloud/ edge computing	data services and information systems	sensing		unmanned vehicles		data analysis		software platforms
					terrestrial	aerospace	aerial	terrestrial	big data	machine learning	
Apmav (763132)	March 2017 (y)	Crop Monitoring	X		X		X		X	X	
Water4Agri (783989)	October 2017 (y)	Water Use				X					
Romi (773875)	November 2017 (n)	Crop Monitoring					X	X		X	
Pantheon (774571)	November 2017 (n)	Orchard Monitoring Water Use			X		X	X	X		
Swamp (777112)	November 2017 (n)	Water Use	X	X	X		X		X		
AfriCultuReS (774652)	November 2017 (n)	Food Security	X	X	X	X			X		multi-platform
GreenPatrol-Robot (776324)	November 2017 (n)	Crop Monitoring	X			X		X			
BigDataGrapes (780751)	January 2018 (n)	Crop Monitoring	X	X	X		X		X	X	
AfarCloud (783221)	September 2018 (n)	Crop Monitoring Livestock Farming		X				X	X		
Dragon (810775)	October 2018 (n)	Crop monitoring Skill Acquisition	X	X	X	X	X		X	X	
FarmingBySatellite (farmingbysatellite.eu)	2012 (n)	Challenge									web-based
ICT-Agri-2 (618123)	May 2014 (y)	Marketplace									web-based
Smart-Akis (696294)	March 2016 (y)	Marketplace									web-based
4D4F (696367)	March 2016 (y)	Marketplace									web-based
Nefertiti (772705)	January 2018 (n)	Thematic Network									web-based platform including knowledge tanks
SmartAgriHubs (818182)	February 2019 (n)	Marketplace									web-based
FAIRshare (818488)	November 2018 (n)	Thematic Network Engagement									data sharing and digital tools promoting
Euraknos (817863)	January 2019 (n)	Thematic Network									e-Knowledge Reservoir
Desira (818194)	June 2019 (n)	Marketplace Engagment									web-based platform

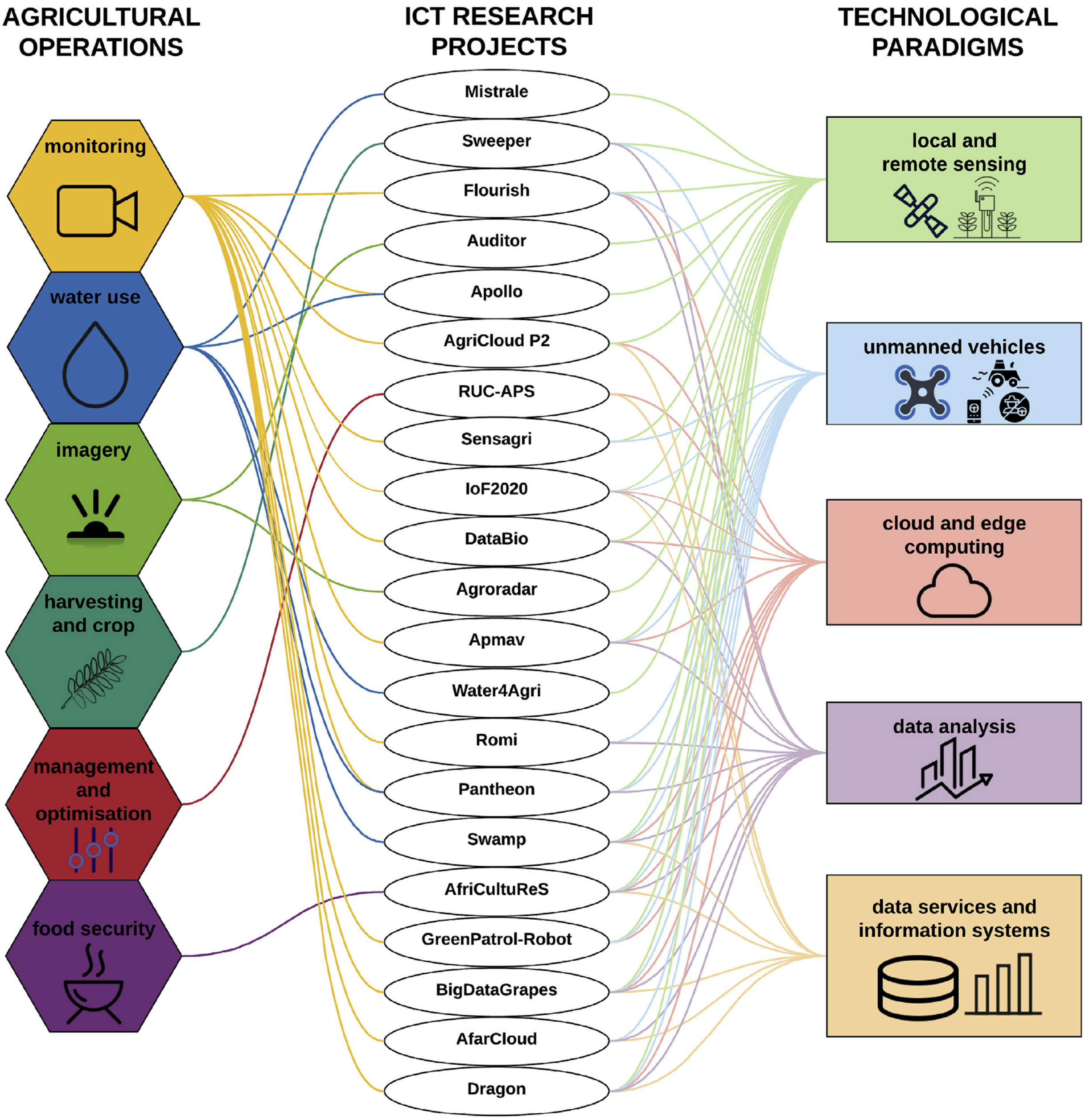

Fig. 1. Most relevant agricultural operations under consideration in the ICT-based R&D projects described in Table 1, and exploited technological paradigms. Both operations and paradigms are ranked according to the number of links.

empowered strategies; strategic interventions have been funded to support the uptake of digital technologies, to develop new digital solutions and to sustain the crucial assessment of the socio-economic impacts of digitisation. In Table 1, 30 recent EU projects closely related to SF are presented: the first 21 projects, spanning from 2015 to 2019, propose, develop, and test the use of digital technologies in this field; the 9 projects in the last rows, spanning from 2012 to 2019, have the complementary objective of strengthen or evaluate the use of ICT in agriculture, for instance through challenge-based strategies, or by setting up marketplaces to browse existing solutions ready for use. Most projects jointly exploit multiple techniques and technologies; here, we highlight only the most prominent ones.

2.1.1. *Cloud/edge-based systems*

Cloud platforms are mainly exploited in projects that are related to monitoring activities, like growth of plants, water availability, soil moisture maps, and so on. There is a clear dominance of cloud solutions with respect to those based on edge solutions, because the former is a more established option than the latter. The *AgriCloud P2* project proposed a cloud-based PF management system for a sustainable and intensive agriculture to secure long-term food supply in Europe. The *APMAV* project consists of an intuitive solution for agricultural management based on UAV technology and an intelligent cloud-based platform that provides farmers valuable, actionable and real-time recommendations for driving down costs and improving crop performance. The *Flourish* project leverages UAVs as well, aiming at surveying a field from the air, then at performing a targeted intervention on the ground with an Unmanned Terrestrial Vehicle (UTV). The idea is to provide a DSS requiring minimal user intervention to target PF applications. The *SWAMP* project develops Internet of Things (IoT)-based methods and approaches for smart water management in the precision irrigation domain, in order to utilize water more efficiently and effectively, avoiding both under- and over-irrigation. The *AfriCultuReS* project, beyond the use of cloud-based technology, also exploits the data

Table 2

Relevant scientific literature on SF. The first two blocks are related to sensing techniques and FMS/FMIS systems connected to robotic solutions to support autonomous operations; the two blocks below cover software systems designed to support agricultural production through IoT-based monitoring and/or leveraging DSSs.

category	works	main objective(s)
Sensing Techniques and Management Systems	[5]	local and remote sensing techniques for PF, highlighting the need for higher spatial/spectral resolution
	[12]	survey on data collection protocols, prototypes, and types of sensor nodes in agricultural scenarios
	[13]	Farm Management Information System (FMIS) and FMS survey, proposing an architecture for cloud-enabled FMSs
	[14]	underground and terrestrial network architectures for several different SF scenarios
Unmanned Vehicles	[15]	use of an UAV to estimate the plowing depth with an Red Green Blue (RGB)-D sensor
	[16]	use of an UAV to distinguish sugar beets from close weeds
	[17]	use of an UAV and terrestrial sensing to measure leaf temperature with infrared thermometers
	[18]	use of an UAV for precision spraying of pesticides in infected areas
	[19, 20]	802.15.4 channel modeling for bidirectional ground-to-air UAVs communications in agriculture
	[21]	UAV with multispectral, thermal, and RGB cameras to discover missing plants in viticulture
	[22, 23]	use of aerial and terrestrial robots (RHEA fleet): weed management in agriculture and forestry; greenhouse management
	[24]	commercial UAVs platforms, both multirotors and fixed wings, for use in SF
	[25]	spectral/imaging sensors review, and guidelines for machine vision systems on board autonomous agricultural vehicles
	[26]	automatic operations: guidance; headland and turn; vision and sensing for variable rate; machinery coordination
IoT Platforms	[27]	IoT platform for greenhouses using low-cost MICAz motes monitoring temperature, humidity, light level, and atmospheric pressure
	[28]	energy-efficient FIWARE-based platform collecting soil data via ZigBee
	[29]	FIWARE-based system (Agricolus) for SF applications, like tobacco crops
	[30]	platform for climate, irrigation, and nutrition control in a greenhouse with tomato plants based on cloud/edge computing
	[31]	transpiration-driven irrigation for greenhouses by an event-based predictive controller
	[32]	garden greenhouse exploiting Arduino for irrigation control
	[33]	survey of IoT use in PF with a focus on both communication protocols and technologies in use
	[34]	scalable platform (SmartFarmNet) based on RDF semantics and IoT
	[35]	semantic framework (Agri-IoT) providing data analysis and reasoning
	[36]	SF platform for irrigation relying on the OGC SensorML standard in a semantic web stack
Decision Support Systems	[37]	DSS to control climate conditions in greenhouses, monitoring temperature, humidity, photosynthetic active and global radiation, CO_2 concentration
	[38]	DSS based on semantic web technologies to handle cattle and monitor soil
	[39]	DSS pushing suggestions generated by an artificial neural network trained on data collected from sensor nodes via LoRa connection
	[40]	REST-based DSS for PF performing data mining to monitor pests in orchards and fields
	[41]	DSS for selecting appropriate alternative crops

collected from different sources (e.g. service providers, weather services) to develop an integrated agricultural monitoring and early warning system, based on remote sensing, to support decision making. The *DataBio* project makes intensive use of big data techniques related to the raw material production from agriculture, forestry, fishery and aquaculture for the production of food, energy, and biomaterials in a sustainable way, by means of a software platform integrating big data and Earth Observation (EO) methods. Data-driven activities are also proposed in the just started *Dragon* project, whose main efforts are directed towards skill transfers to ease PF adoption. Large heterogeneous data sources are considered and analysed to offer agricultural knowledge and information systems by ambitiously leveraging several techniques. The *BigDataGrapes* project makes use of big data techniques in the context of viticulture, supporting decisions by exploiting real-time analysis of large, diverse and multimodal data sources. It has been exploiting the use of UAVs as well in vineyards. Last but not least, the *IoF2020* project is one of the most comprehensive projects from the point of view of SF digital technologies: in particular, this project accelerates the adoption of IoT, in order to secure sufficient, safe and healthy food and at strengthening competitiveness of farming and food chains in Europe. A large scale pilot programme has been started in IoF2020 to develop and test specific technological solutions in the following sectors: arable, dairy, fruits, vegetables, and meat.

2.1.2. Unmanned vehicles

The use of unmanned vehicles is another trend of great interest. Beyond the aforementioned Flourish, APMAV, BigDataGrapes, and Dragon projects, the *PANTHEON* project, by taking advantage of the technological advancements in the fields of robotics, remote sensing and big data management, aims at designing an integrated system where heterogeneous unmanned robotic components (terrestrial and aerial robots) move within the orchards to collect data and perform common farming operations. The *SWEEPER* project has proposed a robotic system to harvest sweet peppers in greenhouses, leveraging on machine vision techniques to acquire both colour and distance information, and then storing collected peppers in an on-board container. Another robotic platform has been developed in the *ROMI* project to assist in weed reduction and crop monitoring, reducing manual labour. Land robots also acquire detailed information on sample plants, and an UAV assists by providing information at crop level. The *GreenPatrol-Robot* project designed and built a satellite-guided autonomous robot for pest control in greenhouses. It exploits Galileo satellite services to navigate, achieving good positioning accuracy inside greenhouses. The *AFarCloud* project aims at the agricultural productivity increase via PF techniques. The proposed solution is a distributed platform for autonomous farming robots that allows the integration and real-time cooperation of agricultural systems to increase efficiency, productivity, and food quality. This platform is integrated with a Farm Management System (FMS) to support monitoring and decision-making solutions based on real-time data

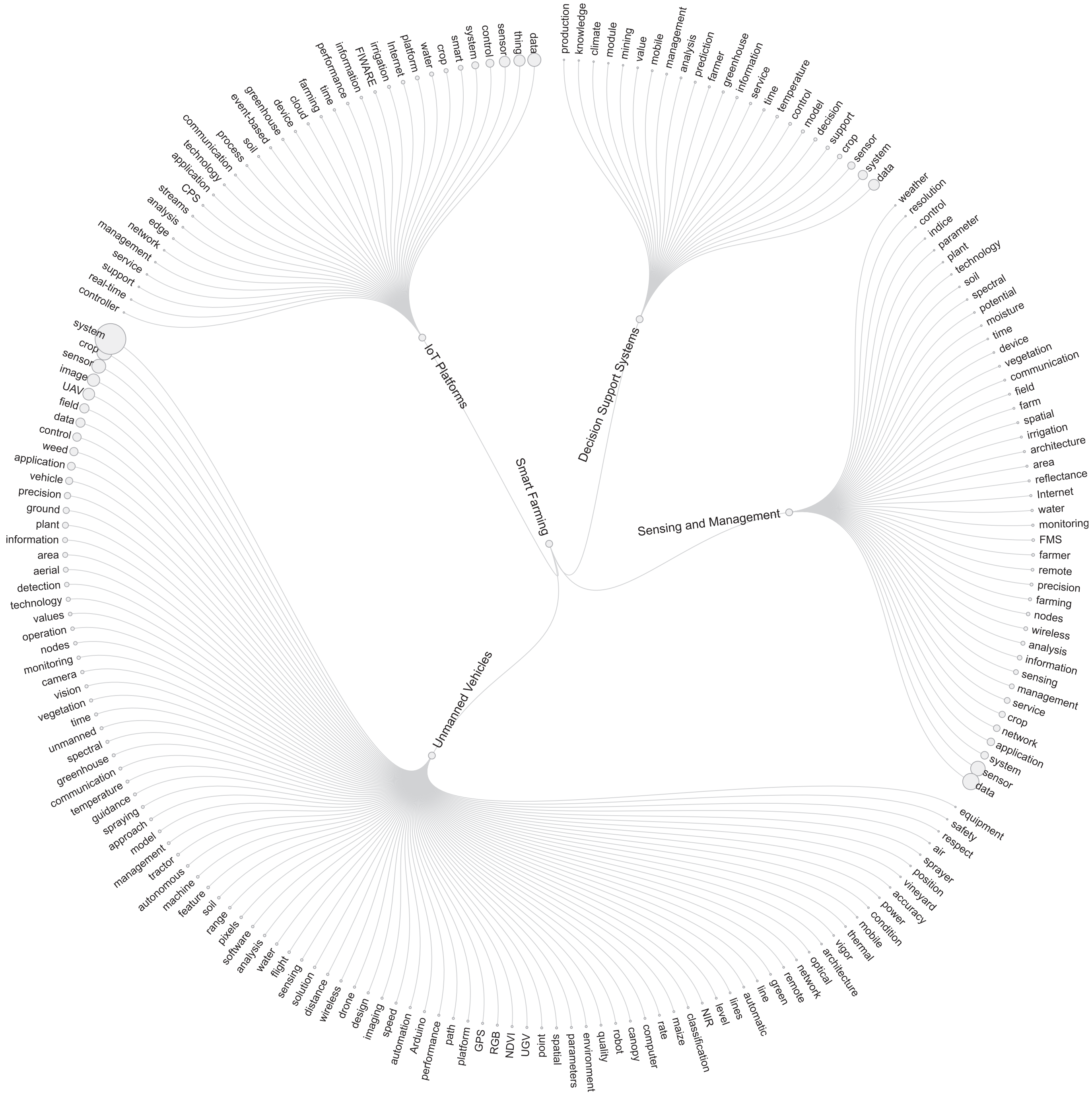

Fig. 2. Number of occurrences of relevant keywords (at least 50) as they appear in the surveyed literature: the 4 categories, as proposed in Table 2, can be read internally, and each keyword is weighted (circle radius) in the cluster it belongs to.

mining techniques. The *RUC-APS* project is centered on management approaches aiming at enhancing SF solutions in agriculture systems, applying operational research to optimise farm production.

2.1.3. Satellite-based activities

Several projects are mainly based on improving the information derived from satellite optical data. The *AGRORADAR* project aims at delivering innovative algorithms and data models that can process Copernicus EO Synthetic Aperture Radar (SAR) data to achieve precise and detailed information. The *AUDITOR* project develops an improved Global Navigation Satellite System (GNSS) augmentation system for services in PF applications. The project enables cost-effective PF services to farmers, like recommendations regarding site-specific application of water, fertilizer and pesticides. The *WATER4AGRI* project combines microwave data obtained from different satellites to provide datasets for retrieving key information about water availability for crops at field level. The *SENSAGRI* project combines optical and radar measurements to develop three prototype services for near real-time operations: surface soil moisture, green and brown Leaf Area Index (LAI), and crop type mapping. The *MISTRALE* project provides soil moisture maps to decision makers in water management using GNSS reflectometry (GNSS-R) via satellites and UAVs. The project has developed a prototype sensor embedded on a dedicated software platform. The *APOLLO* project brings PF closer to farmers through affordable information services, making extensive use of free and open EO data. The proposed services help farmers to make better decisions by monitoring the growth and health of crops, providing advice on when to irrigate and till their fields, and estimating the size of their harvest. The services are designed to be always available thanks to a web platform and a mobile application.

2.1.4. Mitigating digital divide

Other research projects are mainly focused on bringing the advantages of SF to farmers in a way compatible with their needs and digital skills, thus reducing digital divide. The *SMART-AKIS* initiative sets up a self-sustainable thematic network on SF technologies designed for the effective exchange of knowledge among research, industry, and the farming community, disseminating direct applicable research and commercial solutions, and capturing grassroots level needs and innovative ideas. The *4D4F* project (Data Driven Dairy Decision For Farmers) focuses on the benefits provided by sensors in monitoring animals and environment, supporting informed decisions. The project hosts a large repository of ICT solutions freely browseable by farmers. The *SmartAgriHubs* project brings together 164 partners in the European agri-food sector, carrying out 28 flagship innovation experiments for digitisation in five agri-food sectors: arable farming, livestock, vegetable, fruits, and aquaculture. The overall goal of *ICT-AGRI-2* is to strengthen the research within the area of PF and to develop a common research agenda concerning ICT and robotics in agriculture in Europe. Its main objectives are: mapping and analysis of existing research and future needs; development of instruments and procedures for transnational funding activities; development of strategic research agenda and programmes; and establishment of international collaborations and networks. Other projects, like *Nefertiti*, *Euraknos*, and *Desira* are setting up thematic networks with the objective of promote networking activities, data sharing and knowledge exchange. They leverage the vast set of already available ICT tools to promote their use in SF contexts and to foster their adaption to practitioners' needs. The *DESIRA* project, started at June 2019, intends to collect practitioners' needs through 20 national *living labs* in EU and then to design ICT use cases to meet those demands in a Responsible Research and Innovation (RRI) fashion. The *Fairshare* project has data collecting and sharing as foremost objectives, in order to build a network able to reduce the agricultural digital divide. Finally, *FarmingBySatellite* is an initiative to promote the use of Galileo as GNSS and EO services. It launches a biyearly challenge to identify promising ideas using satellite technologies for SF purposes.

2.1.5. Considerations

Summing up, some considerations can be made: monitoring fields and crops is quite diffused at today, leveraging local and remote sensing solutions, i.e., in-field sensors, UAVs, up to satellites. Another major challenge is the optimisation of water use. Unmanned vehicles enable semi- and full-autonomous scenarios, currently representing a major objective for both research institutes and private companies. Anyway, almost all surveyed projects aim at providing DSSs instead of autonomous solutions; in fact, there is still wide scepticism on them by practitioners as viable alternatives to human decisions. To feed DSSs, data analysis techniques are used, also supporting automatic actions based on feedback, and farmers' decisions. Machine learning techniques are typically exploited for dedicated applications in the projects we considered, such as prediction and estimation of farming parameters to optimise livestock production or crop monitoring.

2.2. Scientific literature

SF represents the evolution of agriculture driven by ICT technologies. ICT provides tools, methods, and techniques with the potential to improve both the modeling and the practice in this sector. SF is intrinsically tied to large-scale heterogeneous sensing [9], involving different hardware, algorithms, and protocols, thus too focused approaches have gained little traction at now. In what follows, we survey a very recent and exemplary subset of the scientific literature on such a topic, then schematised in Table 2. To further highlight what is currently trending in recent scientific literature, we show the most used keywords in Fig. 2, according to the four thematic clusters we define in Table 2. Each keyword is presented weighted in its cluster according to the number of occurrences. Finally, Table 3 maps typical application scenarios and data types to commonly used sensing solutions [10,11].

Table 3
Relevant agricultural applications and local or remote sensing systems commonly used [10,11].

application scenarios	sensing solutions
weeds mapping	RGB images, NIR
soil organic carbon	NIR
yield prediction	NIR, NDVI, 3D images
plants growth	NIR, NDVI
crop water stress	thermal images
plant height	ultrasonic, multi/hyper-spectral data, NIR, NDVI
crop cover	RGB images, multispectral camera, spectrograph
real-timecrop conditions	multi/hyper-spectral camera,RGB, NIR
phenotyping	3D, colour digital, spectral images
chlorophyll measurement	spectrometer, satellite

2.2.1. Sensing techniques and management systems

SF makes large use of sensor nodes to collect data on the environment and the phenomenon under observation. For instance, in the case of agriculture, soil sensors, placed at different depths, complement data collected from EO satellites, providing enriched information. More generally, indoor and outdoor Wireless Sensor Networks (WSNs), both mobile and fixed, are used to collect heterogeneous data [14] for evaluating different indexes, such as the Normalized Difference Vegetation Index (NDVI), the excess green index, the LAI, and so on. Given the fundamental role played by data and data sources in this context [12], the historical evolution of sensing for PF in Ref. [5] offers a valuable perspective. At the beginning, three methodological approaches were considered: the first two ones, namely *farming by soil* and *site-specific crop management*, were contrasting because the former promoted soil mapping, while the latter promoted homogeneous actions in sub-units of farm fields, i.e., a punctual approach versus a clustered one. The third approach, namely *proximal soil sensing*, came later, consisting in continuous real-time sensing by sensors mounted on tractors. It can be considered the father of the PF approaches in use nowadays. Thanks to satellites, proximal soil sensing evolved into *remote soil sensing*, introducing spectral analyses. To allow farm managers to exploit all those heterogeneous data sources, increasing complex software platforms were introduced to take advantage of raw data and of subsequent elaboration: they are referred to as FMIS [13].

2.2.2. Unmanned vehicles

Real-time stream processing, analysis, and reasoning are key concepts towards automation in the agricultural field [22], i.e., towards a larger use of robots that can adapt to space- and time-varying conditions with minimal delay. Robots can perform very precise operations, and can operate in fleets, as proposed in Ref. [23], which considers both UTVs and UAVs. Moving systems rely on GNSS techniques for precise positioning, and PF applications need large accuracy. Several commercial systems integrate a GNSS receiver and use one or more fixed Real-Time Kinematic (RTK) reference base stations [26] for providing accuracy up to centimeters. Further than precise positioning, robots depend on machine-vision systems to navigate the environment [25]; according to the technology and the scenario under consideration, specific spectral signatures are of interest, as for instance hyperspectral imagery in both local and remote sensing. Commercial devices, to be used on board, already capture both RGB and Near Infrared Imagery (NIR) bands, and stereovision systems are used for 3D maps [25].

Further than terrestrial vehicles, aerial ones have been revolutionising the practices in this sector. PF is taking large advantage of UAVs, with several commercial systems able to fly at different speeds and altitudes [24], ranging from fixed to rotary wing machines. UAVs are used for monitoring scenarios, further than pesticide spraying, which is a key application for PF [18]. Heavy and large UAVs can be used for such a purpose in the case of large fields, jointly with multispectral techniques to generate NDVI maps to be used for spraying pesticides and fertilizers where needed. Such a potential has been subject to increasing attention in the last years. For instance, UAVs can be used to assess if an area has been subject to plowing, and the plowing depths. The authors in Ref. [15] consider the use of UAVs for such a purpose as an alternative to the use of satellites. In fact, according to the authors, even high-resolution satellites cannot classify the roughness of the terrain, thus motivating the use of UAVs. A RGB camera has been used for data collection and a visual assessment, and collected georeferenced data are analysed to assess the plowing depths. RGB and NIR are collected by means of an UAV also in Ref. [16], with the aim of classifying plants and weeds. The proposed system makes use of the Excess Green Index (ExG) [16] in the case of RGB-only; if NIR is exploited as well, NDVI can be estimated and used because of the richer information it provides. By combining these results with geometric features, sugar beets can be recognised even in the case of overlapping plants. NDVI has been used in viticulture for precision applications [21] as well: in fact, using an UAV to collect detailed images in a vineyard, plant rows can be discriminated from inter-rows, identifying missing plants with good precision.

UAVs can be seen as part of a WSN, acting as mobile nodes [17], thus the analytical characterisation of the channel model between a moving UAV and fixed terrestrial nodes becomes of interest [20]. Low-power 802.15.4-based solutions have been investigated in rural contexts, using UAVs as data mules [19].

2.2.3. IoT platforms

As aforementioned in Section 1, Internet connectivity is a key requirement for SF. In fact, its availability allows IoT-based scenarios to emerge [33], increasing the degree of remote control and automation. This is well supported by IoT features, such as interoperability and easiness of integration [36]. Anyway, in rural contexts, terrestrial connectivity may be lacking. Because of this, aerospace solutions for connectivity are a viable option [8].

Looking at the literature, reference [30] proposes an IoT platform for PF based on FIWARE.[2] It considers the case of a greenhouse, where Internet connectivity is likely available, thus opening to data exchanges via protocol stacks relying on common IoT protocols, like CoAP and MQTT. In greenhouses, the main objectives are typically climate control and soil monitoring. The Agricolus software platform, which is a FIWARE-based DSS for tobacco crops, is described in Ref. [29], designed to collect soil data via 802.15.4-based WSNs. The FIWARE middleware is a software enabler in very different scenarios [13,29]. Along to climate control systems, irrigation systems have been proposed to optimise water use. In Ref. [28], FIWARE cloud components are integrated in a PF application to reduce water use. In Ref. [31], tomatoes in a greenhouse are monitored, and the authors propose an analytical framework to assess the performance of different tested configurations by relying on plant transpiration. The works in Refs. [27,32] consider the use of low-cost and general purpose sensor nodes, built upon the Arduino platform and upon MICAz Motes, respectively, as information sources in greenhouses. Being able to deploy low-cost and easily replaceable sensor nodes is a priority for a larger adoption of SF techniques. A core demand is related to power consumption: battery-powered devices lasting several years, as for instance ZigBee ones in Ref. [27], are fundamental in farm deployments.

Apart from FIWARE, a plethora of different platforms can be identified as enablers for SF [34]. Those platforms aggregate heterogeneous data, then analysed and interpreted in order to provide additional value. Here, semantic analyses have been proposed as well, like for instance the valuable work in Ref. [35]. The Agri-IoT architecture, a layered and complex framework, provides additional value to DSSs because it further facilitates informed and accurate decisions thanks to semantic web and real-time reasoning.

2.2.4. Decision Support Systems

DSSs are one of the most used solutions for SF because they provide support to farmers, offering a point of access to useful information, according to the aim of the system, and suggesting a plausible course of action in a given context. Aims can be very different: minimising the impact of diseases in tomatoes by applying automatic climate control [37]; ‘time-to-sow’ alerts, and cattle monitoring [38]; anticipating potential crop dysfunctions in a proactive way [39]; pest control [40]; selecting appropriate alternative crops in a given area [41]. Those are just few examples of what can be offered by recent developments of DSSs in the agricultural sector.

2.2.5. Considerations

Some considerations can be made also here: for instance, looking at Fig. 2, it is visible how *data* is a relevant keyword for all clusters. This is a key topic in the context of SF, thus deepened in Section 3. A notable exception is visible in the cluster *Unmanned Vehicles*, in which *system* outnumbers *data*: this can be explained by taking into account that unmanned vehicles are typically considered in an autonomous scenario, i.e., within a system composed of several interacting parts. The keywords pertaining to the cluster *Unmanned Vehicles* take the most part of Fig. 2, graphically highlighting the technological complexity of designed systems, and the very large number of operations that can be performed by those. Finally, what in Fig. 1 can be put in relation with what presented in Fig. 2: as an example, in the former monitoring operations are practically ubiquitous, and this is confirmed by the large number of occurrences of keywords like *thing* (as in smart thing or IoT) and *sensor* in the latter.

3. Open challenges

This section briefly discusses the open challenges hampering a larger adoption of SF, summarised in Fig. 3 as well. Several technologies pushing for a larger adoption of SF practices have already been cited within this work, such as fully autonomous flight control, early identification of plant diseases, and reliable virtual fences [1], as well as more general ones, as AI, robotics, high performance computing, IoT, and 5G, which are reported within the EU declaration cited in Section 1. AI probably represents the largest challenge at now and, at the same time, opportunity in several sectors, including the agricultural one. The EU is largely investing on it because convinced it will be the upcoming disruptive game changer. In fact, the AI4EU initiative, started at the beginning of 2019, aims at the transformation of AI into a compelling solution in several application scenarios.

3.1. Technical challenges

Looking at sensor nodes and sensor networks, we refer to the valuable works in Refs. [14,42], which survey the use of fixed and mobile solutions. According to the authors, advances are needed to further lower costs and to design specific solutions for the agricultural context, which requires solutions able to resist to difficult conditions (e.g., specific soil properties, exposition to high/low temperature, water resistance, fine dusts, and so on). Further than costs, solutions are needed toward larger energy efficiency, including energy harvesting techniques, and reliability in data collection and transmission, in order to minimize the need of maintenance for the deployed solutions. Specific issues of the agricultural domain need targeted answers, in particular the deployment strategies, to be designed according to fields segmentation and to farmers' requirements.

One of the main drivers of the diffusion of WSN in agriculture has

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[2] The FIWARE platform encompasses open source components for developing smart solutions.

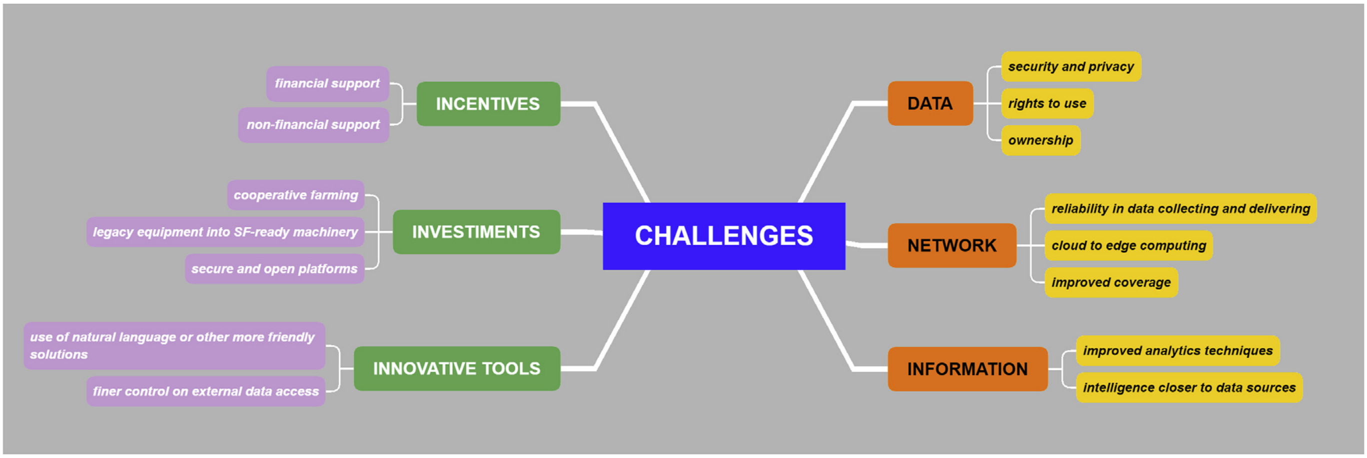

Figure 3. Overview of open challenges in the SF field: technical challenges (on the right) are discussed in Section 3.1, non-technical challenges (on the left) are discussed in Section 3.2.

been IoT: it has marked the transition from closed-source systems and disconnected software solutions towards connected systems built upon interoperable solutions. Those characteristics are favorable to cost reduction and to easiness of integration. Challenges here are overall related to network capabilities, data security, and data privacy [33]. Data is one of the most critical topic in the agricultural sector. Data ownership, protection, and security are perceived as not sufficiently close to farmers' needs, thus becoming threats to be mitigated, if not completely avoided. In more words, nowadays, digital solutions for SF are under-utilised because practitioners fear data misuse and the loss of control over their business. Data protection must be enhanced to transform into a transparent operation, keeping in mind that agriculture is typically a private business activity (i.e., a not transparent activity), and data transfers to external systems (e.g. cloud) must be controllable and well described to increase acceptance. An option towards larger acceptance comes from the possibility for farmers to benefit from business with their data, and to benefit from public and official data released in an open fashion. On this, the valuable work of the EU with the Galileo services is a notable example of good practice, collecting and releasing data through application programming interfaces [43]. Further from data, open and used standards for data handling is compelling to move towards horizontal solutions instead of vertical ones [44].

Large IoT platforms generate huge amounts of data to be analysed, thus calling for data analytic techniques able to extract meaningful information. Nowadays, big data immediately come to mind [45] as a set of strategies towards this objective, but it must be noted that its application to agriculture is recent. Generally speaking, the big data paradigm goes in an opposite direction with respect to acquiring more control over own data by farmers. To counteract that, the possibility for farmers to economically gain from sharing and accessing large volumes of data works as an incentive [46]. In Ref. [47], the authors underline the difficulties in discovering and combining large heterogeneous datasets in the agro-environmental field, often complicated by lacking of metadata. Furthermore, the need for semantic analyses and interoperability is highlighted in Ref. [47]. Natural language processing and machine learning techniques play a role here, facilitated by existing initiatives for building and maintaining open large repositories for training purposes, like CINERGI by Earthcube.

Once meaningful information is available thanks to raw data sources and to analytics techniques, *decision making* is performed. This is where machine learning techniques and, more generally, AI can be fully exploited toward autonomous systems. To this aim, a fundamental challenge is moving intelligence from cloud platforms to closer computation platforms, such as edge solutions, handling and processing data close to the source, thus reducing delays. Multi-Access Edge Computing (MEC), jointly with 5G, is expected to play a role here. In the case of agricultural autonomous systems, real-time constraints are more easily satisfied by edge solutions than remote centralised systems. According to Ref. [48], in order to build sustainable infrastructure, the several emerging architecture paradigms (with different degrees of centralised and distributed entities) must comply to open standards for both easiness of implementation and cost reduction. Environmental monitoring and real-time agricultural data analytics and control can benefit from those paradigms, for instance by providing localized information about pollution and pests in the vicinity of edge servers [49].

3.2. Socio-economic and other non-technical challenges

This section discusses non-technical issues still holding back a larger diffusion of SF, at least in the EU. In fact, uptake in EU is rather low if compared to what expected [50]. Incentives and policies play a large role, considering national and EU rules, economical and skills perspectives. In Ref. [50], the authors show how financial and government incentives are the most influential solution, followed by training and other non-financial support. Farmers' concerns are related to the time to recover the investment, and to the difficulties in evaluating the advantages; small farms have almost no adoption at all, also because the machinery has no support for more advanced technology. Sole farmers show a large interest in SF tools, which may come as unexpected, because it reduces exposure to occupational accidents and injuries; anyway, those barriers still hold back its use [51]. Because of those reasons, initiatives like those presented in Section 1 have a significant socio-economic value: cooperative farming with support services for a better handling of costs and needed investments; hardware solutions to transform legacy equipment into SF-ready machinery to avoid too high initial costs and to have time to familiarise with new technology; secure and open platforms for sharing data and getting back useful information, helping in assessing potential advantages. Research activities aiming at reducing the agricultural digital divide have an impact as well, helping farmers with new ICT-based tools in their daily work; on the other hand, different strategies in designing innovative ICT tools must be considered, like using natural language [52] to explicitly take into account potentially low-literate speakers.

Nowadays, the right to access and use the collected data is at the center of the discussion: COPA-COGECA, an European farming representative organisation, in cooperation with CEMA, the European agricultural machinery association, has recently released a code of conduct to grant the data originator (i.e., the farmer) a leading role in controlling the access to and the use of data.[3] The concerns on data use and access have been explored also in Ref. [4], highlighting existing scepticism by Australian farmers and divergence of expectations between involved actors. On the one hand, marketers and traders expect that big data techniques increase the reliability of predictions in the market dynamics; on the other hand, farmers are convinced that power asymmetries will increase, thus acting as a brake. Similar considerations are in Ref. [53], when looking to Ireland: whilst recognizing that SF is a real opportunity for the farming context, potential challenges and risks should be carefully considered to anticipate and reduce the gap among winners and losers.

4. Conclusions and future directions

In this work, we surveyed the most relevant research activities aiming at improving and encouraging the adoption of SF techniques in agricultural contexts. Large efforts are currently poured to boost ICT use, at least in the EU, where this analysis is focused. On the one hand, the already established use of sensor nodes and heterogeneous data sources, as well as simple analytic techniques, is pushing DSSs in the farms; on the other hand, a growing need is there for ever advancing technology and open standards to consolidate existing scenarios in an interoperable and low-cost manner, as well as programmes to help ICT diffusion in areas suffering from digital divide.

In the future, technology will have a growing role in agriculture [6]. Several operations will be automatised, from planting to harvesting, thanks to increased robotisation, both terrestrial and aerial one. Soil information will be readily available, thus allowing for e.g. a finer control of pests and pesticides, combining local information with other data sources, like weather and pollution data. In the end, an increase in production is expected, joint with a reduction in chemicals today in use, thus reducing pressure on soil. SF has the potential for a rapid and efficient growth in coming years, supported by policies that can fuel both R&D efforts and farmers' adoption through investments. Anyway, the main barriers at today, i.e., vertical solutions, reduced digital skills and high costs for farmers, poor telecommunication infrastructures, and concerns on data ownership and use must be carefully addressed by technical and non-technical actors to facilitate SF adoption.

Declaration of Competing Interest

The authors declare no conflict of interest.

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