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Today's interconnected digital world with its multitude of data-collecting devices and means along with augmented data processing capabilities has unlocked new possibilities for increasing the efficiency of contemporary agricultural supply chains, including production, processing and distribution operations. Furthermore, issues such as climate change, global population increase, the rise of alternative energy sources, agricultural technological advances, and shifting consumer dietary preferences have been reshaping the global contemporary food management landscape. These factors, in conjunction with the limited availability of arable land, present challenges regarding the availability, accessibility, utilization, and stability of food worldwide. We present an up-to-date critical synthesis of the most acute challenges of food security and provide a first effort at identifying ways in which big data could help alleviate them. Specifically, satellite imagery and data, groundwater monitoring, the Internet-of-Things (IoT), viewing advantages through the use of drones, updated global atlases, as well as regional and crop yield mapping, precision agriculture, demand prediction accuracy, and the ease-of-use of terminals such as smartphones and tablets are some of the tools of the information age that demonstrate great potential towards increasing the efficiency and competitiveness of food chains worldwide and, ultimately, ensuring food security.

Keywords: Big Data, Food Security, Agricultural Supply Chains, Sustainability

1 Introduction

According to the Declaration of the World Summit on Food Security (Food and Agriculture Organization (FAO) of the United Nations, 2009), food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their needs and food preferences for an active and healthy life (FAO, 2009). Nowadays, in the developing world, lack of food security, i.e. food insecurity, is primarily related to chronic hunger, while the main concerns in the developed world are obesity, and micronutrient deficiencies. Furthermore, four dimensions of food security emerge through the aforementioned definition, i.e. food availability, physical and economic access to food, food utilization, and their stability over time, while food security also embraces energy, protein and nutrient needs for life, activity, pregnancy, growth and long-term capabilities of both individuals, and population as a whole (FAO, 1996). Although food availability is historically a vital key-pillar of food security, mainly through domestic agricultural production, access to food arises as a pivotal concern for achieving food security in modern societies. Of course, food security has also an intrinsic relation to sustainability and sustainable agriculture, i.e. the capacity of agriculture over time to contribute to the overall welfare by providing sufficient food and other goods and services in ways that are economically efficient and profitable, socially responsible, and environmentally sound (United Nations Conference on Sustainable Development, 2012).

Despite the progress being made during the last two decades through the actions developed within the first of the Millennium Development Goals (MDG), i.e. towards the eradication of extreme poverty and hunger that

were established through the Millennium Declaration following the Millennium World Food Summit (WFS) of the United Nations in 2000, there is still a long way to go. Indicatively, although the MDG of halving the prevalence (proportion) of hunger up to 2015 will be mostly achieved, falling from 23.4% in 1990 to 12.8% in 2015 (projection), the more ambitious target set by the World food Summit of halving the number of undernourished people, will actually be far from being met (missing the target by almost 300M people, FAO-IFAD-WFP, 2014). Although people chronically undernourished declined by approximately 100M during the last decade, the total number of people suffering from chronic hunger is still high estimated to approximately 805M people. Additionally, there are also about 2,000M people suffering from micronutrient deficiencies (hidden hunger) (von Grebmer et al., 2014), and more than 600M people suffering from obesity (Ng et al., 2014). Additionally, in the foreseeable future, external forces such as, indicatively, climate change, the global population increase, the rise of alternative energy sources, the agricultural technological advances, the existing high volumes of food waste, and the changes of the dietary preferences underline the global contemporary food management landscape by directly threatening food security. Furthermore, the recent food security crisis of 2007-2008 brought food insecurity to the forefront of the global sustainable development agenda highlighting the need to reconsider the structure and operations of international agrifood supply networks, and to streamline the relevant policy-making. In terms of availability, domestic food agricultural production remains the main source of food, income, and employment in rural areas. However, the access to food is becoming a major concern for the global community, as there are increasing difficulties regarding

access to food for net buyers and other vulnerable groups that require policy interventions e.g. strengthening safety nets, social protection, etc., in order to be tackled. Additionally, the stability of the global food system is under threat, as conflicts, natural disasters, price hikes, and even poor governance usually trigger prolonged crises with severe impacts on food security. Moreover, regarding the utilization dimension, inappropriate diet changes over time give rise to obesity and diet-related non-communicable diseases, while in those countries undergoing rapid transformations, undernutrition and overnutrition coexist resulting in the double burden of malnutrition.

On the other hand, the ongoing advances in the field of Information and communications technology (ICT) that is widely known as “big data” appear as a promising contribution in mitigating the aforementioned challenges. Big data refers to the availability of large amounts of different types of data produced with high velocity from a high number of various types of sources, as well as the new tools and methods, such as powerful processors, software and algorithms that are required in order to handle today's highly variable and real-time datasets (EC, 2014). In terms of food security and agriculture, the potential advances in weather prediction (including severe and unseasonal weather), food security tracking, real-time monitoring of dietary habits, precision agriculture, field mapping and soil management, crop yields assessment, pinpoint irrigation and application of nutrients demonstrate great potential towards establishing a sufficient and balanced food supply for earth's growing populace.

In this context, food security is considered to be one of the most promising sectors, where leveraging the potential of big data advances in near future

could prove to be a literally life-changing step towards reinforcing agricultural production, and eliminating undernourishment and poverty within a sustainable development context (EC, 2014). Furthermore, big data has been recognized to have a pivotal role in increasing the efficiency of planning and operating the global food system, as well as in supporting policy development and strategic decision-making on the external factors driving its change at national and global level (Foresight, 2011). Moreover, the MDG's Report in 2014 accepts the critical role of data in global sustainable development and policy-making, as it recognizes that reliable and robust data are critical for devising appropriate policies and interventions for the achievement of the MDGs and for holding governments and the international community accountable (UN, 2014).

This paper aims to investigate the potential of big data tools, methodologies, and practices that could be employed in order to reinforce global food security, or, alternatively, to control and efficiently manage global food insecurity, and the ways that this goal could be achieved. Specifically, the major food challenges that stakeholders, such as citizens, governments, and national and international organizations, will have to cope with in the immediate future within a sustainable food security framework, are identified. Moreover, the contribution of big data in mitigating these challenges is also captured and discussed.

The remainder of the paper is organized as follows: in Section 2, the future challenges regarding food security are identified, while the big data potential in efficiently managing these challenges is discussed in Section 3. Finally, pivotal conclusions and meaningful insights are drawn in Section 4.

2 Food Security Future Challenges

The main characteristic of modern food security crises is that despite the fact that the world community has sufficient food to nourish the entire global population, as well as the means to substantiate it, a significant fraction of the overall global population is still living in poverty, lacking access to vital food products (FAO, 2011). To that effect, the overall problem of food insecurity appears to be a lack of systemic interdisciplinary policy-making schema of the globalized food markets and supply networks, where critical stakeholders such as domestic governments and international organizations have the responsibility to guide the world towards food security in a resource efficient and sustainable manner.

Increasing world population seems to be the main threat to food security in the next 35 years. Although the population growth rate seems to be reducing, FAO projects that global population will increase to 9.15 billion people by 2050, nearly 2 billion more than today (Alexandratos and Bruinsma, 2012). At the same time, arable soil is becoming scarcer every year, mainly due to urbanization and agriculture intensification. These factors will bring a gross mismatch between food demand and supply: there simply will not be enough land to produce the food required for the world population's sustenance, given today's land utilization, crop yields and food production and processing techniques. Therefore, agriculture in general will inevitably have to become more efficient to overcome this conundrum (National Geographic, 2015); an additional increase of 50% in food production is required in order to sustain the soaring demand (Charles et al., 2010).

Increasing food consumption per capita exerts further pressures on global food availability. The global GDP is expected to be 2.5 times of what it is

today by 2050, while per capita income will also increase by 80% (Alexandros and Bruinsma, 2012). This, in turn, will cause the average per capita food consumption to increase in terms of kcal/person/day, driving the demand for agricultural products to increase by 60%, more than twice the population rise, which is expected to be about 25%.

Fluctuation of global food prices (Gandhi and Zhou, 2014; Lawrence, Lyons and Wallington, 2010) is another critical factor that affects food security and was the main cause that brought food insecurity to the forefront in the recent past (2007-2008). In general, higher food prices significantly limit the purchasing power of consumers in developing countries, where 60%-80% of the household spending is directed to food products (10%-20% in developed countries) (UNCTAD, 2009), imposing critical limitations to food accessibility.

Food waste is another open issue that critically affects food security. It is estimated that up to one third of all food produced never reaches the consumers' plates. This in turn, means that a staggering 250 cubic kilometers of water are used and 3.3 billion tons of greenhouse gases are produced per year for no reason, inducing an annual cost of 750\$ billion to the world economy (FAO, 2013). These facts greatly highlight the need for interventions targeted towards the improvement of the production, collection, processing and distribution of food worldwide.

Changes in dietary preferences from traditional foodstuff towards higher consumption levels of meat, soya, bread, and processed foods in tandem with the high level of diversification of urban diets have significantly altered the global food production and distribution landscape (Gandhi and Zhou, 2014). "Western-type" diets, which are based more on livestock, rather than

raw fruits and vegetables, put a strain on agricultural production, because of the increased need for animal feed and fertile grazing land. Animal husbandry is inherently more resource-heavy than crop raising; about one third of the world's crop calories are fed to livestock, of which the conversion rate to consumable calories varies from 3% to 40% (National Geographic, 2014). On the other hand, population in many developed and even developing countries suffer from overnutrition, e.g. overweight, obesity, and other chronic diseases related to dietary preferences, (Foresight, 2007). Urbanization, including human settlement and urban infrastructure (e.g. roads, housing, etc.), plays also a key role in cropland reduction (Porter et al., 2014). It is estimated that the ratio of built-up area to cropland area will double by 2050 (from 3.5% in 2000 to 7.0% in 2050), creating an additional threat to food availability and accessibility. Moreover, urban markets provide a fertile ground for the establishment of global supermarket chains, with important implications on food supply chains, while urbanization contributes also in altering consumer preferences towards urban diets of high diversification, and strengthens the gaps between urban and rural populations in terms of transportation, prices, and market homogeneity.

The decline in agricultural investments and lack of sufficient infrastructure is another factor that prevents increase in crop yield around the globe (United Nations Environment Programme, 2009; World Bank, 2008). At the same time, lack in relevant investments further inhibits the growth of domestic production, mostly in developing countries, while the existing funding schemes aim only at fostering self-sufficiency of domestic populations (Anderson, 2010).

Technological advances in agriculture, including seed technology (hybrids and genetically modified crops), fertilizers, and farm machinery, have a critical contribution in the increase of crop yield and agriculture productivity (Dobermann and Nelson, 2011). On the other hand, these beneficial effects are also debatable regarding the way that they are achieved in practice, as they allow for the concentration of economic and decision-making power to just a few agrochemical companies and grain traders (Branford, 2011).

Environmental concerns raised globally during the last decades, regarding greenhouse effects and climate change in general, triggered significant changes in the energy landscape (Porter et al., 2014). In this context, the perception that biofuels, e.g. biodiesel and ethanol, could potentially play a key role in reducing greenhouse gas emissions, especially in the field of transportation (EU target: 10.0% share of the fuel mix by 2020), led to a rapid increase in their production and demand (FAO, 2006), thus rivaling agricultural production in terms of cropland use, which potentially could have critical implications on food availability.

Global climate change directly affects food production, mainly in terms of crop yield, imposing a great degree of variability (Pangaribowo, Gerber and Torero, 2013). Specifically, storms of high intensity, forest fires, droughts, floods and heat waves occur more frequently, while still difficult to be predicted, thus threatening food stability around the globe, especially in developing countries which are more vulnerable due to their agricultural-based economies. Also, given that agriculture accounts for 70%-85% of the total global water consumption, it is unnecessary to mention that the im-

peding threat of water scarcity endangers health, mainly of rural populations, and farmer productivity (United Nations Environment Programme, 2009). Melting glaciers in Central Asia and droughts in Africa are just two examples that highlight the importance of water availability on farm production and livestock breeding.

Trade is another critical factor that determines global food security (Pyakuryala, Roy and Thapa, 2010). In the current food trade terrain, developed countries and a few international corporations exert control either over food consumption in developing countries, through their export policies, or food production, through the purchase of cropland (Branford, 2011). As a consequence, developing countries are gradually becoming more vulnerable in terms of domestically produced food quantities, high prices, and land ownership. Furthermore, trade is also a factor that shapes consumer preferences and diets around the globe (United Nations Environment Programme, 2009).

International wars, internal conflicts, and economic embargoes introduce crucial uncertainties to global food supply networks by vitally undermining their stability performance in terms of supply capacity and continuity (United Nations Environment Programme, 2009).

Governance plays also a key role in food security issues, given that policy-making and diplomacy are among the core factors that shape the global food security landscape (Branford, 2011), while they are crucial for the success of both policies and programmes that are formulated and implemented in the complex modern social, political and economic environments (FAO-IFAD-WFP, 2014). Issuing protective trade regulations, main-

taining beneficial international affairs, protecting domestic cropland property rights, and ensuring food self-sufficiency are a few of the most challenging decision-making fields where governments have to take targeted action in the near future.

Monitoring of the global food system in general is a prerequisite in order to achieve efficient policy-making. The United Nations have recognized the need for improving food security monitoring and metrics, and thus, the requirement for stronger systems of assessment, monitoring and surveillance, as one of the aims of their Comprehensive Framework for Action (High Level Task Force on the Global Food Security Crisis, 2010). Towards this direction, the role of big data is identified to be more than critical (Foresight, 2011).

3 Big Data Solutions

Accurate weather predictions are of pivotal importance on a strategic and tactical planning level for agricultural production. Besides the obvious importance of temperature and rainfall, environmental conditions affect a number of relevant parameters, such as pests and diseases, carbon dioxide and ozone concentrations, and sea level. Additionally, the shifting climate has been the source of many extreme weather events, such as hurricanes, extreme droughts or floods and heat and cold waves (IPCC, 2014).

The ability to forecast weather conditions and to foresee extremes can be greatly augmented both in terms of range and accuracy through the collection and processing of weather data on a massive scale. The consolidation of weather data collection systems and the building of larger and more

complex models backed up both by past observations and real time information can vastly improve meteorological reports. A key observation is that data collection does not necessarily require the installation of specific and expensive equipment. Ever since 2013 with Samsung's introduction of the Galaxy S4 phone model, smartphones have slowly started to include more advanced sensors such as barometers, hygrometers, ambient thermometers and light meters, all of which provide key meteorological data (Johnston, 2013). Additionally, other methods have been put forth, such as correlating a phone's battery temperature with the ambient temperature (Overeem et al., 2013) and collecting Twitter users' own reporting of the weather conditions in their respective areas through monitoring trending weather-related words (commonly known as "hashtags", for example #rain, #sunny, or #humid) (Henschen, 2014).

Precision Agriculture (PA) has been used in practice since the late 1980s, following the commercial availability of the Global Positioning System (GPS). PA consists of observing and analyzing the variability of crops in a field or between fields to aid Site Specific Crop Management (SSCM). In practice, devices ranging from traditional photographic cameras to infrared cameras and sensors that detect the amount of reflected light from plants are mounted on a tractor or similar farming equipment and with the help of satellite-based positioning a map of the field can be designed; this can be used to make decisions about soil treatment, irrigation, and fertilization. However, variables affecting crop yield exhibit both spatial and temporal variations. Therefore, defining specific management zones within a field of a particular crop can prove troublesome (McBratney et al., 2005),

while tracking changes over time requires constant or often repeated monitoring, which is often proven to be expensive and time consuming.

The emergence of big data can usher a new era of PA. The commercial availability and ease of use of Unmanned Aerial Systems (UAS), commonly referred to as “Drones”, greatly augments a farm’s data collecting capabilities. Additionally, sensors monitoring variables such as moisture, nutrients and pests are now commonplace in most farms. All this massive amount of data can be collected wirelessly and then fed through cloud technology to processing systems specialized in handling such data, far away from the farm itself, the result being accurate field mapping, both spatially and temporally. The ultimate goal of big data-fueled PA is building and maintaining a real-time decision support system for farm-wide management aimed towards the optimization of returns on inputs while preserving resources. Careful and precise application of all factors that go into agricultural production can maximize crop yields, minimize waste, pesticide, and water usage and, ultimately, provide more and cheaper produce.

One key aspect demanding further scrutiny is minimizing water usage. Today, 18 countries containing almost 4 billion people are overpumping their water reserves to the point of exhaustion in order to produce grains (Brown, 2013). In a world where drought and desertification consume 12 million hectares of arable land each year (United Nations), managing water is one of the key challenges for sustainable agriculture. A big data supported

irrigation system can dynamically evaluate moisture content and dispense water as needed, cutting down on the excess use of this valuable resource.



Figure 1 A data-governed farm management system (adapted from Porter and Heppelmann, 2014)

Ultimately, with the emergence of concepts such as the “Internet-of-Things” (IoT - connected devices and components communicate with other devices and the Internet, Morgan, 2014) and the wide adoption of cloud services, all farm functions will become part of a larger ecosystem. Such a digital superstructure will be able to collect and analyze vast amounts of data and adjust the allocation of resources dynamically and efficiently, while simultaneously providing useful insights and communicating information throughout the agrifood value chain (Porter and Heppelmann, 2014).

Another aspect of the big data era that agriculture can benefit from is its interlaced existence with “Web 2.0”. Web 2.0 refers to the modern era of the World Wide Web that centers on user-generated content, usability, and interoperability, its byproducts being social networks, forums, message boards, wikis, video sharing sites, etc. Previously, the world’s agricultural knowledge was segmented, leaving producers with their own intuition or the expertise loaned from seed companies or third-party consultants. As a

consequence, up to 70% of agricultural production costs are focused on decisions of seed selection, fertility, and land access (Darr, 2014). Today, booming communities exist online where they can easily be accessed by individual producers through the widespread adoption of smartphones and tablets and serve as a place to exchange advice and crop management techniques, “dos and don’ts” and information about pricing and commodities values. Additionally, initiatives towards publicly available community-based knowledge databases are emerging trends. The vast amount of information about seed and crop varieties is collected and enriched by individuals, systematically categorized and easily accessed by producers, aiding them in the relevant decision taking. Open Data knowledge bases such as the Global Open Data for Agriculture and Nutrition (www.godan.info), the Plantwise Knowledge Bank (<http://www.plantwise.org/Knowledge-Bank/home.aspx>), and the Food and Agriculture Organization of the United Nations’ own statistical service, FAOStat (<http://faostat.fao.org/>), have become useful tools in the hands of producers worldwide in their effort towards more efficient production (van Vark, 2013).

The collection and processing of vast amounts of data from various sources, which is at the heart of the big data concept, has made techniques such as genomic selection possible. Genetic modification has made an ever-increasing assortment of plant varieties available, each with its own characteristics and trade-offs (e.g. water requirements, resistance to extreme weather conditions and/or pests etc.) (Kinver, 2014). Genomic selection utilizes statistical modelling to forecast how a specific variety of plant will perform, well before it has to be field tested. An example of this is Cor-

nell University's Nextgen Cassava project (<http://www.nextgencassava.org/>). The cassava crop serves as the main calorie source for more than 500 million people in the world. The project evaluated and categorized the results of multitudes of breeding projects, with the end result being an open access database containing all the information about cassava breeds and their cultivation (<http://www.cassavabase.org/>).

Summing up, the contribution of big data in this aspect is twofold: On one hand, paired with improved weather forecasts, the accuracy of yield predictions can be significantly boosted. Ultimately, producers take a huge gamble each and every year concerning their choice of what to grow and how to treat it, and being able to better foresee the outcome of their efforts leads to informed decision-making, optimizing both the production of food worldwide and the state of agriculture as a whole. On the other hand, the public availability of information eliminates margins of market manipulation, prices inflation and other shadowy dealings responsible for the high prices both in agricultural production inputs (seeds, fertilizers, chemicals, etc.) and in the food produced. This will fundamentally lead to fair pricing and, subsequently, improved access to food worldwide.

Food traceability has been a major concern for the past years. As early as 2000, the European Commission adopted a consolidated approach to food safety, covering all stages of the food chain, "from farm to table". (European Commission, 2000) in which "the ability to track any food, feed, food-producing animal or substance that will be used for consumption, through all stages of production, processing and distribution" (European Commission, 2007) serves as a cornerstone. Traditionally though, traceability has been mainly implemented as tags containing basic information such as

country of origin, destination, and production date in the form of barcodes or even handwritten labels. Firstly, it is obvious that this information can easily be manipulated, and secondly it is missing vital characteristics of the product pertaining its processing, storage and transport (appropriate temperature, humidity etc.). In the US, 48 million people get sick annually from eating tainted food, of which 128,000 are hospitalized, and 3,000 die (CDC, 2011). In response, the US government signed The Food Safety Modernization Act (FSMA) into law (to be enacted within 2015), which mandates traceability from-farm-to-fork across the entire lifecycle – from source to finished product. A big data-powered solution could take the form of micro-sensors in food lots measuring all the relevant information that ensures its quality and storing them in advanced tags, which could be either Quick Response (QR) codes, or Near Field Communications (NFC) cards. By reading these tags through easy-to-use terminals (smartphones and tablets) both food handlers and consumers can have an instant view of everything that led a particular product to them. Simultaneously, and with the combination of cloud technology, agrifood supply chains can have real-time visibility of their products and their condition throughout their every stage. This will ultimately lead to improved efficiency of food chains worldwide and significantly less food waste that could be otherwise used to feed starving populations.

4 Conclusions

Food security is undoubtedly one of the most pressing matters of sustainability for the future, with practical, as well as humanitarian implications. Its

major challenges include adequately feeding the world's expanding population, while simultaneously closing the gap between the epidemic of obesity in the western world and hunger in developing countries. Considering the world's limited resources, the path to food security lies through the enhancement of agriculture's efficiency throughout all of its stages: planting, growing, collecting, processing and transporting. Agrifood chains will have to ameliorate their capabilities to turn production inputs into food and feed to keep up with growing demand, by cutting down improvidence, extravagance and misuse, or, as the old adage goes, "waste not want not". Luckily, the Information Era and the explosion of big data can provide with a multitude of readily available or in development solutions aimed at enabling growth and productivity in all of agri-production's strata.

The amalgamation of Agriculture and big data has been heralded as the greatest advance in food production technology since the Green Revolution between the 1940s and the late 1960s when one of the biggest waves of research and technology transfer spurred the growth of agricultural production around the world, especially in developing countries (Hazell, 2009). The ability to collect and process vast amounts of observations pertaining to food production and the ease of presentation and manipulation of the results can support the relative decision-making process and facilitate efficacy, competence and growth. In this article, we presented anecdotal references from big data applications in the real-world and further presented opportunities for further unlocking its potential in order to boost the performance of agricultural production. There is strong evidence suggesting that harnessing the capabilities that big data has to offer can be of great service towards securing adequate and nutritious food in the future. It is

our hope that this work will spur further research, both qualitative and quantitative, into this promising subject matter.

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