Agricultural Systems 203 (2022) 103492

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Relatives, neighbors, or friends: Information exchanges among irrigators on new on-farm water management tools☆

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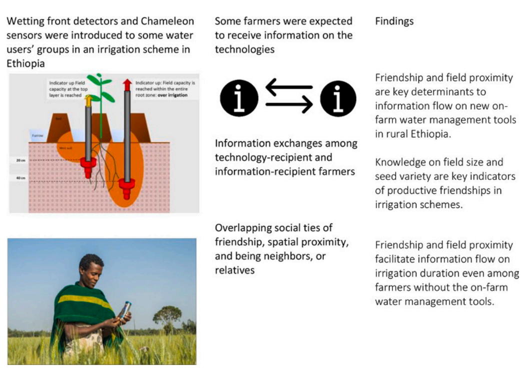
HIGHLIGHTS

- Friendship and field proximity are key determinants to information flow on new on-farm water management tools in Ethiopia.
- Knowledge on field size and seed variety are key indicators of productive friendships in irrigation schemes.
- Friendship and field proximity facilitate information flow on irrigation duration even among farmers without the tools.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Laurens Klerkx

Keywords:
Irrigation
Technology recipient group
Information recipient group
Purposeful friendship
Spatial proximity
Information flow

ABSTRACT

CONTEXT: On-farm water application in Ethiopia, as in much of Sub-Saharan Africa, is dominated by furrow irrigation, which resulted in inefficient water uses and related economic and environmental problems. A recent project introduced two on-farm water management tools, called wetting front detectors and Chameleon sensors, to some farmers in Koga irrigation scheme and facilitated for other farmers in the quaternary canal, who did not receive the technology, to learn from farmers who installed the tools on their plots.

OBJECTIVES: The objective of this study is to investigate the role of different social ties on information exchanges among farmers when some farmers have the signal on how long to irrigate a field during an irrigation event from on-farm water management tools. The study explored the relative importance of being neighbors, friends, spatial proximity of farms, and project induced pairings.

☆ This work was funded by the CGIAR Research Program on Water, Land, and Ecosystems (WLE). The authors thank Desalegn Tegegne, Claudia Ringler, Gashaw Abate, Tekie Alemu, Getachew Adane, Natnael Teka, Eyouel Yimer, Lisa-Maria Rebelo, and Stefan Uhlenbrook for their help and support. We also thank two anonymous reviewers and the guest editor of Agricultural Systems for their useful comments and suggestions on an earlier version of the manuscript. Any and all errors are the sole responsibility of the authors.

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https://doi.org/10.1016/j.agsy.2022.103492
Received 7 February 2022; Received in revised form 5 June 2022; Accepted 24 August 2022
Available online 6 September 2022

METHODS: The study used a household survey data from all members of quaternary canals in the project that were in the technology, information, and control groups, as well as detailed network modules on how farmers with plots in the quaternary canal are associated with each other. A fixed effects econometric approach is used to control for time invariant household level and quaternary canal characteristics, while teasing out how the different social ties affect the information flow.

RESULTS AND CONCLUSIONS: The results show that being in purposeful friendships as indicated by knowing each other's decision on the use of agricultural inputs and its outcome, as well as being spatially proximate as indicated by having farm plots next to each other or usually passing by each other's plots play a significant role in determining whether information-recipient farmers received information from the technology-recipient farmers as expected. Being relatives or neighbors played a minor role to facilitate information exchanges on how long to irrigate. In addition, ad-hoc pairs of farmers between technology-recipient and information-recipient created through the project within the quaternary canal did not play a significant role above and beyond the existing social ties of friendships and spatial proximity.

SIGNIFICANCE: The findings have implications for effective ways of targeting in future scale up of such technologies as it informs that the roll out of such type of technologies and the extension services around it can better help technology diffusion and learning if they use friends and spatial proximates as anchors of information. That is, at times of over-subscription to such on-farm water management tools, information about the technology and the recommended duration of one irrigation turn can diffuse faster if the limited number of tools are distributed in such a way that friends and spatial proximates have access to a tool, rather than distributing the tools based on being neighbors or relatives.

1. Introduction

Irrigation development has become the cornerstone of agricultural development in Ethiopia in the last few years. The newly elected government in 2021 established a separate Ministry of Irrigation and Lowlands, signaling the government's priority to develop the country's irrigation potential. So far, the country has developed less than 10% of its irrigation potential. Almost all of the existing irrigation developments in the country use furrow irrigation to apply water on agricultural fields, creating economic and environmental problems. Soil salinity is already an issue in some large-scale irrigation schemes (Awulachew, 2010). Adhanom (2019) cautioned that there will be a potential danger of sodicity and actual salinity development in some irrigation schemes in Ethiopia and recommended that proper irrigation methods should be designed to preserve soil fertility and therefore productivity in these areas. The lack of functional drainage systems and poor water management practices have significantly contributed to the frequent occurrence of waterlogging and salt build-up in irrigation fields (Gebrehiwot, 2018).

Improving irrigation practices with the adoption of modern irrigation methods such as sprinkler, drip, and sub-surface drip is expected to bring considerable advancement in agricultural water management. An alternative path towards improved water management in irrigation has shifted the irrigation scheduling question from 'when to turn the water on' to 'when to turn the water off' (Stirzaker et al., 2007). Wetting front detectors (WFD) and Chameleon sensors are two technologies that inform farmers when enough water has reached the root zone, and enhance their knowledge and decision making in irrigation. The WFD, is a funnel-shaped device buried in the soil with an indicator above the soil surface, with the indicator turning-up when the field capacity reaches both the top layer and the entire root zone. The Chameleon soil moisture sensor consists of an array of three or four sensors that are permanently installed at different depths in the soil. A portable hand-held reader is connected to each sensor array and displays the soil moisture as colored lights (blue - wet soil, green - moist soil, or red - dry soil) (Stirzaker et al., 2007]. Illustrations of WFD and Chameleon sensors are provided in Figs. A.1 and A.2 in the appendix.

In 2017, an FAO water-productivity project introduced WFD and Chameleon sensors in Koga irrigation scheme in Ethiopia - an irrigation scheme with a command area of 7000 ha comprised of twelve irrigation blocks. The project was implemented in 90 quaternary canals (also called water user groups) located in six irrigation blocks of the scheme. A total of 1051 farmers were irrigating in these 90 quaternary canals, whereas there were 144 WFDs and 72 Chameleon sensors from the project. To deal with this over-subscription and also to explore the extent of information exchange among farmers, 36 quaternary canals were selected for intervention with Wetting Front Detectors (WFD), 18 with Chameleon sensors, and the remaining 36 quaternary canals were controls with no technology intervention. Each quaternary canal has one water users' group and serves an average of 10 farmers. The WFD and Chameleon sensors were installed in the plots of three to four farmers in a quaternary canal and the remaining farmers in the quaternary canal were assigned to the information group. Farmers in the quaternary canal created ad-hoc technology-information pairs that indicate which technology-recipient farmer is expected to provide information to which information-recipient farmer. Details of the project implementation are provided by Haileslassie et al. (2016) and Schmitter et al. (2017).

The on-farm water management tools are expected to provide both social and private benefits. Privately, the information exchange helps to change the water application practice of individual farmers, and the improvement in water application practice provides several individualized benefits to the farmer (such as reducing irrigation timing, saving labor time, reducing water logging and salinization problems on the field) (see Parry et al. (2020) and Abebe et al. (2020)). Socially, improved water application practices provide environmental benefits (such as availing more water to downstream users from reduced on-farm water application upstream and reducing water management-related conflicts (Chilundo et al., 2020; Mdemu et al., 2020; Moyo et al., 2020; Abebe et al., 2020; Grigg, 2008).

This study looked at the role of different social ties on information exchanges among farmers regarding the duration of water application on a field in one irrigation turn. The model used in the study control for all observed and unobserved characteristics of individual farmers that do not vary based on whom they are paired with, conditional on a number of social ties between the pairs. The model controls for observed and unobserved characteristics of the quaternary canal such as being located upstream or downstream of the tertiary canal or the characteristics of the irrigation block within which the quaternary canal is located. The result shows that being in purposeful friendships as indicated by knowing each other's decision on the use of agricultural inputs and its outcome, as well as being spatial proximates as indicated by having farm plots next to each other or usually passing by each others' plots play a significant role in determining whether information-recipient farmers received information from the technology-recipient farmers on how long it takes to irrigate a field in one irrigation turn. Being relatives or neighbors played a minor role to facilitate information exchanges on the on-farm water management tools. In addition, the ad-hoc pairs of farmers created by farmers within the quaternary canal to choose who could share information on the technology to whom did not play a significant role above and beyond the existing social ties of friendships and spatial proximity. The results have implications for effective ways of targeting in future scale up of such technologies because the roll out of such type of technologies and the extension services around it can better help technology diffusion and learning if they use friends and spatial proximates as anchors of information on the new water management technologies. That is, at times of over-subscription to such on-farm water management tools, information about the technology and the recommended duration of one irrigation turn can diffuse faster if the limited number of tools are distributed in such a way that friends and spatial proximates have access to a tool, rather than distributing the tools based on being neighbors or relatives.

2. Conceptual framework

The conceptual framework of the roll out of the on-farm water management tools considers three group of farmers. The first group is "technology-recipient" group. Farmers in this group have either WFD or Chameleon sensors installed on their plots. As a result, farmers with WFD and Chameleon sensors are referred to as "WFD technology-recipient" and "Chameleon technology-recipient" farmers, respectively. The second group is "information-recipient" group. Farmers in the "information-recipient" group are expected to receive information regarding on-farm water application timing from the "technology-recipient" farmers in their respective quaternary canal. Thus, farmers who are paired to receive on-field water application information from WFD and Chameleon technology recipients are referred to as "WFD information-recipients" and "Chameleon information-recipients", respectively. The technology-recipient farmers do get signals from the technology on when to stop irrigating their field and the information on how long the technology-recipient farmer took him/her to irrigate his/her field is expected to flow to information-recipient farmers within their quaternary canal. The third group of farmers are neither technology recipients nor information recipients, which we called control farmers. These farmers serve as a control group and their plots are found in different quaternary canals. On the other hand, there are overlapping social relationships between these technology and information recipient farmers that could serve as platforms to exchange information among them. As such, farmers having irrigated plots in the quaternary canal can have at least five main types of possibly overlapping relationships as they can be (i) relatives, (ii) neighbors,[1] (iii) friends, (iv) spatial proximates, or (v) ad-hoc pairs. These relationships are depicted in Fig. 1.

Information on whether two farmers within a quaternary canal are relatives or friends is directly solicited from respondents using a detailed network module that captures all possible pairings of farmers in a quaternary canal and how they are related to each other. Friendship in this context refers to purposeful relationships that allow one farmer to know more about the production decisions of another farmer. Thus, we have used four indicators of purposeful friendships - whether farmer *i* knows the size of irrigated plots of farmer *j*, the amount he produces, and the seed variety and quantity of fertilizer he uses on his irrigated plot. Farmer *i* is defined as a spatial proximate for farmer *j* if he has plots next to farmer *j* or he usually passes by *j*'s plots. The ad-hoc pairs are farmers who are expected to receive or provide information about the WFD or Chameleon technology, depending on the quaternary canal they belong to. These ad-hoc pairings were done by the farmers and their water users' groups and dictate who is expected to get information from whom. We call these ad-hoc because they are network ties formed during the project implementation within the quaternary canals. These ad-hoc ties are likely to overlap with other social and spatial ties as farmers and water users' groups are likely to take into account existing ties, but it would be interesting to know if they would have any additional information content after explicitly controlling for the existing social and spatial relationships.

Moreover, given that only half of the farmers in the information group reported receiving information on the water management tools from farmers in the technology group, understanding the role of each type of social relationships in the flow of information would have important implications for scaling irrigation technologies elsewhere. Though social networks and linkages facilitate learning and information diffusion among farmers (Schmidtner et al., 2012; Skaalsveen et al., 2020; Hounkonnou et al., 2012), the level of learning, knowledge sharing, and adoption of practice vary across and within the networks (Valente, 1996; Bandiera and Rasul, 2006). For instance, Haensch et al. (2019) argue that neighborhood increases the rate of information flow through communication between neighbors. Krishnan and Patnam (2014) found learning effects from neighbors for adoption of improved seed and fertilizer in Ethiopia. Liverpool-Tasie and Winter-Nelson (2012) related effective social networks to purposeful interaction and friendship for agricultural technology diffusion. The effectiveness of learning and technology diffusion also depends on the characteristics of the farmers such as poverty levels (Liverpool-Tasie and Winter-Nelson, 2012; Magnan et al., 2015) where the networking effect is strong for poorer farmers, and gender of the network actors (Beaman and Dillon, 2018) where women are shown as the most disadvantaged group in network information sharing platforms. Apart from grouping in a network, intimacy in the social network increases the trustworthiness of information disseminated (Wang et al., 2020). For instance, in Vietnam, kinship and neighbor networks are the most trusted channels of communication and sources of advice for farm matters and the adoption of new technologies (Hoang et al., 2006). Technology adoption is also shown to be similar among networks of relatives (Ramirez, 2013).

The effectiveness of the information diffusion varies by the characteristics of the person expected to relay information to others. For instance, Taylor and Bhasme (2018) argue that model farmers play a role in transferring knowledge effectively to other farmers. The social identity of the communicators also determines both learning and adoption of the end-user (BenYishay and Mobarak, 2014). Overall, the success of the network widely depends on farmers' objectives, personal characteristics, and types of approaches or innovations that the farmer wishes to implement (Cofré-Bravo et al., 2019).

3. Data and descriptive analysis

Farm level data was collected from 1051 households in six blocks in the Koga irrigation scheme. These farm households belong to 90 quaternary canals. Farmers in a quaternary canal belonged (i) to a control group, which means no deliberate effort was done by the project to provide access to any technology or information, or (ii) a WFD or Chameleon group, which means WFDs or Chameleon sensors were distributed to famrers in the quaternary canal. Assignment of farmers in these groups was based on a consultative process that includes farmers, water user committee members, scheme managers, agronomists, and extension agents (Schmitter et al., 2017). Within the two technology groups, water user members decided which farmer received the technology, who received the information, and which information farmer received information from which technology farmer. The household survey showed, 16% of the farmers were in WFD technology groups, 7% were in Chameleon technology groups, 25% were in WFD information groups, 14% were in Chameleon information groups, and the remaining 38% were in control groups where the technologies were not installed on the plot of any farmer in their quaternary canal. We also asked farmers how they ended up in their respective groups. Their responses confirm that assignment to a group was not random as either they were interested to join the group or were recommended by other farmers,

[1] In this paper, 'neighbors' refer to individuals whose homesteads in the village are nearby each other, while "spatial proximate" is defined based on the location of farms (a person who has a plot next to the other person or passes by the plot of a farmer).

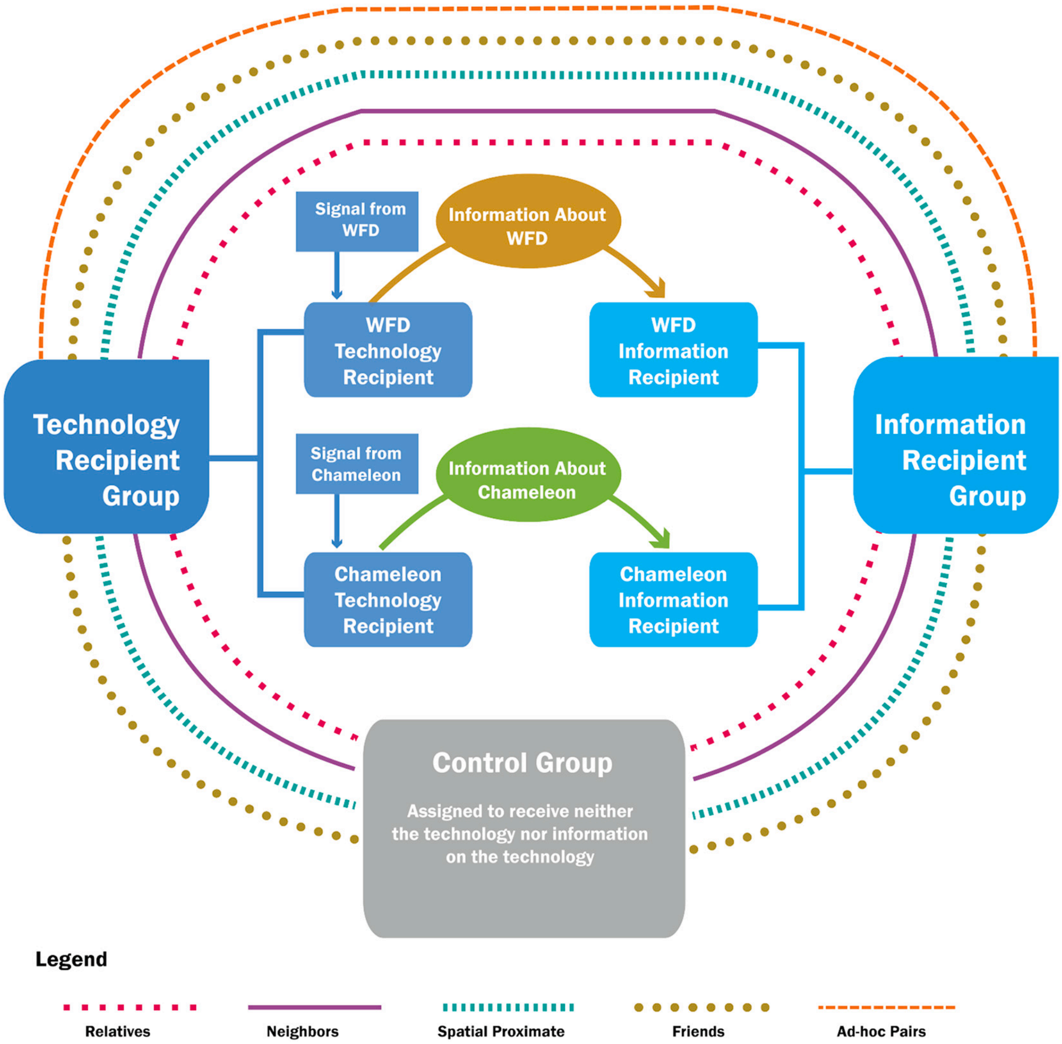

Fig. 1. Schematic of technology-recipient, information-recipient, and control farmers and the overlapping social and spatial ties.

extension agents, or water user committees to join a group.

Table 1 presents selected characteristics of households in our sample. Most of the sample households are male headed (93%) with an average age of 49 years, while only 37% of them can read or write in any language. The average household size in the sample is six, while the average size of land owned is about 1.4 ha. The estimated market value of livestock a household owns is about 85,600 Ethiopian Birr (about 1718 USD in January 2022 exchange rate). Moreover, 46% and 82% of respondents own radio and cellphone in the household, which are important assets for information acquisition and exchange. Only 7 % of households in the sample have access to electricity.

Table 1
Summary statistics of household characteristics.

Household Variables	Mean (N = 1051)	Std. Dev.	Min	Max
Head sex (1 = male)	0.934	0.248	0	1
Head age (years)	48.8	12.31	20	89
Head can read & write (1 = yes)	0.37	0.483	0	1
Head Education (Years)	1.691	2.546	0	16
Household Size (members)	5.944	2.045	1	12
Land size owned (hectares)	1.371	0.747	0.125	8.25
Total livestock owned (ETB)	85,600	54,667	0	431,000
Household owned radio (1 = yes)	0.457	0.498	0	1
Household owned cell phone (1 = yes)	0.817	0.387	0	1
Household has electricity (1 = yes)	0.073	0.261	0	1

Table 2 summarizes farmers' responses on access, sharing, application, and usefulness of the knowledge from the on-farm technologies and information about the technology in various groups. About 73% and 55% of farmers on whose plots the WFD and Chameleon technologies were installed reported that the technology helped them improve their water use on their irrigated plots. WFD and Chameleon recipient farmers were supposed to pass water use knowledge and information onto their respective fellow farmers in the ad-hoc information group. About 70% of WFD and 51% of Chameleon recipient farmers shared the knowledge and information to the information-recipient farmers, indicating that information flows on technologies may not always happen as intended and it gets worse for more complex technologies such as Chameleon sensors than simpler technologies such as WFDs. Majority of the technology-recipients who shared knowledge and information (80% in WFD and 85% in Chameleon) think that the information-recipient farmers used the knowledge and information on their plots. About 46% of farmers with WFD and 37% of farmers with Chameleon sensors reported that other farmers who do not have the technologies reached out to them to use the technologies on their own plots, showing decent levels of interest for the new technologies.

As the lower panel in Table 2 shows, only 61% and 55% of WFD information-recipient and Chameleon information-recipient farmers received information about the respective technologies. Less than half of

Table 2
Access to technologies, information, and farmers' perception on relevance and application of WFD and Chameleon sensors.

Variables (yes = 1, no = 0)	WFD			Chameleon		
	Obs	Mean	Std. Dev.	Obs	Mean	Std. Dev.
Technology groups						
Technology helped improve your water use	171	0.725	0.448	76	0.553	0.501
You shared the knowledge on the technology	171	0.696	0.461	76	0.513	0.503
Information receivers used the shared knowledge	120	0.800	0.402	41	0.854	0.358
Information receivers asked to use the technology	171	0.456	0.500	76	0.368	0.486
Still applying the experience after the technology is returned	171	0.491	0.501	76	0.316	0.468
Information groups						
Received information about the technology	260	0.608	0.489	145	0.545	0.500
The information helped improve your water use	158	0.449	0.499	79	0.456	0.501
You shared the information to others	159	0.333	0.473	79	0.418	0.496
Others used the information you shared	56	0.857	0.353	35	0.743	0.443
Still applying the information after the technology is returned	260	0.192	0.395	145	0.186	0.391

the information-recipient farmers who got information from on-farm water management technology users think that the information was helpful to improve their water use on irrigation plots. Furthermore, users who received information seem to have disseminated the information further to others, resulting in a cascading effect of information throughout the quaternary canals (33% and 42% of the WFD information-recipient and Chameleon information-recipient farmers, respectively). Most of the farmers who have shared information to others reported that other farmers used the information in their irrigation plots.

Sharing the knowledge and information from the technologies to others in their ad-hoc group is not as strong as expected. The main reason reported by farmers with the technologies for not sharing the knowledge and information to others is because they were not convinced about the relevance of the technology. As the technologies were installed on farmers' fields only for two irrigation seasons in 2017 and 2018, we asked technology-recipient and information-recipient farmers if they are still applying the experience and information they have acquired in the past. Their response shows that technology-recipient farmers are more likely to keep applying their knowledge gained from technologies than the information-recipient farmers. Specifically, nearly 44% of the technology users (about 49% from WFD and 32% from Chameleon sensors) and about 19% of the information recipients still apply the knowledge gained from the project. The result indicates that having hands-on experience of the technologies on one's plots has a learning effect that persists longer than the information acquired from others about the technology.

4. Empirical model

The empirical approach of the study models whether a household who was expected to receive information from a technology user has actually received the information and how this information exchange is affected by different social ties such as being relatives, neighbors, and friends. More formally:

$$y_{ijc} = X_{ij}\beta + \alpha_i + \alpha_j + \alpha_c + \varepsilon_{ijc} \quad (1)$$

where y_{ijc} denotes whether individual i (the information-recipient farmer) received the information about the on-farm water management tool from individual j (the technology-recipient farmer), where both i and j are in the same treatment cluster (quaternary canal of the irrigation system). α_i refers to all observed and unobserved characteristics of the information-recipient individual i, which does not vary by j. α_j refers to all observed and unobserved characteristics of the technology-recipient individual (j) providing information about the technology to the information-recipient farmers (i) in his or her quaternary canal, and hence does not vary by i. In other words, α_i captures the information-recipient's fixed effects while α_j captures the fixed effects of the technology-recipient farmer who is expected to provide information to other farmers. α_c refers to observed and unobserved characteristics of the quaternary canal such as being located upstream or downstream of the tertiary canal or the characteristics of the irrigation block within which the quaternary canal is located. ε_{ijc} is the idiosyncratic error term of the (i, j) pair in quaternary canal c.

The fixed effects transformation is used to eliminate α_i and α_c. α_j enters the estimating equation as a dummy (indicator) variable. Differences in cluster sizes cause no problems in this type of set up (Wooldridge, 2002). To account for correlations of ε_{ijc} in a quaternary canal (c), a robust covariance matrix is used with standard errors clustered within the quaternary canal. The number of clusters (quaternary canals) is large (259) compared to the number of units within a cluster (4 to 10), which enables the model to have good statistical properties (Wooldridge, 2002).

The relational variables in X include (i) whether household i and j are relatives, (ii) whether they are neighbors, (iii) indicators of spatial proximity as captured by whether they have plots next to each other and whether household i passes by the farm of household j, and (iv) indicators of strength of relationships as captured by whether household i knows the size of j's irrigated plot, the amount j produces on his/her irrigated plot, the type of seed variety on j's irrigated plot, the quantity of fertilizer on j's irrigated plot, and whether household i was assigned to get information on the on-farm water management tool from j. Note that our interest in this study is not in identifying peer effects, but in understanding social relationships that help or deter information exchange when one individual (j) is given a technology, and another individual (i) is expected to receive information about the technology from j. This helps us abstract away from the reflection problem identified by Manski (1993) - a subject of several network studies in economics.

It is theoretically possible for the four friendship proxies (knowing the other farmer's farm size, quantity of production, seed variety, and quantity of fertilizer used) to be a result of information sharing with potential reverse causality problem. However, in a rural Ethiopian set up where farmers lived together within a village for many years with several avenues and opportunities to be friends with each other, the new on-farm technology is unlikely to be the reason whether farmers are friends or not. To show this empirically, we have done a t-test of mean differences of the four friendship indicator variables when i is WFD information recipient and j is WFD technology recipient vs when both i and j are in the control groups. There is not statistically significant difference in reported friendship indicators between the two comparisons. Likewise, we have done a t-test of mean differences of the four friendship indicator variables when i and j are Chameleon information recipient and Chameleon technology recipients vs when both i and j are in the control group. Again, reported levels of friendships between farmers in the technology and information recipient groups is not statistically different from friendship levels reported when two farmers are in the control group. These results indicate that friendship is not induced by the introduction of the on-farm water-management tools but exists irrespective of the technology in this context. We have included the t-tests in Appendix Table A.1.

Eq. (1) is estimated as a linear probability model (LPM) panel fixed effects regression using STATA version 17 software. Though the dependent variables are binary in nature, we opt not to use a probit model because of its restrictive assumption on the relationship between unobserved effects and other included explanatory variables in a panel data context, which could lead to biased estimates when this strong assumption does not hold. Though conditional logit models can capture fixed effects, we opt not to use it because of the following reasons. First, the conditional logit estimator for panel data only allows replication-based clustering of standard errors such as jackknifing and bootstrapping or likelihood-based clustering such as observed information matrix but not sandwich estimators such as robust or cluster standard errors. Given the nature of the roll out of the on-farm water management tools, we have reason to believe that the standard errors are likely to be correlated within quaternary canals (c), which can easily be captured with LPM. Secondly, the conditional logit model is found to be difficult to converge in the presence of a large number of dummy fixed effects (j). Thirdly, panel fixed effects logistic models drop observations whose values do not vary over time, which would have resulted in a significant loss of observations in our context.

5. Results

Results from the fixed effects estimation of the information exchange between farmers is provided in Table 3. The dependent variables in columns (1) and (2) refer to whether the respondent (i) did receive information on how long the technology user in the same quaternary canal (farmer j) took to irrigate his field during one irrigation event. In column (1), the sample is restricted to the cases where the WFD technology is installed on farmer j's plot and farmer i is assigned to receive information from farmer j on the amount of irrigation needed according to the WFD technology. In column (2), the sample is restricted to the cases where the Chameleon sensor is installed on farmer j's plot and farmer i is assigned to receive information on the sensor from farmer j. The results in columns (3) and (4) of Table 3 show estimation of the model from the perspective of technology-recipient farmers who were expected to provide information about the technology to information-recipient farmers of the respective technology. Thus, the dependent variables in columns (3) and (4) refer to whether the respondent did provide information on how much he took to irrigate his field in one turn to the information-recipient farmer. In column (3), the sample is restricted to the cases where the WFD technology is installed on farmer i's plot and farmer j is assigned to receive information from the technology-recipient farmers. In column (4), the sample is restricted to the cases where the Chameleon sensor technology is installed on farmer i's plot and farmer j is assigned to receive information from the technology-recipient farmers. The results are described below.

5.1. *Friendship and spatial proximity are key determinants to information flow between technology-recipient and information-recipient farmers*

The results show that three types of social ties - being relatives, neighbors, and ad-hoc pairs - did not play a significant role for the information group to receive information from technology users (columns (1) and (2) of Table 3). Rather, being friends and spatial proximates played a significant role in determining whether households in the information group received information. As shown in Section 2, farmers i and j are spatial proximates if they have plots next to each other or if one usually passes by the other's plot. The result shows that having plots next to each other improves the likelihood of receiving information from farmers with the WFD technology by 3.8 percentage points (column 1 of Table 3). When a farmer in the information group usually passes by the plot of a technology user, the likelihood of farmers receiving information on how long to irrigate a field increases by 5.1 percentage points for the Chameleon technology (column 2 of Table 3). Friendships in this analysis is captured by indicators of purposeful or productive friendships that can be reflected in farmer i knowing about details of the input decisions and production levels of farmer j. When farmer i knows the size of j's irrigated plot, then he is 18.9%age points and 9.5 percentage points more likely to receive information on how long farmer j took to irrigate

Table 3
Fixed effects estimation of information exchange on on-farm water management tools.

Variables	(1)	(2)	(3)	(4)	(5)
	Receive Information on		Provide Information on		Discuss how much to irrigate
	WFD	Chameleon	WFD	Chameleon	
Are relatives	−0.0205	0.0323	−0.0257	−0.0159	0.0163
	(0.0242)	(0.0356)	(0.0289)	(0.0355)	(0.0105)
Are neighbors	0.0152	0.0175	0.0512**	−0.0120	0.00997
	(0.0266)	(0.0348)	(0.0233)	(0.0407)	(0.0103)
Have plots next to each other	0.0378*	0.00167	−0.0206	−0.00627	0.0187*
	(0.0200)	(0.0290)	(0.0286)	(0.0316)	(0.00948)
Usually pass by j's plots	0.0321	0.0510**	0.0679**	0.0993*	0.0630***
	(0.0206)	(0.0235)	(0.0329)	(0.0546)	(0.0103)
Knows the size of j's irrigated plots	0.189***	0.0948**	0.0912**	0.166**	0.142***
	(0.0380)	(0.0386)	(0.0407)	(0.0788)	(0.0196)
Knows amount j produces on his irrigated plot	−0.00781	0.0143	−0.00699	−0.0203	0.00746
	(0.0309)	(0.0215)	(0.0235)	(0.0481)	(0.0103)
Knows the seed variety on j's irrigated plot	0.0924**	0.0593*	0.0885**	0.166**	0.0921***
	(0.0441)	(0.0303)	(0.0364)	(0.0717)	(0.0141)
Knows amount of fertilizer on j's irrigated plot	0.0171	−0.0358	−0.0391	−0.00411	−0.0141
	(0.0374)	(0.0240)	(0.0359)	(0.0401)	(0.0138)
Expected to receive tech info from j (ad-hoc pair)	0.0160	−0.0343			
	(0.0264)	(0.0279)			
Expected to share tech information to i (ad-hoc pair)			−0.0280	−0.0350	
			(0.0338)	(0.0364)	
Constant	0.603***	0.743***	0.720***	0.605***	0.659***
	(0.0430)	(0.0371)	(0.0583)	(0.0973)	(0.0200)
Observations	1097	605	1053	598	7331
R-squared	0.328	0.266	0.434	0.504	0.310
Number of individuals	276	146	153	75	651

Robust standard errors in parentheses.
*** $p<0.01$.
** $p<0.05$.
* $p<0.1$.

his field in one irrigation turn when WFD and Chameleon sensors are installed on farmer *j*'s plot. When farmer *i* knows the seed variety on farmer *j*'s irrigated plot, he is 9.2 and 5.9 percentage points more likely to receive information on how long *j* took to irrigate his field in one turn when WFD and Chameleon sensors are installed on farmer *j*'s plot. Irrigation water requirement is a function of the size of the irrigated field and the type of crop [and crop variety] as some crops and crop varieties are water-intensive while others tolerate soil-moisture stress. The information flow on the recommended duration to irrigate a field from the technology-recipient farmers to information-recipient farmers becomes more meaningful if the two farmers know each other's field size and crop variety – hence facilitating information exchanges about the appropriate duration of an irrigation event.

Similar to the results when the model was run from the perspective of information-recipients, the results in columns (3) and (4) of Table 3 show that being relatives and ad-hoc pairs did not play a significant role for technology-recipients to provide information on how long to irrigate a field to the information-recipients, whereas being friends and a spatial proximate play a positive role. When farmer *i* in the technology group usually passes by the plots of farmers in the information group, the likelihood of relaying information on how long it took him to irrigate a field in one irrigation turn increases by 6.8 and 9.9 percentage points for the WFD and Chameleon sensors, respectively. When the technology-recipient knows the size of irrigated land of the information-recipient, the likelihood of relaying information on how long it took him to irrigate a field in one irrigation turn increases by 9.1 and 16.6 percentage points for the WFD and Chameleon sensors, respectively. Likewise, when the technology-recipient knows the seed variety on the information-recipient's irrigated plot, he is 8.9 and 16.6 percentage points more likely to share information on how long it took him to irrigate a field in one irrigation turn.

Unlike the case from the perspective of information recipients, column 3 shows that being neighbors also increases the likelihood of information provision by the technology-recipient farmers to the information-recipient farmers (by 5.1 percentage points) in the case of the WFD technology. Theoretically, the regression results from the information recipients' perspective (columns 1 and 2) must be identical to estimation results from the information providers' perspective (columns 3 and 4). In reality, however, asymmetry may exist. For example, the senders are always aware of their information-sending activity, but the receiver sometimes do not recognize the information they received - an issue that can be further investigated in future research.[2]

The above results hold true when farmers are asked a slightly general question on if he or she ever discusses with the other person to irrigate more or less (column 5 of Table 3). Farmers who have plots next to each other, who usually pass by each others' irrigated plots, who knows the size of each others' irrigated plots, and who knows the seed variety on each others' irrigated plots are 1.9, 6.3, 14.2, and 9.2 percentage points more likely to discuss with each other on whether to irrigate more or less compared to farmers who do not have such ties.

5.2. *Knowledge on field size and seed variety are key indicators of productive friendships in irrigation schemes*

When a technology-recipient farmer *i* knows the size of the irrigated plot of the information-recipient farmer, he is 9.1 percentage points and 16.6 percentage points more likely to provide information on how long he took to irrigate his field in one irrigation turn when WFD and Chameleon sensors are installed in the plots of the technology user. When a technology-recipient farmer knows the seed variety of the information-recipient farmer, he is 8.9 and 16.6 percentage points more likely to provide information on how long he took to irrigate his field in one irrigation turn when WFD and Chameleon sensors are installed in the plots of the technology-recipient farmer.

5.3. *Friendship and field proximity facilitate information flow among farmers in the control quaternary canals*

The results above indicate that pre-existing social ties in the form of friendships and being spatial proximate (and being neighbors in the case of provision of information on WFD technologies) are important platforms to exchange information on new on-farm water management technologies while ad-hoc ties that paired certain farmers who received the technology with other farmers did not have significant impact, conditional on the presence of the other social ties. To investigate this further, we have restricted the analysis to farmers in the control quaternary canals. No one in these quaternary canals was provided with the technologies but they were asked whether they received or provided information to other farmers in their group on duration of one irrigation turn on their field in the last three years and whether they ever discussed to irrigate more less with each other. The result is provided in Table 4 below.

Even though these farmers were in the control group, being a spatial proximate (where they usually pass by each others' plots) and being in purposeful friendships (knowing the land size and seed variety on each others' irrigated plots) determine whether they share information on how much time they took to irrigate their field in one irrigation turn (Table 4).

6. Conclusions

Over-irrigation of water in many modern and semi-modern irrigation schemes is causing significant environmental challenges such as waterlogging and salinity that affected the sustainability of irrigation in many developing countries. Soil moisture based agricultural water management tools such as wetting front detectors (WFDs) and Chameleon sensors that provide information when enough moisture is available in the top soil and root zone of a plant could be promising tools to

Table 4
Fixed effects estimation of information exchange on on-farm water management tools within control quaternary canals.

Variables	(1) Information received	(2) Information provided	(3) Irrigation timing discussed
Are relatives	0.00738	0.0111	0.0177
	(0.0141)	(0.0130)	(0.0133)
Are neighbors	0.00467	0.00345	0.0130
	(0.0126)	(0.0138)	(0.0129)
Have plots next to each other	0.0102	0.0167	−0.00587
	(0.0109)	(0.0101)	(0.0105)
Usually pass by *j*'s plots	0.0509***	0.0549***	0.0711***
	(0.0118)	(0.0121)	(0.0135)
Knows the size of *j*'s irrigated plots	0.161***	0.142***	0.132***
	(0.0322)	(0.0271)	(0.0225)
Knows amount *j* produces on his irrigated plot	−0.00101	−0.00420	0.00603
	(0.0124)	(0.0160)	(0.0160)
Knows the seed variety on *j*'s irrigated plot	0.0940***	0.0934***	0.106***
	(0.0179)	(0.0196)	(0.0206)
Knows amount of fertilizer on *j*'s irrigated plot	0.0305*	0.0272	0.0151
	(0.0176)	(0.0194)	(0.0183)
Constant	0.606***	0.608***	0.594***
	(0.0295)	(0.0282)	(0.0278)
Observations	4382	4382	4382
R-squared	0.336	0.349	0.382
Number of individuals	398	398	398

Robust standard errors in parentheses.
*** $p<0.01$.
* $p<0.1$.

[2] We acknowledge an anonymous referee for pointing this out.

improve on-farm agricultural water management. The WFD, for instance, was awarded the WATSAVE Award for “Conservation of Water in Agriculture” by the International Commission for Irrigation and Drainage in 2003 (Stirzaker et al., 2007) and Schmitter et al. (2017) reported that the adoption of WFD and Chameleon sensors helped to reduce on-farm water application and improved water productivity by about 9 percent in the Koga irrigation scheme in Ethiopia. Liverpool-Tasie and Winter-Nelson (2012), Haensch et al. (2019), Chilundo et al. (2020), Mdemu et al. (2020), Moyo et al. (2020), and Wang et al. (2020) reported the key role of purposeful interaction, friendship and spatial proximity in promoting technology or information diffusion than residential proximities. Similarly, Taylor and Bhasme (2018) and Takahashi et al. (2020) argued learning has facilitated more effectively when the information provider and receiver have something in common such as friendships.

Though these on-farm water management tools, particularly WFD, are cheaper than many alternatives of precision irrigation, they are still beyond the reaches of many smallholder irrigators in Sub-Saharan Africa. Thus, an alternative model of adoption for such technologies is to install these tools on some farms and let other farmers without the technology and with similar soil characteristics and crop choices learn from the farmers on whose fields the tools are installed. But what is the optimal way of grouping farmers into technology and information groups to facilitate better exchange of the information from the technology on the optimal duration of an irrigation turn? Would such information flow better among relatives, neighbors, friends, or close farms? Would prior assignment or pairing of farmers to determine who gets information from which farmer help in the information flow? This study provides answers to these questions in the context of Koga irrigation project where an FAO water productivity project introduced WFD and Chameleon sensors in 2017.

The project had three groups of farmers. The first group is the technology group that comprises farmers on whose plots either the WFD or Chameleon sensors were installed. The second group is the information group and refers to farmers without the technology having plots within the same quaternary canal as in the technology group. A project specific ad-hoc pairing of technology and information farmers were established that indicates which information-recipient farmer is expected to get information from which technology-recipient farmer. The third group is a control group that was assigned neither to the information nor the technology groups. The control groups are in different quaternary canals and no farmer had the the technology in their quaternary canal.

In addition to the ad-hoc pairs of farmers, there are at least four more existing social ties between the farmers as they can be relatives, neighbors, friends, or have plots next to each other or usually pass by each others’ plots (which we called spatial proximates). Friendship in this study is defined as purposeful friendship where one person knows the details of input decisions and levels of agricultural production of another person. In addition to these relationships, the analysis controls for farmer specific and quaternary-canal specific observed and unobserved characteristics that can influence information exchanges between farmers in the technology and information groups. The approach also takes into account the correlations of farmers’ responses across different farmers in their quaternary group by using a robust covariance matrix with standard errors clustered within the quaternary canal.

The result shows that being relatives and ad-hoc pairs did not play a significant role for the technology-recipient farmers to provide information on how long to irrigate a field to the information-recipient farmers, whereas being friends and a spatial proximate play a positive role. In particular, two indicators of purposeful friendships, i.e., knowing the size of irrigated plots of the other person and the seed variety the other person used on his irrigated plot, stand out as the most important linkages to facilitate information exchanges on the technology. From indicators of spatial proximity of farms, farmers who usually pass by each other’s plots are found to provide or receive information on how long they take to irrigate their fields in one irrigation turn. The results indicate that when farmers know each other well, and when transaction costs of information exchanges are reduced among farmers, such as when they usually pass by each other’s plots, then information flow about the new water management tools can be better facilitated among farmers with the technology and those without. Moreover, at times of over-subscription to such on-farm water management tools, information about the technology and the recommended duration of one irrigation turn can diffuse faster if the limited number of tools are distributed in such a way that friends and spatial proximates have access to a tool, rather than distributing the tools based on being neighbors or relatives.

The findings of the study provide insights for effective ways of targeting for scaling up of such technologies and for the broader application of networking for farming practices. The design of information exchanges between farmers with new on-farm water management tools and farmers without the technology needs to consider the strongest social ties among farmers than ad-hoc pairing and need to find ways to reduce the transaction cost of receiving or providing information to other farmers.

Declaration of Competing Interest

Authors have no competing interests to disclose.

Appendix A

Table A.1
Friendship status between farmers with technology linkages and those in the control group.

Farmer i knows j’s	(1)	(2)	(3)	(4)	(5)	(6)
	WFD (i, j) (info, tech)	Control (i, j) (control, control)	Difference	Chameleon (i, j) (info, tech)	Control (i, j) (control, control)	Difference
Farm size	0.733	0.743	−0.011	0.749	0.743	0.006
Quantity of production	0.111	0.106	0.005	0.132	0.106	0.026
Seed variety	0.655	0.632	0.023	0.632	0.632	0
Quantity of fertilizer used	0.071	0.07	0.001	0.099	0.07	0.029
Number of Observations	5319	5319	5319	4828	4828	4828

Note: info refers to farmer is information-recipient; tech refers to farmer is technology-recipient.
None of the mean differences are statistically significantly at the 1%, 5%, or 10% levels of significance.

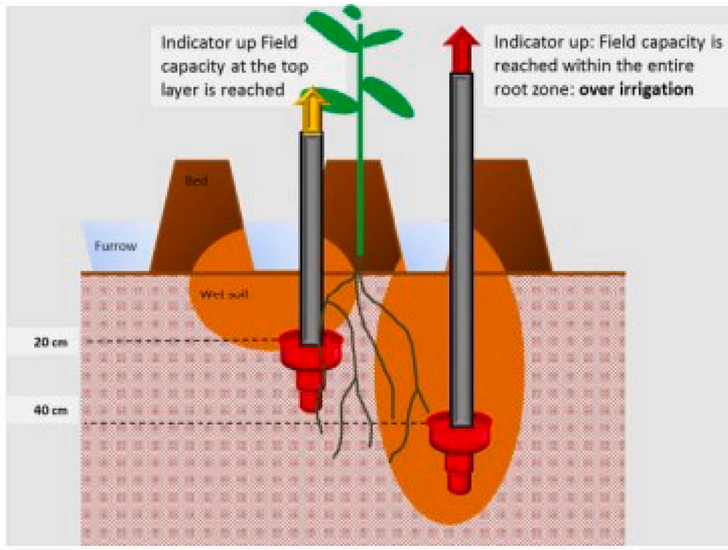

Fig. A.1. Wetting front detectors.
Image source: Haileslassie et al. (2016).

Fig. A.2. Chameleon sensors.
Image source: Maheder Haileselassie/IWMI.

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