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The effects of combined digital and human advisory services on reducing nitrogen fertilizer use: lessons from China's national research programs on low carbon agriculture

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ABSTRACT

In the context of emerging digital advisory services that can make a potential difference in sustainable farming practices, this article analyzes the connection between on-farm human interaction and digital advice. Based on an experimental case from China's largest ever national research initiative on reducing agrochemical use in agricultural production, this study found that introducing university facilitators to promote ICT-based advisory services is conducive to site-specific fertilizer use. Through interactions with farmers, the facilitator complemented digital advisory services to achieve optimal N-fertilizer use in maize production. Digital service providers favoured large farms and usually would not service smallholder farmers, thus limiting the potential of digital advisory services. A main theoretical implication is that digital technology should not be completely relied upon because it may only give part of the answer. A human facilitator still plays an important role in integrating new technologies in interaction with farmers. Human advisory services can interpret or translate data to improve farmers' decision-making, going beyond the advisory capacity of ICT technology. This is an important policy implication for China regarding its national research policies on agricultural sustainability and digital advisory services, and also calls for further research on interactions between digital and human advisory services.

KEYWORDS

Technology adoption; sustainable farming practice; digital agriculture; agricultural extension; variable-rate fertilizer; co-innovation; agritech startup

1. Introduction

In the process of agricultural modernization, technological development seeks to achieve maximum output and enhanced control. Rotations became shorter and monoculture replaced crop diversification, resulting in crop susceptibility to drought, insects, pathogens, disease outbreaks and market vagaries (Lamine et al., 2012). Productivist approaches to agricultural intensification have posed vast challenges globally and locally, also in China. According to the first Chinese National Soil Pollution Situation Survey covering the period April 2005 to February 2013, 16% of soil in the surveyed sites was affected by pollution and degradation (OECD, 2018). In parallel, pollution and eutrophication of surface water and groundwater due to livestock production and the use of fertilizers and pesticides have caused great concern not only with respect to production but also in food safety (Buckley & Piao, 2016). The intensity of nitrogen and phosphate fertilizer consumption on cultivated land in China is 2.5 and 1.9

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times the world average, respectively (Zhao et al., 2008); while in Europe, the rates have been constantly declining (OECD, 2018). While fertilizers have played an important role in achieving China's food security, its excessive use has caused severe environmental problems (Cui et al., 2014; Powlson et al., 2014; Zhu & Chen, 2002).

To improve nutrient management and achieve sustainable farm management, information and advisory services (also referred to as extension) have important roles to play (Klerkx & Jansen, 2010; Vrain & Lovett, 2016). Increasingly, such information and advisory services are provided digitally (Fabregas et al., 2019; Fielke et al., 2020; Klerkx, 2020; Munthali et al., 2018; Oyinbo et al., 2020; Steinke et al., 2021), as part of the recent technological wave in agriculture (e.g. precision farming equipment, robotics, and blockchain) under the influence of digitalization (Klerkx et al., 2019). The information is provided through devices such as smartphones, via applications (apps) or short message services (SMS), and possibly in both forms of generic information and advice tailored to farmers' specific situation (Agyekumhene et al., 2020; Baumüller, 2016, 2017; Eichler Inwood & Dale, 2019; Munthali et al., 2018). Also, information is exchanged via social media (Chowdhury & Hambly Odame, 2013; Kaushik et al., 2018).

Researchers analyzing agricultural digitalization have raised critical questions about how to integrate the established models of knowing and decision-making in sustainable agriculture (Klerkx et al., 2019). Despite the asserted substitution of human planning and action by automated decision-making process (Budaev et al., 2018; Nedelkoska & Quintini, 2018), human interpretive skills for sustainable farm management are still important (Eastwood et al., 2019; Walter et al., 2017). Disruptive entrants such as tech startups and traditional ICT technology suppliers often cannot provide adequate on-farm support due to their lack of farm system expertise or knowledge networks (Eastwood et al., 2016). Even though digital advice has great value, concerns about the access to digital services are raised due to some issues on digital communication and advice platforms, such as connectivity (Cowie et al., 2020; Mehrabi et al., 2021; Pant & Hambly Odame, 2017; Rose et al., 2021; Salemink et al., 2017) and user-friendliness (Munthali et al., 2018; Ortiz-Crespo et al., 2021: Steinke et al., 2021). It thus has been argued that 'human advisors' (or 'analogue advisors') can play an important role in complementing digital advice, curating and interpreting digital information (Eastwood et al., 2019; Ingram & Maye, 2020). Such a digital and human interaction can reinforce each other (Materia et al., 2015). Despite the conceptual development of combined digital and human advisory services in sustainable farming (Berthet et al., 2018; Eastwood et al., 2019; Ingram & Maye, 2020), corresponding purposeful experiments and rigorous examination remain scarce.

This paper aims to address this gap, by examining the combined digital and human advisory services in the context of China's 'Zero-Growth Action Plan for Chemical Fertilizers and Pesticides'. This Plan aims to limit the annual increase in China's use of chemical fertilizers and pesticides to less than 1% between 2015 and 2019 and to achieve a zero-growth by 2020 for major agricultural crops, compared with the average annual increase of 3.9% in nitrogen fertilizer consumption between 2000 and 2013.[1] Over the period of 2016 and 2018, a total of 49 National Key Programs were approved and funded as the national endeavours to support research and technology development in the area.[2] Among the first tranche of the projects in 2016, one project (hereafter, the Project) focuses on digital advisory services.

The present study, independent from the Project, aims to explore the development and application of digital advisory services and solutions to excessive fertilizer use in China's agricultural production, by assessing the impact of SMS-based messages. The main research questions included: (1) how does the provision of digital advisory service impact on sustainable N fertilizer use, and (2) what are the processes of information flow and conversion in the combined digital and human advisory services? An experimental intervention was designed, that is to station a university facilitator in the field to foster a hybrid decision-making process informed by expertise, institutional learning and farm-level adaptations. The results of this research contribute to the literature on digital extension and advisory services, and can inform how to involve smallholder farmers in partnerships with research institutions and private bodies for sustainable development through ICTs (Steinke et al., 2021). The remainder of the paper is organized as follows: first, literature on digital advisory services is examined, followed by presenting the results, and finally, the discussion and conclusion are provided.

2. Literature review

2.1 Impacts of digital advisory services on technology and practice adoption: a mixed picture

The impacts of digital advisory services on adoption of sustainable farming technology are mixed. Experimental studies have found that mobile phone-based services increased farmer knowledge and self-reported adoption of recommended practices (Fu & Akter, 2016; Larochelle et al., 2019). For example, Larochelle et al. (2019) found that mobile phone SMS-based messages can increase farmers' adoption of integrated pest management (IPM) practices in potatoes. Such effect varies with farmers' education level (Carrión-Yaguana et al., 2020). In rural Viet Nam, Internet access increased rice production by 6.8% and the increase was associated with the improved efficiency of fertilizer use, such as the adoption of variable rate of fertilizer application by timing and location (Kaila & Tarp, 2019). In India, mobile phone-based agricultural advisory services significantly influenced farmers' fertilizer-related decisions, and treated farmers were more likely to adopt the recommended fertilizer practices than the control group (Cole & Fernando, 2021). In Tanzania, radio and mobile SMS-based channels were found to have great potential to increase the adoption of the sustainable agricultural intensification (SAI) practices (Kansiime et al., 2021; Silvestri et al., 2021). A meta-analysis of several studies revealed that digital advisory services could moderately increase yields by 4%, and the returns to the investment could be increased by the improved programme design, such as customization to local conditions and video-based interventions (Fabregas et al., 2019). Nonetheless, it has been argued that acquiring knowledge via digital advisory services could result in overestimation of the impacts of self-reported data and unverified behaviour change (Fabregas et al., 2019).

Previous studies often have a methodological limitation, that is, the binary construction of ICT-based service delivery and use (i.e. 'yes' or 'no') without reasoning more deeply about how the decision-making process evolves and the role of human interaction in this process. This may explain the relatively low use. For example, Fafchamps and Minten (2012) declared that only 59% of farmers who had been offered a SMS-based subscription actually used it. Similarly, among the farmers who were offered free mobile phone-based extension services, only 65% listened to the delivered content (Cole & Fernando, 2012).

The access to digital agricultural advisory services and the impacts of such services vary considerably by farm size, income and farmers' social standing (Mehrabi et al., 2021). Although current data are inconclusive, anecdotal studies have reported suggestive evidence of exclusion of disadvantaged farmers (Aker, 2011). Globally, agricultural extension agencies have been found to favour their own social networks and neglect the vulnerable farmers, causing accountability problems (Bandiera et al., 2018; Cunguara & Moder, 2011). As digital agricultural advisory services currently reach only a small portion of farmers in the world (Tsan et al., 2019), the concern of excluding smallholder farmers in data-driven agriculture is prominent, as warned by Mehrabi et al. (2021).

2.2 The role of humans in complementing digital advisory services

Researchers have asserted that digital advisory services alone are not enough to stimulate agricultural decisions without considering the socio-technical system (Fielke et al., 2020; Jakku & Thorburn, 2010; Steinke et al., 2021). In increasingly data-driven agricultural production, cyber-physical systems enable autonomous information sharing, analysis and decision-making (Lioutas et al., 2019; Rose & Chilvers, 2018). But the systems need to include a social element, such as relational and face-to-face interactions that promote trust and agreement (King et al., 2019; Lioutas et al., 2019; Rijswijk et al., 2021). As Eastwood et al. (2019) argued, human advisors provide sensemaking and interpretation of information provided from digital channels. Increasing capacity associated with digital technologies thus requires new platforms for agricultural stakeholders to combine different sources of information, both digital and 'analogue', for decision-making (Fielke et al., 2020; Ingram & Maye, 2020).

The role of human advisors in complementing digital advice can be understood from the perspective of the integrated process of knowledge management proposed by Nonaka and Takeuchi (1995). In line with the perspective, a pyramid model is often used to capture how different data, information, and knowledge are combined and converted (Figure 1). At the bottom of the pyramid is voluminous unstructured

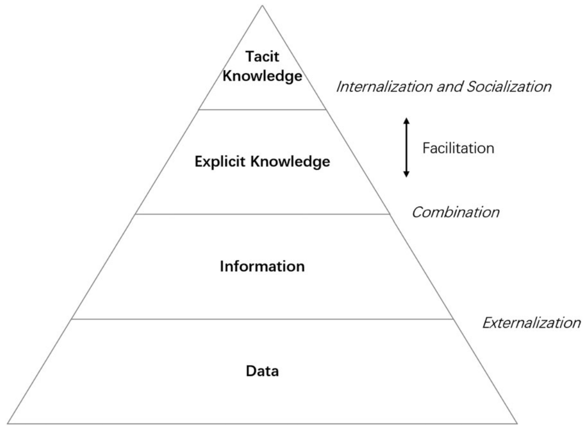

Figure 1. The pyramid model of knowledge management (based on Ackoff, 1989; Nonaka and Takeuchi, 1995).

unexpressed information, defined as *data*, i.e. 'symbols that represent properties of objects, events and their environments' (Ackoff, 1989, p. 3). *Information*, inferred from data, represents a logically constructed relationship of data; it is relevant, usable, meaningful, and to some extent processed (Rowley, 2007). Data *per se* have no value until they are transformed into a relevant form, and the difference between data and information is the latter is 'not (only) structural but functional' (Ackoff, 1989, p. 2). After being generated, stored, retrieved, processed or augmented by additional items, a subset of the data becomes information because of inferred relevance. *Knowledge* is a collection of propositional 'know-that' and behavioural 'know-how' (Snowdon, 2003). In complex decision-making process (such as farm management), not all knowledge is articulated and codified into digitalized components, and plenty of knowledge is difficult to make explicit (Polanyi, 1966). Such *tacit* knowledge is personalized and embedded as experience, expertise or practical skills, and are not easy (or costly) to be acquired and transmitted through conventional communication tools and agent-based management (Gonsalves et al., 2005; Langeveld & Proost, 2004; Röling & Jiggins, 1998).

3. Research design and methods

3.1. Combining digital advice and a human innovation facilitator

The present study was piloted in Binzhou, a prefecture in north Shandong province, China, where scientists of the National Key Program had previously studied soil management. The local climate is warm temperate. Winter wheat and summer maize are planted in rotation, and summer maize is routinely planted throughout June to September.

Previous studies identified excessive nitrogen fertilizer use and knowledge gaps in the region. For example, farmers used too much N-fertilizer at the pre-planting stage of maize when the young crops have no extensive root system to store nitrogen, resulting in reduced efficiency and productivity (Jia et al., 2013). Scientists proposed variable rates of N-fertilizer application to reduce nitrogen loss to the environment, and to increase yield (Matson et al., 1998; Tilman et al., 2002). Despite robust scientific evidence and bold policy advocacy, inappropriate farming practices continued; the agricultural extension system was dysfunctional in addressing the challenges. Only 28% of farmers were able to read the nutrient information on the fertilizer package and 44% wrongly believed 'the more the fertilizer, the better the production' (Jia et al., 2015).

Through the National Key Program, a variety of stakeholders were engaged to reconfigure the knowledge system. A group of soil scientists and agronomists of multiple disciplines from the National Agricultural Research System (NARS) took soil and fertilizer samples in the project area for laboratory analysis. The scientists also conducted field experiments to synchronize soil N availability and N-fertilizer use with nutrient needs. Based on the field diagnosis, the scientists further calibrated their model and drew up a set of guidelines on low carbon practices. Partnering with an entrepreneurial venture (an agritech startup) that provided digital services, the guidelines were delivered to local extension agents and individual farmers in the form of SMS-based messages.

The digital advisory service of the Project was assisted by a variety of ICT applications. For example, to synchronize seed population and the N-fertilizer use with crop N needs, the Project used hand-held chlorophyll meters, a SPAD-based leaf nitrogen estimation tool, as an assistant tool at the tiller forming stage and when the first stem node was visible, and tested the uppermost fully expanded leaf (visible collar) until the ear leaf was identifiable. The chlorophyll meter approaches – earlier developed by scientists to estimate grain N status and determine the need for additional N fertilizer (Follett et al., 1992) – have been combined with intelligence tools installed on smart phones and sensing technologies (Mohan & Gupta, 2019). The results of the field diagnosis were delivered to individual farmers in the form of SMS-based messages; this prevents the possible exclusion of farmers who do not use smart phones or are not familiar with the installed applications.

The scientific knowledge was converted into localized recommendations of nitrogen management on 'as needed' basis. A total of five field advice messages were sent during the growing season of maize by the startup. The advice was site specific and calibrated according to soil testing and field diagnosis. To ensure the localization of farming practice guidelines, the scientists appointed a local extension technician as the contact person for local knowledge. The recommended total N-fertilizer use in the region was 135–240 kg per hectare (convert into purification). To synchronize N-fertilizer use with crop N needs, based on previous research in the region, farmers were advised to break the N-fertilizer application into two, namely 50–80 kg/ha before planting, and 80–160 kg/ha at the 10-leaf stage. The variable rates of N-fertilizer application accounted for the complex soil context, N storage in the soil, weather-driven factors that affect the availability of soil N, and crop-specific attributes.

Table 1. Description of sample and research design of ICT-based climate-smart nitrogen management services in Shandong, China.

	Total	Resident innovation facilitator	Advice sent to farmers via SMS-based messages	Farms not included in the advisory service
Village	25	2	23	25
Farmer	150	30	71	49
Plot	574	116	268	190

Source: Author's survey.

A university facilitator, a full-time master candidate trained in agricultural science and environmental sustainability, was stationed in the villages throughout the growth stage of maize. The facilitator supported farmers to read the delivered information and explained results of the field diagnoses. To further demonstrate the operation and results of advised N-reducing technologies, the facilitator farmed several small demonstration plots in the village. As an integrated part of the Project, the facilitator constantly communicated with the scientists and the partnering ICT startup, and returned feedback from field work for further development.

3.2. Survey and data collection

The research design yielded a comparative construct between treatment and control. There were two types of treatment groups. First, the general treatment group included farmers who were provided with digital services, such as results of field diagnosis and advice of site-specific N-fertilizer use. The startup selected 125 farmers whose size were relatively large in the study area and advised them on sustainable farming practices via SMS-based messages. Second, the intensive treatment group of 37 farmers was selected by the university facilitator who resided in two adjacent villages based on observed needs and established trust. The involvement of the facilitator could potentially enhance the internalization and socialization of knowledge. Besides, this study randomly selected two farmers per village who did not receive any services associated with the Project as the control group. Meanwhile, two maize plots from each farmer were randomly selected for the study.

The design of two-stage dataset at farm and plot level allows for before-after analysis and a control for time-invariable factors. The baseline survey that consists of face-to-face interviews was conducted in mid-November in 2016 shortly after the maize harvest. The survey collected detailed information on farm management and N-fertilizer use on two sample plots of each household throughout the maize growing season. A follow-up survey was conducted in the same period in the next calendar year. While most of the survey questions were identical to those in the baseline survey, farmers were asked about their awareness and perception of the ICT-

Table 2. Characteristics of farms receiving (or not) different advisory services, 2016.

	Farms in villages with resident facilitator		Farms receiving advice by SMS-based messages		Farms not included in the advisory service (Non-service)	
	(N = 30)		(N = 71)		(N = 49)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Farm size (ha)	0.7	0.6	2.6***	5.3	0.7	0.7
Age (year) †	56.5	7.6	54.1	9.4	56.0	8.5
Education level (in years) †	7.0	3.9	6.5	3.5	7.3	3.0
Off-farm experience in the past 5 years (%)†	43.3	0.5	49.3	0.5	42.9	0.5
Installing messaging and communicating applications on smart phone (%)†	10.0	31.5	29.6	46.0	22.4	42.2

Source: Author's Survey.
Notes: † Individual characteristics are those of the main farmer. Two-sample t-tests were used to estimate the difference in means of farm characteristics between the treated and control groups. 'Non-service' group was chosen as the reference. The lack of any stars (*) indicate non significance.*, **, *** indicate statistical significance at the 10%, 5%, and 1% level, respectively.

based services and their communication with other actors, such as the local extension technicians.

Based on the two surveys, a longitudinal dataset at the household and plot level was constructed. The attrition rate between the two surveys was approximately 30% mainly because some questionnaires were not completed and/or some interviewees were away as migrant workers. Therefore, the dataset includes a total of 150 maize growers in 25 villages and contains detailed information concerning the farmers' production management including N-fertilizer use and yield, and their perceptions of and access to ICT-based agroecological services in the maize growing season (Table 1).

4. Analytical results

The service provider tended to provide digital advice of sustainable practices to large farms. Table 2 summarizes the characteristics of both treated and control farmers prior to the experiment intervention of SMS-based advisory services. The average size of the farms who received SMS-based messages was 2.6 hectares, nearly four times larger than that in the control group. This indicates a selection bias of the private entity in providing digital services. Interestingly, the average farm size of the farm treated by the university facilitator is not significantly different from that of the control group. Unlike the service provider, the facilitator was seeking targeted services for smallholder farmers.

The take-up rate of digital advice messages was surprisingly low. Over the growing season of maize in 2017, a total of 505 messages were sent to the interviewed farmers. During the field survey, the interviewers tracked the source dataset from the digital service provider and checked the message receipt at the farm level. The high non-delivery rate was due to several reasons (Table 3). A few messages had been blocked by telecommunication providers, and

Table 3. Farmers' awareness of SMS-based messages from the agroecological service startup and feedback.

	Total		Farmers in villages with a resident innovation facilitator		Only received advice by SMS-based messages	
	(N = 101)		(N = 30)		(N = 71)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Total number of SMS-based messages sent	505	–	150	–	355	–
Farmer's awareness and feedback (1 = Yes; 0 = No)						
Did not receive the message because of blocking by telecommunication providers or by the anti-spam system	0.376	0.485	0.367	0.484	0.380	0.486
Received but did not read the message	0.327	0.469	0.233	0.424	0.366	0.482
Read the message and followed the advice	0.297	0.457	0.400	0.492	0.254	0.436
Sent back additional inquiry	0.073	0.262	0.167	0.376	0.011	0.105

Source: Author's Survey

Table 4. Estimations of farmers' reactions to SMS-based messages based advisory services in 2017, Logit model.

	Alerting to the message (1 = Yes; 0 = No)
Innovation promoter (1 = Yes; 0 = No)	0.24***
	(0.061)
Site-specific and non-communicative information (1 = Yes; 0 = No)	0.00
	(0.043)
Had soil tested (1 = Yes; 0 = No)	0.32***
	(0.066)
Household control variables	
Farm size (in hectares)	−0.01***
	(0.004)
Age (in years)	−0.01***
	(0.003)
Education level (in years)	0.02***
	(0.006)
Off-farm experience in the past 5 years of (1 = Yes; 0 = No)	0.23***
	(0.069)
Messaging and communicating applications were installed on the farmers' smart phone (1 = Yes; 0 = No)	0.03
	(0.048)
Pseudo R2	0.27***
	(0.000)

Notes: Robust standard errors in parentheses. *, **, *** indicate statistical significance at the 10%, 5%, and 1% level, respectively. The total number of observations was 505.

most by the anti-spam system installed on the smartphones. Only 29.7% of farmers received the message and followed the advice, and the rate was significantly higher in the villages with a resident university facilitator than in those without such a facilitator. As a consequence, 16.7% of farmers asked for additional information from the facilitator when digital services were combined with human facilitation, whereas the rate was only 1.1% when farmers received only digital services.

To further examine the role of the university facilitator, a multivariate analysis was conducted in which other covariates (e.g. climatic, economic and social factors) were controlled for. Table 4 shows that the estimated coefficient is significant and positive. This demonstrates that the university facilitator raised farmers' awareness of ICT-based advisory services, such as by helping older farmers use smart phones and guiding them through technical problems. Farmers' awareness was also closely associated with some farm and household characteristics. For example, off-farm experience and farm size significantly increased and decreased the awareness, respectively.

The suggested N-fertilizer management was only partially followed. The reduction in N-fertilizer was only observed at the 10-leaf stage, though excessive N-fertilizer needed to be reduced at various stages (Table 5). Combined with field facilitation, the digital advisory services effectively reduced N-fertilizer use by 63.2 kg per hectare in maize production. But the reduction was only significant at the 10-leaf stage (74.1%); the overall compliance with the guidance was far from optimal.

Combined digital and human advisory services were conducive to technology adoption but their effect on immediate N-fertilizer reduction was limited. Given that this study could not control for every factor that potentially influences farmers' N-fertilizer use, a multivariate model was used to estimate the impacts of site-specific services on farmers' N-fertilizer use. The longitudinal structure of our data allowed fixed effect estimations to control for time-invariant unobserved factors. The estimate coefficient of field facilitator, -0.04, negative but not significant, implying a downward effect of human facilitation in reducing N-fertilizer use compared with receiving only digital advisory services (Table 6, column 1). The coefficients of farms not receiving service are all positive, suggesting that digital services in general resulted in N-fertilizer reduction, *ceteris paribus*.

5. Discussion

This paper aimed to assess impacts of and interactions within combined digital and human advisory services. The main research questions that guided the enquiry were: (1) what were the effects of digital advisory service provisioning on sustainable N fertilizer use and (2) what processes of information flow and conversion took place in the combined digital and human advisory services? We will now discuss the findings and reflect them against extant knowledge to elucidate theoretical, policy and practical implications.

5.1 Adoption of sustainable agricultural practices and digital advisory services

The study confirmed that the impact of digital services on reduction of N-fertilizer use is heterogonous and limited. Going beyond previous studies that only focused on digital service access' impact on the overall reduction of fertilizer use or expenditure (Ma & Zheng, 2021; Yuan et al., 2021), the present study investigated the impacts of digital services on N-fertilizer use at different and specific growth stages (e.g. the basal and 10-leaf stage). The findings are in line

Table 5. N-fertilizer use according to the maize growth stage and climate-smart fertilizer management services in Shandong (China), 2016-2017.

	Farmers in villages with a resident innovation facilitator		Farmers who only received advice by SMS-based messages		Farms not included in the advisory service (Non-service)	
	(N = 116)		(N = 268)		(N = 190)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Total N-fertilizer (kg/ha)						
2016	279.8	125.3	226.4***	108.4	290.0	111.2
2017	241.2	113.9	190.8***	109.5	265.1	130.5
△	−38.7	131.9	−35.6	123.7	−24.9	111.2
Pre-planting N-fertilizer (kg/ha)						
2016	85.8	33.1	90.7	49.6	92.5	56.8
2017	110.3	56.0	99.7	49.7	104.1	52.5
△	24.5	67.4	8.9	61.4	11.7	79.8
N-fertilizer at 10-leaf stage (kg/ha)						
2016	194.0	101.6	135.7***	107.9	197.5	87.5
2017	130.8**	101.4	91.1***	90.0	161.0	111.0
△	−63.2**	91.1	−44.5	110.9	−36.5	101.7
Farmers who reduced N-fertilizer use (%)						
Total	62.1	48.7	56.0	49.7	53.7	50.0
Pre-planting	36.2	48.3	38.1	48.6	40.0	49.1
At 10-leaf stage	74.1***	44.0	56.7	49.6	57.9	49.5
Yield (ton/ha)						
2016	8.2	1.3	8.5***	1.2	8.1	1.7
2017	7.5*	1.6	7.8	1.2	7.8	1.2
△	−0.7*	1.9	−0.6**	1.4	−0.3	1.7

Source: Author's survey.

Notes: Two-sample t-tests were used to estimate the difference in means between the treated and control groups. 'Non-service' group was chosen as the reference. The lack of any stars (*) indicate non significance.*, **, *** indicate statistical significance at the 10%, 5%, and 1% level, respectively.

Table 6. Estimations of farmers' use of N-fertilizer for maize production in Shandong (China) using fixed-effect models, 2016-2017.

	N-fertilizer (kg/ha)		
	Total (1)	Pre-planting (2)	At 10-leaf stage (3)
Presence of innovation promoter (1 = Yes; 0 = No)	−0.04 (0.00)	16.95 (1.57)	−16.99 (1.04)
Non-service farms (1 = Yes; 0 = No)	12.16 (0.74)	3.12 (0.34)	9.04 (0.65)
Control variables			
Farm size (in hectares)	−1.42 (0.31)	2.93 (1.13)	−4.34 (1.11)
Off-farm experience in the past 5 years of (1 = Yes; 0 = No)	34.48 (1.49)	−25.95** (2.00)	60.42*** (3.09)
Messaging and communicating applications installed on farmers' smart phone (1 = Yes; 0 = No)	32.72 (1.17)	39.13** (2.48)	−6.42 (0.27)
Dummy year 2016 (1 = Yes; 0 = No)	36.18*** (3.43)	−7.77 (1.31)	43.95*** (4.93)
Constant	200.40*** (11.46)	96.73*** (9.85)	103.67*** (7.00)

Notes: Absolute values of t-ratio in parentheses. *, **, *** indicate statistical significance at the 10%, 5%, and 1% level, respectively. The total number of observations was 574.

with the results of Ma and Zheng (2021), who noted that in China, smartphone-based information intervention has a negative but insignificant impact on fertilizer expenditures at the 40th quantile, but significantly decreases pesticide expenditure at the 60th and 80th quantiles, for wheat farmers in China. It is also in line with Yuan et al. (2021) who reported that Internet use increased farmers' human capital and then reduced chemical fertilizer use.

Our findings showed that the impacts of digital advisory services on N-fertilizer use in China's grain production varied with farm size. This agrees with previous findings that SMS-based messages have heterogeneous effects determined by farm size, though farmers with large or small farms both found SMS valuable (Camacho & Conover, 2019). But it is in contrast to the findings of Fafchamps and Minten (2012) who estimated the benefit market and weather information delivered by SMS-based messages and found no evidence of heterogeneous effects by farm size.

As a key addition to previous works, the present study found that the combined digital and human advisory services increased the rates of advice acceptance and feedback. The university facilitator had a positive effect on reducing N-fertilize use, though the effect is not significant compared with only receiving the digital advisory service. In theory, farmers who have interpersonal communication with the facilitator would develop stronger 'trust' in extension agents and learn more (Buck & Alwang, 2011), and hence, they are more likely to reduce fertilizer application than those without such communication, which shows the 'trust' is crucial to fully benefit from the digital advice. According to Aker et al. (2016), whether the information is provided via a trustworthy source will affect how the information is interpreted, accepted, and acted upon. It has been noted that digital advisory services have been suffering from a lack of feedback mechanisms, insufficient trust in information sources, and a mismatch with farmers' needs (Steinke et al., 2021). In this regard, the added value of a human or 'analogue' source of advice becomes apparent (also echoing McCampbell et al., 2021).

5.2 Challenges of enacting digital advisory services

The experimental assessment of ICT-based advisory services on technology adoption of sustainable farming and its impacts (as discussed in section 5.1) resonate with ongoing debates on challenges and opportunities associated with digital advisory services in agriculture (e.g. Fielke et al., 2020; Ingram & Maye, 2020; Klerkx, 2021; Steinke et al., 2021). The entrepreneurial venture of digital services in the Project selectively targeted large farms who used N-fertilizer more efficiently than smallholders. As Khan et al. (2020) indicated, the limited access to ICT by small farmers has inhibited their adoption of agricultural technologies, negatively affecting the farm productivity and wellbeing. This supports earlier exclusion concerns and suggests that policy efforts should ensure the coverage and general affordability of providing rural subsidies, avoiding heterogeneous impacts and the exacerbation of a 'digital divide' (Aker et al., 2016; Wyche & Steinfield, 2016).

The present study also provides some practical guidelines for designing digital services in sustainable agriculture, which emphasize 'user-friendliness' (Steinke et al., 2021) and take into account 'user-readiness' of digital services (McCampbell et al., 2021). In this study, each SMS-based messages that delivered field diagnosis to individual farmers was no more than 400 words and can be read within one minute. Moreover, the SMS-based messages were sent five days prior to the fertilizer application, not only as an information provider but also as a task reminder. Such a knowledge-building effect was also observed in Ecuador, where mobile phone SMS-based messages improved the adoption of sustainable agricultural practices as such messages increased farmers' knowledge and reduced inattention (Larochelle et al., 2019). The case of Ecuador also demonstrated the importance of a well-timed messaging strategy.

The present study points to a cautious understanding of the potentially overstated role of digital services in sustainable agriculture. The insignificant effects of digital services (see section 5.1) may be due to Chinese farmers' deep-rooted cognition and experience about the benefits of fertilizers. Early studies found that almost half of grain growers wrongly believe that increasing fertilizer can promote production without limit (Huang et al., 2008; Jia et al., 2015). Although farmers have learned through digital advisory service that there is no need to overuse fertilizer to increase production, it takes time to change their fertilizer application behaviours in the long term. The downward effect on N-fertilizer use is a good start but not nearly enough, which also indicates that digital advice on a particular element in farming is only one element of the overall transition towards sustainable agriculture.

5.3 The role and the impact of the human facilitator

The university facilitator increased farmers' awareness of attending digital advice messages and following the advice (see Section 4). In the Project, following the concept of the knowledge pyramid, *externalization* referred to retrieving and transmitting data from an implicit and unknown situation (e.g. soil fertilizer testing and leaf nutrient diagnosis). The externalized data were bundled into information shared between scientists and local digital service providers, and were further combined and modelled for structured information in the explicit form of SMS-based guidelines of N-fertilizer use. As the external information needed to be further validated and evaluated by the end-users (i.e. farmers), *internalization* occurred when the end-users combined the external information with their tacit knowledge, and then their decision-making process may be deviating from the external knowledge and present as a socialized behaviour. The field facilitators become important in the decision-making process unknown to others because they can further externalize farmers' 'tacit knowledge' for agricultural advisory service providers, scientists or policy-makers and inform the socialized and complex process of behaviour changes.

Our results suggest that farmers still need human advisory support to benefit from digital tools, a finding that echoes the result of Eastwood et al. (2019), who highlighted the important role of advisors in enhancing the value of digital advisory tools by combining their knowledge of farm systems with an understanding of such tools. Reaching farmers with one-way SMS-based messages may limit the amount of information that can be conveyed (Fabregas et al., 2019). Hence, the technology should not be completely relied upon because it may only give part of the 'answer', and the facilitator still plays an important role in integrating new technologies into their interaction with farmers (echoing Eastwood et al., 2016). Human advisory services can interpret or 'translate' data to improve farmers' decision-making that goes beyond the advisory capacity of ICT technology. Such human facilitation can be partly digital when interactive media are used (Aguilar-Gallegos et al., 2022; Klerkx, 2021; Steinke et al., 2021).

6. Conclusions

Excessive dependence on agrochemicals has been a major obstacle to achieving agricultural sustainability in China. This study experimented with a redesigned farming system that included a university facilitator in the framework of China's National Key Program of reducing chemical fertilizer use through digital advisory intervention. The findings showed that the impacts of digital advisory services on reducing N-fertilizer use in China's grain production varied with farm size. Compared with large farms, smallholder farms were less responsive to digital advice on low-carbon farming. The university facilitator played a significant role in facilitating the learning process before farmers' behavioural changes eventually took place. The study found a high non-delivery rate of SMS-based advisory services and a low level of feedback, in the absence of human facilitation and combined digital and human interaction. Lastly, private providers of digital services biased towards large farms and the digital exclusion concern is not unwarranted.

The research findings may inform China's endeavours to transform the national agricultural advisory systems. In recent years, there have been a few innovative practices in China, such as the Science and Technology Backyard (STB) platform, a university-based extension programme advancing technology transfer by stationing scientists in rural villages (Martindale, 2021; Zhang et al., 2016). While both STB and the studied pilot project have demonstrated positive environmental effects of the presence of scientists in the farming system, questions remain unanswered about the institutions and associated governance of advisory services (e.g. finance, incentives and institutions of field facilitators). It is still not clear whether field facilitation is a type of farm advisory services or profession aspired for, especially for the next generation of tech-savvy rural youth that may want to focus on developing digital advisory applications (see also Yoon et al., 2021).

While the empirical work focused on the context of China, as shown in section 5, such a discussion is not limited to China but is emerging globally in rural advisory services and agricultural extension (Fu & Akter, 2016; Klerkx, 2021; Steinke et al., 2021). Future research also is needed in other countries to investigate how such hybrids between digital and human advice develop, what the optimal combination between the two is, and what impact such combined advice has.

Notes

1. Information source: http://www.moa.gov.cn/govpublic/ZZYGLS/201503/t20150318_4444765.htm
2. During 2016 and 2018, a total of 363.6 million USD was approved and used on these projects. The number of projects are 13, 21 and 15 in each of the three years.

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References

Ackoff, R. (1989). From data to wisdom. *Journal of Applied Systems Analysis*, *16*, 3–9.

Aguilar-Gallegos, N., Klerkx, L., Romero-García, L. E., Martínez-González, E. G., & Aguilar-Ávila, J. (2022). Social network analysis of spreading and exchanging information on twitter: The case of an agricultural research and education centre in Mexico. *The Journal of Agricultural Education and Extension*, *28*(1), 115–136. https://doi.org/10.1080/1389224X.2021.1915829

Agyekumhene, C., Vries, J., Paassen, A. V., Schut, M., & MacNaghten, P. (2020). Making smallholder value chain partnerships inclusive: Exploring digital farm monitoring through farmer friendly smartphone platforms. *Sustainability*, *12*(11), 4580. https://doi.org/10.3390/su12114580

Aker, J. C. (2011). Dial "A" for agriculture: A review of information and communication technologies for agricultural extension in developing countries. *Agricultural Economics*, *42*(6), 631–647. https://doi.org/10.1111/j.1574-0862.2011.00545.x

Aker, J. C., Ghosh, I., & Burrell, J. (2016). The promise (and pitfalls) of ICT for agriculture initiatives. *Agricultural Economics*, *47* (S1), 35–48. https://doi.org/10.1111/agec.12301

Bandiera, O., Burgess, R., Deserranno, E., Morel, R., Rasul, I., & Sulaiman, M. (2018). *Social Ties and the Delivery of Development Programs*: Working paper: https://cdn.givingcompass.org/wp-content/uploads/2019/01/22154443/socConnections.pdf.

Baumüller, H. (2016). Agricultural service delivery through mobile phones: Local innovation and technological opportunities in Kenya. In W. F. Gatzweiler, & J. von Braun (Eds.), *Technological and institutional Innovations for marginalized smallholders in agricultural development* (pp. 143–162). Springer International Publishing.

Baumüller, H. (2017). The little we know: An exploratory literature review on the utility of mobile phone-enabled services for smallholder farmers. *Journal of International Development*, *30* (1), 134–154. https://doi.org/10.1002/jid.3314

Berthet, E. T., Hickey, G. M., & Klerkx, L. (2018). Opening design and innovation processes in agriculture: Insights from design and management sciences and future directions. *Agricultural Systems*, *165*, 111–115. https://doi.org/10.1016/j.agsy.2018.06.004

Buck, S., & Alwang, J. (2011). Agricultural extension, trust, and learning: Results from economic experiments in Ecuador. *Agricultural Economics*, *42*(6), 685–699. https://doi.org/10.1111/j.1574-0862.2011.00547.x

Buckley, C., & Piao, V. (2016). Rural water, not city smog, may be China's pollution nightmare. The New York Times, 11 April 2016. https://www.nytimes.com/2016/08/18/world/asia/china-coal-health-smog-pollution.html.

Budaev, D., Lada, A., Simonova, E., Skobelev, P., Travin, V., Yalovenko, O., Voshchuk, K., & Zhilyaev, A. (2018). Conceptual design of smart farming solution for precise agriculture. *International Journal of Design & Nature and Ecodynamics*, *13*(3), 309–316. https://doi.org/10.2495/DNE-V13-N3-309-316

Camacho, A., & Conover, E. (2019). The impact of receiving SMS price and weather information on small scale farmers in Colombia. *World Development*, *123*, 1–11. https://doi.org/10.1016/j.worlddev.2019.06.020

Carrión-Yaguana, V. D., Alwang, J., & Barrera, V. H. (2020). Promoting behavioral change using text messages: A case study of blackberry farmers in Ecuador. *Journal of Agricultural and Applied Economics*, *52*(3), 398–419. https://doi.org/10.1017/aae.2020.7

Chowdhury, A., & Hambly Odame, H. (2013). Social media for enhancing innovation in agri-food and rural development: Current dynamics in Ontario, Canada. *The Journal of Rural Communiy Development*, *8*(2), 97–119.

Cole, S., & Fernando, A. (2012). *The value of advice: Evidence from mobile phone-based agricultural extension*. Harvard Business School.

Cole, S., & Fernando, A. N. (2021). 'Mobile'izing agricultural advice: Technology adoption, diffusion and sustainability. *The Economic Journal*, *131*(633), 192–219. https://doi.org/10.1093/ej/ueaa084

Cowie, P., Townsend, L., & Salemink, K. (2020). Smart rural futures: Will rural areas be left behind in the 4th industrial revolution? *Journal of Rural Studies*, *79*, 169–176. https://doi.org/10.1016/j.jrurstud.2020.08.042

Cui, Z., Dou, Z., Chen, X., Ju, X., & Zhang, F. (2014). Managing agricultural nutrients for food security in China: Past, present, and future. *Agronomy Journal*, *106*(1), 191–198. https://doi.org/10.1088/1748-9326/9/11/115003

Cunguara, B., & Moder, K. (2011). Is agricultural extension helping the poor? Evidence from rural Mozambique. *Journal of African Economics*, *20*(4), 562–595. https://doi.org/10.1093/jae/ejr015

Eastwood, C., Ayre, M., Nettle, R., & Rue, B. D. (2019). Making sense in the cloud: Farm advisory services in a smart farming future. *NJAS - Wageningen Journal of Life Sciences*, 90–91. Article no. 100298. https://doi.org/10.1016/j.njas.2019.04.004

Eastwood, C. R., Jago, J. G., Edwards, J. P., & Burke, J. K. (2016). Getting the most out of advanced farm management technologies: Roles of technology suppliers and dairy industry organisations in supporting precision dairy farmers. *Animal Production Science*, *56*(10), 1752–1760. https://doi.org/10.1071/AN141015

Eichler Inwood, S. E., & Dale, V. H. (2019). State of apps targeting management for sustainability of agricultural landscapes. A review. *Agronomy for Sustainable Development*, *39*(1), 8. https://doi.org/10.1007/s13593-018-0549-8

Fabregas, R., Kremer, M., Lowes, M., On, R., & Zane, G. (2019). *SMS-extension and Farmer Behavior: Lessons from Six RCTs in East Africa*. Working Paper.

Fabregas, R., Kremer, M., & Schilbach, F. (2019). Realizing the potential of digital development: The case of agricultural advice. *Science*, *366*(6471), eaay3038. https://doi.org/10.1126/science.aay3038

Fafchamps, M., & Minten, B. (2012). Impact of SMS-based agricultural information on Indian farmers. *World Bank Economic Review*, *26*(3), 383–414. https://doi.org/10.1093/wber/lhr056

Fielke, S., Taylor, B., & Jakku, E. (2020). Digitalisation of agricultural knowledge and advice networks: A state-of-the-art review. *Agricultural Systems*, *180*, 102763. https://doi.org/10.1016/j.agsy.2019.102763

Follett, R. H., Follett, R. F., & Halvorson, A. D. (1992). Use of a chlorophyll meter to evaluate the nitrogen status of dryland winter wheat. *Communications in Soil Science and Plant Analysis*, *23*(7-8), 687–697. https://doi.org/10.1080/00103629209368619

Fu, X., & Akter, S. (2016). The impact of mobile phone technology on agricultural extension services delivery: Evidence from India. *Journal of Development Studies*, *52*(11), 1561–1576. https://doi.org/10.1080/00220388.2016.1146700

Gonsalves, J., Becker, T., Braun, A., Campilan, D., Chavez, H. D., Fajber, E., Kapiriri, M., Rivaca, C., & Vernooy, R. (2005). *Participatory research and development for sustainable agriculture and Natural Resource management: A sourcebook (volume 2: Enabling participatory research and development)*. International Development Research Centre.

Huang, J., Hu, R., Cao, J., & Rozelle, S. (2008). Training programs and in-the-field guidance to reduce China's overuse of fertilizer without hurting profitability. *Journal of Soil and Water Conservation*, *63*(5), 165–167. https://doi.org/10.2489/jswc.63.5.165A

Ingram, J., & Maye, D. (2020). What are the implications of digitalisation for agricultural knowledge? *Frontiers in Sustainable Food Systems*, *4*(66), 1–6. https://doi.org/10.3389/fsufs.2020.00066

Jakku, E., & Thorburn, P. J. (2010). A conceptual framework for guiding the participatory development of agricultural decision support systems. *Agricultural Systems*, *103*(9), 675–682. https://doi.org/10.1016/j.agsy.2010.08.007

Jia, X., Huang, J., Xiang, C., Hou, L., Zhang, F., Chen, X., Cui, Z., & Bergmann, H. (2013). Farmer's adoption of improved nitrogen management strategies in maize production in China: An experimental knowledge training. *Journal of Integrative Agriculture*, *12*(2), 364–373. https://doi.org/10.1016/S2095-3119(13)60237-3

Jia, X., Huang, J., Xiang, C., & Powlson, D. (2015). Reducing excessive nitrogen use in Chinese wheat production through knowledge training: What are the implications for the public extension system? *Agroecology and Sustainable Food Systems*, *39*(2), 189–208. https://doi.org/10.1080/21683565.2014.967436

Kaila, H., & Tarp, F. (2019). Can the Internet improve agricultural production? Evidence from Viet Nam. *Agricultural Economics*, *50*(6), 675–691. https://doi.org/10.1111/agec.12517

Kansiime, M. K., Njunge, R., Okuku, I., Baars, E., Alokit, C., Duah, S., Gakuo, S., Karanja, L., Mchana, A., Mibei, H., Musebe, R., Romney, D., Rware, H., Silvestri, S., Sones, D., & Watiti, J. (2021). Bringing sustainable agricultural intensification practices and technologies to scale through campaign-based extension approaches: Lessons from Africa Soil Health Consortium. *International Journal of Agricultural Sustainability*, https://doi.org/10.1080/14735903.2021.1976495

Kaushik, P., Chowdhuy, A., Hambly Odame, H., & van Passen, A. (2018). Social media for enhancing stakeholders' innovation networks in ontario, Canada. *Journal of Agricultural & Food Information*, 19 (4), 331–353. https://doi.org/10.1080/10496505.2018.1430579

Khan, N. A., Gao, Q., Ali, S., Shahbaz, B., Khan, P., & Abid, M. (2020). Analyzing ICT-enabled agricultural advisory services in Pakistan: Evidence from a marginalized region of Punjab province. *Electronic Commerce Research*. https://doi.org/10.1007/s10660-020-09442-z

King, B., Fielke, S., Bayne, K., Klerkx, L., & Nettle, R. (2019). Navigating shades of social capital and trust to leverage opportunities for rural innovation. *Journal of Rural Studies*, *68*, 123–134. https://doi.org/10.1016/j.jrurstud.2019.02.003

Klerkx, L. (2020). Advisory services and transformation, plurality and disruption of agriculture and food systems: Towards a new research agenda for agricultural education and extension studies. *The Journal of Agricultural Education and Extension*, *26*(2), 131–140. https://doi.org/10.1080/1389224X.2020.1738046

Klerkx, L. (2021). Digital and virtual spaces as sites of extension and advisory services research: Social media, gaming, and digitally integrated and augmented advice. *The Journal of Agricultural Education and Extension*, *27*(3), 277–286. https://doi.org/10.1080/1389224X.2021.1934998

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS - Wageningen Journal of Life Sciences*, *90-91*, 100315. https://doi.org/10.1016/j.njas.2019.100315

Klerkx, L., & Jansen, J. (2010). Building knowledge systems for sustainable agriculture: Supporting private advisors to adequately address sustainable farm management in regular service contacts. *International Journal of Agricultural Sustainability*, *8*(3), 148–163. https://doi.org/10.3763/ijas.2009.0457

Lamine, C., Renting, H., Rossi, A., Wiskerke, H., & Brunori, G. (2012). Agri-food system and territorial development: Innovations, new dynamics and changing governance systems. In I. Darnhofer, D. Gibbon, & B. Dedieu (Eds.), *Farming systems research into the 21st century: The new dynamic* (pp. 229–256). Springer. https://doi.org/10.1007/978-94-007-4503-2_11.

Langeveld, H., & Proost, J. (2004). Participative learning for the future: Using interactive farmerresearch networks in the development of new plant production systems in The Netherlands In *Proceedings of the 6th European IFSA Symposium (p537–548))*: Vila Real, Portugal.

Larochelle, C., Alwang, J., Travis, E., Barrera, V. H., & Dominguez Andrade, J. M. (2019). Did You really Get the message? Using Text reminders to stimulate adoption of agricultural technologies. *The Journal of Development Studies*, *55*(4), 548–564. https://doi.org/10.1080/00220388.2017.1393522

Lioutas, E. D., Charatsari, C., La Rocca, G., & De Rosa, M. (2019). Key questions on the use of big data in farming: An activity theory approach. *NJAS –Wageningen Journal of Life Sciences*, *90–91*(1). Article no. 100297. https://doi.org/10.1016/j.njas.2019.04.003

Ma, W., & Zheng, H. Y. (2021). Heterogeneous impacts of information technology adoption on pesticide and fertiliser expenditures: Evidence from wheat farmers in China. *Australian Journal of Agricultural and Resource Economics*, *59*, 1–21. https://doi.org/10.1111/1467-8489.12446

Martindale, L. (2021). From land consolidation and Food safety to taobao villages and alternative Food networks: Four components of China's dynamic agri-rural innovation system. *Journal of Rural Studies*, *82*, 404–416. https://doi.org/10.1016/j.jrurstud.2021.01.012

Materia, V. C., Giarè, F., & Klerkx, L. (2015). Increasing knowledge flows between the Agricultural Research and advisory system in Italy: Combining virtual and Non-virtual interaction in communities of practice. *The Journal of Agricultural Education and Extension*, *21*(3), 203–218. https://doi.org/10.1080/1389224X.2014.928226

Matson, P. A., Naylor, R. L., & Ortizmonasterio, I. (1998). Integration of environmental, agronomic, and economic aspects of fertilizer management. *Science*, *280*(5360), 112–115. https://doi.org/10.1126/science.280.5360.112

McCampbell, M., Adewopo, J., Klerkx, L., & Leeuwis, C. (2021). Are farmers ready to use phone-based digital tools for agronomic advice? Ex-ante user readiness assessment using the case of Rwandan banana farmers. *The Journal of Agricultural Education and Extension*, 1–23. https://doi.org/10.1080/1389224X.2021.1984955

Mehrabi, Z., McDowell, M. J., Ricciardi, V., Levers, C., Martinez, J. D., Mehrabi, N., Wittman, H., Ramankutty, N., & Jarvis, A. (2021). The global divide in data-driven farming. *Nature Sustainability*, *4*(2), 1–7. https://doi.org/10.1038/s41893-020-00631-0

Mohan, P. J., & Gupta, S. D. (2019). Intelligent image analysis for retrieval of leaf chlorophyll content of rice from digital images of smartphone under natural light (LicenseCC BY-NC-ND). *Photosynthetica*, *57*(2), 388-398, https://doi.org/10.32615/ps.2019.046

Munthali, N., Leeuwis, C., van Paassen, A., Lie, R., Asare, R., van Lammeren, R., & Schut, M. (2018). Innovation intermediation in a digital age: Comparing public and private new-ICT platforms for agricultural extension in Ghana. *NJAS - Wageningen Journal of Life Sciences*, *86-87*, 64–76. https://doi.org/10.1016/j.njas.2018.05.001Getrightsandcontent

Nedelkoska, L., & Quintini, G. (2018). Automation, skills use and training. *OECD Social, Employment and MigrationWorking Papers*, *202*. https://doi.org/10.1787/2e2f4eea-en

Nonaka, I., & Takeuchi, H. (1995). *The knowledge creating company: How Japanese companies create the dynamics of innovation*. Oxford University Press.

OECD. (2018). *Innovation, agricultural productivity and sustainability in China*. The Organisation for Economic Co-operation and Development (OECD). https://www.oecd.org/publications/innovation-agricultural-productivity-and-sustainability-in-china-9789264085299-en.htm.

Ortiz-Crespo, B., Steinke, J., Quirós, C. F., van de Gevel, J., Daudi, H., Gaspar Mgimiloko, M., & van Etten, J. (2021). User-centred design of a digital advisory service: Enhancing public agricultural extension for sustainable intensification in Tanzania. *International Journal of Agricultural Sustainability*, *19*(5-6), 566–582. https://doi.org/10.1080/14735903.2020.1720474

Oyinbo, O., Chamberlin, J., & Maertens, M. (2020). Design of digital agricultural extension tools: Perspectives from extension agents in Nigeria. *Journal of Agricultural Economics*, *71*(3), 798–815. https://doi.org/10.1111/1477-9552.12371

Pant, L. P., & Hambly Odame, H. (2017). Broadband for a sustainable digital future of rural communities: A reflexive interactive assessment. *Journal of Rural Studies*, *54*, 435–450. https://doi.org/10.1016/j.jrurstud.2016.09.003

Polanyi, M. E. (1966). *The tacit dimension*. Doubledge.

Powlson, D., Norse, D., Chadwick, D., Lu, Y., Zhang, W., Zhang, F., Huang, J., & Jia, X. (2014). Contribution of improved nitrogen fertilizer use to development of a low carbon economy in China. *World Agriculture*, *4*(2), 10–18. http://www.world-agriculture.net/article/contribution-of-improved-nitrogen-fertilizer-use-to-development-of-a-low-carbon-economy-in-china

Rijswijk, K., Klerkx, L., Bacco, M., Bartolini, F., Bulten, E., Debruyne, L., Dessein, J., Scotti, I., & Brunori, G. (2021). Digital transformation of agriculture and rural areas: A socio-cyber-physical system framework to support responsibilisation. *Journal of Rural Studies*, *85*, 79–90. https://doi.org/10.1016/j.jrurstud.2021.05.003

Röling, N., & Jiggins, J. (1998). The ecological knowledge system. In N. Röling, & M. A. Wagermakers (Eds.), *Facilitating sustainable agriculture: Participatory learning and adaptive management in times of environmental uncertainty* (pp. 283–311). Cambridge University Press.

Rose, D. C., & Chilvers, J. (2018). Agriculture 4.0: Broadening responsible innovation in an era of smart farming. *Frontiers in Sustainable Food Systems*, *2*. Article no. 87. https://doi.org/10.3389/fsufs.2018.00087

Rose, D. C., Wheeler, R., Winter, M., Lobley, M., & Chivers, C.-A. (2021). Agriculture 4.0: Making it work for people, production, and the planet. *Land Use Policy*, *100*. Article no. 104933. https://doi.org/10.1016/j.landusepol.2020.104933Getrightsandcontent

Rowley, J. E. (2007). The Wisdom hierarchy: Representations of the DIKW hierarchy. *Journal of Information Science*, *33*(2), 163–180. https://doi.org/10.1177/0165551506070706

Salemink, K., Strijker, D., & Bosworth, G. (2017). Rural development in the digital age: A systematic literature review on unequal ICT availability, adoption, and use in rural areas. *Journal of Rural Studies*, *54*, 360–371. https://doi.org/10.1016/j.jrurstud.2015.09.001

Silvestri, S., Richard, M., Edward, B., Dharmesh, G., & Dannie, R. (2021). Going digital in agriculture: How radio and SMS can scale-up smallholder participation in legume-based sustainable agricultural intensification practices and technologies in Tanzania. *International Journal of Agricultural Sustainability*, *19*(5-6), 583–594. https://doi.org/10.1080/14735903.2020.1750796

Snowdon, P. (2003). Knowing how and Knowing that: A distinction reconsidered. *Proceedings of The Aristotelian Society*, *104*(1), 1–29. https://doi.org/10.1111/1467-9264.t01-1-00001

Steinke, J., van Etten, J., Müller, A., Ortiz-Crespo, B., van de Gevel, J., Silvestri, S., & Priebe, J. (2021). Tapping the full potential of the digital revolution for agricultural extension: An emerging innovation agenda. *International Journal of Agricultural Sustainability*, *19*(5-6), 549–565. https://doi.org/10.1080/14735903.2020.1738754

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature Biotechnology*, *418*, 671–678. https://doi.org/10.1038/nature01014

Tsan, M., Totapally, S., Hailu, M., & Addom, B. K. (2019). *The digitalization of African agriculture report 2018-2019: Executive summary*: CTA/Dalberg Adviser.

Vrain, E., & Lovett, A. (2016). The roles of farm advisors in the uptake of measures for the mitigation of diffuse water pollution. *Land Use Policy*, *54*, 413–422. https://doi.org/10.1016/j.landusepol.2016.03.007

Walter, A., Finger, R., Huber, R., & Buchmann, N. (2017). Opinion: Smart farming is key to developing sustainable agriculture. *Proceedings of the National Academy of Sciences*, *114*(24), 6148–6615. https://doi.org/10.1073/pnas.1707462114

Wyche, S., & Steinfield, C. (2016). Why don't farmers Use cell phones to access market prices? Technology affordances and barriers to market information services adoption in rural Kenya. *Information Technology for Development*, *22*(2), 320–333. https://doi.org/10.1080/02681102.2015.1048184

Yoon, B. K., Tae, H., Jackman, J. A., Guha, S., Kagan, C. R., Margenot, A. J., Rowland, D. L., Weiss, P. S., & Cho, N.-J. (2021). Entrepreneurial talent Building for 21st century agricultural innovation. *ACS Nano*, *15*(7), 10748–10758. https://doi.org/10.1021/acsnano.1c05980

Yuan, F., Tang, K., & Shi, Q. (2021). Does Internet use reduce chemical fertilizer use? Evidence from rural households in China. *Environmental Science and Pollution Research*, *28*(5), 6005–6017. https://doi.org/10.1007/s11356-020-10944-4

Zhang, W., Cao, G., Li, X., Zhang, H., Wang, C., Liu, Q., Chen, X., Cui, Z., Shen, J., Jiang, R., Mi, G., Miao, Y., Zhang, F., & Dou, Z. (2016). Closing yield gaps in China by empowering smallholder farmers. *Nature*, *537*(7622), 671–674. https://doi.org/10.1038/nature19368

Zhao, J., Luo, Q., Deng, H., & Yan, Y. (2008). Opportunities and challenges of sustainable agricultural development in China. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 893–904. https://doi.org/10.1098/rstb.2007.2190

Zhu, Z. L., & Chen, D. L. (2002). Nitrogen fertilizer use in China – contributions to food production, impacts on the environment and best management strategies. *Nutrient Cycling in Agroecosystems*, *63*(2/3), 117–127. https://doi.org/10.1023/A:1021107026067