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Do Digital Climate Services for Farmers Encourage Resilient Farming Practices? Pinpointing Gaps through the Responsible Research and Innovation Framework

Elisabeth Simelton ^{1,*}  and Mariette McCampbell ²¹ World Agroforestry (ICRAF), 249A Thuy Khue Street, Hanoi 10000, Vietnam² Knowledge, Technology and Innovation Group, Wageningen University, Hollandseweg 1, 6706 KN Wageningen, The Netherlands; mariette.mccampbell@wur.nl

* Correspondence: e.simelton@cgiar.org; Tel.: +84-24-3783-4644

Abstract: Digital climate services can support agricultural management decisions under uncertain climatological conditions and may contribute to achieving the ambitions of the fourth agricultural revolution. However, do they encourage social and environmental aspects? Our analysis builds on the four dimensions of the Responsible Research and Innovation framework and evaluates, among other things, which production systems are promoted in climate service apps; how the services contribute to or challenge (inter)national targets for sustainable development, ecosystem restoration, and climate resilience. From a longlist of apps, we present the best documented ones as case studies: nine weather-based and two non-weather-based digital services. We target apps of relevance for Southeast Asian smallholder farming systems, where both supply of and demand for such apps have thus far been limited in contrast to the access to phones, and where particularly the supply of apps is poorly documented. The key findings point out several gaps. First, digitalization in Southeast Asia's farming system is driven by foreign investments, while partnerships with public agencies, in particular national Met Offices, were rare. Services were developed for farmers but not necessarily with farmers, thereby overlooking needs and social factors such as (digital) literacy and trust. While some of the weather-based apps included more than one crop, they primarily support single solutions and none of them targeted mixed or integrated farming systems. This calls for developers of digital climate services to innovate applications in an inclusive manner, and to support governments in achieving their commitments to global climate, biodiversity, and sustainability goals. Difficulties in generating comparable information about the reviewed apps regardless of the study's geographical focus demonstrates a need for more transparent means and protocols for users to assess and compare digital climate services.

Keywords: digital agriculture; ecosystem services; climate resilience; apps; responsible innovations; smallholder farming; southeast Asia; citizen science



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1. Introduction

1.1. The Push for Digital Agriculture

The fourth agricultural revolution, or Agriculture 4.0, proliferated as a concept in the 2010s [1–3] by raising expectations about its contributions towards ensuring food security to a growing population using limited environmental resources and while minimizing its impacts on climate change [4]. In contrast to the Green Revolution's diffusion, of improved agriculture inputs, artificial intelligence (AI), technological precision (i.e., precision farming) and digital innovations are now expected to help farmers minimize inputs of water, fertilizers, and pesticides [1,4–6]. In fact, the World Bank refers to “digital and non-digital innovations that enable farmers and agribusinesses to leapfrog” towards productivity, efficiency, competitiveness, nutrition outcomes and climate resilience, thereby including technologies ranging from mobile apps to bio-fortified foods, as ‘Disruptive

Agricultural Technologies’. Digital agriculture involves a range of ICT (Information and Communication Technology) services that support farm management decisions, such as technical advice, financial services, information on standards and norms, and extension services [7]. Technologies range from low-tech (basic phones) to high-tech (e.g., AI, precision agriculture) and medium-tech (e.g., drones, sensors, smartphones).

Globally, around 2018, digital technology in agriculture was a trillion dollar industry [7,8], and worth 2.6 billion dollars in Africa alone [9]. In the global North, the push for digital agriculture comes from three main types of multinational private actors: ag-business and ag-tech, venture capital and (big) tech companies, and start-ups [10]. In contrast, in developing countries the demand for digital agriculture technologies is stimulated by donors, nonprofit- and research (for development) organizations [11] through projects and competitions. For example, since 2010, the Asian open-source community FOSSASIA (<https://fossasia.org/>) has held annual summits with hackathons. In 2014, the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) ran a hackathon where young Latin Americans were tasked with solving specific problems for climate-smart agricultural technologies (<https://www.cgiar.org/research/program-platform/platform-for-big-data-in-agriculture/>). In 2019, the World Bank arranged a knowledge and innovation challenge conference on scaling up disruptive digital technologies in the agricultural sector in Kenya [12], and in 2020, an agriculture risk innovation competition for South Africa with 122 contributions from 33 countries (<https://www.worldbank.org/en/events/2020/03/09/agriculture-risk-innovation-challenge>). The competitions can motivate local and international start-ups to establish collaborations with international research institutes and the private sector (e.g., CGIAR Inspire challenge <https://bigdata.cgiar.org/inspire/>).

Digital technology allows two previously disconnected types of information—weather forecasts and agricultural management advice—to be merged and delivered as ‘climate services’ that can be broadly defined as decision-making support tools that translate climate information into user-relevant advice for agricultural management [13]. The growth in digital agriculture has been stimulated by improved internet connectivity and a rapid increase in smartphone usage in most parts of the world [14], allowing farmers to collect data for analysts who may return (contextualized) information to agricultural advisors and farmers that contributes to (better-) informed decisions [15,16]. This so-called ‘citizen science’ originally denoted the public (actively) contributing ‘crowdsourced’ data to scientific knowledge [17]. Increasingly however, it has come to include the public sharing and (passively, and sometimes unknowingly) sending data without transparency about what the data is used for [18]. Lack of transparency surrounding ownership and use of data collected by digital (agricultural) services has raised a range of concerns stemming from possibilities of AI-technologies introducing new systemic and sustainability risks [6], to ethical concerns about asymmetrical relationships between users and developers of those services [6,19–22].

1.2. Literature Review

Research on asymmetrical relationships in digital agriculture shows gaps on both the supply and demand side. While some reports claim that climate services tend to focus on supply and delivery mechanisms [23–25], social scientists tend to underscore the importance of delivering *user*-relevant climate services for different types of farmers’ needs [26] and effects of digitalization on power relations in production systems [27]. The qualitative case study and explorative approaches reflect that digital agriculture is a young research field in social sciences [26,27]. Other studies shed light on possible shortcomings in empirical data and quantitative reviews. For example, using machine learning, [28] could filter out 315 of 7000 publications about digitally enabled agricultural services across Sub-Saharan Africa, Latin America and Southeast Asia, but found insufficient empirical data to draw conclusions on use or outcomes. While the study provides a quantitative overview on a wide range of important aspects of digital agriculture, it did not list or inventorize specific apps. When it comes to apps specifically for sustainable agricultural

landscapes, scientists retained 16 publications out of 6100 citations from Web of Science, and complemented this with a search on iOS and Android app stores [29]. These examples indicate gaps between the supply of apps and the limited shares covered with qualitative and quantitative research approaches. Furthermore, no studies attempted to systematically or qualitatively assemble similar information about multiple apps providing agricultural advice for farmers.

In developing countries research on digital agriculture has primarily been concerned with (geographical) comparisons of access. For example, surveys show that in 2019, smartphone adoption had reached about 64% in Asia Pacific compared to 45% in Sub-Saharan Africa [14], notwithstanding variability in access to and use of smartphones between individual countries, as well as between rural versus urban areas. Research related to apps for agriculture have primarily covered western [30] or African and South Asian countries [29]. More specifically, the review including (300) 7000 publications, showed that over 75% of all evidence on digital advisory and extension services comes from just seven countries (India, Indonesia, Kenya, Uganda, Tanzania, Ghana, and Nigeria) [28].

Moreover, despite the increased access to smartphones, digital solutions in agriculture have been difficult to scale. This can be traced to a range of socioeconomic access inequalities. A review of 157 papers on information and communication technologies for rural development identified two urban-rural divides that affect adoption of ICTs: (i) technical disparities in access and connectivity, and (ii) social disparities that hamper diffusion and adoption of technologies, such as education and economy, which in turn also often affect to access [31]. Literacy and e-literacy are not necessarily equivalent when it comes to being able to receive, understand, and be capable of acting on information provided through digital services [11,32]. Generally, men more than women, and younger more than older users are found using ICT among both farmers and agricultural extension staff [33,34], however, farmers' capability in interacting with phones varies [35]. For example, telecom companies adapt their services and rates to the most updated mobile phones, making services more expensive for those with old phones and poor internet connection [36]. Typically, the least educated, poorest, most remote smallholders will be the last ones to benefit from the services they need the most [7].

When it comes to Southeast Asia, some of the explanatory variables from other regions are difficult to piece together. Despite the comparatively higher adoption rates of phones in Southeast Asia compared to Africa, the opposite holds true for access to climate and geospatial products and services. Historically, a diversity of transnational, public digital products has been generated through UN humanitarian relief actions for Africa. Although farmers were not the direct target audience, open access to time series of digital technologies has generated digital innovations, including knowledge and map-based tools providing weather-agriculture information (see Supplementary Material Table S1). The same cannot be said about Southeast Asia.

Nevertheless, the combination of severe exposure to natural hazards and climate change in Southeast Asia with a high dependency on agriculture makes the relatively limited use of AI and digitalized information services remarkable [6]. As a result, there is an absence of studies on the supply of on-farm apps and particular factors explaining the limited use in Southeast Asia. Although many farming households have at least one mobile phone or smartphone, they rarely use services and applications that are specifically developed for disseminating agricultural information [37]. In the specific case of Southeast Asia, farmers frequent use of smartphones but limited use of apps [38] may reflect both a limited supply of apps and a limited demand for apps during the early stages of adoption [38] combined with informal arrangements [39]. During this transition phase, farmers prefer an amalgam of digital and non-digital, two-way communication, i.e., personal meetings, call centers, and social media [38]. However, shifts may be on the way. First, Southeast Asian countries list a wide range of adaptation actions in their Nationally Determined Contributions (NDC, <https://climateactiontracker.org/climate-target-update-tracker/>), such as climate-smart agriculture, agroecology, ecosystem-based adaptation, or nature-

based solutions, which often have diversification and good agricultural practices to reduce the use of chemicals in common. Second, digital agriculture is part of a larger digitalization strategy across Southeast Asia, which received increased interest during the COVID-19 pandemic when many existing market links collapsed. For instance, in Cambodia the *Cam-AgriMarket* was soft-launched by the Ministry of Agriculture in March 2020 and appears to be fully launched in 2021 (Table S2). However, although many apps can offer weather forecasts with agricultural advice sometimes bundled in with other services, their main utility is market connections, such as the World Bank's Digital Agriculture Transformation initiative in Vietnam [40].

1.3. Responsible Innovations in Digital Agriculture

Juxtaposing calls for climate-resilient food systems and agrobiodiversity, such as the UN Decade on Ecosystem restoration [41] and UN Food Systems Dialogues in 2021, on the one hand, and innovative digital information services that support farmers' decisions in implementing climate-resilient practices on the other hand [42], results in a set of questions about smartphone applications relevant to smallholder farmers in developing countries. [43] drew up three lines of questioning around the intentions of a product (here, smartphone application), the process, and the purpose: asking, e.g., 'how are risks and benefits distributed' (product), 'who will take responsibility if things go wrong' (process), 'why are researchers (developers) involved in the innovation process' and 'are their motivations transparent' (purpose). For digital climate services, this enquiry starts technically with how the application combines weather information into actionable decision support for climate-resilient agricultural practices. The enquiry then shifts to added values: e.g., does the application integrate advice for agricultural practices that are associated with sustainable development outcomes, like diversified land use, agroecological or nature-based solutions at ecosystem or landscape scales [29,44–47]? Does the application align with social equity and ambitions to reduce vulnerability?

The above-described enquiry should avoid to place the app developer at the centre and instead focus on the context and conditions that determine adoption and use of an innovation, or service. One frequent explanation for farmers' limited use of digital technologies is that they were not involved in the development of digital applications [48,49] and therefore do not recognize the full potential of the technology, or the technology may not meet their needs or capacity [50]. Mismatches between supply and demand of digital technologies can reflect an education gap between software engineers and users that risks exacerbating problems of inclusion and uptake [15,51]. Examples of such gaps include:

First, developers do not ask farmers why they adopt and adapt management practices. Instead advocates of digital agriculture pay more attention to economic and environmental benefits than to farmers' desired values and benefits such as investment costs versus efficiency or convenience [52]. When it comes to adoption of mobile apps, a study using the Extended Technology Acceptance Model in Nigeria showed that perceived usefulness, social influence, information awareness, and intention to use, all had a positive influence on farmers' adoption, while perceived risks and costs had a negative impact [53]. Particularly, if users consider the information irrelevant or incorrect, they sooner or later lose confidence in the climate service product [54]. To address these shortfalls and enhance uptake and user-relevance among farmers and practitioners, [29] suggest that designers and developers of digital decision support tools consider performance, reliability, and user experience from the start. This calls for well-trained professionals [15] who can translate data into actionable information together with farmers.

Second, farmers are diverse and farming is complex. In developing countries, digital solutions often appear inspired by or wanting to resemble western agriculture, while for many reasons (social, economic, technical, institutional, environmental, efficiency) this is not necessarily appropriate [2]. In the context of western agriculture, the rigidity of apps is critiqued: for example, much of the information in agricultural apps is geared to 'single solution' apps for field and farm level decisions with limited information that links farms

to the broader agricultural landscape and community knowledge bases [29]. A study from North America concludes that agronomic crop data selection disincentivizes the development of tools for unconventional or organic growers [22]. Similarly, [42] conclude that digital agricultural technologies support the status quo of industrial agriculture and food systems overall, which may have negative effects on the delivery of ecosystem services.

Third, why should farmers trust the app, its information, and an anonymous sender? The issue of trust spans wider and over into equity [55]. Reflecting the growing power of big ag and big tech companies, and social media [56], voices call for “responsible innovations” questioning what digital technologies are for, who benefits, and who drives the process [3,22]. Such concerns account for uneven distribution of the benefits of digitalization and profits exported to the global North [19,21]. These developments have raised demand for inclusive processes [2] and “an ethical research agenda” that put farmers at the centre [57]. Nevertheless, overall codes of conduct for data protection are largely driven by the west, e.g., EU and New Zealand [58,59] and in the absence of global binding agreements, numerous voluntary principles and guidelines for responsible innovation and (data or digital) rights in digital agriculture development have emerged [11]: e.g., the UN’s Global Pulse initiative’s principles for data and privacy which provide simple checklists to assess risks, harms and benefits associated with collection, transmission, analysis, storage and publication of data [60–62], and principles for digital development [63].

The responsible research and innovation (RRI) framework delineates four dimensions for deliberating ethical concerns in technological innovations: anticipation, inclusion, reflexivity, and responsiveness [20]. For digital technologies, innovators should (i) anticipate the consequences of, including problems caused by, a digital technology such as a smartphone app; (ii) include diverse actors in the innovation process to accommodate for concerns of various actors—this refers to involving farmers in the design as well as tighter connections throughout the entire value chain; (iii) adopt a reflexive and flexible approach to development; and (iv) respond to emergent problems [3] caused not only by the technology itself but also grand issues such as the impacts of climate change and environmental degradation or meeting Sustainable Development Goals. The anticipated intentions with the app and the ability to foresee impacts on the type of production system it captures are central themes in questions about the added values that digital services bring for smallholder farmers. While the RRI framework was used in a qualitative study assessing the normative value of designers of agricultural apps in North America [22], such studies are uncommon in the context of developing countries.

The overall objective of this study is to examine a selection of digital climate service applications relevant for Southeast Asian smallholder farmers in view of their contributions to socioeconomic and environmental resilience. Specifically, we build on the dimensions of the responsible innovation framework to guide the case study format that aims to identify (i) how the (developers of) apps anticipate the needs faced by Southeast Asian farmers, (ii) what actors are included in the process, (iii) the building of transparency and trust, and (iv) the apps’ responsiveness to emerging sustainability problems.

2. Materials and Methods

This is an explorative study aiming to gather secondary information without necessarily generating generalizable results, presented as a selection of cases without causal relationships or intention to rank or compare relative performance of the apps [37,64]. In contrast to [37] our ambition is to gather qualitative information about specific apps rather than at an aggregate level. The decision for case studies was taken based on the outcomes of an initial scoping. The previous global reviews had provided us an approximation of the number of apps to expect and we prepared Table S2 to organize the first information from the search query, aiming to target only apps from Southeast Asia. We would then work through the questions in Table 1 (to complete Table 2). When it proved difficult even to complete the basics of Table S2, we widened the scope and searched for promising examples elsewhere. All weblinks were

last accessed while the manuscript was prepared for submission in July and August, 2021, we have therefore not stated access dates after each one.

Table 1. Conceptual and methodological framework. Adapted from [3,20].

Responsible Innovation Criteria	Overarching Question Are Innovators ...	Specific Enquiry and Review Indicators On the Impact of the App
Anticipation	... anticipating the consequences of, including problems caused by a digital technology	What is the (developer's) anticipated purpose of the app? What are the functions of the app? What are the expected impacts? Indicators: What are the stated/expected impacts of the app? Eg. goal statements, purpose and technical descriptions
Inclusion	... including diverse actors in the innovation process to accommodate for the various concerns of various actors	To what extent were users (farmers) involved in the process of developing the service. Indicators: Who drives the process? Who invests and advertises in the product? What do they contribute? Evidence of actors in-/excluded in the development?
		Bridging inclusion and reflexivity: How can the user interact with the product developers? What type of documentation is available to indicate a developer's intention towards transparency and building trust with an existing or potential user community? Indicators: Feedback functions between the developers, agricultural advisors, user community? Transparency about developers, donors and investors, budgets. Secondary sources on developers, donors, investors
Reflexivity	... adopting a reflexive approach to development	Bridging anticipation and reflexivity: Are there reports indicating reflexivity on the product's impact (together with users)? Bridging anticipation, reflexivity, and responsiveness: To what extent is the software promoting adaptive management and no-regret options? Indicators: product information, objective or scientific publications describing or comparing the product
Responsiveness	... responding to emergent problems	Type of agricultural production and management principles. To what extent is the software promoting environmentally sustainable solutions? Is the app linked to monitoring policy goals? Indicators: Type of agriculture production and management principles (monoculture, integrated farming systems, agroecological principles, landscape level impacts)

Table 2. General description of selected digital services for agriculture information, advice, or recommendations. Status based on search in July 2020 and July 2021.

Application	Anticipation	Reflexivity	Inclusion	Responsiveness	Relevance for SEA	
	Target user Geography	What is it for? Types of crops, Cropping systems	Functions Weather, agriculture other	Interactive functions map, feedback	Inclusion—driver Responsiveness Documentation	
Site Pyo Available on aplure.com	Myanmar Target 150,000 farmers users	10 to 11 crops	Weather forecast Farming advice	Crop protection, land management, emergency alerts Market price information	Funded by: Dfid (2015–?) Developer: Miaki Budget: unknown	Lessons learned and taken up in the subsequent MYVAS4AGRI app
MYVAS4AGRI Htwet Toe Available on Google Play http://www.htwettoe.com/	Myanmar Target 850,000 farmers	7 crops Rice, green and black gram, maize, groundnut, potato, sesame	Weather information Market prices Access to finance	Example of service providers paying to make information free for farmers Website in Burmese.	Funded by: G4AW (2018–2020) Budget: 4.1 mn Euro Developers: Awba Group, Department of Agriculture, VillageLink, Miaki, TerraSphere, WeatherImpact, SarVision Documentation: project report on donor’s website, no technical description found	Example of Department of Agriculture being involved
GreenCoffee app Available on Google Play and AppStore in Vietnamese and English https://g4aw.spaceoffice.nl/en/g4aw-projects/g4aw-projects/23/greencoffee.html	Coffee farmers Target 100,000 users Central Highlands, Vietnam	1 crop Robusta and arabica coffee General advice for durian, black pepper, mango	Advice for coffee based on 5-day weather forecast Agricultural advice static, independent from forecast	No interaction Google Map Limited Q&A Website in Vietnamese (http://thongtincaphe.vn/index.php?r=site%2Findex&lang=en).	Funded by: G4AW Budget: 3.5mn Euro (2016–2019) Partners: AKVO, eLEAF, ERIPT, IPSARD and NIAPP under MARD, Nelen and Schuurmans, TTC Mobile, UTZ, WaterWatch Projects Documentation: project report on donor’s website, not in the app; Source of advice and forecast unknown, no technical description found	Simple design Low-cost Free download
Angkor Salad Available on Google Play and website https://www.angkorsalad.com/	Vegetable farmers, collectors, traders Target 100,000 farmer Cambodia	Vegetables Agriculture advice and market prices	Satellite based weather updates with advice for irrigation, fertilizer, crop calendar	Website in khmer Instruction videos	Funded by: G4AW Budget: not specified (2018–?) Partners: Akvo, Angkor Green, General Directorate of Agriculture, Nelen and Shurmans, SMART Axiata, VanderSat, World Vegetable Center Documentation: no project report on donor’s website or technical description found	Checklist to support GAP Website with videos Value-chain focus

Table 2. Cont.

Application	Anticipation	Reflexivity	Inclusion	Responsiveness	Relevance for SEA	
<p>SAM Smart Agriculture Myanmar</p> <p>Not yet available on Google Play</p> <p>https://g4aw.spaceoffice.nl/en/g4aw-projects/g4aw-projects/18/sam.html</p>	<p>Myanmar</p> <p>Target 550,000 farmers, sellers and buyers</p>	<p>2 crops</p> <p>Rice and maize</p>	<p>Agronomic and satellite-based models, personalized crop calendar</p>	<p>Aims to connect farmer, sellers and buyers, develop financial products and reduce disaster related crop loss</p>	<p>Funded by: G4AW (2018–2021)</p> <p>Budget: 3.3 mn Euro</p> <p>Partner: ImpactTerra, Ministry of Agriculture, Satelligence, Wageningen University, Financial Access</p> <p>Documentation: on donor's website, no technical description found</p>	<p>Example of Department of Agriculture being involved</p> <p>Builds on existing app Golden Rice Platform (Table S2)</p>
<p>ThirdEye</p> <p>Not available on Google Play</p> <p>https://www.futurewater.nl/wp-content/uploads/2016/06/DescriptionThirdEyeTechnology.pdf</p>	<p>(a) 1600 ha Mozambique;</p> <p>(b) Area unknown in Kenya</p>	<p>Unspecified</p>	<p>No information to suggest there is a forecast</p> <p>Crop status converted to recommendations for irrigation, fertilizer and pesticide inputs</p>	<p>GoogleEarth, NDVI and IR 50x50m photo feedback via data collection from land-based sensors</p> <p>Table mapping by drone pilots</p> <p>Website</p>	<p>Funded by: USAID, Sida, The Foreign Affairs of the Netherlands (a 2014–2017). Kingdom of the Netherlands, implemented by SNV (b 2016–2019).</p> <p>Budget: unknown</p> <p>Partner: FutureWater, HiView</p> <p>Documentation: unclear product description</p>	<p>Of possible interest for water limited areas.</p> <p>Resolution fit diverse agriculture in complex terrain.</p> <p>Laws on drone usage?</p> <p>Experiences scaling from start-up?</p>
<p>Agricloud</p> <p>Available on Google Play with complete information</p> <p>https://agricloud.ro/;</p> <p>https://g4aw.spaceoffice.nl/en/g4aw-projects/g4aw-projects/19/r4a.html</p>	<p>Farmers, extension agents South Africa</p> <p>Targets 125,000 users</p>	<p>General advice, specific advice for grapes, maize</p>	<p>Realtime to 10-day forecast</p> <p>Focus on pesticides</p> <p>Fall army worm surveillance</p>	<p>No interaction</p> <p>Map with polygon (adm borders), temperature and rainfall as time series graphs</p> <p>Bigger farms can view their activities</p> <p>Users connected via API</p>	<p>Funded by: G4AW</p> <p>Developed in the Rain4Africa project (2015–2018)</p> <p>Budget: 4.7 mn Euro</p> <p>Partner: South Africa Agriculture Research Council, HydroLogic, Royal Netherlands Meteorological Institute, Mobile Water Management, Netherlands Space Office, South African Weather Service, Waterschap Groot Salland, Weater Impact, WineJob</p>	<p>Possibly in arid areas or for monitoring pest infestation/spread</p> <p>Example of national Met Office involved in project</p> <p>https://www.weatherimpact.com/wp-content/uploads/2019/10/WeatherImpact-White-Paper.pdf</p>
<p>CropMon</p> <p>Not available on Google Play</p> <p>https://g4aw.spaceoffice.nl/en/g4aw-projects/g4aw-projects/13/cropmon.html;</p> <p>https://www.agrocares.com/en/cropmon</p>	<p>Kenya</p> <p>Aimed to demonstrate with 150,000 smallholder to medium scale farmers, 190,000 subscribers to weekly SMS at the end of the project</p>	<p>3 crops</p> <p>Coffee, maize, grass, sorghum</p>	<p>Weekly forecast and crop condition</p> <p>Information on crop growth limiting factors (climate, soil fertility, water supply) and remedy on reducing the limiting factor by adjusting farm management</p> <p>Alert message when crop growth is non-optimal based on real-time satellite imagery</p>	<p>Cost 0.1–1.0 Euro per message</p> <p>Opportunities to sell data to aggregators, e.g., (local) governments, banks, insurance companies, fertilizer industry and agro-dealers</p> <p>Website</p>	<p>App developed in the Rain4Africa project (2015–2018)</p> <p>Funded by: G4AW</p> <p>Budget: 3.3 mn Euro</p> <p>Partner: Cereal Growers Association, Coffee Management Services, Equity Foundation, International Fertiliser Development Center, NEO Geomatics and Earth Observation, Netherlands Space Office, SoilCares, SoilCares Research, Springg, Sugar Research Institute, Weather Impact</p> <p>Documentation: limited information from project website.</p>	<p>Potential lessons learned from using satellite information and from selling data</p> <p>Takeover by local partners after project termination</p>

Table 2. Cont.

Application	Anticipation	Reflexivity	Inclusion	Responsiveness	Relevance for SEA	
6th Grain https://www.6grain.com/	Covers 66 Mha in Africa, Europe, Latin America, Asia. 18 countries in Africa and Asia Target agribusinesses, government agencies, farmer organization	4 crops maize, wheat, barley, soybean, sunflower, satellite data (10m) trained for 5 crops, can include trees	Rainfall, historical rainfall data, seasonal forecast for rain up to 6 months Different level in the free and pay version Unclear from the free version what kind of advice is given, or if the model simply visualizes data	Data shown interpolated on map for specific period (not as time series graph): Open Street Map Soil PH and rainfall	Budget: unknown, commercial Donors/developers named but unclear roles. Among the Clients and Partners: Syngenta, Q-BASF, UPL Open Ag, Tetra Tech, Bill and Melinda Gates Foundation, African Fertiliser and Agribusiness Partnership, Rusagro Group, African Development Bank, Actura, NASA Harvest Consortium led by Harvest Hub at University of Maryland Documentation: technical description not found	Agribusiness, government agencies, farmers organization Example of pay model where agribusiness pays for small farms Example of Agricloud and ThirdEye at larger scale
Examples of non-weather-based innovations related to reflexivity and responsiveness to crises						
Plantix Free download Available on Google Play and website https://plantix.net/en/	Global, focus on India, Pakistan, Bangladesh 18 languages States 10 million downloads	30 crops	No weather information Identifies over 350 crop disease problems on 65 crops Fertilizer calculator	Visual library and questions (photos) Multiple ways to interact with the community	Budget: unknown Partner: Peat, ICRISAT, CIMMYT, CABI, Leibniz Centre for Agricultural Landscape Research (ZALF), Government of Andra Pradesh	Examples of combining multiple crops and integrated farming systems, and for handling multilingual information exchange
Global Crop Monitoring Tool Rapid Response Tool https://cgiarcsi.community/2020/04/17/monitoring-crop-harvest-using-satellite-remote-sensing/ ; https://wrd_iwmi.users.earthengine.app/view/global-cropland-monitoring-tool	India Nepal	Estimates harvest date	No weather forecast Satellite data converted to planting date	Google Map with various free satellite information User can choose map layer and zoom	Budget: unknown Beta-version (no documentation) Developed by ICARDA 2020	Example of quick development of tool during crisis for a specific problem

Step 1—Scoping. The scoping can resemble the search approach of an imagined smallholder farmer in Southeast Asia. Therefore, the entire study targeted open source or freeware apps for the Android operating system, which offers more options for affordable phones [38] (three independent practitioners have confirmed the authors' observations that farmers across Southeast Asia use Android-compatible phones as "farmers cannot afford iPhones"). The initial search in the Google Play App store for "agriculture AND map" and "agriculture app" (in English) rendered 250 and 125 results, respectively (on 3 August 2020). We used the broader term 'agriculture' rather than crop specific applications to include the widest range of crops or farming systems. The review by [29] had demonstrated that including search terms such as sustainability, could limit our scope rather than adding value. Furthermore, more technical terms may not resemble farmers' searches and risk being lost in direct translation between languages. Among their 100 first apps returned from "agriculture" search in 2018, the share of apps on information management (about 30%) and agronomy reference (just above 10%) were similar for iOS and Android [29]. Our approach generated a similar distribution of the results. About 40–50% of the returned applications were excluded immediately (games, notebooks, banking services), while the remainder appeared to have some relevance to farmers. Most apps had been user rated above 4 out of 5 stars and were free to download but presented only short messages to publicize the app rather than providing objective information. At this stage, we renewed the search by specifying the app's name and focused on determining basic information about their main functionalities. As the search engine is biased by previous search results and we did not repeat the search on independent devices, this approach offers a snapshot of available Android applications [29]. We provide an incomplete longlist with 18 of the best documented apps in Table S2. For inexperienced users with limited previous knowledge, we judge already at this stage it could be difficult to select one specific app over another (even in their own language).

Step 2—Systematization. Next, we used Google search engines to trace information about the applications found on the Google Play App and additional apps encountered via cross referencing and references in scientific literature. In the resulting non-exhaustive longlist, we attempted to systematize information around key questions associated with the four aspects of the responsible research and innovation framework [3,20] (Table 1): anticipation, inclusion, reflexivity, and responsiveness. We maintained the inclusion criteria that the product, (i) or some aspect of the product, has relevance for, but does not need to be developed in Southeast Asia; (ii) is available as a free download; and (iii) has product information available in English without registration requirements. We added "objective documentation" as desirable criteria to indicate transparency and responsiveness (Table 1).

Step 3—Case studies. The sparse and scattered information available lends itself poorly to quantitative assessments. As such, this approach may not generate repeatable search results. Instead, the objective is to illustrate issues pertaining to ethical considerations evident in the transparency of product content and purpose information, and whether the foci of apps encompass greater development goals. While applying the RRI framework, our ambition was that the case studies would demonstrate examples of each criterium. We selected the best documented applications from Step 2 for a qualitative case study and complemented with targeted search on Web of Science. In total, we present nine weather-based apps in which five apps are from the region of Southeast Asia and four apps from elsewhere that reflect notable differences in spatial coverage and technical approaches. Among the latter four apps we decided to include two commercial products with features we had not found among the Southeast Asian apps but envisaged having potential as affordable products or services that could be adapted for the region. Lastly, since examples of 'responsiveness' were largely missing among the nine weather-based apps, we included two non-forecast-based apps to illustrate what this may look like.

Caveats. Many of the reviewed applications did not meet all our requirements on objective information. In the original RRI framework [20], anticipation stretches beyond the questions we formulated about what the apps do and their intended impacts, to also

anticipating the positive and negative consequences of the digital technology. The strength of ‘anticipation’ in the actual responsible innovation framework is that it makes an effort to capture or anticipate unexpected, unintended, or unwanted consequences as well. Our reviews are for the most part limited to impacts anticipated by the app developer, which in the absence of objective evaluations, will most likely be positive and intended. Similar findings were identified in a global review by [28]. Furthermore, we realize that the case studies are biased towards the apps that are best documented. This follows from the need to objectively evaluate the apps against RRI criteria, which required the data required for such evaluation to be available. Yet, we cannot estimate how these applications compare to others that are poorly documented. In our attempt to be transparent about the selection process, we provide a collection of apps that were discarded because of redundancy, limited documentation, and/or having user fees (Tables S1, S2). Another set of apps (not shown) were excluded since basic information needed to complete Table S2 was inaccessible. This pointed out two shortcomings: the lack of standards for comparing applications, and the challenges that scientists, and not to mention smallholder farmers with low (digital) literacy, will face when searching for applications.

3. Results

3.1. Initial Observations on Overall Search Results

Two initial observations offer partial explanations of the overall mismatch in supply and limited uptake of apps for accessing climate information services for agriculture in Southeast Asia, despite being prone to disasters.

First, geovisualisation tools using remote sensing data to support weather and agricultural information more readily lend themselves to vast subcontinents, such as large parts of Africa [65], India, and North America. In complex terrains, such as in Southeast Asia, microclimates and farming methods are poorly represented as 0.5–1 km pixel information [66]. Although there were multilingual apps, the lack of a unifying language hampers knowledge exchange in Southeast Asia. An interesting exception to the notion of spatial coherence is in Nepal where, despite its complex terrain and microclimates, different early warning systems [67] with SMS-based weather forecasts and agro-advisory services are provided to lead farmers. In such areas, apps where users can share point information about crops, soil types and pest control (*Plantix*, Table 1; *LandPKS*, Table S2) can be useful.

Second, two types of app providers dominate the supply: private, often local enterprises, and international project-based collaborations with development funds. Examples of apps initiated by local private enterprise were found in India and Nepal, such as the Green SIM-card of the Indian Farmers Fertilizers Cooperative and Airtel, which transmits daily voice messages in local languages for different types of farming (<https://vikaspedia.in/agriculture/crop-production/tips-for-farmers/green-sim-cards-for-farmers>; <http://iffcokisan.com/home/services>). In addition to weather forecast and crop information, smartphone apps providing price information to commercial smallholders are common (*Krishi Guru*, Table S2). Similarly in Southeast Asia, several apps focused on markets and were therefore not covered in the case studies, such as the *Khmer Agriculture Suite* which includes weather forecast, market information and e-connects farmers to enhance distribution links (Table S2). Among the Southeast Asian apps, international projects with public partners from donor countries played an important role in knowledge transfer. In 2019, RIMES collaboration on meteorological observation stations was expected to lead to improved forecasting skills and access to specific agro-meteorology information through the *SESAME* app, which is available in several Southeast Asian countries (Table S2). As of July 2021, the Dutch Geodata for Agriculture and Water (G4AW) facility dominated the search results with 25 projects in 15 countries across Africa and Asia. Among these were eight apps in Southeast Asia (Table 2 and Table S2): two in Myanmar (*MYVAS4Agri*, *SAM*), two in Vietnam (*GREENCoffee*, *Sat4Rice*), one in Cambodia (*AngkorSalad*), and three in Indonesia (*Smart Seeds* for vegetable farmers, *Spice Up* for black pepper, *G4INDO* for crop insurance).

3.2. Case Studies

We selected eleven apps, wherein the first five are from Southeast Asia and the following six are from other regions to exemplify certain relevant functions that were missing among the first apps. The available information for each app varied but is presented in Table 2, as comparatively as possible based on the four aspects of the responsible innovation framework (Table 1).

Site Pyo, Myanmar. The app advises on crop protection, land management, emergency alerts and market price information for ten crops. The project was initiated in 2015, funded by DFID and involved Miaki, a Burmese start-up specializing in mobile services. The app allegedly gained fame for having a trusted Burmese meteorologist advocating for it. By 2017 the target of 150,000 registered users had been reached, however, less than 20% were active users.

A key learning point on how to stimulate user engagement was to use weather forecasts to engage with users frequently. Based on this, developers added interactive communication, prompts and reminders about the app, based on an evaluation by [68]. Miaki incorporated these functions in a new app, *MYVAS4AGRI*.

MYVAS4AGRI, Myanmar. Also known as *Htwet Toe* for higher yield in Burmese, is a mobile app that includes seven crops (rice, green and black gram, maize, groundnut, potato, sesame) and targets two value-chain segments: (1) farmers obtain weather information plus advice on crop management, pests and disease, market prices, answers to questions, and access to finance; and (2) pre-farm value chain actors are expected to use the platform for data to adequately meet farmer demand.

The project (2018–2020) aimed to reach 850,000 smallholder farmers and food producers in two main agricultural zones of the country, the Dry Zone and the Delta. The lead of the app is Awba, an agriculture input supplier. Partners include the Department of Agriculture, VillageLink—an agri-tech company that specializes in remote sensing data and farmer advisories—and Miaki. The app’s business case is that joining organizations and companies (e.g., banks, insurance, input suppliers) are expected to pay so that farmers can obtain the information for free, and it is for anyone who is “interested in using farmer data and getting farmer insights”.

Green Coffee Information Service, Vietnam. This application targets coffee growers in the Central Highlands. The app (developed in 2016–2019) is a public-private partnership, led by ICCO Cooperation and includes two institutes under the Ministry of Agriculture and Rural Development and at least six Dutch partners specializing in water quality, satellite-based data and applications, software development, mobile networks, water management consultancy, and certification labeling for coffee. At the outset, the project targeted 4.5 million people directly and covered 500,000 ha by 2021, while the actual value (unclear in what year) was 100,000 and 5000 ha.

The interface has different functions that are accessed separately via icons. The user selects a pin on the map (GoogleMap) for place-specific, five-day weather forecast and concrete agricultural advice. Recommendations are provided for durian, mango and black pepper in coffee systems, in separate modules, not as integrated systems. The advice for fruit trees does not change with location or with weather forecasts. By selecting icons at the front interface, the user is connected to information for Good Agricultural Practice (GAP) advice, general information about crop protection and pest, market prices, games, and can log-in to the Rainforest Alliance/UTZ certification. The Q&A section is attended irregularly, and it is unclear who responds. Advice for ecological farming is missing.

The app lacks documentation about the developer and information sources, such as the weather forecast. Agricultural recommendations allegedly come from Rainforest Alliance but lacked references.

Angkor Salad, Cambodia. This G4AW-app uses satellite information and sends weather updates about management practices that support Cambodia GAP standards (a self-audit checklist) and reduce water and chemical inputs. The advice includes infor-

mation on irrigation, fertilizer, crop planning, market information with buying prices and buyer profiles, and Khmer GAP compliance with a self-audit checklist.

The app's website states that the project will use geodata to deliver services for at least 100,000 vegetable farmers in Cambodia. The bilingual website provides user guides and videos for farmers, collectors, and dealers. Feature articles with the app mentioned in media are also provided.

Smart Agriculture Myanmar program (SAM), Myanmar. The app aims to improve rice and maize yields and reduce crop losses due to natural disasters, targeting 550,000 farmers. The app uses agronomic and satellite-based models, big data and machine learning to personalize crop calendars and aims to add value to the existing *Golden paddy* mobile app for rice and maize (Table S2). Using profiles of actors across the value-chain, the app is expected to connect farmers with sellers and buyers, and to develop financial products "by making risk, delivery and operational costs transparent and manageable".

The lead partner (2018–2021) is Burmese and provides the platform (ImpactTerra), with the Ministry of Agriculture as a partner. Technical insights and financial services are all Dutch. Developers state that the intention is to keep the app free for farmers, and potentially setup subscription functions for users who "extract significant value from its services".

Among the initiatives and commercial products we found limited corresponding examples of from the Southeast Asia, include affordable, free or quasi-commercial apps developed with open-source products (e.g., QGIS, ESRI, Google Earth) and the ag-tech industry. The first four examples have transnational coverage or cover multiple crops while the last two exemplify wider applications for agricultural digitalisation. Contrary to the Southeast Asian apps, these products typically started from hackathons or as start-ups within development projects.

ThirdEye, Mozambique and Kenya. The app translates recommendations about irrigation, fertiliser and pesticide needs based on remote Near-Infrared (NIR) and Normalized Difference Vegetation Index (NDVI) data and sensors on land. A network of drones at 100 m altitude collects daily observations of NIR and NDVI and returns high resolution images (50 × 50 m, where each pixel represents 2 cm) using KMZ on Google Earth as a digital topographic database. The drone pilots use tablet mapping to investigate areas requiring particular guidance and add details. In Mozambique, eleven sensors cover 3500 medium to large-scale farmers on 1600 hectares and the drone pilots transfer information to 400 small scale farmers. The app was developed from a start-up for advising farmers in Mozambique and Kenya (2014–2017). The project is financed from three countries, led by Dutch consultants and a drone company.

Documentation was unclear regarding the fee to participate and if the advice is based upon current status only or if a weather forecast is included. The Publication-page on the project website was empty.

Agricloud, South Africa. The app advises on suitable conditions for spraying agrochemicals for maize. Recommendations are provided for the suitability of planting within ten days, applying fertilisers or harvesting, number of days outside optimal minimum and maximum temperatures, drought risk, and probability of irrigation needs. A notable function is the surveillance of the fall armyworm.

The application is for agribusinesses and advisors in South Africa and is available in eleven languages. Of potential interest to Southeast Asia is how small-scale farmers can register through their advisor and receive location specific advice in real-time, while businesses pay for the service. Users are connected via an application programming interface, which enables agribusinesses to monitor the weather on a dashboard with an updated map, for example, of planting dates in a polygon representing an administrative boundary, and graphs for temperature and rainfall. The information draws on real-time weather observations and forecasts from the national weather service. The service is expected to reach 125,000 users in four years.

The Agricloud app (-2019) was funded through the G4AW facility and developed within the development project Rain4Africa, a collaboration between South African weather services and the Agricultural Research Council, a Dutch platform, and the Netherlands' Space Office (from where they received 55% of the project funding). Consultants at WeatherImpact tailor tools for planners and farmers based on satellite and farmer information for sms services, and provide some documentation. The Rain for Africa has a selection of digital products for meteorological and agricultural advisory services.

CropMon, Kenya. The app provides weekly forecast and information via SMS about crop status and farm management advice for coffee, sugarcane, maize, wheat and grass.

Crop-Monitoring Service-Kenya (2015–2018) aimed for 150,000–200,000 subscribing small and medium-sized farmers. The partners are four Dutch and 4–5 national companies or organizations under the G4AW-facility. The developers' objectives included to build business models, deliver financially sustainable services and empowering farmers. At the onset it was stated that opportunities were going to be explored to “sell data to aggregators” including governments, banks and fertilizer industry and agro-dealers. At the closing workshop in 2019, it was discussed that the service would continue “in a commercial context”. According to the website (<https://www.weatherimpact.com/products/kenya/> 2 August 2021) the local partner continues delivering the service, while corresponding updates elsewhere were not found.

6th Grain, multiple countries. This application is adapted for five separate crops (wheat, barley, maize, soybean, sunflower) and can extend to sugarcane, flax, canola, coffee, and cashew. The map application uses machine learning and data is produced in four steps: ground observation for ground truthing with expert knowledge, photos and household surveys, Sentinel satellite data at 10 m resolution, a classification model, and an evaluation of the map with error margins. The system stores geographical information and is said to give specific information depending on crop rotation (crop persistency analysis tool) and the size of fields. The user can upload information on Open Street Map, such as climate, land and elevation data, and market information as sellers, distributors, warehouses, and silos. The app can digitize farmer fields and maintain records to measure farm profitability. The user can select a polygon and receive further information for the area, such as statistics, and print it as a pdf. The website states that Farm Registration is a powerful interactive online visualization tool that combines information from farmers, satellite and weather information, crop models and geographical information.

The commercial web-based application covers 66 million hectares of small and larger farms in 18 countries in Africa. Prices are missing. User information is sold further on. For example, to participate in *6th Grain*, the developer requests that 5% of the area is covered and in return annual country-crop maps are available at USD 20,000. The website provides a mixed list of philanthropical investors/donors and banks, three agrochemical companies, a French agro supplies marketing network, a Russian land holding company and producer of various agricultural products, including feed grains, and NASA Harvest but it is unclear who is client and who is partner. The consortium “brings together world-renowned experts working on environmental, economic, and social aspects of agriculture in universities, research centers, industry, space agencies, humanitarian organizations, ministries of agriculture and more”, “sharing through open platforms”.

Plantix, multiple countries. Lastly, in relation to the crop management apps which all targeted monocultures, we highlight one app without forecast-based agricultural advice, that singlehandedly focuses on pest control management. The app is included to demonstrate potential for polycultures, and perhaps with weather-based information in the future. The app can identify 400+ crop problems on 30 to 60+ crops from photos, focusing on disease detection, pest control and yield increase. The main functionality is a community where users can send photos and ask questions through the app, the community and WhatsApp. The website has blogs that cover issues of alternative practices, such as IPM. The app also offers live tracking of fall armyworm in India. The app was developed by the German startup Peat, in collaboration with international agriculture research centres

and the Government of Andhra Pradesh. The app is available in 18 languages (including Vietnamese and Bahasa Indonesian). On the notion of responsible innovations, the website states they “anonymize and aggregate all data received from our (millions of) farmers to protect our farmers’ identities”, but no more detail or what this entails when using WhatsApp as receiver is stipulated.

Global crop monitoring tool, India. During COVID-19 lockdown in India, transportation needed to be coordinated for farm laborers to reach their fields and delivering harvests to markets. The *Global crop monitoring tool* was deployed as a rapid response tool, where researchers could estimate expected harvest time based on historical planting and harvest dates and by comparing old and new open-source satellite images of water and greenness index (NDVI) from 2020 (Table 2). The maps of harvest information were intended for local planners’ operations, rather than farmers directly. We include this last case to demonstrate benefits of historical information and global open access datasets for mitigating risk during such emergencies.

4. Discussion

We devote in the discussion one section to each of the four criteria of the responsible research and innovation framework, before making recommendations for developing digital climate services that encourage resilient farming practices, particularly in Southeast Asian contexts. Where relevant we also bring in confirming or conflicting evidence from the apps presented in Table S2.

4.1. Anticipation—Anticipated Purpose and Expected Impact of the App

The nine weather-based apps presented as case studies were stated as being developed based on mutual needs between agro-tech developers and users (farmers) of the service. In contrast, imbalances were noted in terms of gains. The apps presented clearly stated anticipated purposes for farmers (although the originality of a unique value proposition around increased yields can be discussed), some commercial examples also identified benefits to non-farmer clients (e.g., *6th Grain*), while the developers’ own gains were less explicitly stated. The business ideas of commercial apps are instructive and illustrated by these somewhat conflicting messages: “those who feed us, need us” and “we are not a charity” (*Ricult*, Table S2). Similar imbalances were found among other apps globally [29].

During our search for apps, we could effortlessly find the metrics of users, e.g., targeted number of farmers reached or number of downloads (including apps in Table S2), but not of impacts on yields. However, the developers’ choice of download metrics did not reflect how many of the users were active (the exception was *Site Pyo*, Miaki), perhaps because users’ activity rates fluctuate [68], and the active user rates may be 20–40% of the downloads of farmer apps, such as in Africa [9]. For mobile applications in general, upward trends in download metrics is considered a developer’s strategy to feature in top charts and generate downloads, particularly of free apps, which in turn can be interpreted as a the number of separate users giving their word-of-mouth approval [69]. Whether farmers in developing countries or Southeast Asia in particular, respond similarly to such signals, could be a natural next research step moving forward from the conventional focus on technical and economic access adoption studies [53,70,71].

Among the possible explanations for limited uptake of farming apps in Southeast Asia, two interrelated aspects stood out from this study. On one hand, the limited supply of apps can depend on that farmers are still in the earlier stages of digital adoption, where ‘face-to-face’ and ‘peer group dialogues’ are important steps leading towards ‘active discovery’ and ‘digital service engagement’ with apps [38]. On the other hand, developers can alter the supply to push the boundaries towards more engagement. Here, app developers seem to have failed to recognize how Southeast Asian farmers’ needs vary depending on their stage in the trajectory. In the meantime, users prefer local chat groups that build on existing trust and relationships, so that people feel comfortable learning from peers and with people they know [38,55]. Promising examples from Myanmar showed that sending forecasts

can both be a tool to encourage users to interact with the app, and improving forecasts skills and thereby benefiting farmer priorities [72]. If developers can capture farmers' specific needs, the next generation of Southeast Asian apps may well follow African and Indian examples, where individual farmers as part of a community merge their information (situational updates, planting dates, pest attacks, soil moisture, weather observations) with other users to ground truth satellite information and contribute to improving the precision of the larger product or its functions—and in return receive some information and advice (e.g., farmers' observations of rainfall data in *Agricloud* [73]). Among the Southeast Asian apps that we studied, farmers' contributions to improve apps appear so far underutilized (See Inclusion below).

Among the reviewed apps, besides some individual success stories we found little evidence of tangible impacts owing to information in these apps, such as averted crop losses. The G4AW's project dashboard illustrates well challenges with monitoring anticipated indicators, such as percent yield increase of 100,000s of smallholder farmers with diverse baseline conditions.

A possible circumstance is that targeting an ambitious number of individual farmers increases chances to access competitive funds from donors, such as a new fund-raising initiative for digital climate-informed advisory services, which targets 300 million small-scale producers by 2030 [74]. This could funnel interests towards developing apps with monetary transactions [e.g., 39], which readily provides exact metrics on user engagement [37]. In the global review of digitally enabled agricultural services, failures to reach scale were largely ascribed technical infrastructure shortcomings [28]. In Southeast Asia, the barrier is more about motivation than technical limitation. The question is not if, but when farmer apps are available and used. We theorize that the developer's hunt for downloads [75,76] rather than impacts, reinforces app-designs for individual users that may lead to design flaws [77] and maladaptation [78]. A few examples of this are described in the following sections.

4.2. Inclusion—Actors Involved in the Process of Developing Apps

Content around inclusion focused on the concerns of various actors accommodated for in the innovation process. Based on the findings, we have identified three categories of actors: active 'drivers', passive 'passengers', and the invisible 'missing in action'.

4.2.1. The Drivers—Developers

A majority of the reviewed free apps were outcomes of 3–4 years projects, sometimes initiated by IT start-ups or western consulting firms funded by a mix of aid, loans from development banks and commercial products (Table 2 and Table S2). Developing free or commercial apps for farmers is part of a business strategy that can be compared to any other media: some are free, others by subscription, and users can have multiple. Therefore, the investment flows are interesting. The total value of all G4AW projects, the only ones we found with transparent budgets, was 18.9 million Euro, where the Netherlands Space Office received between 55 and 67% of each budget line (in December 2020). This could be referred to as a principled approach to aid that can serve national interests without sacrificing global development ambitions [79]. However, research showed that every dollar Germany spent on aid in general was returned by up to 50% [80], while 123 recipient countries observed no net effect of aid on their export [81]. We have not found data for how this translates to digital applications. In parallel to public agency-led consortia, national IT start-ups were common in India [37], Nepal and, to some extent, Myanmar (Table S2), often as multi-stakeholder consortia with multinational enterprises. Similar trends may follow across Southeast Asia as food systems and agri-business become more digitalized [82]. In contrast to India, China's otherwise dominant role in AI-technologies [6] is not reflected in Google App stores [83]. Commercial apps were not in focus for this study, although some early examples from the region were present among the blogs (Table S1) we were unable to verify. More concerted efforts are needed on research partnerships with businesses for

empirical evidence about their operations [28], to determine feasible models for making apps affordable, e.g., cost-sharing or selling data to aggregators (*CropMon*).

4.2.2. The Passengers—Smallholder Farmers

Many project websites show photos of a smiling farmer holding a smartphone, while little evidence of farmers' involvement in the prototype and development phases in either of the products was present. Similar to WMO's conclusion a decade ago, most of the products are developed *for* farmers, but it is difficult to tell to what extent tools are developed *with* farmers [84]. Despite their inherent interest in promoting economy of scale and scope, developers of climate service apps seem to pay little attention to social factors that limit inclusion, such as understanding where or how farmers can find information about apps they may not know exist. Promising attempts at reducing access gaps from the African apps included combining services, enabling smallholder farmers to connect via their local extension officer (*Agricloud*) or receive free services paid for by agribusinesses (e.g., *6th Grain*). However, access to both ICTs and extension can be restricted by gender and socio-cultural norms, which may aggravate asymmetric e-literacy [26]. Studies suggest that developers underestimate the role of neighbor farmers as a community for information and trust [7] and recommend that if those marginalized groups are included in the design process [33,85], apps could reach individual farmers directly [27,38]. Others question whether apps could exacerbate digital divides or asymmetric information. Are smallholders' exclusion gaps widening because of their limited education and digital access (internet, technology, e-literacy) [86], while those with access and economic means can make better informed and self-serving decisions, e.g., agribusinesses? To illustrate the problem, we repeated the same search terms on Google Play one year after the initial review for this paper (on 19 July 2021). This time, the search returned the maximum 250 hits, even when typed in the Vietnamese language (such as nông nghiệp Việt Nam) although many apps had no obvious relevance for a Vietnamese farmer, nor in providing farming advice. This (over)supply of alike and generic apps requires that potential users know very specific search terms and have some degree of digital literacy to distinguish a useful app from an unuseful app.

With the RRI lens, one issue that runs through the case studies is the importance of demonstrating how users interact with the developer, the app and user community. For most apps, the information that we could access failed to declare in what ways users could provide feedback or engage with app developers or agricultural extension. This also reflects back on the developers, who thereby missed two opportunities to increase downloads [69]: the Q&A sections, where available, showed sparse and slow interaction, and few developers used the App store's forum to interact with users and respond to their feedback. One exception was *Plantix*, with fast feedback and interaction with experts and/or community through in-app forums including voice, call or photo messaging (instead of typing), responsiveness in app stores, and having the app available in multiple languages, thus making itself accessible to wider user groups.

To date, co-design processes focus mainly on solving existing divides that are local and visible. Reflecting on failures of non-user-centered designs, PACT's blog from Cambodia reminds about the importance of co-creating and to build prototypes [48,49,87]. Rather than one-way ground truthing of data, promising apps are instead those that integrate farmers' tacit knowledge (and enable them to further develop it) with the strengths of big data and digital technologies [88]. Where it may be too soon for apps, it may be legitimate to explore alternative digital tools [89]. For example, the Myanmar cases corresponded with findings from a survey with Burmese farmers [34] and illustrated the need for multiple digital and non-digital channels to reach and engage with more farmers, which additionally widens the access to information for more user groups [90–92]. To build Southeast Asian farmers' trust in agricultural advisory apps, co-design requires that developers, programmers and software communities gain a better understanding of farmers' interactions on other social media platforms and how they adapt messaging apps and self-managed chatrooms for

sharing forecasts, agroadvisories and knowledge [34,38,93], teaching themselves to build up e-literacy. More research is needed on the interactions between developers and farmers, and also on farmers' experiences using different apps across the region [38].

4.2.3. Missing in Action—Public Leaders

A critical reflection of this study, besides the lack of inclusion of smallholder farmers in the design of applications, was the limited involvement of national public agencies in the process. If included, government institutions, often had unclear roles or minor shares in the project budgets.

In this study the Southeast Asian apps (more than the African cases) tended to include departments of agriculture rather than national meteorological offices. Instead, meteorological data was derived from independent satellite observations or other open access sources. Public authorities in developing countries are generally underfunded and have limited technical and human capacity to prepare and transfer agricultural advice for an entire nation. As a result, they are rarely fast enough to pick up on ICT and to translate agriculture and meteorological information into mobile phone services, despite this being in the national interest. Other (international, private) actors thus step in to fill the gaps to reach individual farmers. Therefore, the low presence of public partners in the countries that apps are intended for, is concerning. Their degree of engagement may depend on requirements in the project's donor arrangement or differences in accountability and power structures between donor and recipient countries [94], which may lead to a situation in which project-leads are not expecting public agencies to contribute to the completion of projects [95] or countries lacking interagency and international data sharing policies [96]. Consequently, rather than collaborating with public institutions that already have a national realm (or working towards improving it), many developers seem to start from scratch. This counters with the UN Human Rights Council, which delineates the obligations of States towards ensuring equity in climate action and stipulates that all persons should have the capacity to adapt to climate change, which extends accountability between as much as within States [97]. Investments to modernize national meteorological services to facilitate decision support and public infrastructure [25] that enables equal access to climate information services, is therefore a critical concern for entire societies' capacity to adapt to climate change. From a responsible innovation perspective, the minor or missing engagement with public partner institutions in digital agricultural information is peculiar given developing countries' own contributions to loans for national programs that provide infrastructure to apps. We will point to two positive exceptions.

The first exception of a public meteorological authority partnering in the implementing country is the South African Weather Service listed as partner (about 20% of the funding) to Rain for Africa. This contrasts with Southeast Asia, where G4AW typically included national agricultural departments among its funding and implementing partners, albeit with minor shares of the budget (in Myanmar less than 5%). Interestingly, the two Southeast Asian apps with some visible ownership and inclusion of public actors in supporting policy implementation (*SAM*), and for advice (*MYVAS4AGRI*) were both from Myanmar.

The second exception is the *SAMIS/LACSA* project in Lao PDR (Supplementary Material S1), which is initiated as a part of the WMO global framework for climate services (GFCS) and aims to improve climate products and collaboration between meteorology and agriculture [84]. Here, both ministries have a protruding contribution, including co-authored scientific papers [98]. Perhaps contributing to this, is the fact that GEF-funds allow governments to take an active role in deciding executive agencies, while in bilateral agreements, funds are tied to a particular donor's interest or consensual commitments [94].

In the absence of public agencies or legal guidelines for digital innovations, app developers maneuver by developing a platform that simply brings together diverse information without analysing or processing it (such as the *GreenCoffee*), thus limiting the developer's responsibility. Implementing this may depend on laws that restrict the use of public meteorological data for forecast and advise.

Within Southeast Asia, the ASEAN collaboration could push towards common public digitalization strategies. For example, when it comes to the use of digital information and drones, there are varied and partly (still?) unregulated conditions (<https://www.drone-made.com/>). For the use of meteorological data, as of December 2020 none of the ASEAN countries had yet embarked on the process with the national Global Framework for Climate Services (https://gfcs.wmo.int/NFCS_status), although there are some ongoing processes in Vietnam, Myanmar, Thailand and Indonesia.

Stressing the importance of public engagement, [99] showed that disaster preventive information systems are useless without cross institutional collaboration. This is shown when public finance contributes to the continuity of data or tools which can enable rapid access towards fighting hunger and poverty when new and accelerating threats appear, such as *FAO GIEWS* and *FewsNet* (Supplementary Material S1); experts who quickly map or forecast the spread of locust swarms between East Africa and Asia (<https://earthobservatory.nasa.gov/images/146495/could-satellites-help-head-off-a-locust-invasion>); or take open source data to simulate harvest time so farmers can be granted access to fields during COVID lockdown restrictions (*Rapid Response Crop Monitoring Tool*, Table 2). To benefit requires that national agencies are included in the process, not bypassed, which brings us to reflexivity and responsiveness.

4.3. Reflexivity—Developers' Intent towards Transparency and Trust

Regarding reflexivity, closely related to who is included in the process and what type of perceived partnerships those actors have, as discussed above, are questions like; to what extent transparent documentation was available to build trust between users and developers? Poorly documented apps were somehow expected given that the extensive global scientific review by [29] resulted in similar findings, although we searched for each app's specific name (Table 2, Tables S1 and S2). Poor documentation also leads to questions about developers' interest in building capacity among their users, which is particularly relevant in developing countries. The identified documentation gaps include easily accessible information that users could request, interpret and decide upon, as well as scientific studies about the design, testing, or comparing of apps. The least available documentation, if any, was found among apps lacking the visible involvement of international donors (*AgriBuddy*) or commercial apps (*6th Grain*; *FarmDog*, *Ricult*; Table 2 and Table S2). This demonstrates the difficulties for both users and scientists to making objective intercomparisons and informed decisions about app selection. The apps with some product information often involved public funds and research institutes. Promising examples include open-source maps with the enforced statement of origin of data, which could be implemented across all sorts of data in apps (for users). Both *FAO GIEWS* and *FewsNet* (Supplementary Material S1) are examples of publicly financed tools, albeit with limited interactivity but often documented, transparent methodologies. *FewsNet* devotes a section to scientific and other publications with partners that are clearly stated on the front interface. A tab for 'agricultural climatology' shows climate and forecasts as graphs for a location and crop that the user selects from an interactive map. The tab 'Knowledge based products' includes country-specific products and NOAA global precipitation forecasts for one and seven days.

Compared to the visibility of outreach and the number of downloads, transparent information about data security were clearly a lower priority. Few words, if any, were devoted to answering what user information is collected? Where the information goes? Who owns the data? What information is being used or sold? No examples were found of an assigned tab for Data sharing policies prior to download or headline. Thus, key items in, e.g., the UN Data privacy and data protection principles and the GODAN principles, transparency and data sharing transfer [60–62], were rarely applied. Cyber security is increasingly on the agenda among western farmers, and so is responsabilization, i.e., who is accountable when something goes wrong [100]. Perhaps some Southeast Asian farmers have a natural reluctance towards data sharing for other reasons (the GNI Statement of concern regarding a proposed cybersecurity law in Myanmar is one example [101,102]).

For example, is information not being used by powerful investors for their own gains [103], or potentially for land acquisition [44,104]?

With agencies capable of doing research involved in developing the apps, technical descriptions and evaluations should be easily available. Data protection and digital literacy training should be an integral part of agricultural digitalization initiatives. The systematic monitoring and overview of G4AW-projects, which served academics more than farmers, can help initiate standards for transparent and systematic product information to enable more objective app intercomparison criteria. This format needs to be developed with users and can contribute to building digital literacy and breaking information asymmetries.

4.4. Responsiveness—To Emergent Sustainability Problems

Finally, with responsiveness we were searching of evidence of apps promoting sustainable farming systems and landscape solutions as a response to emergent problems, an issue that also resonates with developers' anticipation of problems. We have reported on apps monitoring fall army worm and the *Crop Monitoring Tool*, which were efficaciously designed in response to emergent problems. The latter further shows the benefits of opensource data to quickly respond to unexpected crises.

Similar to studies from around the world [29,30,32], the approach to development illustrated by the apps can be summarized as promoting status quo and single-solutions, with little integration of users and their knowledge. Like [29] for illustrating potential contributions to biodiversity or ground-water levels we depended on other types of tools, e.g., *Plantix*, which uses image recognition to diagnose crops and crop pests, and potentially *LandPKS*, which uses mobile phones to monitor restoration [105,106]. Farmers' crowd-sourced data can then be recycled using machine learning methods to train satellite imagery for predicting land cover information or crop types. We underscore that the users of, in this case *Plantix*, data cautioned that "preservation of privacy (. . .) will need to be addressed before crowdsourcing can (. . .) be used in smallholder systems" [8]. These examples contrast to other apps' foci on farming recommendations for monoculture production. Despite providing advice for multiple crops, no app appeared to offer similar updated advice for those crops in mixed systems. Instead, recommendations for subsidiary inter-croppable crops and fruit trees were put in separate blogs or posts without forecast-based advice (e.g., both *Green Coffee* and *Plantix*). Tentatively promising entry points towards more responsive apps were those that target resource use efficiency at the farm level by timing inputs (fertilizer, water, pesticides), include advice for certification compatibility (e.g., GAP), in-app libraries for users about plant pests (*Plantix*), or specific tabs for reports and publications.

Single-crop apps bring us to two further challenges. First, Southeast Asian smallholders may practice monocultures but rarely live from single commodity farming. Siloed market information apps may therefore contradict smallholders' business strategies with flexible production systems and fail to integrate farmers in value-chains [52]. Second, separating or even excluding the placement of non-conventional practices, e.g., GAP recommendations, from the generic advice may reflect partnership with companies whose products are optimised for monocultures, for example, providing weather forecasts for spraying (*Agricloud*), selling seeds or chemical fertilisers (Awba in Myanmar; BASF and Syngenta in *6th Grain*). The message as to what alternatives exist to their products and farming system management options, or the extension agent's invested interest can easily get confounded. In the absence of public actors, it is difficult to judge to what extent irrigation or spraying recommendations have been co-ordinated with authorities and actual water (or pest and disease stress) availability beforehand. To summarize, technology allows users to be connected: to monitor or report pest spread, such as fall armyworm (*Agricloud*, *Plantix*); as a network of crowd-sourcers or ground-truthers of satellite information across large areas (*Plantix*, *6th Grain*), and to receive information (*6th Grain*, *Agricloud*) as alerts when crop performance declines (*CropMon*, *MimosaTek*), and to make landscape level assessments (*LandPKS*, Table S2). Still developers keep users and land uses disconnected.

In the long run, the tendency of apps to focus on monoculture and conventional practices seems to run counter to global and national adaptation strategies for agriculture. Are governments monitoring the advice? Should they? If the app industry is not (or deliberately ignoring this), then who is responsible for developing and maintaining apps and data that encourage diversification and the proliferation of ecosystem services? The last question is warranted in the case of greenhouse gas mitigation interventions when supporting ecosystem services are ignored. The fact that diversified farming systems repeatedly are outperforming monoculture in terms of delivering food security and ecosystem benefits to farmers in Africa [107,108] and Asia [109,110], seems to be accepted in national adaptation policies in Vietnam and Philippines and the region [111–113], yet receives surprisingly little traction in high-level policy and visions for digital agriculture as these are predominantly supporting the status quo [42]. For example, with the ambition of attracting USD7 billion in investments for digital climate-informed advisory services, the World Resources Institute drew up six principles for success, including data quality, equity, co-creation, accountability, financial sustainability, and scalability [74]. Some success factors overlap with the dimensions of the responsible innovation framework (e.g., inclusion and responsiveness). Yet, the focus on economic gains dismisses a push of ambitions towards the anticipation and reflexivity of landscape solutions and ecosystems resilience—promoted in the UN Decade of Ecosystem Restoration. This is interesting as recently the Rockefeller Foundation, a major investor in agriculture research, intended to steer more research to linking big data and ecosystem information at a landscape level [103]. So the question is: Are these current principles sufficient? Based on our findings we think they are not. We hope that the examples have highlighted some points in need of attention, particularly for the upcoming generation of apps in Southeast Asia, to enable responsible innovations that support conversions to ecological practices or climate adaptation response.

4.5. Recommendations for Further Action and Research

In placing the dimensions of the responsible innovation framework for digital agriculture, we derive some recommendations for further action and research:

Develop an app intercomparison protocol for longitudinal studies on the supply and life cycles of apps. Our examples in the Supplementary Material of scattered information about free and commercial apps from around the world point out the need for a systematic overview and intercomparison of apps and user engagement. Scholars have asked if easier access to open source and map-based interfaces could lead to an oversupply of smart apps [54] without the capacity to be sustained after the projects end. How can data collected via private apps maintain the similar consistency in information sharing as when provided by public and UN institutions? Will the oversupply of freeware apps enable farmers to pick and choose, download and delete apps until they find some they prefer?

Establishing an objective app intercomparison protocol that builds on co-creation, putting farmers higher on the agenda: their desired information, technical information and responsible criteria for documenting and sharing information via apps (digital footprints). The user protocol must be developed with inclusive and intersectional stakeholder categories, tasked with identifying how to best bridge needs and solutions that can encompass more diversity on the ground and in the value chain. Both app developers and national institutes can learn from open-source communities regarding (i) adapting information for users with diverse technologies and skills, (ii) clear documentation of an app, its developers and investors, (iii) assurance about continuity in data, (iv) defining who has rights to data supplied by users, and (v) understandable user contracts.

Develop criteria for ecologically and socially responsible digital data with quality control. While Southeast Asian farmers are gaining digital skills, decision makers have a narrow window of opportunity to proactively consider how such tools can contribute to wider inclusion and sustainability objectives.

In line with this there are rising concerns that the divide between the Global North and Global South, with the former being the dominant developer of applications and owner of

data collected by those applications, may create a new form of ‘digital colonialism’ [114]. In Asia, more research is needed on the influence of regional agri-tech industries in digitalization of agriculture and how their products relate to the complex reality and needs of diverse smallholder farmers in Southeast Asia, and to agro-ecological solutions and sustainable food systems. As a minimum standard, apps with agricultural advice, market or finance information functions (e.g., Table S2), need to offer options that do not lock farmers into unsustainable practices with intensive monoculture. Specifically, we recommend:

First, engage national public actors to embed digital solutions in national agriculture planning and advisory systems. The generated data could guide authorities in adaptive planning on production, for concerted efforts on pest control, or monitoring disaster damages for their own actions or reporting. Second, promote South-South exchange around data stewardship. The primary goal of data stewardship is to prevent any sort of misuse and mismanagement and applies to public and private use of data generated in apps. One example of action towards global standards on responsible innovations includes the Global Open Data for Agriculture and Nutrition (GODAN) initiative, which focuses on high-level public-private institutional support for open data relevant for agriculture and nutrition, notably weather and forecast data, geodata, and market data [62] and issues pertaining to data privacy and data ownership of smallholder farmers [115]. Protocols for application intercomparisons can draw on the Open Up Guide for Agriculture (<https://openupguideforag.info>), where over 1000 partners including governments, international organizations and private sector actors, systematically map over 140 data standards for agriculture (<https://vest.agrisemantics.org/>). The guide starts from the perspective of SDG2 on food security, which is viewed as compulsory potential impacts for policy, production and finance, while no routine indicator is yet provided for ecosystems or biodiversity restoration. The data category titled ‘Production Advise Data’ could include case studies on agro-advisory applications with indicators of ‘reflexive’ and ‘responsive’ evidence, such as proposed in the responsible innovation framework. To enable objective analytics beyond case study comparisons, requires that indicators are adopted in new search taxonomies for impacts of digital agriculture technologies [116,117]. To develop a more robust understanding of what is available globally, a machine learning model could aid with the assembly of a dataset and review of applications, as used previously in literature reviews on digital agriculture research [e.g., 27].

Finally, standards may encourage donors to push for app development with suites of crops and diverse agronomic practices, e.g., including biological pest control, which would better help farmers prepare for environmental stress. Scaling trade-offs are subject to further research, such as how to maximise the number of users (or app downloads), and hence potential commercial benefits, without compromising impacts towards national targets on sustainable development goals, including actions to combat climate change, soil and biodiversity degradation.

5. Conclusions

Overall, the studied digital applications for climate services and agriculture management showed little evidence on all four criteria in the responsible research and innovation framework. The apps were driven either by international development consortia or national private companies, while farmers and public partners, especially meteorological departments, were largely invisible in the development of apps (Inclusion). Applications targeted conventional monoculture and productivity increase (Anticipation), while advice contributing to integrated systems or agroecological cultivation practices, and landscape ecosystem services were missing (Reflexivity). These gaps contrast with many smallholders’ production systems in Southeast Asia, and with ambitious goals set for the Decade of Ecosystem Restoration and three Rio Conventions on climate, biodiversity, and land degradation (Responsiveness). Based on the gaps that were evident from this study, we recommend two key standardized protocols: one for app intercomparison developed by and serving farmers, practitioners and developers that can enhance digital literacy, inclusion

and promote apps that build resilience, and one protocol for data stewardship that can foster transparency among developers and serve societal goals.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/agriculture11100953/s1>, Supplementary Material S1 Southeast Asian (trans)national initiatives and Supplementary Material S2 Incomplete lists of apps for agriculture information with Table S1: Selected blogs and websites with lists of apps for farmers and Table S2: Longlist. Incomplete overview of apps, websites and maps with agriculture related information excluded in the case studies.

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