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How digital is agriculture in a subset of countries from South America? Adoption and limitations

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ABSTRACT

Digital agriculture (DA) can contribute solutions to meet an increase in healthy, nutritious, and affordable food demands in an efficient and sustainable way. South America (SA) is one of the main grain and protein producers in the world but the status of DA in the region is unknown. A systematic review and case studies from Brazil, Argentina, Uruguay, and Chile were conducted to address the following objectives: (1) quantify adoption of existing DA technologies, (2) identify limitations for DA adoption; and (3) summarise existing metrics to benchmark DA benefits. Level of DA adoption was led by Brazil and Argentina followed by Uruguay and at a slower rate, Chile. GPS guidance systems, mapping tools, mobile apps and remote sensing were the most adopted DA technologies in SA. The most reported limitations to adoption were technology cost, lack of training, limited number of companies providing services, and unclear benefits from DA. Across the case studies, there was no clear definition of DA. To mitigate some of these limitations, our findings suggest the need for a DA educational curriculum that can fulfill the demand for job skills such as data processing, analysis and interpretation. Regional efforts are needed to standardise these metrics. This will allow stakeholders to design targeted initiatives to promote DA towards sustainability of food production in the region.

Keywords: agriculture 4.0, digital agriculture, digital technologies, IoT, regional development, south america, sustainability, technology adoption.

Introduction

The rapidly growing population has driven a significant increase in demand for healthy, nutritious, and affordable food and feed, while land and water scarcity, and climate change (Tilman *et al.* 2002; Fischer and Connor 2018), necessitates maintaining the current cropping area when meeting this demand (Lobell *et al.* 2009; Andrade 2016; Cassman and Grassini 2020). Novel technologies to attain this goal should focus towards increasing resources and input use efficiency. This is particularly important for nutrients and pesticides applications as they pose potential negative environmental impacts (Sadras and Denison 2016).

South America (SA) is one of the main grain and protein producers in the world and accounts for approximately 10% of the world's agriculture product export (FAO 2021*a*). The rapid growth of SA food production and the increasing prices of commodities such as soybean (*Glycine max* L.) (Wingeyer *et al.* 2015) has been tied to a consistent increase in global demand and new access to markets (Tilman *et al.* 2002; Naylor *et al.* 2007). Agriculture transformation in SA is continuously evolving due to joint efforts from research entities, who have developed new technologies, improved agronomic practices, entrepreneurial investment, and government support (Odusola 2021). An evaluation of the level of adoption and limitations of recent innovations in agriculture technologies in Brazil, Argentina, Chile, and Uruguay (from here on 'the

Region'), is vital to guide future research, extension, and investment to satisfy future food demand.

Quantitative methods such as utilising surveys were implemented to explore adoption of a given technology in the Region (Roel and Plant 2000; Melchiori *et al.* 2018; Bolfe *et al.* 2020). Since the 1980s, the use of precision agriculture (PA) technology has been proposed for improving input use efficiency. Precision agriculture technologies aims to: (1) reduce inputs while maintaining yields; (2) increase yields while maintaining levels of input use; or (3) increase input use without reductions in input use efficiency (Byerlee 1992; Stafford 2000). The growing connectivity in rural environments, in addition to greater integration with data from sensor systems, remote sensors, equipment, and smartphones has paved the way for new concepts from the so-called digital agriculture (DA) or Agriculture 4.0 (Zhai *et al.* 2020).

Digital agriculture was defined by the United Nations as 'the use of new and advanced technologies, integrated into one system, to enable growers and other stakeholders within the agriculture value chain to improve food production' (United Nations 2017). DA has four essential requirements: (1) increasing productivity; (2) allocating resources reasonably; (3) adapting to climate change; and (4) avoiding food waste. it is considered part of fourth revolution in agriculture (Klerkx *et al.* 2019; Trendov *et al.* 2019). DA technologies include PA (the most developed branch), IoT (Internet of Things), blockchain, big data, machine learning, and artificial intelligence, robotics, and automation (Robertson *et al.* 2019).

DA was proposed as an effective way to optimise agriculture production systems by improving yields, profitability, and reducing environmental impacts from agricultural practices (Balafoutis *et al.* 2017; Klerkx *et al.* 2019). Despite concerns related with the adoption of these technologies across countries, food production sectors, and size of stakeholders, there is evidence of benefits driven by rapid access to connectivity and phone apps (GSMA 2020). Worldwide mobile phone adoption has dramatically increased both in developed and developing countries (Taylor and Silver 2019). These devices have a positive impact in agriculture since they can provide access to information, training, markets, and financial services and improve growers farming opportunities (Aker 2011; Rotondi *et al.* 2020). For example, in India, the access to market prices via phone apps resulted in an 8% increase in profits for fish producers (Jensen 2007). In contrast, growers lack of knowledge about DA benefits can pose limitations for adoption (Melchiori *et al.* 2018; Thompson *et al.* 2019; Bolfe *et al.* 2020; DeLay *et al.* 2022). Most of the literature reported benefits from DA using economic metrics related with PA technology (Bongiovanni and Lowenberg-Deboer 2000; Timmermann *et al.* 2003; Borghi *et al.* 2016). References on other benefits of DA, such as time-saving (Casaburi *et al.* 2019), and increase input use efficiency (Balboa 2014; Kayad *et al.* 2021) are limited.

In this review, we aimed to characterise the status of DA in a subset of countries of SA: Argentina, Brazil, Uruguay, and Chile. We conducted a systematic review (i.e. official reports, surveys, and peer reviewed publications) and interviews (case studies) to: (1) quantify adoption of existing DA technologies; (2) identify limitations for DA adoption; and (3) summarise existing metrics to benchmark DA benefits on food production systems. The information summarised in this review could aid in guiding priorities for future research and extension activities and to assist in designing policies towards effective adoption of DA technology in SA.

Materials and methods

To achieve the objectives of this review two sources of data were used: (1) a literature review; and (2) case studies. The literature review (see Supplementary Table S1) allowed us to characterise the Region in terms of DA (section *Features of the Region and cropping systems*), summarise different surveys about adoption and limitation of DA (section *Adoption and DA technology in the Region*), compile and classify mobile apps and digital platforms (section *Mobile Apps and Digital Platforms in the Region*), identify the support provided by technology agricultural companies and public efforts towards DA adoption (sections *Role of regional agricultural technology companies in DA* and *Regional public efforts to address DA adoption limitations*), and retrieve a list of metrics to benchmark DA benefits (section *Benchmarking metrics for DA benefits*). A total of 34 case studies were implemented by conducting a semi-structured, stratified, in-depth interview to a set of early adopters identified in the Region (section *Case studies*).

Literature review

The literature review on DA included a subset of countries in South America, Chile, Argentina, Uruguay, and Brazil. Papers were retrieved from Web of Science Core Collection, Scopus, Springer, Agricola, and Google Scholar using the following keywords, individually and in combination: Digital Agriculture, Argentina, Brazil, Chile, Uruguay, South America, IoT, Precision Agriculture, Big Data, digital platforms, DA survey, DA adoption, and DA benefits. Remarkably, several references were included as grey literature (i.e. literature that is 'produced on all levels of government, academics, business and industry in print and electronic format, but is not controlled by a commercial publisher') (Saleh *et al.* 2014). An overall description of the Region is provided in section *Features of the Region and cropping systems*. The literature review (Table S1) allowed to find surveys with different data collection methods that limited quantitative comparison between countries of the Region. However, the methodology is an impressionistic comparison providing an overall picture of the state of DA (Lowenberg-DeBoer and Erickson 2019).

We compiled surveys conducted by public research institutions from Brazil (Brazilian Agricultural Research Corporation, EMBRAPA; Borghi *et al.* 2016; Bolfe *et al.* 2020), Uruguay (Berger *et al.* 2019), and Argentina (Melchiori *et al.* 2013, 2018) to characterise the adoption of DA and PA technologies (section *Adoption and DA technology in the Region*). To the best of our knowledge, there is no official survey records in Chile and we reported findings from a survey conducted by the Agronomical Engineer Association in Chile (Palacios Duran *et al.* 2021). No new surveys were conducted in this study.

A review of the mobile apps and digital platforms available in the Region was conducted to characterise their availability and complexity. Google search engine was used to look for agricultural mobile apps by country using the following key words individually and in combination: app agriculture, digital ag platform, agro app, farm mobile application, sowing, harvest, spraying, fertilisation, weather, nutrients, pests, herbicides, management, precision agriculture, and market price. Searches were performed in Spanish for Argentina, Chile, and Uruguay and in Portuguese for Brazil.

The search was oriented to mobile apps and platforms developed or adapted in each country (mobile apps developed exclusively outside of the Region were not considered). Agricultural mobile apps can be classified following different criteria (Karetsos *et al.* 2014; Patel and Patel 2016). In this review, mobile apps and digital platforms were classified in categories (section *Mobile apps and digital platforms in the Region*) following four types of data analytics (Banerjee *et al.* 2013; Smith 2019): (1) descriptive, those providing general information related to agriculture (i.e. weather, commodities prices, management guides); (2) diagnostic, those helping to diagnose a particular situation (i.e. pest, nutrient deficiency); (3) predictive, those requiring user log in and data entry from growers, and including data analysis and interpretation to generate a product based on user farm data (i.e. digital platforms with crop model to predict yields); and (4) prescriptive, those requiring user log in and data entry of more than one source to provide data-driven input recommendation prescriptions (i.e. digital platform able to generate a nutrient prescription). For each mobile app the name, website, country, and category were recorded. The complete list of mobile apps can be found in Table S2.

The literature review allowed to identify an emerging type of technological companies focused on providing new agricultural services based on application of new technologies on data analytics, IoT, connectivity, along the agricultural value chain. Their role in DA and a summary of the services that they provide is highlighted in section *Regional agricultural technology companies' role in DA* and Fig. 5. Regional public efforts to promote adoption of DA were summarised in section *Regional public efforts to address DA adoption limitations*.

Based on the reviewed papers, a list of sustainability indicators was compiled to benchmark DA benefits (section *Benchmarking metrics for DA benefits*, Table 2). Examples of those indicator to benchmark DA benefits are in Table 3.

Case studies

A total of 34 case studies were implemented by conducting a semi-structured, stratified, in-depth interview (section *Case studies*). The case studies were stratified by agriculture activity, operation size, and occupation/role. A description of the participants from case studies are in Table S3. The set of semi-structured questions were focused on obtaining rich descriptions from growers (G), crop consultants (CC), and service providers (SP), to understand the process of adopting DA technology, learn the limitations for adoption, and understand metrics being used to measure the impact of DA technology (see Supplementary Material Appendix A). Questions were open, no options provided, to avoid biasing participants answers. To describe the number of users per DA technology, we categorised the mention of different technologies from question four into GPS technology, remote sensing, IoT, mapping, robotics, apps, and digital platforms ('Types'). The use of autopilot, autosteering and automatic section control was summarised under GPS. Drone and satellite images used to scout or monitor crop indexes (e.g. normalised difference vegetation index, NDVI) for prescribing nitrogen (N) fertilisers decisions or to delineate management zones (MZ) were categorised under remote sensing. Data shared with telemetry was included under the IoT category. Yield maps, soil maps such as grid sampling and apparent electrical conductivity maps (ECa), and gamma emissions (GE) were categorised under mapping. To described how participants measure the 'Impact' of DA technology adoption in their operations, we classified their answers in question seven into increase of yield, efficiency, savings, profit, and sustainability. Lastly, the 'Limitations' for DA adoption were analysed by grouping answers from question six into the following factors: area, machinery, complexity, connectivity, knowledge, training, benefits, cost, technical support, labour, generational, risk and extension.

The definition of DA provided by the participants was analysed using a visual representation of word frequency 'Word cloud'. The more times the term appears within the text being analysed, the larger the word will appear in the generated image. Data processing and analysis was done using the R software (R Core Team 2021).

Results and discussion

Features of the Region and cropping systems

The study Region includes 552 million ha of production across four countries with a heterogeneous composition on farm size as well as production type (e.g. row crops, intensive crops, cattle). According to country census, the total number of

Table 1. Literature review: number of farms, area, agricultural exports, markets, mobile phone, rural internet access, use of digital Ag app tool by country in the Region of study.

	Brazil	Argentina	Uruguay	Chile
Farms	5 073 324	220 060	44 781	278 660
Area (million ha)	351.3	157.4	16.36	29.78
Farms less than 50 ha (%)	81%	43%	42%	88%
Area farms less 50 ha (%)	12%	1%	2%	7%
Mobile phone (%)	85	82	92	90
Significant rural connectivity (%)	40.3	35	34.5	46.8
Farm computer (%)	29	34	NA	31
Use of mobile DA app (%)	84	79	70	95
DA start-ups (*n*)	233	104	19	45
Main agricultural exports	Soybean, sugar, corn, cellulose paste, beef	Soybean flower, soybean oil, soybean, corn, wheat, beef	Beef, cellulose paste, soybean, dairy	Grapes, berries, plums, cherries, dehydrated apples, walnuts, wine
Main markets	China, United States, Europe	China, Brazil, United States,	China, European Union, Brazil, United States	United States, China, Japan, United Kingdom, Brazil

Sources: mobile phone (GSMA 2020); rural internet access (IICA 2019); Chile Agricultural Census (INE 2007); Brazil Agricultura Census (IBGE 2017); Argentina Agricultural Census (INDEC 2019); Uruguay Agricultural Census (DIEA 2011); DA Start-ups (IDB 2019).
NA, not available.

growers in the Region is 5.61 million, the main country Brazil, accounts for 90% of the total number of farmers, whereas 5% are in Argentina, 4% in Chile, and 1% in Uruguay. Brazil accounts for 64% of the agricultural area in the Region followed by Argentina (28%), Chile (5%) and Uruguay (3%) (Table 1). According to the 2017 Brazilian Agricultural Census 81.5% of the farms has a size of less than 50 ha, 15% between 50 and 500 ha, and 2% between 500 and 10 000 ha.

In Argentina, the second largest agricultural country in the Region, 43% of farms have a size less than 50 ha accounting only for 1% of the total agricultural area (INDEC 2019). Regarding farm number and size in Brazil and Chile, 88% of total number of farms have an area <50 ha representing 12 and 7% of the total agricultural area for Brazil and Chile, respectively (Table 1). Results presented in this review were not focused on a specific farm size in the Region.

China and United States are the common markets for the Region. Main export products are soybean (Brazil, Argentina, Uruguay), corn (*Zea mays* L.) (Brazil, Argentina), soybean flour and oil (Argentina), cellulose paste (Brazil, Uruguay), beef (Brazil, Argentina, Uruguay), grapes (*Vitis vinifera* L.), blueberries (*Vaccinium corymbosum* L.), plums (*Prunus domestica* L.), and cherries (*Prunus avium* L.) (Chile). Chile production systems are characterised by intensive crop production (vineyards and fruits).

Internet access in rural areas has been shown as a key factor for development of DA (Sotomayor *et al.* 2021). The significant rural connectivity index (IDB 2019) indicates the percentage of the rural population with internet access. Chile has the largest percent of rural population with internet access with 46.8% followed by Brazil (40.3%), Argentina (35%), and Uruguay (34.5%) (Table 1). According to the countries official agricultural census, no more than three farms out of ten have a computer to log and manage farm data (Table 1). In contrast, it was reported (GSMA 2020) that more than 80% of growers have a mobile phone (with some variation between countries of the Region). This can be considered as one of the main drivers for growers in the Region to adopt a broad variety of mobile apps related to agriculture. All countries in the Region showed that at least eight out of 10 growers are using a mobile DA app tool in their daily operations. The number of DA starts up shows the degree of development of DA in the Region. Brazil concentrated 58% (233) of the DA Start up in Latin America and the Caribbean followed by Argentina with 26% (Table 1).

Adoption and DA technology in the Region

Technology adoption is a path to increase farm productivity and improve food security. The process of technology adoption is heterogeneous across farms and across the Region (Chavas and Nauges 2020). The literature review allowed to compile a list of surveys, reports, and manuscripts to describe the level of adoption of DA and their limitations (Table S1). Adoption percentages (expressed as % of the responses to each survey) by technology by country in the Region is in Fig. 1. Percent of adoption from surveys cannot be compared between countries since they were assessed by different methodologies; however, they provided a baseline to describe the use of DA technologies in the Region.

The GPS, mapping tools, mobile apps and remote sensing were the most used DA technologies across the Region, except for Chile, with relatively low adoption of all the mentioned

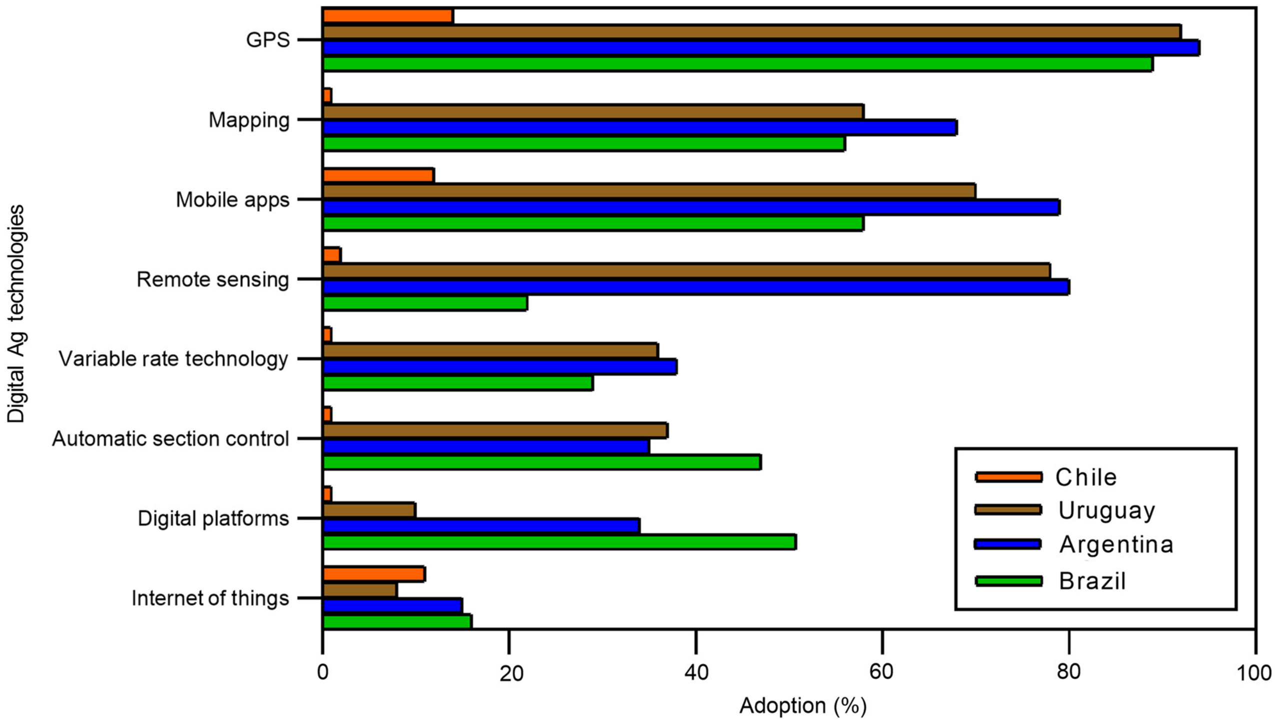

Fig. 1. Adoption (%) of digital agriculture technology (DA) for Argentina, Brazil, Chile, and Uruguay. Data sources: Argentina (Melchiori *et al.* 2013, 2018; Kemerer *et al.* 2020; Villarroel *et al.* 2020), Chile (Villalobos Mateluna *et al.* 2009; R. Ortega, pers. comm.; Palacios Duran *et al.* 2021), Uruguay (Berger *et al.* 2019), Brazil (Borghi *et al.* 2016; Bolfe *et al.* 2020). The % of adoption is indicated in relation to responses to each survey.

tools (Fig. 1). These findings were similar to what was reported in United States with 60% adoption of GPS guidance systems (Erickson *et al.* 2017) and in Australia with 77% (Llewellyn and Ouzman 2014). Global Navigation Satellite Systems (GNSS) guidance and associated technologies have been adopted as fast as other major agricultural technologies throughout history while variable rate technology (VRT) does not exceed 20% of adoption at world level (Lowenberg-DeBoer and Erickson 2019).

In Argentina, the 2018 INTA survey had 306 responses. 86% of the responses were from the Pampas Region where most of the agricultural production is concentrated in the country. The DA technologies that reported the highest level of adoption were GPS (94%), remote sensing (80%), mobile apps (79%) and mapping (68%) (Fig. 1). The adoption of IoT devices was below 20% in Argentina and was the technology with less adoption in all countries in the Region. According to this survey, adoption of PA technologies increased from 2013 to 2018 for the use of automatic pilot (40–61%), automatic section control (ASC) in Planters (7–21%), VRT seeding (27–35%) and VRT fertiliser (29–41%). Among users, 85% reported to import and visualise data and 80% performed field management zones (MZ). Only 56% of this pool of participants used MZ to direct soil sampling. It was reported that 45% and 50% of growers that performed MZ were used for variable rate seeding and fertiliser prescriptions, respectively. Those percentages remained approximately stable from 2013 to 2018 (Kemerer *et al.* 2020). We hypothesised that higher adoption of VRT for inputs might be pushed forward by new DA tools such as digital platforms, connectivity, data interoperability, and new hardware (electric motors to action mechanisms). These new advances could solve problems reported by technology adopters related to data management and processing, to process from field data layers (yield, soil, and EC maps) to input prescriptions.

Technology cost (50%), lack of specialised labour (38%), limited training opportunities for agronomist and machine operators (27%), reduced number of services providers (33%), and the lack of clear agronomic and economic benefits (18%) were reported as the main factors limiting the adoption of DA technologies in Argentina (Bragachini *et al.* 2004; Melchiori *et al.* 2018; Kemerer *et al.* 2020). In addition, once technology was adopted, the main problems reported by users were greater specialisation for data processing (62%), compatibility issues between software and/or hardware (46%), lack of post-sale service from companies (39%), and agronomic background for input variable rate decisions (36%). The survey concluded that more training (83%), availability of agronomic data to support decisions (96%) and discussion and interchange sessions among PA tools users (70%) could increase the level of adoption of PA technologies (Kemerer *et al.* 2020).

The reviewed survey from Uruguay had 124 responses covering 300 000 ha (25% of the cropping area). Adoption of GPS, satellite imagery, light bar, georeferenced soil sampling, automatic pilot, and yield maps was greater than 50% (Berger *et al.* 2019). The GPS was the tool known by more than 90% of survey respondents followed by remote sensing (78%) and mapping (58%). Tools like detailed soil maps, georeferenced soil sampling, yield mapping, and autopilot had an average gap between knowing the tool and using it of 20%. More than 50% of participants attended workshops and ~40% took training courses. Only 35% of participants had specific software training in Uruguay. The percentage of participants that never received training was 32%. Among responses in Uruguay, 20% used weed sensors or sensors for variable rate N application. Variable seeding rate was implemented by 24% of participants. In Uruguay, the main driver for adoption was associated with economic aspects such as increases in profits (68%), crop yields (63%), production quality (43%), and decreases in input use (56%), environmental impact (48%), and labour hours (32%). Lack of labour specialised to use technology (50%), lack of training courses for growers/agronomists (43%), and machinery operators (42%), few companies providing DA services (39%) and high technology cost (36%) were the main limiting reasons reported in Uruguay that limits adoption (Berger *et al.* 2019). The INIA Uruguay is investing efforts developing IoT sensors networks to promote their adoption in intensive systems (Silveira *et al.* 2021).

A survey in Brazil with 502 respondents indicated that 84% of growers used at least one digital agriculture tool (Bolfe *et al.* 2020). Most of the growers (70.4%) reported to have connectivity on their property and 58% use mobile apps, digital platforms, or software to gather general information. In Brazil, 95% of growers use smartphones (Michels *et al.* 2019) and 71% use mobile apps to assess specific management practice or pest and diseases detection and prediction. The technology with highest adoption was GPS (89%), followed by mobile apps (58%), mapping (56%) and automatic section control (47%). The main drivers of DA adoption identified were increased productivity, better process quality, reduced cost, and greater knowledge of the farming area (Pivoto *et al.* 2019). Technology implementation cost (68%), lack of internet connection (45%), cost of service providers (45%), and lack of knowledge about technology (42%) were the main factor identified by growers that limited adoption of DA (Bolfe *et al.* 2020). In a study conducted in the Parana State in Brazil (Kolling and Rampim 2021), 95% of the farmers that responded to the survey have access to a smartphone and 63% to a laptop. Moreover, 87% of the farms have access to internet at their headquarters. These numbers represent most of the farmers assessed, which shows that internet has become very accessible in rural areas. Nevertheless, 57% of farmers consider internet connection in the total perimeter of the farm as regular and 25% consider it poor connection. These conditions allow farmers to upload and download data to the machinery and access information at the headquarters, while in the field internet connection still needs to be upgraded.

There are no official records about the percentage of adoption of DA or PA technologies in Chile. Only one survey was conducted by the Agronomical Engineer Association. The use of PA technologies in Chile agriculture started in 2000. In 1997, research studies demonstrated high variability in soils properties and crop yields in Chile, which justified the use of variable spatio–temporal management (Ortega and Esser 2003; Ortega and Santibáñez 2007). Nowadays, the main technologies incorporated were GPS and remote sensing tools. A major obstacle is the limited number of companies providing DA-related services and adequate training programmes. Research efforts are focused on identifying technologies to measure and diagnose spatial variability rather than improving data interpretation and developing prescription frameworks. Cost reduction and increase in production quality were reported as the two main drivers for technology adoption in Chile. Conversely, the lack of knowledge about DA technology from farm and company managers is one of the main limitations for adoption (Villalobos Mateluna *et al.* 2009; Best *et al.* 2014). The reviewed survey from the Agronomical Engineer Association in Chile was conducted in 2021 and showed that 95% use at least one DA mobile app in their daily activities. This survey identified connectivity, training, and generational issues as main limitations for DA adoption. As a result, a special commission for Innovation and digital transformation was created in the Association. Only 5% of the area in Chile is managed using PA technologies, vineyards and fruit crops represented most of the area (Palacios Duran *et al.* 2021).

A small and fragmented DA industry and the lack of research and development difficult the promotion of DA benefits across Chilean agriculture producers (Best and Vargas Quiñones 2020). Adoption of DA techniques is driven by the larger export sector with a 60% adoption in vineyards and 30% in horticulture while the level of adoption for extensive crops is close to 15% (Best 2021).

Mobile apps and digital platforms in the Region

Agricultural mobile apps and DA platforms are some of the most developed tools of DA. The development of agricultural mobile apps based on smartphone devices increased exponentially in the past 5 years (Mendes *et al.* 2020), and SA followed the trend. Our literature review of digital mobile apps available in the Region found 231 mobile apps that met the search criteria established. Following our proposed classification criteria, 41% were categorised as descriptive, 27% as diagnostic, 19% as predictive and 13% as prescriptive apps (Fig. 2). A 68% (descriptive + diagnostic) of

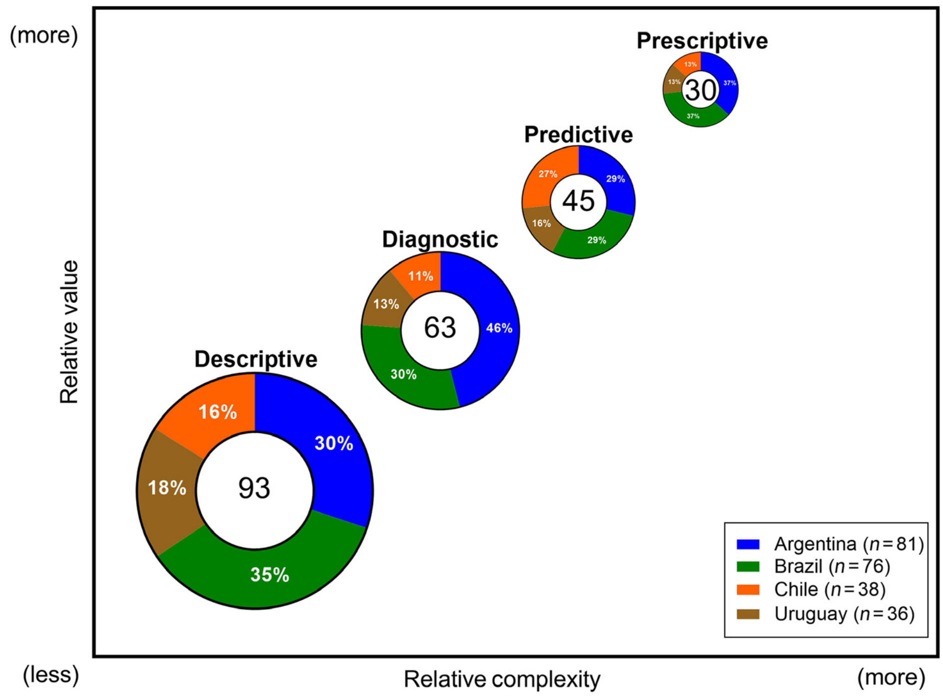

Fig. 2. Mobile apps compiled for Argentina, Brazil, Chile, and Uruguay grouped by data analytics categories (descriptive, diagnostic, predictive, prescriptive) and their relative value and complexity. Number centred in the circles and circle size represent the number of applications in each category and the relative proportion compared to the total number of mobile apps reported (n = 231). Percentages within each country represents the proportion of mobile apps for the category.

mobile apps in the Region provided growers with information about markets, weather, service providers, and growing season conditions. A group of apps allowed them to diagnose nutritional deficiencies, pests, weeds, and diseases. Predictive and prescriptive apps represented 32% of the available apps. These apps allowed farmers to handle data such as crop vegetation indices and field specific data layers (e.g. ECa, soil maps) and they require user log in and uploading specific data from the farm and field (Fig. 2).

The largest two growing countries, Argentina and Brazil, had the highest percentages of mobile apps across all categories (66, 76, 58 and 73% of the apps for descriptive, diagnostic, predictive and prescriptive categories, respectively) (Fig. 2, Table 1). These numbers reflect the level of developments of these tools in the Region that agrees with the size of the agricultural markets that these two countries represent in the Region.

A survey about DA apps and technology adoption in Argentina conducted by INTA reached 1044 responses and showed that 79% of growers and crop consultants used mobile apps and web platforms in their fields. A total of 67% of participants reported that the use of web platforms and mobile apps increased production profits. Survey participants included growers (35%), crop consultants (46%), rural contractors (5%), machine operators (3%), researchers (2%) and others (8%). The survey included 45% of growers with more than 1500 ha, 29% between 300 and 1500 ha, and 26% with 300 ha or less (Villarroel *et al.* 2020). Crop consultants that worked in more than one operation declared to use mobile apps to record data from multiple fields and to use data to assist management decisions. Apps mentioned in this survey were related to weather (75%), spraying (58%), sowing (54%), fertilisation (47%) and harvest (32%). Only 32% of respondents reported to use apps for crop scouting purposes.

Apps for real time machine monitoring and tracking allow growers and crop consultants to control their operations but also allow service providers to monitor the equipment and adjust technical parameters for better performance. Sprayers can be monitored and tracked for certification and traceability purposes or to avoid conflicts related with applications closer to urban areas. Web digital platforms for data management, crop scouting, MZ generation using yield maps, soil maps and satellite imagery are becoming popular in the Region (Fig. 1; Kemerer *et al.* 2020; Villarroel *et al.* 2020). Apps reported by INTA's survey were characterised by being highly intuitive, with flexibility to add more functionality and have the capacity to be integrated with other apps or web platforms. The capability of using apps without internet connectivity was an important feature in the Region since rural connectivity is limited (Table 1).

The most used mobile apps from the INTA's survey were classified as related to weather (21%), spraying (18%), sowing (17%), fertilisation (15%), harvest (10%), and others (19%) (Villarroel *et al.* 2020). The use of smartphones with GPS, and the deployment of 4G internet access across countries contributed to acquire, compile and process different data layers allowing remote management decisions without the need to travel to the field. Limited rural internet connectivity (Table 1) is not allowing full benefits of this technology since data is transferred to the cloud or platforms on a delay when devices reach an area with internet connectivity. Apps that allowed remote management of field equipment based on sensor data are not popular in the Region. For example, the control of pivot irrigation based on soil moisture sensors, weather stations, and potentially combined with other sources of data. These apps can potentially increase crops water use efficiency (Maia *et al.* 2017; Capraro *et al.* 2018; Villarroel *et al.* 2020). In Argentina, it was estimated that no more than 5% of irrigation equipment is controlled by this type of apps (F. Scaramuzza, pers. comm.).

In recent years, there has been a fast growth of local companies and start-ups in the Region looking to jump into the business providing new applications for DA based on relatively new connectivity technologies like LoraWAN (Miles *et al.* 2020; Valente *et al.* 2020). This technology is characterised by the capability of transferring small amounts of data in through long distances and with low energy cost. A review on IoT technologies in agriculture Tovar Soto *et al.* (2019) identified that temperature (22%) and moisture (19%) sensors are the two categories most implemented in agriculture followed by RFID (11%), luminosity (8%), pressure (7%) and UV intensity (7%). A positive impact of mobile phones in agriculture is related to better access to information, trainings, markets, and financial services and by improving growers' ability in terms of planning and managing farm-related activities (Aker 2011; Rotondi *et al.* 2020).

Case studies

Description of participants impression about DA

Of the 34 total case studies within Argentina, Brazil, Chile, and Uruguay, 73% of participants were growers (G), 23% crop consultants (CC) and 5% service providers (SP). The size of the farming operations for G and CC ranged from 200 to 46 000 ha (Table S3). A total of 55% of the participants raised row crops (e.g. corn, soybean, rice, cereals), 25% livestock and the remaining 20% dairy production, horticulture, or forestry farms.

Across countries and case studies, there was no clear definition of DA, and it was often considered the same as PA. A total of 30% of the participants did not define DA and were mostly from the cattle sector. The words 'technologies', 'agriculture', 'use' were frequently used to define DA. Other common mentioned words to define DA were, 'data', 'management', 'information', and 'better decisions' (Fig. 3).

Across the region, in 65% of the cases, the adoption of DA started during the past decade and 80% of the participants did not feel positioned to embrace leading-edge technologies in their teams when adopting complex DA tools (e.g. prescriptive tools, web platforms). This was mostly related to a lack of training, knowledge, and interest in the agriculture working sector. This suggests immediate action is needed to set priorities in the Region considering the role of DA to contribute to sustainable intensification of the cultivated land (Lobell *et al.* 2009; Andrade 2016) to meet the increasing demand for food and feed while maintaining high input use efficiency (Sadras and Denison 2016).

DA technologies, impact, and limitations for adoption

Across participants, apps (38%), VRT (32%), remote sensing (29%), and digital platforms (29%) were mentioned as DA technologies most used (Fig. 4). The row crop G and CC acknowledged that VRT for fertilising and seeding, yield monitor data, vegetative indexes, and the ability to quantify field variability were among the DA tools that allowed them to make informed decisions compared to their peers. In the cattle sector, the number of tools utilised was lower than agriculture and intensive crops (data not shown). The common theme within cattle case studies was the use of apps for logistics, commercialisation, and for digital tracking of animal weights. The overlapping of DA technologies between agriculture and cattle sector was minimal (e.g. for Chile, the use of water sensors and images to guide irrigation schedules were the only tools mentioned). Percent of adoption of VRT and digital platforms reported in the case studies agreed with results from regional surveys reviewed in section *Adoption and DA technology in the Region* (Figs 1, 4). In contrast, adoption of remote sensing and mobile apps reported in the case studies were 30% below than the adoption rate reported in the regional survey review.

The main drivers of DA adoption were yield, efficiency, savings, and profits. The definition of the term 'efficiency' varied across sectors. For example, 'efficiency' in cattle or horticulture sector was related to labour and time saving, while for row crop was input use efficiency (e.g. fertiliser, seed). For CC, the main drivers for adoption were related to the ability to offer a more competitive service, differentiate consulting from others, and being able to scale-up the service to more fields (>5000 ha). The ability to scale up was reported to create positive feedback attracting bigger farms already demanding CC with expertise in DA.

Despite the complexity involved when adopting these tools, especially for small-scale growers, participants expressed that when economic and productivity benefits from technology were clear, there was no hesitation to scale-up the use of DA and promote the value of the technology among peers. Interestingly, the lack of clear

Fig. 3. Word cloud of 34 definitions of digital agriculture term across Brazil, Argentina, Uruguay, and Chile. The more often a term appears in answers, the larger the word appears in the cloud.

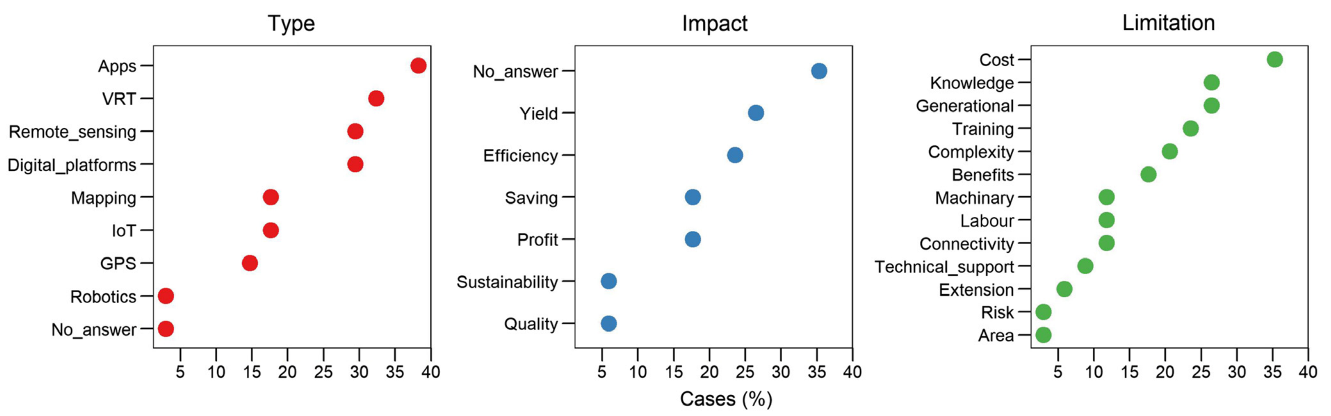

Fig. 4. Type of digital agriculture technologies (DA), metrics used by participants to measure impact of DA and limitations to DA adoption across 34 case studies within Argentina, Brazil, Uruguay, and Chile.

benefits from DA technology was found as an important factor limiting the adoption (18%, Fig. 4). These results highlight the importance to use existing metrics to quantify and evaluate the impact of DA technology in production systems to ensure a more effective and consistent adoption (Cook *et al.* 2022).

The cost of DA (35%), knowledge (26%), growers' age (26%), and available training (24%) were among the most important limitations to adoption of DA (Fig. 4). These results agreed with a recent survey from Bolfe *et al.* (2020) in Brazil where the cost and initial investment in PA technology were the main challenge towards adoption followed by lack of connectivity and knowledge. A similar analysis carried out in USA indicated that the main barrier in PA adoption was related with the costs associated with precision agriculture technologies (Erickson and Lowenberg-Deboer 2020).

Qualified operators to drive machinery and skilled personnel to properly set up and use the DA technology are lacking (Darnell *et al.* 2018; CSB 2020). Trainings for agronomists are limited in the public sector, and most of the times technology providers offer specific training for the operators. However, 'when you want to send an operator to get training it is not easy to find', said a CC during the interviews. In Uruguay, one of the row crop growers said, 'in our farm, we have young operators that are on top of everything, and they really know how to manage different technologies but also there are old operators that are not open to new technologies.' While in Argentina, a crop grower stated, 'we are looking to hire a technician to monitor and analyse real time data that is being generated in order to make real time decisions'. For this grower, data is not analysed fast enough to make use of it, a main limitation on the digital transformation of agriculture (Cook *et al.* 2022). To mitigate these limitations, implementation of public and private training programs along with extension efforts could support the use of DA and reduce the initial risk associated with testing new technologies (Hermans *et al.* 2019; Fuglie *et al.* 2020).

In contrast to row crops, metrics that measure the impact of DA appear to be embedded in dairy and cattle operations providing a ready to use benchmark for their operations. For example, the metric of productivity as litres of milk per cow per day in the dairy farm is digitally recorded in automatised dairy farms, which has dramatically increased data flow (Barge *et al.* 2013; Zhang *et al.* 2020). This enabled quicker realisation of the benefits that in turn promoted further investment, training, and motivation for adoption of other DA technologies (Stone 2020).

In row crop production, case studies revealed several challenges when it comes to measuring the impact of DA. Most of the participants recognised that data processing and analysis is a limitation when it comes to determining metrics for DA impact (Cook *et al.* 2022). Data processing and data analysis were mentioned as the 'bottleneck' among the biggest farming operations (>5000 ha) to move into real time data management decision making. This is important to adapt to frequently changing conditions such as weather or market prices, but also, to promote the development of infrastructure for the next level of DA capable to deliver real time information (Borghi *et al.* 2016; Robertson *et al.* 2019).

Looking into the future of DA, all participants had positive comments. They reported that adoption of DA technologies will increase rapidly due to changes in farming generations, a strong linkage between DA and the need to reduce agricultural footprint, the creation of new jobs related with DA tools and data, increased knowledge sharing about DA, and the need to reduce the workload in food production systems (e.g. dairy and cattle sector). Our findings are supported by several recent reports suggesting that the pace of DA adoption will increase in the near future (Ramasubramanian 2008; Keogh 2019; Trendov *et al.* 2019; US FDA 2019; IBRD, WB 2021).

Despite the positive feedback about the future of DA among case studies, 30% of the participants did not have a clear vision of what technology they would like to have access to. This raised a key point of discussion about the lack of vision among CC and G that could pose a challenge for industry and DA developers to find a quick market fit for the next level of DA based on feedback from consumers (Shepherd *et al.* 2020). We believe an overwhelming market of apps and web platforms available (Fig. 2) and the excessive day-to-day responsibilities in the agriculture sector favoured this trend. Thus, there is a need to step back and critically think about new technologies and tools that could be developed based on the existing knowledge and science to improve productivity and sustainability of agriculture systems (Monzon *et al.* 2018; Bolfe *et al.* 2020; Birner *et al.* 2021).

From all interviews, none of the responses stated that data privacy, trust, transparency, and distribution concerns were factors limiting DA adoption. In Australia (Jakku *et al.* 2019), Canada (Phillips *et al.* 2019), United States (Ferris 2017), and Europe (van der Burg *et al.* 2021) data privacy and ownership are a barrier to adopt DA. In the US, the American Farm Bureau along with a group of major farm organisations established a set of data principles for an Agriculture Technology Provider (ATP). This ensures growers own and control the data that is generated on their farms. Ownership, education, collection, access and control, notice, transparency and consistency, choice, portability, data availability, disclosure, use and sale limitations, data retention and availability, and security safeguards are principles covered by this policy (American Farm Bureau Federation 2014).

Role of regional agricultural technology companies in DA

Our literature review revealed that agricultural technology companies (AgTech) plays a key role in DA innovations and they could contribute to increase adoption of new technologies (IDB 2019; Peña and Nickel 2020; AgTechGarage 2021; Figueiredo *et al.* 2021). The AgTech companies provide knowledge-based DA services at all stages of the agricultural value chain (IDB 2019; Lachman and López 2019). With their expertise and products, they mitigate some of the limitations found within the reviewed regional surveys and case studies such as connectivity, data collection, transmission, storage, accessibility, and interoperability (Fig. 5). AgTech companies are adopting new techniques in data analysis and interpretation such as machine learning and artificial intelligence that could make data processing more efficient (Chlingaryan *et al.* 2018; Smith 2019). These efficiencies in turn address the limitation in real time decision making identified in the case studies. The ability to make decision in real-time positively impacts

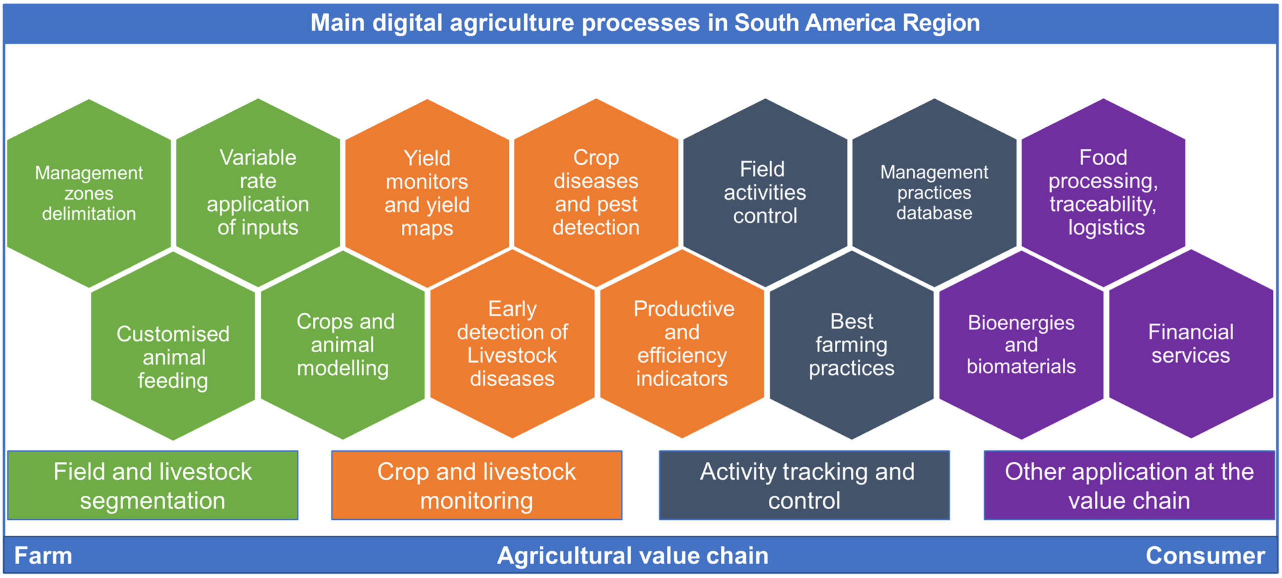

Fig. 5. Digital agriculture processes within the farm and the agriculture value chain in the South America Region. Processes are grouped in four main categories.

productivity, efficiency as well as adaptability to climate changes (Lajoie-O'Malley *et al.* 2020; Shepherd *et al.* 2020).

Results from the case studies determined that there is currently a limited number of DA providers. However, in the past year, the Inter-American Development Bank reported more than 450 AgTech start-ups within the agriculture value chain in Latin America and the Caribbean providing a diverse range of agricultural processes. Brazil accounted for 51% and Argentina 23% of the total AgTech companies. Digital agriculture processes within the farm and the agriculture value chain in the South America Region are presented in Fig. 5. and were grouped according to the services that they provide: segmentation, monitoring, control, others (Supplementary Material Appendix B).

Incubation and acceleration programs from the government or private companies have been a key factor to the development of AgTech in the Region. These companies export their services (16% Brazil and 58% Argentina), which positively contributes to the country trade balance and to the recognition of the value added in the Region. Remarkably, more than half (55%) of AgTech start-ups in Brazil developed their activities with participation of academia (Peña and Nickel 2020).

Regional public efforts to address DA adoption limitations

Public institutions in the Region have been participating in research and development related to DA in the last decade. The INIA Chile has a National Program on Digital Agriculture that covers climate and modelling, remote sensing and sensors, information technology analytics and communication, smart mechanisation, and electronics. They developed an integrated olive (*Olea europaea* L.) growing and viticulture model for data acquisition, analysis, and interpretation, showing how DA can be implemented to improve production and quality (Ortega and Esser 2003; Villalobos Mateluna *et al.* 2009; Best *et al.* 2014).

The INIA Uruguay developed a support system for decision making with an emphasis on prevention and mitigation of risks associated with climate events. One of the tools is the 'INIA Termoestres', a farm level forecast of temperature and humidity index (THI) for dairy or livestock systems to prevent animal heat stress (INIA GRAS 2021).

In Argentina, INTA is a pioneer in PA and DA and continues developing a broad research and extension programme to expand the use of DA tools (Bragachini 1999; Bragachini and Mendez 2005; Bongiovanni *et al.* 2006; Bragachini *et al.* 2010; Melchiori *et al.* 2018; Kemerer *et al.* 2020). The University of Rio Cuarto is also pioneer on PA (Esposito 2013; Balboa 2014; Cerliani *et al.* 2018; Hernandez *et al.* 2018) and DA research, they launched the project to establish the first Digital Agriculture Farm aimed to demonstrate how DA can improve production and productivity integrating PA sensing tools, imagery from UAVs, real time field data, livestock sensors, a LoRa Network, and modelling tools (Balboa 2020).

The Cordoba Agricultural Ministry (Argentina) implemented the use of an online Digital Phytosanitary Prescription that connects in real time the crop advisor, farmer, machine operator, chemical supply provider, ministry, and inspector to follow best practices on all spraying operations across the province. (Cordoba Agriculture and Livestock Ministry 2021). The largest Argentinean Farmers' Cooperative (ACA) developed a DA Platform (in English, ACA My Field') that integrates farm management, precision agriculture, weather, markets, and inputs prices (Asociacion de Cooperativas Argentinas 2021). This initiative allows small farmers to take advantage of DA since they are not typically clients of big DA providers.

Brazil have developed DA programs related to precision agriculture. Since 2000, the Aquarius Project at Federal University of Santa Maria (Amado *et al.* 2016; Corassa *et al.* 2018; Schwalbert *et al.* 2020), and the precision agriculture lab at the University of Sao Paulo (Gimenez and Molin 2004, 2018; Trevisan *et al.* 2018; Molin *et al.* 2020; Tavares *et al.* 2021) develops research, innovation and extension on precision farming. The Brazilian national agricultural research organisation EMBRAPA have also contributed to the development of DA (Bolfe *et al.* 2020; EMBRAPA 2020).

International collaboration is required to establish research priorities in the Region and to develop strategies to promote wide adoption of DA. In this sense, the Economic Commission for Latin American and the Caribbean (United Nations) launched in 2021 the Agro 4.0 Project. The overall goal of this project is to develop strategies towards a more sustainable and efficient agriculture practices in Latin America through the adoption of DA (ECLAC 2021).

Benchmarking metrics for DA benefits

The review and case studies revealed the importance of current and future research and extension programs to present clear metrics to benchmark benefits from DA technologies. For this purpose, we compiled from the literature a set of agriculture indicators that can be grouped into economic, social, and environmental (Table 2). Most of the published research quantified benefits using economic metrics (Table 3). Despite local, regional, or worldwide research and extension efforts, there is a perception from growers and stakeholders of lack of local knowledge and experimentation to demonstrate the benefits of DA. There is a need for more socioeconomical studies to demonstrate benefits on DA (Klerkx *et al.* 2019). A large proportion of reported indicators are related to application of PA tools and techniques. Benefits are the result of an increment in production, with the same or with less quantity of inputs (thus improving input productivity) (Table 3). From the environmental point of view, increasing concerns from society about the impact of production practices are pushing to incorporate research objectives to evaluate environmental indicators. such as carbon (Bondeau *et al.* 2007; Accorsi *et al.* 2016) and N balance (Tenorio *et al.* 2020). These metrics could provide a benefit to farmers considering that there are markets offering an increase in price for a product if the seller can provide traceability of the product and demonstrate that it was produced sustainably (Rejeb *et al.* 2020).

Table 2. Literature review of sustainable indicators that can be used to benchmark digital agriculture benefits.

Classification	Indicator	Unit	Reference
Economic	Output	$, quantity	Lebacq *et al.* (2013); FAO (2017); Chopin *et al.* (2021)
	Inputs	$, quantity	
	Net profit	$	
	Output quality	A	
	Total factor productivity	Outputs $inputs^{-1}$	
	Partial factor productivity	Output $input^{-1}$	
Social	Advisory contact per year	*n* $year^{-1}$	Lebacq *et al.* (2013); Chopin *et al.* (2021)
	Quality of life	Not reported	
	Education	Not reported	
	Total labour	Person d ha^{-1}	
	Time-saving for a labour	h $labour^{-1}$	
Environmental	Input efficiency	product $input^{-1}$	Lebacq *et al.* (2013); Chopin *et al.* (2021)
	Pesticides usage	kg ha^{-1}	
	Agro-diversity	(*n*) crops per farm	
	Greenhouse gas emission	Mg CO_2 eq ha^{-1}	
	Farm gate *N* balance	kg ha^{-1}	
	Water use efficiency	l kg^{-1}	
	Soil loss	Tn ha^{-1}	
	Crop rotation		
	Crop diversification	N crops $year^{-1}$	

[A]Several units; i.e. % of protein for wheat (*Triticum aestivum* L.).
$, USD.

Conclusions

The level of adoption of DA tools was led by Brazil and Argentina, followed by Uruguay and at a slower rate in Chile. Results indicated that GPS guidance systems, mapping tools, mobile apps and remote sensing were the most adopted DA technologies in SA. In the Region, rapid adoption of agriculture apps was promoted by access to mobile phones by growers and the support of private sector and public institutions.

Technology cost, lack of training, a limited number of companies providing services, and the unclear communication of benefits from DA were the most reported limitations for adoption according to our systematic review and case studies in the Region. Among early adopters represented in the case studies, there was no clear definition of DA. Our

Table 3. Examples of indicators and benchmarks values for digital agriculture benefits reported in the literature.

Indicator	Production system	Treatment/tool	Level of impact[A]	Country	Reference
Inputs	Corn, soybean	Lime	<10%	Brazil	Borghi *et al.* (2016)
			10–20%		
			20–30%		
		Fertiliser	<10%		
			10–20%		
		Herbicide	<10%		
		Software and equipment	<10%		
Output profits	Maize, sunflower, soybean, wheat, barley	Site-specific crop management	+54%		Monzon *et al.* (2018)
			+46%		
Inputs	Maize	Site-specific weed treatment	−42 € ha^{-1}	Germany	Timmermann *et al.* (2003)
	Winter barley		−25 € ha^{-1}		
	Winter wheat		−32 € ha^{-1}		
	Sugar beet		−20 € ha^{-1}		
Profits	Corn, soybean	Lime SSM agronomic	19.55 $ ha^{-1} 4.82%	USA	Bongiovanni and Lowenberg-Deboer (2000, p. 200)
		Lime SSM economic	7.24 $ ha^{-1} 1.78%		
		Lime information strategy	14.38 $ ha^{-1} 3.54%		
Profits	Corn	VRT seed and fertiliser	42 $ ha^{-1} 32%	Argentina	Puechagut *et al.* (2019)
PFPN	Rice	*N* rate with Green Seeker	+2.45 (8.15%)	India	Singh *et al.* (2016)
Profit	Early planted corn	EONR by MZ	+22 (5%)	Argentina	Esposito (2013)
	Late planted corn	EONR by MZ	+5 (1.2%)		
		EONR by MZ	No benefit		
AUE	Corn	EONR by SEMM	+4.89 (46%)	Argentina	Balboa (2014)
Output	Corn	10 years nitrogen VRT	+31%	Italy	Kayad *et al.* (2021)
Input			−23%		
PFPN			+33 (61%)		
WUE	Wheat	Smart irrigation system	+0.42 (47%)	Saudi Arabia	Al-Ghobari and Mohammad (2011)
Output	Sugarcane, cotton, rice, corn	Digital agricultural advice	+4%	Kenya, Rwanda	Fabregas *et al.* (2019)
Profits	Fish	Access to market prices	+8%	India	Jensen (2007)
Output price	17 crops	Access to market prices	+13%	Peru	Nakasone (2013)
Timesaving	Supply chain	Phoneline to reduce late delivery	−23%	Kenya	Casaburi *et al.* (2019)
Output	Dairy farmers	iCow platform for advice	+25 u$s $month^{-1}$	Kenya	FAO (2021*b*)
Output	Potato, olluco, barley	Access to information to sell	+14%	Peru	Nakasone (2013)

[A]Level of impact reported in the same unit, percentage or range as mentioned in the reference.
SSM, site-specific management; PPPF, partial factor productivity of the fertilizer; EONR, economical optimum nitrogen rate; MZ, management zone; SEMM, spatial econometric mix model; AUE, agronomical use efficiency; WUE, water use efficiency; $, USD.

findings suggest the need of new educational curriculum to fulfilling in demand job skills such as data processing, analysis, and interpretation to mitigate some of these limitations. In addition, we proposed a set of economic, social, and environmental metrics to support future research and extension efforts to better communicate the benefits from DA.

Social implications of DA adoption were not covered in this manuscript. However, the future adoption of DA is expected to keep evolving and the institutional support will be fundamental over the long-term. Regional efforts like Project Agro 4.0 are needed to standardise surveys and metrics to quantify adoption and identify limitation. Future review needs to incorporate all countries of South America by implementing a standardised methodology and covering aspect like social implications of DA adoption. This will allow stakeholders to design better initiatives to promote DA towards increased efficiency and sustainability of food production in the Region.

Supplementary material

Supplementary material is available online.

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