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JICA-RI Working Paper

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No. 196

October 2019

JICA Research Institute



JICA Research Institute

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JICA Research Institute
10-5 Ichigaya Honmura-cho
Shinjuku-ku
Tokyo 162-8433 JAPAN
TEL: +81-3-3269-3374
FAX: +81-3-3269-2054

Technology Adoption, Impact, and Extension in Developing Countries’ Agriculture: A Review of the Recent Literature*

Kazushi Takahashi[†], Rie Muraoka[‡], and Keijiro Otsuka[§]

Abstract

Given the stagnant agricultural productivity and persistent food insecurity in low-income countries—notably in sub-Saharan Africa (SSA)—there has been continued interest in the adoption of new technology and its impact on productivity in these regions. Interestingly, there are signs of Green Revolution in maize and rice in SSA, reflected in sharply increasing yield trends in advanced regions. To increase crop yields and sustain yield gains, recent case studies of technology adoption unanimously recommend the adoption of integrated farm management systems, particularly in SSA. On the other hand, since the 2010s, there have been increasing numbers of studies on social network or farmer-to-farmer technology extension. These studies explore more efficient extension systems than traditional public-sector extension approaches. This article reviews both recent case studies of technology adoption and its productivity impacts as well as studies on agricultural extension to identify common findings, shortcomings, and major remaining issues.

JEL classification: O13, O33, Q16

Keywords: technology adoption, productivity impact, agricultural extension, technological diffusion

* We thank Yuma Noritomo for excellent research assistance and Kei Kajisa, Yoko Kijima, Yukichi Mano, Mushfiq Mobarak, and Yuko Nakano for useful comments. Financial support for this research from the National Graduate Institute for Policy Studies is gratefully acknowledged. The remaining errors are the sole responsibility of the authors.

[†] National Graduate Institute for Policy Studies, Tokyo, Japan

[‡] National Graduate Institute for Policy Studies, Tokyo, Japan and Japan International Research Center for Agricultural Sciences, Tsukuba, Japan

[§] Social System Innovation Center, Kobe University, Kobe, Japan, Corresponding author, otsuka@econ.kobe-u.ac.jp

This paper has been prepared as part of a JICA Research Institute (JICA-RI) project entitled “An Empirical Analysis on Expanding Rice Production in Sub-Sahara Africa.”

1. Introduction

Given the stagnant agricultural productivity and persistent food insecurity in low-income countries—notably in sub-Saharan Africa (SSA)—there has been continued interest in the adoption of new technology and its impact on productivity. In particular, how to increase maize yield and sustain its yield gain are major issues for agricultural development in SSA. Such interests are supported by changes in favor of the adoption of new agricultural technologies, such as the release of improved crop varieties and the widespread use of mobile phones, which is expected to reduce transaction costs (Aker, 2011; Aker and Mbiti, 2010); and the buoyant use of microcredit and index-based weather insurance, which would help remove cash constraints and excessive exposure to production risks (de Janvry et al., 2017; Magruder, 2018). In fact, there are signs of Green Revolution in maize and rice in SSA, reflected in sharply increasing yield trends in the advanced regions of Africa (Otsuka and Muraoka, 2017).

A widely observed puzzling phenomenon in SSA is the low adoption rate of seemingly profitable technology (Macours, 2019; Sheahan and Barrett, 2017). The first major question that the literature on technology adoption ought to ask is whether truly productive and profitable technologies are available in SSA and other low-income countries. The related question is what the appropriate agricultural technologies are that can bring about significant and sustainable improvement in productivity.

The first purpose of this review article is to identify common findings of the studies on technology adoption regarding its determinants, impacts, and shortcomings. We especially focus on maize and lowland rice, which are considered the most promising staple crops in SSA (Otsuka and Larson, 2013, 2016). A major and common argument in recent studies is that, in addition to the use of modern inputs, integrated farm management systems could lead to significant and sustained gains in productivity. These systems include application of organic

fertilizer and intercropping or rotation with leguminous crops in the case of maize and application of bund construction, leveling, and straight-row transplanting in the case of rice.

Even if profitable technologies are potentially available, they may not be diffused widely, partly because of credit, insurance, and other market-related constraints and partly because of the ineffective information dissemination system, largely arising from the absence of effective agricultural extension systems.¹ The extension system is particularly weak in SSA because of the structural adjustment policies implemented in the 1980s and 1990s, which suppressed public-sector activities. To uncover efficient technology extension systems, the 2010s witnessed a surge in studies on social network or farmer-to-farmer technology dissemination. These works were triggered by Foster and Rosenzweig (1995) and Conley and Udry's (2001, 2010) pioneering studies. Whereas these studies have relied on observational data, the recent trend has moved toward the use of experimental data based on the randomized controlled trial (RCT). This technique has been applied to various fields of development economics to rigorously examine the causal impact of interventions such as roles of credit, index-based weather insurance, and contract farming. Because other review articles are available on other issues,² the second purpose of this article is to review recent articles on technology diffusion through farmer-to-farmer extension.³ More specifically, we will examine the effectiveness of farmer-to-farmer extension systems, qualification of appropriate farmer-trainers, and incentivization of farmer-trainers. Although the available evidence is inadequate, we will attempt to speculate an efficient extension system that combines the traditional public-sector extension with the effective farmer-trainer systems.

¹ In this article, "technology adoption" refers to the adoption of new improved technologies by individual farmers in a certain area, whereas "technology diffusion" refers to widespread adoption of new technologies by a larger number of farmers in wider areas.

² See de Janvry et al. (2017), Magruder (2018), Otsuka et al. (2016), and Macours (2018) for related reviews.

³ Feder et al. (1985) and Foster and Rosenzweig (2010) provide excellent reviews on the earlier literature on technology adoption.

Before reviewing the case studies of technology adoption in Section 3 and recent studies of technology diffusion in Section 4, we examine over-time changes and cross-sectional differences in maize and rice yields by major regions of the world in Section 2. This allows us to sketch the technological changes and their regional differences in productivity from the global viewpoint. Also examined in Section 2 is the distribution of topics dealt with by articles recently published in leading journals of development economics and agricultural economics by crop and region.

2. An Overview of Recent Research Areas and Yield Trends

2.1 Recent studies of technology adoption and diffusion

To understand the recent trend of empirical microeconomic studies in developing countries, we review published articles in major field journals in both development and agricultural economics from 2010 to the end of July 2019.⁴ There are 4,752 and 2,826 original research articles published in development and agricultural field journals, respectively, out of which 90 and 190 distinct articles are empirical studies on technology adoption and diffusion in developing countries using microdata (e.g., plot and household level data), respectively.

Table 1 summarizes the number of published articles, classified by regions and type of crops, separately for development and agricultural economics journals. Because one paper in the development journal covers regions over two continents, the total number becomes 91 in the upper part of the first column in this table. Note that technology here includes not only cultivation practices, such as input use and management methods, but also financial products related to agricultural production, such as microcredit and weather index insurance.

⁴ The reviewed development economics journals include *Economic Development and Cultural Change*, *Journal of Development Economics*, *Journal of Development Studies*, *World Bank Economic Review*, and *World Development*, whereas agricultural economics journals include *Agricultural Economics*, *American Journal of Agricultural Economics*, *Food Policy*, and *Journal of Agricultural Economics*.

It is clear that most studies pertain to Africa, including SSA, accounting for more than 70% of all publications on this issue. South Asia follows, accounting for about 10% of the total publications. These two regions are places where the vast majority of the global poor reside. Here, food insecurity and vulnerability to various shocks are still serious concerns amidst the looming climate change that would have particularly significant negative impacts on regional crop production (Baldos and Hertel, 2014; Rosegrant et al., 2014). Thus, most published articles are problem oriented.

Reflecting the fact that maize and rice are major cereals in these two regions, these two crops are intensively studied in the literature. Though the importance of maize in production and consumption in SSA has long been recognized, an increasing number of studies point out the potential of rice to boost food production in this region. In fact, the consumption level of rice has sharply increased in recent times (Otsuka and Muraoka, 2017).

2.2 Changes in maize and rice yield by region

Given the intensive interest in maize and rice research for developing countries, we would like to compare changes in maize and rice yields in SSA, South America, South Asia, and Southeast Asia from 1961 to 2017. We also show the average yield of the top five countries in SSA. If a yield growth of the best performing countries in SSA is comparable with that in South and Southeast Asia and South America, it is likely that other SSA countries located in similar climate conditions would have the potential to achieve high yield growth.

Several interesting observations can be made from the comparison of the maize yield trends in Figure 1. First, maize yields were similar between SSA, South Asia, and Southeast Asia before 1980, indicating that the yield gap due to agroclimatic differences was small before the Green Revolution. Second, less developing countries seem to exploit their backwardness as an advantage. The yield of maize in South America began to increase gradually after around 1970; Southeast Asia followed the growth of South America from the

1980s; South Asia followed Southeast Asia from around 1990. Thus, the Green Revolution created the yield gap across continents, but latecomers did catch up with advanced countries over time. Third, the yield stagnated in SSA in contrast to other regions, but it slowly began to increase around 1990, which may suggest that the Green Revolution had begun in this region. Fourth, the group of the top five countries in SSA, namely, South Africa, Ethiopia, Zambia, Kenya, and Uganda, has almost the same growth trend of yield as South Asia. This indicates a possible Green Revolution in maize in the well-performing areas of SSA. Therefore, there is a possibility to transfer high-yielding maize farming practices from these high-performing regions to other stagnant regions in SSA. Through a literature review in the section, we will examine what promising maize technologies can help realize a technology transfer.

Figure 2 displays the difference in rice yield growth among regions. Similar to maize yield trends, the yields of SSA, South Asia, Southeast Asia, and South America stagnated in the 1960s and 1970s. The rice yield in Southeast Asia began to grow from around 1970, whereas the yield in South Asia and South America rapidly grew around 1980. Although the yield in SSA had been stagnant from the 1960s to the mid-2000s, gradual growth has been observed since the mid-2000s. Furthermore, the yield of the top five countries in SSA, namely, Kenya, Mauritania, Niger, Brundi, and Madagascar, especially saw a sharp increase after around 2000, implying that a Green Revolution in rice must have occurred therein. Like the case of maize, we would like to explore the transferability of rice farming technologies from advanced regions to stagnated areas in SSA in the next section.

3. Case Studies of Technology Adoption

Because the adoption of modern agricultural technologies (improved varieties and inorganic fertilizer) and integrated farm management system is considered essential components of

productivity growth in the literature, we review determinants of such adoptions and their impact in order to understand sustainable farming technologies in developing countries.

3.1 Adoption of improved varieties

The effort of research and development of new improved varieties suitable for local agroclimatic environments and their diffusion are considered the most important means to boost crop yield and improve the well-being of farmers in developing countries (Evenson and Gollin, 2003). We observe striking heterogeneity among developing countries upon examining the adoption rate of improved crop varieties. For example, using the Living Standards Measurement Study–Integrated Surveys on Agriculture (LSMS-ISA) dataset, Sheahan and Barrett (2017) show the percentages of land under improved maize varieties by countries in SSA around 2010–12 as follows: 28% in Ethiopia, 43% in Malawi, 95% in Nigeria, 35% in Tanzania, and 54% in Uganda. Table 2 also indicates large variation in the percentage of area under improved maize varieties across countries in SSA, ranging from 32% in Ethiopia in 2010–11 (Zeng et al. 2015, 2017) to 83% in Kenya in 2009–10 (Smale and Olwande, 2014).

As presented in Table 2, adoption of improved varieties generally has positive effects on yield and farmers' welfare. Specifically, the adoption of improved maize, legume, and other cereal varieties significantly increases yield (Villano et al., 2015; Zeng et al., 2015), crop and household income (Bezu et al., 2014; Kassie et al., 2011; Khonje et al., 2015; Manda et al., 2019; Mathenge et al., 2014; Smale and Mason, 2014; Verkaat et al., 2017; Villano et al., 2015), consumption (Asfaw et al., 2012ab; Bercerril and Abdulai, 2010; Bezu et al., 2014), nonland asset or wealth (Bezu et al., 2014; Smale and Mason, 2014; Manda et al., 2019; Mathenge et al., 2014), and child nutrition (Zeng et al., 2017). It particularly reduces poverty (Asfaw et al., 2012a; Bercerril and Abdulai, 2010; Kassie et al., 2011; Khonje et al., 2015; Manda et al., 2019; Mathenge et al., 2014; Smale and Mason, 2014; Verkaat et al., 2017; Zeng et al., 2015).

Nevertheless, a large number of farmers does not adopt these seemingly promising and welfare-enhancing technologies. Studies note that poor access to information through extension services and inadequate seed supply constrain the adoption of improved crop varieties (Asfaw et al., 2012ab; Kassie et al., 2011; Khonje et al., 2015; Shiferaw et al., 2015; Suri, 2011; Villano et al., 2015). Shiferaw et al. (2015) demonstrates from their study of improved groundnut adoption in Uganda that, out of 41% of non-adopters, only 10% of farmers do not want to adopt, whereas 31% of farmers who do, face constraints that impede them from adoption. He empirically shows that slow uptake of improved groundnut can be attributed to lack of technological information, seed supply, and credits.

An explanation of non-adoption provided by Suri (2011) was based on the heterogeneous returns to the use of modern inputs among farmers. In a study on Kenya, she finds that farmers with high net returns adopted hybrid seeds, whereas farmers with low net returns did not. She suggests that removing supply and infrastructure constraints such as long travel time to seed and fertilizer distributors for farmers would be a cost-effective policy to raise hybrid seed adoption rates and maize yields. Michiler et al. (2018) extend Suri's analysis to improved chickpea production in Ethiopia and find that the adoption of improved chickpeas does not contribute to yield gain. However, it does decrease production costs, thereby leading to higher profitability than local varieties. They argue that this high profitability explains the rapid increase in adoption of improved chickpea seeds in Ethiopia. Additionally, Kijima et al. (2011) show that low profitability under the variable rainfall environment of NERICA rice in Uganda leads to the massive dropout. These studies commonly indicate the importance of analyzing profitability of improved varieties to understand the low adoption rate.

Lunduka et al. (2012) point out that the observed plateaus of adoption of modern maize varieties could be due to different traits of modern and traditional maize seeds and farmers' preference. They empirically show that, though farmers value high yield and early maturity of modern varieties, they also value the storability, taste, and processing traits of local

varieties. This calls for seed breeding research to focus not only on crop yield, but also on ease of storage, high poundability, high flour–grain ratio, and favorable taste reflecting farmers’ demand (Lunduka et al., 2012).

Bold et al. (2017) find that more than 50% of hybrid maize seeds are not authentic seeds and 30% of nutrients are missing in inorganic fertilizer in their survey areas in Uganda. This results in low return from hybrid seeds and inorganic fertilizer adoption, leading to low take-up of these modern inputs. Thus, we may need to develop inspection systems that assure quality of the modern inputs available to rural smallholders.

The recent development of improved storage technology could increase adoption of improved varieties. The kernels of hybrid maize varieties are softer and less protected from insect attacks than traditional varieties (Smale et al., 1995). A study using Malawi’s data collected by Ricker-Gilbert and Jones (2015) shows that acquiring chemical storage protectants after the previous harvest increases adoption of improved maize varieties. Additionally, in Omotilewa et al.’s (2018) RCT in Uganda, the authors distributed improved hermetic storage bags for eliminating insect pests in storage to randomly selected households. They find that households that receive the improved bag more likely plant hybrid maize than control households by 10 percentage points. These studies show that newly developed technology, which could overcome the drawback of improved varieties, could improve adoption of improved seeds.

Generally, improved varieties are developed to enhance crop yields. In addition to the yield-enhancing trait, the development of abiotic stress-tolerant varieties, which could mitigate weather shocks affecting crop yield, has become especially important, possibly due to rapid climate change. In fact, Kostandini et al. (2013) estimate that adoption of drought-tolerant maize could generate gains of US\$ 362–590 million and a 0.01–4.29% reduction in poverty by 2016. Emerick et al. (2016) conduct an RCT to distribute a flood-tolerant rice variety randomly in India. They find that the use of this risk-reducing variety leads to higher adoption of other

improved agricultural inputs and practices, such as adoption of a more labor-intensive planting, inorganic fertilizer application, and credit utilization. One issue of abiotic stress-tolerant varieties is that the benefits of adoption become visible only when the specific stress, which they are tolerant to, appears (Yamano et al., 2018; Yorobe et al., 2016). The study of submergence-tolerant rice variety adoption in Bangladesh shows that experience of submergence in the previous year increases adoption (Yamano et al., 2018). Additionally, the study of drought-tolerant maize adoption in Malawi demonstrates that previous early season dry spells and access to seed subsidy increases adoption (Katengeza et al., 2019). Thus, if normal seasons continued, we could predict that farmers tend to switch to other varieties. Therefore, Yamano et al. (2018) stress the importance of education for farmers about the benefits of stress-tolerant crop varieties through extension activities.

One concern about empirical studies of adoption of improved varieties is accuracy of adoption status reported by farmers. Most studies use farmers' self-reported data and assume that farmers correctly know the varieties that they planted. However, the self-reported data of varieties status could be misclassified, which may lead to biased estimates (Wossen et al., 2019b). In fact, farmer may not know the accurate status of seeds that they planted possibly due to seed recycling, imperfect input markets, and lack of technical information on the improved seeds (Kosmowski et al., 2016; Maredia et al., 2016; Wossen et al., 2019b). To tackle this issue, new technology was developed to identify the types of crop varieties, which is DNA-fingerprinting of seeds (Floro et al., 2018; Kosmowski et al., 2016; Maredia et al., 2016). Wossen et al. (2019b) report that 25% of farmers report improved cassava varieties as traditional ones and 10% of them report traditional cassava as improved one in Nigeria. This misreporting occurs systematically, causing biased estimates of 22 percentage points in productivity impact of adoption. They also find that the adoption of improved cassava reduce poverty by 4.6 percentage points and this is sensitive to the measurement of adoption status (Wossen et al., 2019a). Floro et al. (2018) also demonstrate that Colombian farmers

substantially overestimate their use of improved cassava varieties, which leads to significant differences in the determinants estimation between studies based on farmer self-identification and DNA fingerprinting. It appears that the lack of credible extension system leads to confusion about improved varieties among farmers. This is especially true if there are many available varieties in local markets. Indeed, based on finding that 89% of farmers' classification of lentil varieties are accurate in Bangladesh, Yigezu et al. (2019) argue that the necessity of DNA fingerprinting may be low when there are only a few varieties and most farmers obtain varieties through formal systems.

3.2 Use of inorganic fertilizer

Adoption of improved varieties alone is not sufficient to boost crop yield. Application of inorganic fertilizer is necessary to exploit the full yield potential of improved varieties. In fact, simultaneous adoption of improved varieties and inorganic fertilizer is the core technology of Green Revolution in Asia and Latin America (Hayami and Ruttan, 1985). Therefore, inorganic fertilizer use, in addition to improved seed adoption, has been widely promoted to realize considerable yield growth, especially in SSA.

When we look at the inorganic fertilizer use by region, it is striking that inorganic fertilizer application is much lower in SSA compared with other regions. For example, nitrogen application in SSA is only 5–6% of that in South Asia and Southeast Asia (FAOSTAT, 2019). From 1980 to 2000, the annual growth rate of inorganic fertilizer application in SSA was only 0.93%, whereas that of South Asia was nearly 5% (Morris et al., 2007). There is, however, heterogeneity in the use of inorganic fertilizer among countries and even within countries in SSA. Sheahan and Barret (2017) demonstrate that the adoption rates of inorganic fertilizer in six countries range from 3.2% in Uganda to 64.3% in Nigeria; the mean nutrient usages range from 0.7 kg per hectare in Uganda to 64.3 kg per hectare in Nigeria. Heterogeneity of the yield response rate to inorganic fertilizer use and value-cost ratios is also surprisingly large,

presumably due to heterogeneity in soil, rainfall, and market conditions in various countries (Jayne and Rashid, 2013).

How can we increase inorganic fertilizer application to boost crop yield, assuming that its use is potentially profitable? Empirical studies indicate several constraints affecting inorganic fertilizer use. Capital and credit constraints impede farmers from continued adoption of inorganic fertilizers in DR Congo (Lambrecht et al. 2014), Ethiopia (Croppenstedt et al., 2003), and Malawi (Holden and Lunduka, 2013). Accessibility to inorganic fertilizer is another constraint. Minten et al. (2013) show that transaction and transportation costs together add at least 20% costs to actual inorganic fertilizer price that farmers pay in the most convenient location and 50% in the most remote location. Additionally, farmers who live in the most remote areas face not only higher input prices, but also lower output prices, resulting in 75% less inorganic fertilizer use and improved seeds compared with farmers in the most convenient location (Minten et al., 2013)

The other well-known constraint of inorganic fertilizer use is risk that farmer faces. Based on data from India, Dercon and Christiansen (2011) demonstrate that inorganic fertilizer application decreases when farmer faces downside risk in consumption. Similarly, previous year's rainfall level is positively associated with the intensity of fertilizer use in the current year in Ethiopia (Alem et al., 2010). Alem et al. (2010) also show that rainfall variability negatively affects inorganic fertilizer application decision, indicating that risks and uncertainly constraint inorganic fertilizer use. These studies suggest that measures such as the adoption of abiotic stress-tolerant varieties and introduction of effective insurance program to remove downside risks could improve the adoption of yield-enhancing technologies (Alem et al., 2010; Dercon and Christiansen, 2011), which is empirically validated by Cai et al., (2015), Cole et al. (2017), and Karlan et al. (2014).

Farmers' motivation and procrastination may also matter. Duflo et al. (2011) find that willingness to purchase inorganic fertilizer is high at the time of harvest among farmers in

Kenya, but they may procrastinate purchasing inorganic fertilizer and fail to save enough money for the next crop cycle. The authors experimentally show that small nudges, like providing vouchers to purchase inorganic fertilizer immediately after harvest, help present-biased farmers overcome procrastination problems and commit to fertilizer use. On the other hand, Holden and Lunduka (2013) find that some farmers in Malawi are willing to sell maize at the planting time when its price is higher, and then purchase inorganic fertilizer.

However, it may not be an appropriate strategy to increase inorganic fertilizer application alone without consideration of its profitability. The estimated yield response rate to inorganic fertilizer application in the trial plots managed by agronomic researchers in SSA ranges from 18 to 40 kg of maize per kilogram nitrogen applied (Vanlauwe et al., 2011). At the prevailing market prices, these response rates to inorganic fertilizer use could result in high profitability of fertilizer application (Jayne et al., 2018). However, table 3 shows that the average output computed from farmers' fields ranges from 7.6 kg to 25 kg of maize per kilogram of nitrogen (Burke et al. 2017, 2019; Liverpool-Tasie, 2017; Liverpool-Tasie et al., 2017; Sheahan et al., 2013; Matsumoto and Yamano, 2013). These empirical analyses reveal that the low response rate to nitrogen application results in low profitability of inorganic fertilizer use. In fact, a significant portion of farmers in Kenya, Nigeria, and Zambia apply inorganic fertilizer at the economically optimum level, given the response rate to inorganic fertilizer use and prevailing prices (Burke et al., 2017, 2019; Liverpool-Tasie, 2017; Liverpool-Tasie et al., 2017; Matsumoto and Yamano, 2013; Sheahan et al., 2013). These studies emphasize that, to increase profitability of inorganic fertilizer use, it is important to improve the response rate of inorganic fertilizer application. This finding seems to imply that improvement of soil health is the key to achieving these objectives.

Marenya and Barrett (2009) empirically show the complementarities between soil organic matter (SOM) and applied nitrogen. Using data from western Kenya, they demonstrate that maize yield response to nitrogen application is low when SOM is low and increases

rapidly with improvement of SOM. In their samples, one-third of the plots, which were mainly cultivated by the poorest farmers, suffered from degraded soil. This limits the crops' response rate and profitability of inorganic fertilizer application at the prevailing market prices. Soil degradation is a great challenge especially for SSA because increasing population pressure on the land leads to a reduction in fallows and more continuous farming without fertilizer application, which, in turn, depletes soil nutrients (Drechsel et al., 2001; Tittonell and Giller, 2012). Therefore, a means to replenish soil nutrients and improve soil health should be developed and diffused for farmers in order to maintain soil fertility, thereby achieving high yield response rates and profitability of inorganic fertilizer application.

Though there has been a revival of large scale input subsidy programs (ISPs) for boosting inorganic fertilizer application and crop yield since the early 2000s, there exists strong empirical criticism of ISPs. Because private sectors tend to be crowded out (Mason and Jayne, 2013; Ricker-Gilbert et al., 2011; Xu et al., 2009), targeting generally does not work well (Kilic et al., 2015; Mason et al., 2013; Pan and Christiaensen, 2012; Ricker-Gilbert et al., 2011). Hence, the impact is small compared with the large fiscal burden (Jayne et al., 2013; Jayne et al., 2018). This large fiscal burden undermines the investment in agricultural research and extension services (Jayne and Rashid, 2013; Jayne et al., 2018). Today, it is imperative to build knowledges of farm management practices that could enhance soil health and sustainable yield growth suitable for local conditions (Burke et al., 2017, 2019).

3.3 Integrated farm management system

As we discussed in the previous section, soil erosion and nutrients depletion are becoming serious issues, especially in SSA, due to lack of appropriate soil management practices and water conservation. For example, soil nutrients, measured in terms of nitrogen, phosphorus, and potassium (NPK), had been lost at a rate of more than 30 kg/ha per year from 2002 to 2004 in 85% of the African farmland (185 million ha) (Henao and Baanante, 2006). Therefore, it is

essential to develop farm management practices that can enhance soil fertility and prevent soil erosion and land degradation. Such practices could sustainably improve crop yield and profitability of farming. In this subsection, we would like to introduce the promising farm management practices for maize and rice, the two most important crops in developing countries.

3.3.1 Maize-based integrated farming system

In the recent literature, integrated soil fertility management (ISFM) is considered an important means to achieve sustainable crop yield and profitability through enhancing soil health (Holden, 2018; Jayne et al., 2018; Jayne et al., 2019; Larson et al., 2016; Otsuka and Muraoka, 2017). It aims to maintain and rehabilitate soil quality, without scarifying crop yield, by application of animal manure, compost, and crop residues; adoption of natural or improved fallow and intercropping or rotation with legumes, biomass transfer, and reduced disturbance; and use of inorganic fertilizer and improved seeds (Marenya and Barrett, 2007; Place et al., 2003; Vanlauwe, 2010). Fundamental to ISFM is it recognizes that a single adoption of these practices cannot meet the requirements of adequate soil fertility management and sustainable yield growth (Marenya and Barrett, 2007; Place et al., 2003). In fact, Lal (2011) estimates that adoption of multiple soil management practices for soil organic carbon restoration—which includes applying manure and compost, biological nitrogen fixation, and proper use of inorganic fertilizer—could increase maize yield in Africa by 0.8–1.3 million tons per year.

A typical way to implement ISFM is to simultaneously apply inorganic and organic fertilizers. It is well known that these two types of fertilizers have complementary effects because SOM supplemented by organic fertilizer makes external nutrients more absorbable to crops (Bationo and Mokwunye, 1991; Marenya and Barrett, 2009; Vanlauwe and Giller, 2006). Empirical analysis based on household panel data in India shows that application of organic

fertilizer raises the marginal product of inorganic fertilizer, especially when soil fertility is low (Kajisa and Palanichamy, 2011).

Intercropping or rotation with legumes is another common practice under ISFM because the legumes fix nitrogen from the atmosphere and make it available in the soil. It could also enhance crop yield sustainably by reducing plant disease, weeds such as striga, and insects, and by increasing the soil carbon content (Hutchinson et al., 2007; Manda et al., 2016). In fact, empirical analysis using data from Tanzania indicates that maize–pigeon pea adoption significantly increases income and consumption among sample households (Amare et al., 2012).

Although sometimes conservation tillage is included as a component of ISFM, its effect on crop yield is controversial. It entails minimum soil disturbance and is often combined with retaining crop residue to enhance soil aeration and fertility, carbon sequestration, and water-holding capacity (Hobbs et al., 2008). However, reduction in crop yields under conservation tillage is commonly observed, especially when no mulch is applied (Vanlauwe et al., 2015). Rusinamhodzi et al. (2011) find that conservation tillage could bring a positive effect when it is combined with mulch in low rainfall environments on light-textured soil.⁵

Conservation agriculture (CA) or climate smart agricultures are another related practice for sustainable agricultural intensification. These sets of techniques aim to sustainably improve food security and farm profitability by reversing trends in land degradation and mitigating the impact of rapid climate change. (Farris et al., 2017). They have three key principles: minimum or zero tillage, permanent soil cover, and diversified crop rotation (Farris et al., 2017; Giller et al., 2009). However, Vanlauwe et al. (2014) argue that the fourth principle

⁵ There are strands of farming practices similar to ISFM, that is, sustainable agricultural practices (SAPs) and sustainable intensification practices (SIPs). Both aim to improve the underlying biophysical functioning of the farming system and enable crop production to withstand variation in moisture, temperature, and biotic conditions (Kassie et al., 2015). SAPs and SIPs generally include practices adopted in ISFM (De Souza et al., 1993; Lee, 2005; Pretty et al., 2011; Wollni et al., 2010). Therefore, we categorize SAPs and SIP in the same group as ISFM.

should be required in CA in SSA, which is use of inorganic fertilizer to enhance organic residue availability and crop yield.

Though considerable efforts have been made by national and international organizations to encourage farmers to disseminate ISFM, its adoption rate is still low (Kassie et al., 2009; Somoda et al., 2002; Tenge et al., 2004, Wollni et al., 2010). Empirical studies reveal that asset, labor availability, social capital and networks, access to extension services, market and credits, soil conditions, rainfall, tenure security, education, and experience affect the adoption of ISFM (Kassie et al. 2013; Kassie et al. 2015; Manda et al., 2016; Teklewold et al. 2013; Zeweld et al. 2019). Adoption of ISFM requires up-front investments of substantial labor; it also takes several years to realize its benefits (Jayne et al., 2019). For example, Schmidt et al. (2017) show that soil-water management investment must be maintained for at least seven years to achieve significant increases in value of production. Therefore, resource-rich farmers are more willing to make such investments than resource-poor farmers who tend to prioritize their immediate needs for sustenance (Jayne et al., 2019). Asfaw et al. (2016) argue that adoption of crop residues and organic fertilizer can be characterized by low capital investments, high labor inputs, and long time to achieve results, whereas that of inorganic fertilizer and improved seeds requires higher capital investments, low labor inputs, and short times for results. Thus, the difference in resource endowments and needs of farmers is likely to result in different patterns of adoption of ISFM technologies. Aside from the location specificity, ISFM includes demonstrably knowledge- and management-intensive practices. Therefore, farmers' education and training through extension services is necessary for diffusion of ISFM.

What are then the effects of ISFM adoption? Kassie et al. (2018) report that adoption of improved maize seed, inorganic fertilizer and legume intercropping increases maize yield significantly in Ethiopia. They report that these improved maize production technologies reduce maize production costs because legume intercropping reduces fertilizer costs, leading

higher net crop income. Similarly, Teklewold et al. (2013) find that, in Ethiopia, adoption of maize–legume rotation, improved maize varieties, and conservation tillage increases maize income, particularly when these practices are adopted in combination. Additionally, based on data from Niger, Asfaw et al. (2016) show that adoption of inorganic fertilizer, improved seeds, and organic fertilizer is positively associated with crop productivity and income, but not crop residue. In the case of Zambia, Arslan et al. (2015) demonstrate that legume intercropping increases maize yields and reduces probability of low yield even under critical weather stress. They also find that reduced tillage and crop rotation have no significant effect on maize yield. These findings suggest that adoption of certain combination of ISFM brings positive effect on maize yields, but some components of ISFM do not work well. This is not surprising, given the heterogeneity in soil, agroclimate, and market conditions in various places. Therefore, it is necessary to develop localized ISFM technologies adjusted for specific agro-ecological and socioeconomic conditions.

Available evidence is generally limited to the impact of ISFM on yield or, at best, on income. There are very few studies analyzing of profitability of ISFM, which deducts not only the paid-out cost, but also the imputed cost of family-owned resources, such as labor and machine, from the gross output value. This is problematic because complex knowledge-intensive technologies, like ISFM that require care and judgment, are mainly performed by family labor. Though it is challenging to estimate profit because of the difficulty in imputing the cost of family labor, more research efforts need to be devoted to assessing the profitability of new package of technologies. Otherwise, we cannot judge the viability and scalability of new technology.

3.3.2 Improved rice cultivation practices

New labor-intensive management practices, such as system of rice intensification (SRI), have been proposed for lowland rice cultivation to improve the efficiency of natural resource use

and prevent environmental degradation (Uphoff and Randriamiharisoa, 2002). SRI consists of four core components: early transplanting of seedlings, shallow planting of one or two seedlings per hill, sparse planting, and intermittent irrigation. However, scholars question the yield and profitability impacts of SRI (Glover, 2011; Sheehy et al., 2005). Though Noltze et al. (2013) demonstrate that SRI in Timor Leste significantly increases crop yield and income, Takahashi and Barrett (2014) present contradicting evidence: SRI increased yield by about 64% on average, but did not increase household income because it required a shift of labor from other activities.

Recently, a new rice farming system has been introduced in some areas; this includes not only farm management practices, but also modern input use. According to Nakano et al. (2018a), a new rice farming system, which consists of practices such as seed selection in salty water, straight-row dibbling or transplanting, wide spacing, application of inorganic fertilizer, and adoption of improved rice varieties, has been introduced to rural Tanzania. They call this system “modified SRI (MSRI)”. They examine the impact of MSRI training in rural Tanzania and found that the rice yield of MSRI plots is higher by 1.3–1.8 tons per ha, with profits increasing by US\$ 119–137 per ha compared with other plots.

Improved rice cultivation practices (IRCPs), which are similar to MSRI, have also been introduced in some areas in SSA. IRCPs include not only the application of modern inputs, such as improved lowland rice varieties and inorganic fertilizer, but also improved management practices, such as leveling, bund construction, as well as straight-row transplanting for soil, water, and weed management (Kijima et al., 2012; Takahashi et al., 2019). The major advantage of lowland rice is the high transferability of recommended practices developed and diffused widely in Asia to SSA (Otsuka and Lawson, 2013). The difference between IRCPs and MSRI lies in their management practice components. Like ISFM for maize, IRCPs are knowledge-intensive technologies based on the idea that, beyond adoption of modern inputs, even appropriate soil and water management practices are essential

to boost lowland rice yields significantly and sustainably. The IRCP training was provided for rural farmers in some countries in SSA, followed by impact evaluation of the training by researchers (Kijima, 2019). Studies have found that this training encourages adoption of IRCPs (Kijima et al., 2012; Takahashi et al. 2019), significantly increases rice yield (deGraft-Johnson et al., 2014; Nakano et al. 2018b), income (Takahashi et al., 2019), and profit (deGraft-Johnson et al. 2014; Kijima et al. 2012), with positive spillover effects on non-trained farmers over time (Nakano et al. 2018b; Kijima, 2018; Takahashi et al. 2019). Although empirical findings indicate that they have the potential to boost rice yield and profits in SSA, IRCPs are not prevalent in rice farming in this region presumably because of weak extension systems (Otsuka and Larson, 2013, 2016).

4. Technology Diffusion among Farmers

The existing case studies clearly suggest that improved agricultural technologies, such as modern varieties, inorganic fertilizers, and a variety of improved agronomic practices, are available. However, their adoption rates are not generally high, especially in SSA.

An increasing number of recent studies focus on failures that impede appropriate information flow from laboratories or experimental stations to farmers. Public extension workers have traditionally played a central role in the overall process of technology diffusion. However, it may be prohibitively costly to directly train all individual farmers to increase their awareness and knowledge of new technologies, and thus promote technology adoption and wider diffusion. This is especially true in many low-income countries where the dominant mode of agricultural production is small-scale farms that are located in geographically dispersed areas. In these regions, the quality of infrastructure is often low, which further increases the cost of disseminating information to them (Anderson and Feder, 2007). Also, extension workers sometimes feel unmotivated; as a result, information loss from extension

agents to farmers becomes severe (Niu and Ragasa, 2018). To complement the extension system from public agents to farmers, the potential of the farmer-to-farmer extension (F2FE) approach has been extensively investigated in recent years.

This section presents an overview of the literature on F2FE, focusing on the extent to which and under what conditions its approach is effective, how to best select farmer-trainers who play a major role in disseminating technological information, and whether monetary or other incentives are required to motivate farmer-trainers.

4.1 Effectiveness of farmer-to-farmer extension systems

Because learning new technologies is a complex process, farmers may need to rely on multiple sources of information before they adopt a new technology (Beaman et al., 2018; Fisher et al., 2018; Genius et al., 2014). The importance of public extension services may be paramount at the initial stage of new technology diffusion—that is, when farmers have limited opportunities to learn from each other (Anderson and Feder, 2007). Over time, when an increasing number of farmers become aware of and start to adopt a specific technology, the impact of such an extension may diminish and the role of an F2FE system expands (Krishnan and Patnam, 2014).

The effectiveness of an F2FE system or social learning for the diffusion of agricultural technologies has been widely recognized since the pioneering works by Conley and Udry (2001, 2010) and Foster and Rosenzweig (1995), even though it sometimes fails to achieve the stated objectives (Kondylis et al., 2017). Theories of social learning suggest that, when technologies are new, there is higher uncertainty about their expected returns and risks as well as the best practices (e.g., appropriate input levels). Farmers can update their beliefs by not only testing it themselves, but also observing peers' behavior or sharing knowledge with them. This learning process is effective especially when the information is reliable and there is no heterogeneity in farming conditions and technological parameters (Munshi, 2004; Tjernstrom, 2017). In such cases, information about early adopters provides appropriate signals; it

increases knowledge about technologies and expected profits, thereby boosting subsequent adoption by others (Bardhan and Udry, 1999).

Empirically measuring the impact of social learning involves several challenges because of the difficulty in exactly defining the networks (Maertens and Barrett, 2012) and because of confounders that make geographically and socially proximate people behave similarly, aside from pure learning effects (Manski, 1993). With the availability of accurate network data and the spread of an experimental approach that creates exogenous variation in exposure to technology adoption, an increasing number of studies successfully identify the type of network and extension method most effective in disseminating agricultural technologies.

Some studies find various types of social networks, such as membership in social groups and informal forms of mutual insurance, to be effective in exchanging information among members (Mekonnen et al., 2018). However, many other studies commonly illustrate that the learning effect is larger among members who are linked by kinships or voluntarily formed groups for exchanging agricultural information (Bandiera and Rasul, 2006; Conley and Udry, 2010; Liverpool-Tasie and Winter-Nelson, 2012; Matsumoto, 2014; Matuschke and Qaim, 2009; Pratiwi and Suzuki, 2017). These studies suggest that farmers do not rely on all members of the village for gathering agricultural information. Therefore, the use of the average community-level adoption rate as a proxy for an opportunity to learn would be misleading. In particular, having a benefiting adopter in a network is proven to be important in increasing adoption through productivity spillovers, especially for new and knowledge-intensive technologies (Conley and Udry, 2010; Magnan et al., 2015; Van den Broeck and Dercon, 2011; Yamano et al., 2018). This finding is important in view of the argument that new desirable technologies in SSA, such as integrated farm management systems, are likely to be knowledge-intensive, and hence complex. Van den Broeck and Dercon (2011) find that positive productivity spillovers among farmers may arise among kinship groups, but not

geographical neighbors or informal insurance network members, presumably because kinship among farmers ensures a conscious effort to explain complex technology compared with members in other network types.

To improve female learning, the existing studies underscore the importance of information linkages formed among female peers. For example, Vasilaky and Leonard (2018) conduct a field experiment in Uganda to create a new information link by randomly pairing female cotton farmers at a training session with whom they had not previously interacted. The authors encouraged them to share technological information in the production process. This intervention resulted in a significant increase in the productivity of the treated pair, signifying the importance of linking females who tend to be outside the agricultural information network. Similarly, having a female instructor reduces gender bias, creates awareness, and helps in the adoption of new technologies by female (Kondylis et al., 2016; Shikuku, 2019), and such network effects are larger among female than male farmers (Mekonnen et al., 2018).

The significant gendered segmented network is observed partly because of cultural norms that prohibit women from interacting with men external to their family members (Kondylis et al., 2016). However, it may be also because individuals have a tendency to disproportionately learn from those who are similar to them. This is called homophily, which contrasts with heterophily, wherein knowledge diffusion takes places more often among people who are different from each other (Feder and Savastano, 2006; Shikuku et al., 2019). The relative importance of homophily and heterophily becomes an important issue not only to improve female productivity, but also to facilitate overall social learning.

The relevance of this argument is clear if we realize that, due to budgetary constraints, public extension agents can often train only a limited number of farmer-trainers or “contact farmers” who are later expected to share the information with other non-trained community members. This contact farmer approach is now widely used in many developing countries, including SSA. However, it is not entirely clear who should become the farmer-trainers.

Specifically, the following question is left unanswered: Should those individuals be farmer-trainers who are influential in terms of network connectivity and opinion leadership, who are innovative with entrepreneurship ability, or who are ordinal and representative of the majority population in the community?

4.2 Qualifications of appropriate farmer-trainers

The literature considers three types of potential farmer-trainers: (1) those who are at the center of the information network; (2) those who are innovative, eager to take risks associated with the adoption of new technologies, and often knowledgeable and productive; and (3) those who have socioeconomic and farm characteristics similar to the majority of farmers in a community. Whereas (1) and (2) are conceptually distinguishable, they often overlap and tend to have higher status in a society (hereafter called “lead farmer”) (Dar et al., 2019; Feder and Savastano, 2006; Rogers, 1995).

The advantage of selecting types (1) and (2) is that the number of trainee farmers would increase because lead farmers have various connections with others, information would be more accurately disseminated because they are more knowledgeable, and demonstration effects in terms of productivity and profitability improvement would be larger because they are more productive. Moreover, such innovators would effectively integrate new knowledge into local practices when adaptation is required in the local context. By strategically delaying own adoption, peer farmers can free-ride and reduce the uncertainty associated with the adoption of new technologies (Bandiera and Rasul, 2006; Foster and Rosenzweig, 1995; Maertens, 2017).

On the other hand, if gains of new technology are heterogeneous, reflecting the variety in growing conditions and farmer characteristics, there is no guarantee that lead farmers’ success can be replicated by other farmers (Magnan et al., 2015; Shikuku, 2019; Suri, 2011; Tjernstrom, 2017). In other words, better performance cannot be solely attributed to the advantages embedded in technology, but to observable and unobservable characteristics of lead

farmers and their agricultural plots (Barrett et al., 2004). In this case, it would be easier for followers to learn from farmer-trainers who are endowed with similar, but not outstanding, characteristics.

The empirical findings of these competing views are mixed. Maertens (2017) provides evidence indicating that lead farmers play a more significant role than ordinary farmers when peer farmers learn about technological characteristics from their learning links. Similarly, the lead-farmer approach, implemented in SSA countries, has a positive impact on the uptake of new technologies among fellow farmers (Wellard et al., 2013). Dillon et al. (2018) compare the degree of technological diffusion by selecting farmer-trainers (1) randomly, (2) on network size, and (3) based on network centrality measured by Eigenvector centrality. The results suggest that the network-based targeting approach is more effective in encouraging broader adoption. Beaman et al. (2018) also find results similar to Dillon et al.'s (2018) findings, whereas Beaman and Dillon (2018) and Lee et al. (2019) show that the network-based targeting approach is not necessarily superior to random selection of entry points to improve the knowledge of other farmers.

The superiority of homophily is presented in an analysis by Matuschke and Qaim (2009) and Weimann (1994). They contend that vertical flow of information from the lead farmer to peer farmers often fails, and successful information exchange is likely to be based on horizontal, socially proximate relationships. Based on an RCT in Malawi, BenYishay and Mobarak (2019) demonstrate that ordinary farmers perform better than lead farmers as farmer-trainers in terms of efforts and resultant technology diffusion, especially when ordinary farmers are incentivized. Takahashi et al.'s (2019) RCT in Cote d'Ivoire also shows that randomly selected training participants, who are representative of the majority in a community, effectively work as a catalyst to disseminate information to non-training participants. This F2FE approach is as effective in improving practices as the initial training provided by extension services.

Somewhere between these two views is the perspective provided by Feder and Savanstano (2006). These authors find that farmers are more inclined to learn from peer farmers who are slightly superior to them, but not excessively so. Referring to Rogers (1995), Fisher et al. (2018) also share this view and discuss the differential roles of homophily and heterophily networks as follows:

“[h]omophilous and heterophilous networks have distinct and complementary roles in the diffusion of innovations. Heterophilous networks, such as that between lead and follower farmers, are more important in triggering awareness of a new technology, because new ideas most often enter a system through individuals who have higher status and are more innovative. Homophilous networks are, however, more useful than heterophilous ties in persuading potential adopters of the merits of the innovation [...] If F2FE is to have a greater role in encouraging follower farmers to adopt innovations it may be necessary to identify lead farmers that are capable and motivated to train other farmers but not too socially distant from the target population of farmers in terms of personal characteristics and innovativeness.” (pp. 321–322)

As discussed by Fisher et al. (2018), if lead farmers are more suitable as entry points to disseminate new information, but ordinary farmers are more suitable to the wider diffusion of a specific technology, compromising these two views would be potentially the most effective approach. That is, an approach wherein lead farmers receive initial training to train new technologies to socially proximate farmers who are slightly more capable than ordinary farmers. Then, the latter set of farmers teaches the same technologies to other farmers comprising the majority of the community. This argument can be reinforced if the new technology is complex, as discussed in the previous section. This stepwise approach is exactly the case presented by Nakano et al. (2018b) in Tanzania, where 20 lead farmers were initially selected and trained in IRCs. The trained lead farmers were responsible for training five other farmers close to them, who were then encouraged to diffuse the improved practices to other ordinary farmers. The study found that the yield gap between lead and intermediary farmers, as well as other ordinary farmers, widened immediately after the training because the former had

adopted new practices faster than the latter. However, intermediary farmers soon caught up with the lead farmers and ordinary farmers caught up belatedly with the lead and intermediate farmers. Eventually, the yield gap among these groups gradually declined.

However, Davis et al. (2016) criticize Nakano et al.'s (2018b) study for relying on recall data on rice yield in the past and for the small sample size. Thus, the effectiveness of such a stepwise technological diffusion path would be worth investigating in other contexts to examine its external validity.

4.3 Incentivizing farmer-trainers

Aside from the issue of selection of best farmer-trainers, increasing attention has been paid to the question of how to motivate farmer-trainers to maximize technology diffusion. Generally, in the lead-farmer approach, the selected farmer-trainers do not receive any monetary rewards. Because the training of other farmers entails a cost of efforts for communication and demonstration, the farmer-trainers sometimes fail to perform the expected role and function in disseminating information to other farmers (Ragasa, 2019). Regardless of whether they are lead or ordinary farmers, well-motivated farmer-trainers might be key to improving knowledge diffusion and adoption of new technologies and practices by fellow farmers (Fisher et al., 2018; Holden et al., 2018). Recent studies also experimentally reveal the relevance of the provision of material and financial incentives.

For example, Shikuku et al. (2019) investigate the role of private and social material rewards in improving the efforts of farmer-trainers, and whether their behavior changes by pro-social preferences. A private reward (e.g., a weighing scale) is secretly provided to a farmer-trainer if the technical knowledge of other farmers surpasses the threshold level. A social reward (the same weighing scale) is provided to a village chief with a public announcement that the device is gifted in recognition of a farmer-trainer's performance. The results show that the provision of social rewards has a positive and significant impact on

farmer-trainers' experimentation and diffusion efforts, which has a larger impact than the provision of private rewards. These effects remain, regardless of the pro-social preference of farmer-trainers. Note that because this study assumes farmer-trainers are better extension agents if they are similar to other farmers, they are selected from among farmers who are not starkly different from ordinary farmers in terms of wealth, education, and landholdings.

BenYishay and Mobarak (2019) provide another experimental evidence to prove that offering small incentives to farmer-trainers based on knowledge and the adoption rate of other farmers significantly increases farmer-trainers' efforts to communicate with other farmers. Moreover, it also improves their own experimentation to demonstrate the input level and yield outcomes. Interestingly, this incentive scheme works only for farmer-trainers who are selected from among ordinary farmers, but it does not work well for farmer-trainers selected from lead farmers. According to the authors, ordinary farmers are more sensitive to incentives because it is easier for them to convince other farmers owing to similarities among them. Thus, it is easier to reach the required number of adopters to receive the incentives. Though not mentioned in their study, another interpretation can be that ordinary farmers would be better extrinsically incentivized to increase their efforts, whereas such extrinsic incentives may not be effective or may even hurt lead farmers when they are already intrinsically motivated. Indeed, motivation of lead farmers selected by communities is generally not financial rewards, but to improve their own farming knowledge and to help others based on altruism (Kiptoto et al., 2016).

Though the provision of material and financial incentives can increase the effectiveness of F2FE systems, how such extension systems attain scalability is disputed. As Shikuku et al. (2019) note, collection of data on others' knowledge of new technology and its adoption is likely to be prohibitively expensive. Takahashi et al. (2019) provide evidence that F2FE systems can potentially work without any financial incentive to farmer-trainers, which makes the cost-effectiveness of performance-based incentive schemes questionable. Nonetheless, it is also important to note that the Takahashi et al. (2019) study was conducted in

a very unique setting where information exchange between trained and non-trained farmers was encouraged after confirmation of the positive impact of the rice-growing technology package taught in the training and where this was announced to all the farmers under study. As Kijima (2019) rightly points out, ordinary farmers who receive training (farmer-trainers) would have little reason to actively teach technologies to and monitor activities of fellow farmers unless incentives are provided. It is thus fellow (non-trained) farmers that should take the initiative to seek new information. In this sense, the existence of profitable technology would need to be informed to as many farmers as possible, which is likely to increase information-seeking behavior in non-trained farmers and thereby lead to wide technology diffusion.

Given the lack of sufficient evidence and consensus, the question of whether financial and monetary incentives should be provided must be rigorously examined in the future research.⁶

5. Concluding Remarks

A review of the case studies on technology adoption provides support for the hypothesis that there are profitable technologies that are not diffused widely because of a weak extension system. Recent case studies commonly argue that desirable improved technologies, particularly in SSA, are management-intensive. They require integrated management of soil, nutrient, and water. Such technologies are likely to be complicated and their impacts are likely to be heterogeneous depending on agro-climates, soil quality, and farmers' abilities. For successful diffusion of new agricultural technology, effective extension systems are indispensable. For this reason, a surge in extension studies is warranted.

⁶ The same applies to the case wherein farmer-trainers are selected through network-based targeting. Though this approach has potential, collecting detailed network data is expensive. Hence, its scalability and cost-effectiveness can be questioned.

One shortcoming of the studies on technology adoption is the lack of analysis of profitability of new technologies, especially in maize-based ISFM. Notably, it is extremely difficult to measure profit—that is, the return on the fixed factor of production—primarily because of the difficulty in imputing the value of unpaid family labor. It is often observed, particularly in the context of SSA, that when family labor cost is imputed by the prevailing market wage rate, the estimated residual profit is negative, indicating that this imputation method is inappropriate. This does not imply, however, that we do not have to estimate profit, because we cannot judge the viability and scalability of new technology without estimating profits. A practical solution is to assume that the estimated profit is not a cardinal, but an ordinal number. That is, it is not its absolute value, but its relative values that may be useful for assessing changes and differences in profitability. Another solution is a collaboration between agricultural economists and scientists, particularly agronomists, to experiment combinations of technologies and input uses in order to estimate the profits of various technologies under a variety of external environments.

Diffusion studies in general do not carefully assess the profitability of a technology under examination, except with a few exceptions. Yet, it is absurd to examine the adoption of new technology and the role of social information network if the technology itself is not profitable. Another difficulty is the absence of interactions with case studies of technology adoption. Though case studies recommend integrated farming systems or “packages” of new inputs and management practices, still many diffusion studies focus only on a single technology, such as improved seed variety, improved planting method, and use of compost. We recommend closer collaborations between the two groups of economists interested in these intimately related issues.

However, criticisms against the diffusion studies discussed above do not deny their significant contributions to the literature on technology adoption and diffusion. The question raised by these studies about the information channels has been neglected for long in the

economics literature, yet it is pertinent for the establishment of effective extension systems. Because information on new technology is a “local public good,” we believe that a public-sector extension system is needed. Because the public extension system is often inefficient, it is desirable to use farmer-trainers who are trained by extension workers. The critical questions are what types of farmers are appropriate for farmer-trainers and whether incentives should be given to them.

Given the heterogeneous impacts of new technology, providing training to outstanding key farmers may not lead to wider adoption of new technology by ordinary farmers. However, although ordinary farmers have many peers who are willing to use the same technology, they are less capable than lead farmers in learning new and complicated technology. If desirable technology is complicated, as is likely to be the case in SSA, it may well be that farmer-trainers ought to be entrepreneurial key farmers. They are likely to disseminate new information to their peers, whose ability may be above the average in the rural community, even if they do not receive particular rewards. These peers may, in turn, further disseminate new information to less capable peers. On the other hand, if the desirable technology is simple and the identification of “ordinary farmers” with relatively large network connectivity is not costly, the best strategy may be to select ordinary farmers as farmer-trainers. Note, however, that ordinary farmers may have to be incentivized to serve as effective extension agents. Or, it may be more practical to provide information about technology to ordinary farmers to stimulate them to search for such new information. Judging from the extant literature it is too soon to present an optimum extension system with finality. Further research on the role and effectiveness of trainer-farmers in the diffusion of new technologies in a variety of contexts is thus necessary.

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Table 1. Number of published papers on agricultural technology adoption in developing countries

	Journals on development economics	Journals on agricultural economics	Total
<u>Regions</u>			
Africa	60	149	209
South Asia	19	13	32
Southeast Asia	5	15	20
Northeast Asia	5	6	11
Latin America	2	6	8
Middle East	0	1	1
Total	91	190	281
<u>Crops</u>			
Maize	16	50	66
Rice	13	20	33
Legume	3	11	14
Maize–legume	2	3	5
Bt cotton	3	9	12
Cassava	1	4	5
Banana	0	4	5
Wheat	1	5	5
Others	10	33	43
Not specified	41	51	92
Total	90	190	280

Table 2. Recent estimates of adoption of improved varieties in developing countries

Authors	Country & year	Varieties	Adoption rates	Determinants of adoption	Impact on production	Impact of improved varieties on welfare indicators
Improved varieties						
Zeng et al. (2015)	Ethiopia in 2010/11	Improved maize (OPVs & hybrid)	39.1% of maize area		47.6-63.3% more yield & 23.1-27.8% more cost increase than traditional varieties	Adoption reduces poverty headcount ratio, by 0.8-1.3%.
Zeng et al. (2017)	Ethiopia in 2010/11	Improved maize (OPVs & hybrid)	39.1% of maize area			Additional 0.25 hectare of improved maize increases child height-for-age & weight-for-age by 0.257 standard deviation (SD) & 0.176 SD respectively. Impact is larger for children with poorest nutrition outcomes.
Suri (2011)	Kenya in 1997, 1998, 2000, 2002, & 2004		65.8% in 1997 60.4% in 2004	There is heterogeneity in returns across the sample farmers. Farmers with high net returns adopted hybrid seeds & farmers with low net returns did not. Supply & infrastructure constraints such as long travel time to seed & fertilizer distributors become high costs for farmers & constraints of adoption.		
Mathenge et al. (2014)	Kenya, in 1997, 2000, 2004, 2007, & 2010.	Hybrid maize	68.1% of maize area in 2000 61.1% in 2004, 73.1% in 2007 82.0% in 2010			Adoption leads to 7% increase in household income, 9% increase in assets, 2.9% decrease in poverty gap in all areas.

Smale & Olwande (2014)	Kenya in 2009/10	Hybrid maize	82.80%	Male-headed households with more education, assets, & landholdings tend to plant hybrid seeds more. The seed-to-grain price ratio is negatively related to hybrid area planted.	
Bezu et al. (2014)	Malawi in 2004, 2007, & 2009	Improved maize (OPVs & hybrid)	48.6% of maize area in 2004, 55.4% in 2007 45% in 2009	The amount of improved maize planted is increased with access to subsidized inputs, education, land holdings, & male labor. Higher rainfall variability discourages planting improved maize.	1% increase in the area planted modern varieties would increase household income by 0.48%, the maize available consumption by 0.34%, & asset wealth by 0.24%.
Lunduka et al. (2012)	Malawi in 2010	Modern maize (OPVs & hybrid)	76%	Farmers value high yield & early maturity of modern varieties & they also value the storability, taste & processing traits of local varieties. Cash constraints hinder them from growing hybrid. Receipts of maize seed or fertilizer vouchers enhances adoption of modern seeds but this effect does not last long.	
Smale & Mason (2014)	Zambia in 2002/3 & 2006/7	Hybrid maize	37.4% in 2002/3 42.6% in 2006/7		Each kg of hybrid is associated with a 32,230 ZMK increase in total household income & decrease in severity of poverty that is 0.17 percentage points. At the mean, each kg of hybrid is associated with a 29,245 ZMK increase in total productive assets.
Khonje et al. (2015)	Zambia in 2012	Any improved maize	63.8%	Adoption is related to education, group membership, access to extension & market, household size, owning oxen & assets.	Adoption increases crop income by 20 percentage points & food security by 2-21 percentage points & reduce the probability of poverty by 11-21 percentage points.
Smale et al. (2015)	Zambia in 2011	Hybrid maize	68%		They interviewed to women. Adoption Increases the number of food groups & the number of food groups that are sources of vitamin A for women & children.

Becerril & Abdulai (2010)	Mexico in 2010	Improved maize (creolized, hybrid, OPVs)	Chiapas: 80.2% Oaxaca: 31.9%		Adoption increased household per capita expenditure by 136-173 pesos on average & reduced the probability of falling in poverty by about 19-31%. Small farmers benefit more from adoption of improved varieties than large farm.
Verkaart et al. (2017)	Ethiopia in 2006/7, 2009/10, & 2013/14	Improved chickpea	31.2% in 2006/7 63.0% in 2009/10 79.0% in 2013/14		10% increase in the area planted with improved chickpea increases per capita income by 12.6% & total income by 12.3% & reduces the probability of being below the median poverty line by 3.9%.
Michler et al. (2018)	Ethiopia in 2007, 2010, & 2014	Improved chickpea	31.1% in 2007 63.0% in 2010 79.1% in 2014	There is no impact on yield compared to local varieties.	Adoption reduces production costs & thus increases farm profits.
Asfaw et al. (2012a)	Tanzania & Ethiopia in 2008	Tanzania: improved pigeonpea Ethiopia: improved chickpea	Tanzania: improved pigeon peas: 32% Ethiopia: improved chick peas: 33%	Access to local supply of seed, access to information & perception about new varieties are key constraints for adoption.	Adaptors of improved pigeon peas in Tanzania & chick peas in Ethiopia have significantly higher consumption per adult equivalent.
Asfaw et al. (2012b)	Tanzania in 2008	Improved pigeonpea	33%	Inadequate local supply of seed & access to information, & perception about new varieties are key constraints for adoption.	Adoption increases per capita consumption by 18-31 percentage points, reduces the depth of poverty by 8-10 percentage points, & reduces severity of poverty by 4.4-8.1 percentage points.

Kassie et al. (2011)	Uganda in 2006	Improved groundnut	55.6%	Adoption is constrained by uneven availability of improved varieties, lack of development of market infrastructure, & poor access to information & extension services.		Adoption of improved groundnut significantly increases net crop income by 130-254 USD & reduces poverty headcount index by 7-9 percentage points. The gain in net crop income is especially higher for households in the bottom 3 quintiles in farm size & in the top 2 quintiles in education. The poverty impact is greater for households in the bottom 2 quintiles in farm size.
Shiferaw et al. (2015)	Uganda in 2006	Improved groundnut	58.7%	Adoption is constrained by imperfect markets for information & access to improved seed & credits.		
Manda et al. (2019)	Nigeria in 2017	Improved cowpea	41.5%			Adoption increases per capital income & asset by 17 & 24 percentage points respectively. It also reduces income poverty & asset poverty by 5 percentage points.
Kijima et al. (2011)	Uganda in 2004 & 2006	NERICA rice	65.7% in 2004 35.7% in 2006 in NERICA growing area			Though NERICA improved food security & reduce poverty in 2002, more than half of the NERICA adopters in 2004 deadadapted in 2006. This is partly due to low profitability of NERICA relative to alternative crops in variable rainfall areas. Low profitability could be due to weak dissemination of appropriate information on seed production to rice farmers.
Villano et al. (2015)	Philippines in 2006/7	Certified rice seeds	30%	Access to extension services & credits encourage adoption.	Adopters have about 11% output advantages compared with non-adopters.	Adoption increases net income in rice farming.
Cavatasso et al. (2011)	Ethiopia in 2002/03	Modern sorghum varieties	11.00%	While farmers experience moderate production stores & climatic risk tend to adopt MVs,		

those who are most vulnerable to extreme weather events tend to use the landraces. This implies that MVs are not effective means to cope with the catastrophic risk.

Smale et al. (2018)	Mali in 2014/15	Improved & hybrid sorghum	22%	Adoption of hybrid widens the range of food item consumed, reduces the share of sorghum in food purchase & contributes to a greater share of the harvested sorghum sold.
Shiferaw et al. (2014)	Ethiopia in 2011	Improved wheat	29.55%	The average treatment effect on the treated are 976 ETB & 2.7 percentage points for food consumption & binary food security outcome variables respectively. The average treatment effect on the untreated are 861 ETB & 4.5 percentage points for food consumption & binary food security outcome variables respectively.
Stress-tolerant varieties				
Kostandini et al. (2013)	Angola, Benin, Ethiopia, Ghana, Kenya, Malawi, Mali, Mozambique, Nigeria, Tanzania, Uganda, Zambia, Zimbabwe from 2001 to 2006.	Drought-tolerant maize	5% of maize area in 2006 in Angola, 15% in Benin, 19% in Ethiopia, 25% in Ghana, 72% in Kenya, 15% in Mali, 22% in Uganda, 11% in Malawi, 25% in Mozambique, 18% in Nigeria, 35% in Tanzania, 35% in Uganda,	Adoption can generate USD 362-590 million by 2016. 0.01-4.29% reduction in poverty by adopting drought tolerant maize by 2016.

Katengeza et al. (2019)	Malawi in 2006, 2009, 2012, & 2015	Drought-tolerant maize	3% in 2006 25% in 2009 40% in 2012 43% in 2015	Previous early season dry spells & access to seed subsidy increases adoption & adoption intensity.	
Yamano et al. (2018)	Bangladesh in 2013 & 2015	Submergence-tolerant rice	12.4% in 2012 30.2% in 2013 38.4% in 2014 37.5% in 2015 in the area where ST rice was distributed.	Experience of submergence in the previous year increases adoption. This effect is larger for farmers whose neighbors were early seed recipients.	
Yorobe et al. (2016)	Philippines in 2011 & 2012	Green super rice (GSR: high-yielding with tolerance with multiple abiotic stresses)	41% in 2012 in the area where GSR rice was distributed.	Adoption increases yield particularly at the high rainfall levels.	Adoption increases net farm income particularly at the high rainfall levels.

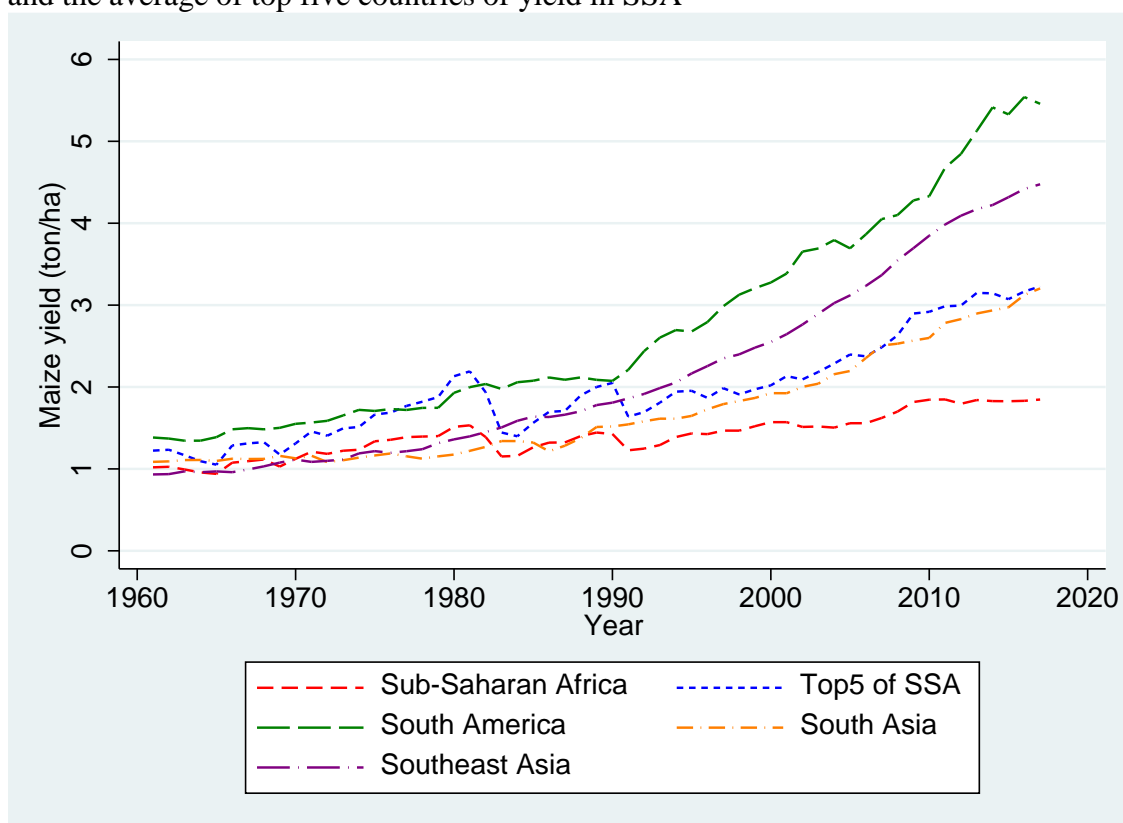
Table 3. Recent estimates of adoption of fertilizer, crop-fertilizer response rates and value-cost ratios in developing countries

Authors	Country & year	Adoption rates	Quantity of nitrogen adopted	Response rate	Value-cost ratio
Sheahan et al. (2013)	Kenya in 1997, 2000, & 2004, 2007, & 2010	64% of maize area with commercial fertilizer in 1997 73% in 2000 79% in 2004 83% in 2007 76% in 2010	26 kg N/ha in 1997 30 kg N/ha in 2000 32 kg N/ha in 2004 35 kg N/ha in 2007 40 kg N/ha in 2010	APP=21 kg maize /kg N MPP=17 kg maize /kg N	AVCR= 1.3-3.7 MVCR= 1.0-4.6
Matsumoto & Yamano (2013)	Kenya in 2004 & 2007 Uganda in 2005	74% in Kenya 3% in Uganda	18.41 kg N/ha 0.76 kg N/ha	MPP=14.1-19.8 kg hybrid maize /kg N in Kenya MPP=23.4-25 kg hybrid maize /kg N in Uganda	MVCR= 1.05-1.24 in Kenya (hybrid maize) MVCR= 0.74-1.05 in Uganda (hybrid maize)
Liverpool-Tasie (2017)	Nigeria in 2010 & 2012 in rice plots		61.7 kg N/ha in 2010 59.1 kg N/ha in 2012	APP=8.7-8.8 kg rice/ kg N MPP=8.9-9.0 kg maize/ kg N	
Liverpool-Tasie et al. (2017)	Nigeria in 2010 & 2012 in maize plots		40.2 kg N/ha in 2010 46.6 kg N/ha in 2012	APP=7.6-7.7 kg maize /kg N in 2010 APP=7.56 kg maize /kg N in 2012 MPP=7.75 kg maize /kg N in 2010 MPP=7.71 kg maize /kg N in 2012	% of maize plots with AVCR ≥ 1 :51% in 2010: 56% in 2012 MVCR ≥ 1 :49% in 2010: 51% in 2012
Burke et al. (2017)	Zambia in 2004 & 2008			APP=2.6-5.0 kg maize/kg top dressing fertilizer depending on soil type and tillage methods	AVCR of basal application = -1.4-5.3 depending on pH of soil
Burke et al. (2019)	Zambia in 2012			APP= insignificant (0) to 7 kg maize/ fertilizer kg depending on soil characteristics	AVCR= 1-2

Source: Reproduced table 1 in Jayne et al. (2019)

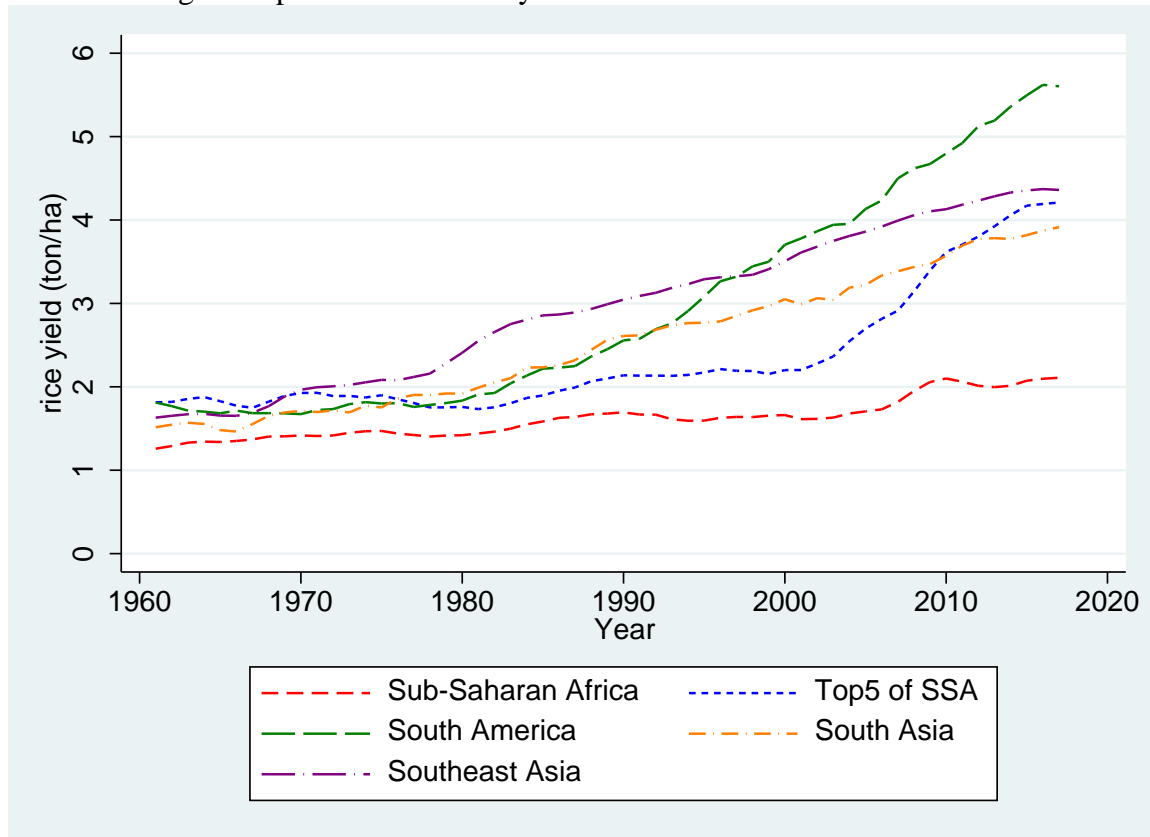
* APP: average physical products of fertilizer, MPP: marginal physical products of fertilizer, AVCR: average value cost ratios, & MVCR: marginal value cost ratio

Figure 1. Changes in maize yields in SSA, South Asia, Southeast Asia, South America, and the average of top five countries of yield in SSA



Source: FAOSTAT (2019)

Figure 2. Changes in rice yields in SSA, South Asia, Southeast Asia, South America, and the average of top five countries of yield in SSA



Source: FAOSTAT (2019)

Abstract(in Japanese)

要約

低所得国、特にサハラ砂漠以南のアフリカ(SSA)では、農業の生産性の停滞や食糧の慢性的不足が続いており、こうした地域における新技術の採用やその生産性への効果について研究者から大きな関心が寄せられている。興味深いことに、最近になって SSA でも「緑の革命」の萌芽が、先進地域を中心にして見られるようになった。また最近の多くの研究では、穀物生産の収量を持続的に向上させるためには、土壌の肥沃土の維持を含む「総合的な農業経営」が重要であることが強調されるようになった。他方、過去 10 年間においては、農業技術の普及における社会的ネットワーク、あるいは農民から農民への知識の伝達の役割についての関心が高まってきた。こうした研究では、伝統的な政府による普及システムよりも効率的な普及システムが探求されている。本論文は、最近の農業技術の採用とその効果に関する事例研究と、農業普及に関する研究とを包括的にレビューし、何が共通する普遍的発見であるか、何が分析上の弱点か、さらに今後究明すべき研究課題は何かを、明らかにしようとするものである。

キーワード：技術採用、生産性への効果、農業普及システム、技術普及



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