A Strategic Framework for Adoption and Impact Studies
in the CGIAR Research Program on Wheat (WHEAT)

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CGIAR
RESEARCH PROGRAM ON Wheat

CIMMYT
International Maize and Wheat Improvement Center

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Science for resilient livelihoods in dry areas

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1. Introduction

The CGIAR centers in collaboration with the national agricultural research systems (NARS) across the global South have developed a number of agricultural innovations that helped lower the cost of producing their major food staples and increase food security among the poor (Evenson and Gollin, 2003; Evenson, 2001). Economists and other social scientists have long sought to establish the developmental outcomes of these technological interventions in agriculture under various agro-ecological, socio-economic, demographic and institutional contexts. Documenting technology adoption and establishing the associated impacts are essentially important for agricultural research for two reasons. First, they provide a simple measure of performance of agricultural research for development (R4D) programs (Glover et al., 2016). Second, the lessons obtained from adoption-impact assessment studies can be used for subsequent improvements in agricultural R4D (Walker and Alwang, 2015; Douthwaite et al., 2003). Although a large number of studies have demonstrated that growth in agricultural productivity and reduction in rural poverty is inextricably intertwined with investments in agricultural research and extension (Pray et al., 2017; Thornton et al., 2017; Evenson and Gollin, 2003), agriculture R4D remains to be an under-invested domain in many developing countries (Raitzer and Maredia, 2012; Hurley et al., 2014). Decades of decline in the real price of food had generated a false optimism on adequacy of food production, which in turn affected the relative importance of R4D spending in agriculture.

In the wheat agri-food systems, R4D interventions are proven to have significant livelihood implications and stimulated in depth stakeholder dialogue. Wheat is cultivated widely by marginal and resource-poor smallholder farmers and is a major source of calories and protein for both urban and rural consumers in the developing world (Shiferaw et al., 2013). In the recent past, wheat productivity has been growing in a sluggish pace, lagging behind the world population growth. There are a multitude of contributing factors for this phenomenon. Some of the challenges faced especially by smallholder farmers in cultivation of wheat are novel (e.g., virulent strains of wheat rust [Mottaleb et al., 2018; Hovmøller et al., 2010]), while some others (e.g., declining potassium in the soil and terminal heat [Ortiz et al., 2008; Ladha et al., 2003]) are increasing in their intensity. While there has been no slowdown in the rate of release of rust resistant, drought tolerant and more productive varieties, a large portion of wheat area in many countries is still cultivated with older improved varieties (Atlin et al., 2017; Krishna et al., 2016; Yigezu et al., 2016) and local ones. The slowdown of public and private investments in breeding research have made the situation worse putting pressure on both national and international wheat productivity improvement programs. Given that the challenges faced by the agri-food systems are dynamic, one of the major global challenges in the years to come would be transferring the relevant agricultural innovations quickly and consistently into the hands of the world's poor farmers, such as those living in South Asia and sub-Saharan Africa.

The CGIAR Research Program on Wheat (WHEAT) aims to "ensure that publicly funded international agricultural research helps most effectively to dramatically boost farm-level wheat productivity, while renewing and fortifying the crop's resistance to globally important diseases and pests, enhancing its adaptation to warmer climates, and reducing its water, fertilizer, labor and fuel requirements" (WHEAT, 2016). Through different research programs carried under WHEAT, about 17.5 million more farm households are expected to adopt improved wheat varieties and associated crop management practices by year 2022 and that wheat yields will increase on average by 1.4 percent each year. About 5.7 million people, half of which are women, would be assisted to escape poverty and to meeting the minimum daily carbohydrate requirements in the same timeline. These objectives will be achieved through germplasm improvement and sustainable intensification of wheat production systems, while ensuring significant improvements in water and nutrient use efficiency and a reduction of farming-related carbon-dioxide emission in the wheat farming systems during the period of program implementation.

The socio-economic research component of CRP WHEAT is expected to facilitate attainment of the aforementioned goals. To this effect, past trends on technology diffusion in wheat production systems are continuously documented, which would aid priority setting and foresight. Socioeconomic research could also help create a conducive policy and institutional environment across all the nodes of wheat value chains for rapid diffusion and transfer of innovations among farm households belonging to different socioeconomic strata. Finally, comprehensive assessments on the level of adoption and impacts of the different technologies and managerial practices will be generated to provide credible evidence on how much of the planned outputs and outcomes are realized in the field. Against this backdrop, this document presents a strategy framework to facilitate assessment of diffusion and impacts of technology interventions in wheat systems. The framework will be revised every 3 years or so, by including the latest literature on adoption and impacts of technology interventions in wheat agri-food systems and by incorporating lessons learnt from implementing the strategy in the field.

2. A conceptual framework for adoption and impact assessment

The main objective of the adoption and impact assessment cluster of activities in WHEAT is to institutionalize a formal procedure to address the increasing demand for quantifiable, relevant and credible research evidence on the outcomes of R4D activities of the CRP by employing an approach that is methodologically rigorous, financially efficient, and socially inclusive in all respects. In this section, a conceptual framework for adoption and impact assessment for wheat production systems is developed, which is expected to help position the research agenda and explore gaps in the existing literature. The framework is expected to help the CRP team better prioritize the research activities in the field. Figure 1 shows the connection between investment in wheat R4D and development of the agrarian economy through a number of intermediary steps is depicted. The impact assessment envisages a two-tier assessment of interventions – both at the macro and at the micro-levels.

Directly linking R4D investment to economic growth and poverty reduction is a common approach in the macro-studies to evaluate the returns to research investments (Pardey et al., 2016; Hurley et al., 2014). Macro-studies are conducted both within a single crop (e.g., Nalley et al. [2010]) and across different crops (e.g., Raitzer and Kelley [2008]). The macro-studies in wheat agri-food systems ideally focus on estimating aggregate impacts of the program interventions across the entire developing world, by keeping a systematic inventory of technology releases, area coverage of individual technologies, and aggregate changes in the rural economy and farmers' livelihoods that are attributable to the R4D made. A distinctive outcome of such effort is evidenced in the recently-released report on aggregate impacts of international wheat improvement research (Lantican et al., 2016).

Micro-level studies provide relevant information to clarify the impact pathways and to trace out the constraints and challenges in transferring and scaling out technologies and innovations. These studies are commonly carried out through examination of data from farm-household surveys. Such data are then used for estimating the determinants of adoption of agricultural technologies and/or for estimating the field level impacts of adoption such as yield and net returns as well as household-level impacts such as household income, consumption, nutrition and other important outcome variables. In addition to household surveys, an array of tools are currently available to study micro-level adoption and impacts, ranging from elicitation of expert opinions, DNA finger printing, examination of digital footprints left behind in the transaction logs of mobile phones and high-resolution satellite imageries. The expensive and time-consuming farm-household surveys can be partly substituted with data derived from any of the abovementioned tools or with open access datasets at the micro level (e.g., Living Standards Measurement Study, LSMS). Deriving common variables from already existing household surveys conducted in different parts of the world to test generic but unexplored research hypotheses is another less expensive way to estimate the spread of technology interventions.

Keeping track of the spread of technologies derived from R4D investment is the first step toward effective monitoring and impact evaluation. Slow level of scaling out and diffusion of technologies in smallholder farming systems is often cited as the key factor explaining stagnating agricultural yields (Pamuk et al., 2014). This warrants in-depth adoption studies detailing the constraints of adoption, which may be particularly severe for certain strata of farming communities. There are two main factors that complicate the adoption analysis: (i) diversity of forms of agricultural interventions that prevents application of generic analytical methods, and (ii) constant reinvention of technologies by farm households. Based on the form, technology interventions could be biological (e.g., improved varieties), chemical (e.g., herbicides), mechanical (e.g., seed drill), agronomic (e.g., intercropping), informational (e.g., market selection) or a combination of all (Sunding and Zilberman, 2001), and the methodology of adoption studies vary accordingly. Farmers continuously reconstruct the technological information they were passed on (Douthwaite et al., 2003), and this reinvention results in an array of non-uniform technological inputs in a process mediated by a multitude of socio-economic factors and constraints. As a result, partial adoption of certain elements, dis-adoption and discontinuous adoption other than the dichotomy of full and non-adoption can be observed. Measures of adoption may also indicate either or both the speed and extent of new technology utilization by farm households. This inherent complexity of adoption studies is reflected in the statement by Sunding and Zilberman (2001): "Adoption behavior may be depicted by more than one variable. It may be depicted by a discrete choice, whether or not to utilize an innovation, or by a continuous variable that indicates to what extent a divisible innovation is used. For example, one measure of the adoption of a high-yield seed variety by a farmer is a discrete variable denoting if this variety is being used by a farmer at a certain time; another measure is what percent of the farmer's land is planted with this variety." (p. 229).

In Figure 1, the adoption decision is represented as continuum between (a) immediate and continuous adoption of all technology components on the whole farm (or at least all relevant crop plots), and (b) non-adoption of any technology-component. As indicated above, this continuum includes a number of different combinations rather than simple dichotomous choice. The adoption studies are expected to make conscious efforts to capture this complexity while evaluating the spread of innovations in the agri-food systems. Future adoption studies in WHEAT may additionally include the behavioral (e.g., role of risk aversion) and institutional (e.g., land tenure, contract farming) factors, complementarities between newly introduced and already existing technologies, and subjective expectations of farmers on impact of the technology. There is a vast literature that describes the observable heterogeneity of farming community that restricts scaling out of technologies. Various studies across developing countries have highlighted the unavailability and untimely and slow delivery of the technologies and unfavorable climactic conditions as adoption constraints (Suri, 2011). In addition, an active investigation is required of the supply side factors, such as the production and distribution of certified seeds of improved varieties, the role of policy environment and extension methods, in order to design effective and inclusive dissemination strategies.

Adoption studies are often complemented by ex-post impact evaluations that quantify the economic and social outcomes of the technology intervention (Maredia et al., 2014). Once the adoption rates are calculated, the impact assessments would involve estimating a single parameter – the average effect size. However, the process of estimation of effect size is not straightforward. Depending on the nature of the technology and the socio-economic, institutional and agro-ecological conditions, farmers' adoption decision could lead to a multitude of outcomes, including even some undesirable or unforeseen ones. Depending on the research question at hand, the timeframe of impact pathway, and the size, scale and landscape of intervention, the methodological approach to attribute the outcomes to intervention varies widely – from partial equilibrium economic surplus models to social accounting matrices, micro-econometric and general equilibrium models.

Against the abovementioned backdrop, a major task of the WHEAT CoA adoption/impact is to **quantify and assign monetary values to the technology impacts** in wheat agri-food systems with methodological rigor. Adoption of a technology potentially reduces the use of certain inputs, increases output quality and/or quantity and hence reduce/increase prices, reduces yield variability, and/or enhances environmental services from the wheat production systems (Figure 1). The key performance indicators derived from this figure are shown in Table 1, with associated sub-IDOs and SLOs. While many of these indicators focuses on farm-households, the technological changes would also affect the livelihoods of urban poor consumers, and the households that provide production inputs (e.g., agricultural laborers, machinery service providers etc.). If the demand for inputs changes at a large scale, it could even affect the demand for locally produced commodities and hence the output price. Such multiple impact pathways make the estimation of aggregate effect of a technology complex and often non-linear.

A number of studies have noted that no single framework or methodology could fit all impact evaluation exercises in the development field. Emergent understanding on scaling up and scaling out of technologies necessitates a constructivist paradigm of rural development, in which farmers take part in the learning process actively and construct knowledge by fitting technological information in to their existing world view. Thus, flagship project (FP) 1 will actively engage in identification of a range of realistic impact pathways in wheat agri-food systems. We carry out this by strengthening the feedback loops between research, the agricultural development community, and farmers. In this regard, importance of strengthening importance of extension services should be also highlighted. A sound impact evaluation requires diverse evaluation methods (e.g., qualitative, participative) complementary to the conventional economic impact assessment methods (Douthwaite et al., 2003). For instance, qualitative methods help in the deeper understanding of findings obtained from quantitative methods by shedding light on the processes and causal relationships. Some of the research will therefore be carried out jointly by both quantitative and qualitative social scientists and by using participatory research approaches to inform the adaptation of WHEAT innovations especially at the initial stages of their development, scaling, and adoption.

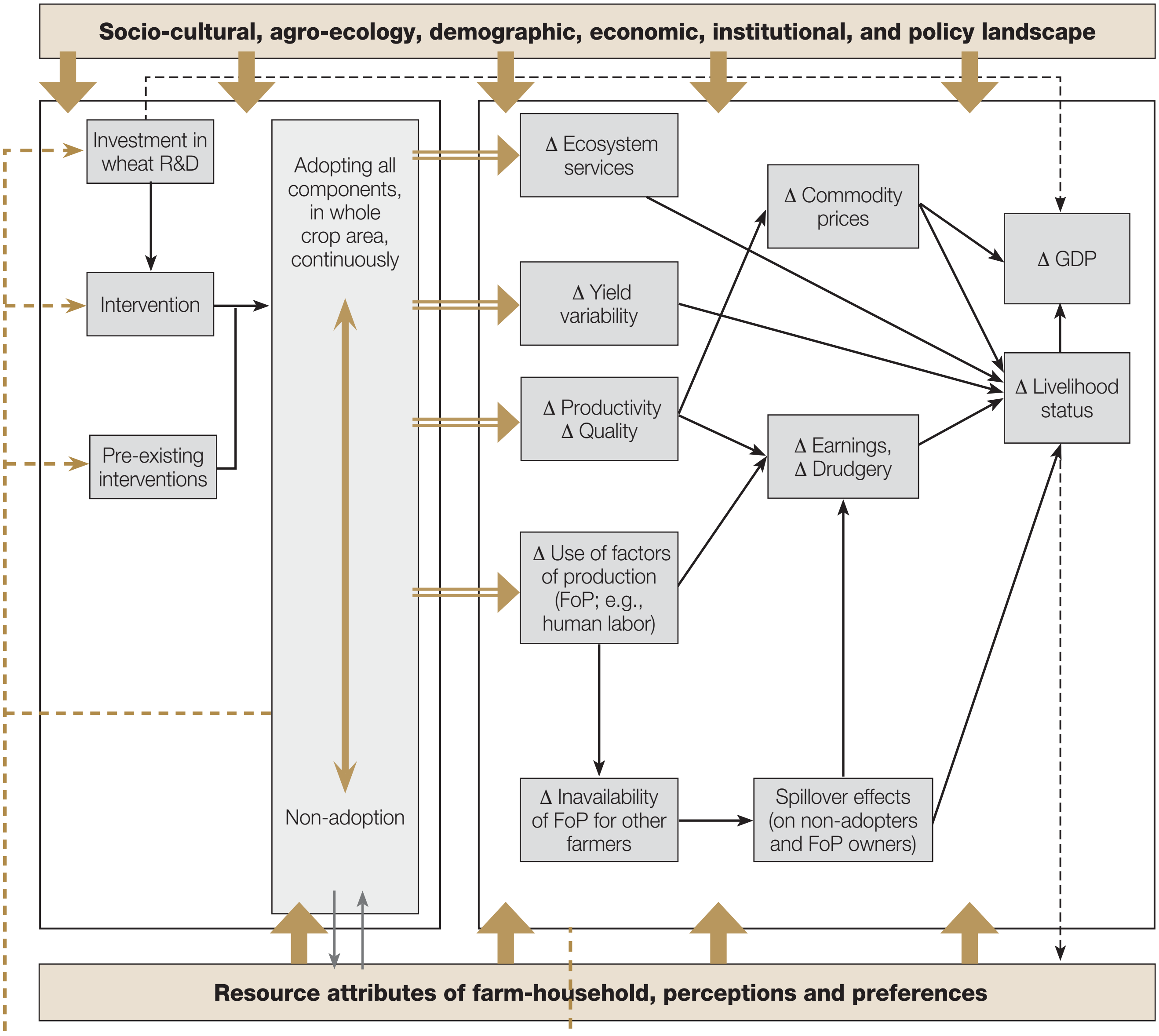

Figure 1. Framework of Adoption-Impact Studies

Table 1. CRP WHEAT Key Performance Indicators

Key Performance Indicator	Sub-Intermediate Development Outcomes (Sub-IDOs)	System Level Outcomes (SLOs)
1. Technology adoption - New varieties, sustainable intensification practices etc.	Enhanced genetic gain; More efficient inputs use; Reduced production risk.	Reduced poverty; Improved natural resources systems and ecosystems services
2. External input use	More efficient inputs use; Reduced production risk.	Reduced poverty; Improved natural resources systems and ecosystems services
3. Farm mechanization	More efficient inputs use.	Reduced poverty; Improved natural resources systems and ecosystems services
4. Diversity (varietal/crop/farm)	Enhanced genetic gain; Increased availability of diverse nutrient-rich foods; Agri-systems diversified, intensified.	Reduced poverty; Improved natural resources systems and ecosystems services
5. Grain yield	Reduced pre- and post-harvest losses.	Reduced poverty
6. Yield gap	Reduced pre- and post-harvest losses; Closed yield gaps.	Reduced poverty
7. Post-harvest loss	Reduced pre- and post-harvest losses.	Reduced poverty
8. Cost of cultivation	More efficient inputs use.	Reduced poverty
9. Production risk	Reduced production risk; Enhanced capacity to deal with risk.	Reduced poverty
10. Input-use efficiency	Reduced pre- and post-harvest losses; More efficient inputs use.	Reduced poverty; Improved natural resources systems and ecosystems services
11. Gross margin	Increased value captured by producers.	Reduced poverty
12. Crop income	Increased value captured by producers.	Reduced poverty
13. Household income	Increased livelihood opportunities, Increased value captured by producers.	Reduced poverty; Improved food and nutrition security for health
14. Involvement of women & youth in decision-making	Technologies that reduce women's labor and energy expenditure developed and disseminated; Improved capacity of women and young people in decision-making.	Reduced poverty; Improved food and nutrition security for health
15. Capacity building	Enhanced capacity to deal with risk; Increased capacity of beneficiaries to adopt research outputs; Enhanced institutional capacity of partner research organizations.	Reduced poverty
16. Dietary diversity 17. Nutritional intake 18. Food insecurity & poverty	Increased availability of diverse nutrient rich food; Increased access to diverse nutrient rich food; optimized consumption of diverse nutrient rich foods.	Reduced poverty; Improved food and nutrition security for health

3. Studies at the macro-level

A number of studies have examined how public and private sector agricultural R4D leads to desirable economic, social and environmental outcomes. Particularly, it reduces poverty, alleviates malnutrition, and builds resilience against biotic and abiotic stresses. Moreover, the new crop and livestock technologies generated by R4D increase the quantity and quality of agricultural output per unit of land, labor, water, and other resources (Pray et al., 2017). In general, at an aggregate level, investment in agricultural R4D is estimated to have significantly high returns (Alston et al., 2012; Renkow and Byerlee, 2010).[1] For example, Lantican et al. (2016) estimated the benefit-cost ratio of CGIAR wheat improvement efforts ranging from 73:1 to 103:1. However, some researchers have observed that the distribution of impacts from agricultural research among target groups / types of beneficiaries is highly skewed and the high rates of return calculated for individual cases of success are unlikely to be representative of the overall research portfolios (Maredia and Raitzer, 2010). The benefits from individual investments vary widely and targeting of investments is required to generate the greatest possible livelihood and/or environmental effects.

CGIAR programs and Centers develop technologies in collaboration with national partners. Historically, CGIAR-related varieties are being cultivated in about 64% of wheat area in the developing countries (Lantican et al., 2016). This has resulted in substantial increase in yields, improved grain quality, reduced yield variability, and improved tolerance to biotic and abiotic stresses (Byerlee and Dubin, 2010). Unlike the agronomic and financial impacts, the livelihood and poverty impacts of CGIAR interventions have not been well documented in macro-level impact studies. An exception would be Nalley et al. (2010), which examined the reduction in yield variability in wheat due to CIMMYT-bred cultivars in Yaqui Valley of Mexico. Another study is Marasas et al. (2003), which is on the economic impact of rust resistance breeding program by CIMMYT. Nevertheless, only a few studies have addressed the poverty, environmental, or health impacts of agricultural R4D in general (Maredia and Raitzer, 2010). One possible reason is that extending macro-impact studies to livelihood and poverty dimensions require richer datasets. Use of potential data sources like high-resolution satellite imageries needs to be explored in this connection. Satellite imageries could retroactively provide estimates not only of vegetation changes (Lobell et al., 2013), but also indicators of poverty and economic wellbeing (Jean et al., 2016). Another source of data would be on the mobile phone usage; machine-learning algorithms can infer households' socioeconomic status ("phone-based proxies for wealth") directly from their mobile phone use (Blumenstock, 2016). Such rich datasets could be combined with crop simulation modelling and climate analysis, to carry research on topics like estimation of economic value of variance-reducing interventions (Mushtaq et al. 2017).

Another research gap in the field of macro-economic impact assessments is regarding interventions in agronomy and natural resource management (Renkow and Byerlee, 2010). While several location-specific and system-specific studies have quantified the yield advantages realized due to genetic improvements, few studies have addressed the contribution of CGIAR institutions on improving the agronomic practices and management techniques. There has been a significant research focus in CGIAR on developing sustainable intensification practices for wheat-based systems that reduce farmer dependence on external inputs and generate lesser negative externalities (like Green House Gas production). Technology-driven intensification is also land-saving with a potential to arrest deforestation if accompanied by stronger institutions to govern natural resources (Byerlee et al., 2014; Stevenson et al., 2013). Quantification of these impacts of sustainable intensification practices in economic terms at the macro level would be one of the major objectives of the second phase of WHEAT. Both tracking technology diffusion and ascribing economic value to the technology impacts in environment and social spheres are more challenging for agronomic interventions than crop genetic improvement. Secondary information on adoption of agronomic practices are scant in most developing countries. Compared to genetic intervention, attribution is more difficult with respect to diffusion of agronomic practices. Many sustainable intensification practices (e.g., crop rotations) are *de facto* followed by farmers or disseminated by developmental agencies outside the CGIAR. Attributing all acreage change to CGIAR centers could inevitably lead to overestimation. Combination of conventional methods like expert surveys with new opportunities provided by satellite imageries could provide novel methodologies to capture diffusion of agronomic practices.

1 Addressing several methodological concerns and scrutinizing investment evaluations reported in 372 separate studies from 1958 to 2011, Hurley et al., (2014) recalibrated estimates of the rate of return as about 10 percent per year, which are still substantial enough to question the current scaling back of public agricultural R&D spending in many countries.

To avoid duplication of efforts as well as to create panel datasets that are amenable to analysis of the longitudinal and spatial dimensions of adoption and impacts, WHEAT FP1 will strengthen its efforts to assemble past, current and future datasets in a common repository. This will be made openly accessible for any individual or institution interested in using the data over a fixed period. Along with the establishment of a common data repository, FP1 will make more macro-level studies possible by standardizing sampling designs and survey instruments for all socio-economics studies under WHEAT. Such standardization will not only make it possible to assemble data from different studies in the same country or region but also to make comparative studies across the countries or regions of interest as well as to conduct longitudinal analysis to see changes across time. Given such data, aggregation of impacts to larger geographic regions or agro-ecological zones will also be possible.

4. Measuring adoption, beyond the dummies

The notion of adoption as a process governing the utilization of innovations (Sunding and Zilberman, 2001) is central for a coherent understanding of technological change in agriculture. A large number of empirical studies seek to explain why farmers of developing countries do (do not) take up different agricultural technologies which is key to transformation of farming system and a way out of poverty in many developing countries. Feder et al. (1985) had outlined the conventional methodology of adoption studies, which includes representing adoption using a dummy variable, selection of number of potential explanatory variables to include in the analytical models, and testing the statistical relevance of the explanatory variable using logistic or probit regression models. Glover et al. (2016) criticizes the adoption concept as commonly used in development research literature and practice indicating that it leads to inaccurate and misleading conclusions. Addressing agricultural research in Africa, the authors opine that the concept of adoption used in many studies are "too linear in both spatial and temporal terms, too binary, too focused on individual decisions, and blind to many important aspects of technological change" (Glover et al., 2016: p4). This criticism could be directed adoption studies in other parts of developing world, as well.

Even three decades after publishing the seminal review paper of Feder et al. (1985), the approaches of adoption studies in the field of agriculture have not changed significantly. Technological changes are depicted often by relatively simple farmer choice that can be represented by dichotomous variable, overlooking farmer's learning process shaped by his or her socio-cultural and demographic context. Many of the studies assume technological change as replacement of old inferior practices with new superior ones, thereby making them inherently incapable to address the processes of adaptation, creolization, hybridization and incorporation (Glover et al., 2016; Douthwaite et al., 2003; Douthwaite et al., 2001). Developing a sound adoption and impact strategy for WHEAT requires review of more recent studies addressing the diffusion of modern varieties and sustainable intensification practices in wheat agri-food systems. To this effect, a review of such studies carried during 2008-2017 period is provided below.

A complete list of adoption studies published in Scopus and Web of Science journals is shown in Table 1. Only six studies addressed adoption of seed-based technologies during 2008-2017 (Abay et al., 2017; Nazli and Smale, 2016; Krishna et al., 2016; Ali et al., 2015; Shiferaw et al., 2014; Matuschke and Qaim, 2009). The major objective of these papers was to understand the determinants of speed and reach of diffusion of new varieties. Some of these studies, although aiming to examine both adoption and effects of adoption, focused only on the effects, overlooking the complexities of adoption decision. One contributing factor for low abundance of varietal adoption studies could be that researchers consider the topic as age-old and 'thoroughly studied' already in the Green Revolution era, with only limited potential for publication at present. Indeed, owing possibly to methodological and contextual shortcomings, past adoption literature have identified only a few variables that are consistently important for explaining the adoption decision by farmer. As a result, unless they see substantial methodological improvements, many good journals refrain from accepting manuscripts on adoption. Having said that, in many parts of global South, recent varietal changes do not resemble that in the Green Revolution era. Varietal change no longer involves a drastic transformational technology shift from landraces to modern varieties, but an incremental shift from one modern variety to another more recently released variety. Furthermore, more and more varieties are coming up with attributes other than yield enhancement. Farmer preference for varieties with biotic or abiotic tolerance could be systematically different from those with higher mean yield potential. As shown by Nazli and Smale (2016), the adoption decision need not be solely dependent on the expected yield, but also on input requirements and consumption utilities.

Compared to varietal adoption, farmer adoption of sustainable intensification practices in wheat systems is featured more frequently in the literature. Of the 22 papers shown in Table 1, a majority were conducted by researchers associated with CIMMYT. With a few exceptions, the geographical focus of these papers was South Asia. Major research questions addressed varied widely, from farmers' dis-adoption of technologies to inter-dependence of adoption of different technologies. They have also provided valuable insights into carrying out quick but effective monitoring of diffusion process. Magnan et al. (2015) could be particularly mentioned for the methodological vigor. Using randomized control trials, the study examined the diffusion of a resource-conserving technology, the effects of which are heterogeneous in the target community.

Table 2. Technology adoption studies in wheat production systems (2008-2017)

Study	Country	Technology	Data sources	Data type	Analytical tool	Remarks
Ali and Erenstein (2017)†	Pakistan	climate change adaptation practices	farm survey (n = 950)	cross-sectional	probit, censored least absolute deviation	determinants of use and number of practices used.
Abay et al. (2017)	Ethiopia	chemical fertilizers, improved seeds, and irrigation	farm survey (n = 7500)	longitudinal	multivariate probit	implication of farmers' locus of control on their technology adoption decisions.
Keil et al. (2017)†	India	conservation tillage	farm survey (n = 990)	cross-sectional	probit with sample selection	determinants of adoption correcting non-exposure bias.
Rahut and Ali (2017)†	Pakistan	climate-risk mitigating strategies	farm survey (n = 500)	cross-sectional	multivariate probit	determinants of choice of adaptation strategies by farmers.
Joshi et al. (2017)	Nepal	climate-risk adaptation	farm survey (n =120)	cross-sectional	logit	determinants of climate change adaptation technologies and practices.
Mottaleb et al. (2016)†	Bangladesh	scale-appropriate machinery	agricultural census (n = 25.35 million) and sub-sample (n = 1.16 million)	cross-sectional	multinomial probit	determinants of ownership of machineries.
Singh et al. (2016)	India	zero tillage	farm survey (n = 40)	cross-sectional	logit	determinants and reasons for adoption.
Ali et al. (2016)†	Pakistan	irrigation	farm survey (n = 950)	cross-sectional	multivariate probit	determinants of farmers' choice of water pumps.
Kumar et al. (2016)†	India	zero tillage	farm survey (n = 240)	cross-sectional	descriptive	knowledge, attitude, and perception toward technology.
Keil et al. (2016)†	India	conservation tillage	survey among service providers (n = 277) and farmers (n = 991)	cross-sectional	Heckman selection	determinants and profitability of conservation tillage service provision.
Nazli and Smale (2016)	Pakistan	new varieties	farm survey (n = 1116)	time-series	duration model	demand for varietal traits; farmer heterogeneity.
Teshome et al. (2016a)†	Ethiopia	soil and water conservation	farm survey (n = 272)	cross-sectional	ordered probit	adoption phases.
Meena et al. (2016)	India	zero tillage	farm survey (n = 180)		multinomial logit	reasons for non- and dis-adoption and constraints in adoption
Krishna et al. (2016)†	India	new varieties	secondary data from public seed sector	time series	descriptive	trend in demand for breeder seeds and production.
			farm survey (n = 323)	cross-sectional	ordinary least squares	determinants of varietal turnover in farmers' field.
Teshome et al., (2016b)†	Ethiopia	sustainable land management	farm survey (n = 300)	cross-sectional	multivariate probit	role of farmer perceptions on investment.
Ali et al. (2015)†	Pakistan	certified seeds	farm survey (n = 367)	cross-sectional	binary variable (not specified)	adoption modelling as a preliminary step for impact assessment.
Mahmood et al. (2015)	Pakistan	water-saving technologies	farm survey (n = 270)	cross-sectional	none	adoption level of water-saving irrigation interventions.

Study	Country	Technology	Data sources	Data type	Analytical tool	Remarks
Magnan et al. (2015)	India	laser land leveling	randomized control trial (n = 478)	experimental	ordinary least squares	role of heterogeneous information on adoption.
Shiferaw et al. (2014)†	Ethiopia	improved varieties	farm survey (n = 2017)	cross-sectional	probit	determinants and impacts of farmer adoption of improved varieties.
Singh et al. (2012)†	Bangladesh, India, Nepal, Pakistan	resource-conserving technologies	village survey (n = 56)	cross-sectional	descriptive	extent of exposure and adoption of technologies.
Kassie et al. (2011)†	Ethiopia	soil conservation	farm survey (n = 148)	cross-sectional	logit	adoption modelling as a preliminary step for impact assessment.
Erenstein (2010a)†	India, Pakistan	conservation tillage	secondary data, supply-side surveys (n = 78), farm surveys (n = 858)	cross-sectional	descriptive	presents a triangulation approach to assess technology diffusion.
Erenstein (2010b)†	India	conservation tillage	village survey (n = 170)	case-studies	descriptive	village surveys to explore technology dynamics.
Matuschke and Qaim (2009)	India	new varieties	farm survey (n = 282)	cross-sectional	Tobit, probit	effect of social networks on adoption.
Erenstein and Farooq (2009)†	India, Pakistan	conservation tillage	farm survey (n = 527)	cross-sectional	bivariate analysis	determinants of adoption and dis-adoption.
Kassie et al.(2009)†	Ethiopia	conservation tillage, compost and chemical fertilizers	farm survey (n = 130) and plot-level data (n = 348)	cross-sectional	trivariate probit	estimated inter-dependence adoption of 3 practices.
Singh et al. (2008)	India	zero tillage	farm survey (n = 100)	cross-sectional	descriptive	knowledge, attitude, and perception toward technology.
Torkamani and Shajari (2008)	Iran	Irrigation	farm survey (n = 187)	cross-sectional	probit	relative risk premiums to estimate adoption model.

† Studies conducted by CIMMYT/ICARDA researcher(s).

Strategy for future adoption studies under WHEAT:

- Given the pronounced research gap with respect to varietal technology adoption in wheat and against the backdrop of emerging biotic/abiotic stresses in wheat systems, WHEAT socioeconomists should focus on conducting more systematic studies on varietal diffusion.

- A major factor that prevents widespread adoption studies is that the conventional method of household-level data collection is highly resource demanding and time consuming. A substantial lag between data collection and publication of results reduces the value of these studies for monitoring the technology dynamics. Erenstein (2010b) suggests the use of village surveys as a rapid and less resource intensive complement. Secondary datasets (e.g., Situation Assessment Survey in Indian Agriculture, LSMS surveys etc.) could also provide some useful information. A recent study that effectively used an existing datasets is Mottaleb et al. (2016).

- New data collection methods like satellite imageries and use of unmanned aerial vehicles (UAVs) could be effectively employed to generate data on adoption of cropping practices. While the former is already used technology monitoring (e.g., (Lobell et al., 2013; Zheng et al., 2014), the potential of UAVs to acquire images from low altitudes is not adequately utilized. The UAS are shown to have advantages of having lower cost of operation, higher picture resolution, and high flexibility in image acquisition programming (Zhang and Kovacs, 2012). WHEAT will study the pros and cons of different methods of acquiring data on varietal diffusion and develop protocols for data collection using the selected methods.

- Apart from enhancing precision in data collection, WHEAT calls for a deliberate focus on less-studied but socially relevant aspects of diffusion process, such as social inclusion, access to production resources, and economic inequalities. Only a small subset of adoption studies incorporated the social and economic heterogeneities in the analysis, although many suggest the relevance of these variables in shaping the adoption pattern. Not only that the existing resource inequalities could affect the diffusion of agricultural technologies, but also that the diffusion process could enhance these inequalities if not adequately implemented.

- There has been limited investigation on the relevance of inherent technology attributes in determining the scaling out patterns and rate. Most of the existing adoption models focus on farmer attributes and altogether omit the technology traits, which are relevant factors in the decisionmaking. Apart from increasing the wheat grain yield at lower resource use, the adoption models overlook the role of technology traits like fodder yield or increased dependence on some other inputs. In the varietal adoption literature outside wheat systems, studies have demonstrated that technology traits influence decision-making in a non-separable manner.

- Finally, understanding the adoption problem from a system perspective is highly warranted. As observed by Glover et al. (2016) for technological change in African agriculture, through oversimplification of research problems to make it amenable for econometric analysis, adoption research often provides an inaccurate and misleading picture for the policy makers and evaluators. To this effect, future adoption and impact studies under WHEAT will include the major enterprises in the production system. For example, in wheat agri-food systems, legumes are used as rotation crops and the decision to rotate can influence the type of wheat variety to be adopted. Demand for animal feed may also influence the decision and extent of adoption. Wheat farmers who opt for the adoption of certain agronomic practices might also be interested in specific varieties, which are compatible with their preferred management.

5. Measuring impacts, beyond the 'mean yield'

Over the last decade, wheat production systems across the developing world experienced significant changes. Climate change is posing a greater threat (Lobell et al., 2012), and the pathogens with resistance toward pesticides are emerging and spreading (Oliver, 2014). High levels of climatic variability involving changes in distribution of rains and resource scarcity, especially of irrigation water, are becoming more evident. In response to such changes, R4D efforts continued to generate and disseminate different climate-smart technologies and innovations such as conservation agriculture (CA). Significant progress has also been made in breeding for stress-tolerance (Aktar-Uz-Zaman et al., 2017) and farmers are increasingly adopting high-yielding and water-efficient varieties (Lantican et al., 2016). In this section, we examine the adequacy of the literature on measuring the effects of the technological interventions during 2008-2017. A list of studies covering the effect of technology adoption in wheat in South and West Asia and sub Saharan Africa published in the international peer-reviewed journals is given in Table 2.

While some of these studies display commendable scholarship to track impact pathways of wheat R4D in the developing countries, some weaknesses are pervasive across these studies. First, the number of studies is inadequate to cover the ongoing R4D efforts in wheat in the developing world. In comparison, the number of studies investigating the effects of maize and rice technologies are higher. Second, similar to the adoption studies, there is a strong geographical bias towards South Asia. Of the 25 studies listed, 13 were carried out in India, while only four were in West Asia and three in sub Saharan Africa. Third, not many studies covered the effects of varietal improvement in wheat. Fourth, the outcome variable is predominantly agronomic (changes in input use and yield), while livelihood impacts are not covered by most studies and none addressed possible spillovers. Fifth, most studies focus on estimating the average treatment effect while neglecting the distributional aspect. Sixth, many of the studies could not establish causality and certain methodological issues were present, weakening the reliability of estimated impact parameters. The last three points require detailed discussion.

Addressing the livelihood effects. As depicted in Figure 1, the first stage of impact assessment would be identifying and quantifying the changes in the production process, like changes in mean yield, input use, yield variability etc., due to the technology intervention. The limitation of the existing literature on impact assessment is not that the productivity variables are used as dependent variable, but that the estimation stops there. By limiting the impact analyses to yield and marginal revenue, most of these studies inherently assume that the livelihood status of farm households will change correspondingly. In other words, heterogeneities in farmer strategies, constraints, and opportunities to improve their livelihood status by employing the additional profit from crop production are overlooked. Considerable debate is ongoing about the extent to which gains in crop yield have translated into livelihoods enhancement. The differential effects of agricultural innovations on livelihoods is evident in the nutritional studies (Yamano et al., 2016). Berti et al. (2004) reviewed the effect of 30 agricultural interventions on human nutrition and observed that while most interventions increased food production, they did not necessarily improve nutrition or health within the participating households in the short-run. While some studies attempted to address the livelihood effects of technology adoption in the wheat production systems (e.g., Ali and Erenstein, 2017; Shiferaw et al., 2014), they have not verified whether the time gap between technology adoption and observation is sufficient enough for these effects to manifest.

Heterogeneity and relevance of context. Most of the impact studies in wheat systems focus on the mean effect of the technology intervention, despite having a large variability in the estimates. However, the effect of agricultural growth on rural livelihoods depends on inequality in the distribution of production resources, especially land (Thirtle et al., 2003).[2] Depending on the institutional and agro-climatic conditions, the 'treatment effect' of interventions would be different for different groups of farm households. Variation in the treatment effects across different social groups is noted in a number of studies carried over in non-wheat systems. A better understanding of impact heterogeneity is essential for designing the scaling out strategies that can help avoid

2 Large farmers are more productive and they are early adopters of technology. The recent adoption literature that stresses on social learning theorizes that access to new technologies are related to capital endowments of farm households. Page et al. (2009) note that technological interventions "have had limited impacts on poor farmers because they are usually disseminated via on-farm demonstrations and field days; farmers who have sufficient land to guarantee food security and can bear the risk of adopting the new technologies, are inevitably invited to participate" (p.101).

Table 3. Technology impact studies in wheat production systems (2008-2017)

Study	Country	Technology	Data sources	Data type	Method to address the selection bias	Key output/outcome variable(s)
Ali and Erenstein (2017)†	Pakistan	climate change adaptation practices	farm survey (n = 950)	cross-sectional	matching	food security, poverty
Abro et al. (2017†	Ethiopia	rust-resistant varieties	farm survey (n = 2069)	2-year panel	panel data (fixed effects)	yield
Ali et al. (2017)†	Pakistan	Irrigation	farm survey (n = 917)	cross-sectional	matching	yield, income, poverty, land rent, water scarcity
Rahut and Ali (2017)†	Pakistan	climate-risk mitigating strategies	farm survey (n = 500)	cross-sectional	matching	yield, income, poverty
Kathpalia and Chander (2017)	India	agricultural machinery	farm survey (n = 100)	cross-sectional	none	NA (simple tabulation of farmer perceptions)
Singh (2017)	India	groundwater management	farm survey (n = 240)	cross-sectional	none	yield, net income
Singh et al. (2016)	India	zero tillage	farm survey (n = 40)	cross-sectional	none	yield, net income
Khatri-Chhetri et al. (2016)†	India	improved seeds, laser leveler, zero tillage	farm survey (n = 1267)	cross-sectional	none	input costs, grain yield
El-Shater et al. (2016†	Syria	zero tillage	farm survey (n = 621)	cross-sectional	endogenous switching, matching	net returns and wheat consumption
Rahut et al. (2016)†	Pakistan	Irrigation	farm survey (n = 950)	cross-sectional	matching	food security, income, poverty
Aryal et al. (2016)†	India	zero tillage	farm survey (n = 208)	2-year panel	none	grain yield (under normal and excess rainfall)
Keil et al. (2015)†	India	zero tillage	farm survey (n = 1444)	cross-sectional	none	grain yield
Aravindakshan et al. (2015)†	Bangladesh	conservation tillage	farm survey (n = 328)	cross-sectional	none	energy use efficiency
Aryal et al. (2015a)†	India	laser leveling	farm survey (n = 198)	cross-sectional	none	grain yield, irrigation time
Aryal et al. (2015b)†	India	zero tillage	farmers field trials (n = 40)	3-year panel	none	CO2 emission, profits
Krishna and Veettil (2014)†	India	zero tillage	farm survey (n = 180)	cross-sectional	none	grain yield, technical efficiency
Yigezu et al. (2014)†	Syria	improved supplemental irrigation	farm survey (n = 461)	cross-sectional	none	quantity and value of irrigation water
Shiferaw et al. (2014)†	Ethiopia	improved varieties	farm survey (n = 2017)	cross-sectional	endogenous switching, matching	per capita food expenditure, food security indicators
Lobell et al. (2013)†	India	time of sowing	satellite imageries	time series	none	grain yield
Yigezu et al. (2013)†	Syria	sprinkler irrigation	farm survey (n = 385)	cross-sectional	none	water use efficiency

Study	Country	Technology	Data sources	Data type	Method to address the selection bias	Key output/outcome variable(s)
Grover and Sharma (2011)	India	resource-conserving technologies	farm survey (n = 120)	cross-sectional	none	factor productivity
Kassie et al. (2011)†	Ethiopia	soil conservation	farm survey (n = 148)	cross-sectional	matching	crop income
Erenstein (2009)†	India, Pakistan	zero tillage	farm survey (n = 858)	cross-sectional	within-farm comparison	input use, grain yield, profit
Erenstein et al. (2008)	India, Pakistan	zero tillage	farm survey (n = 391)	cross-sectional	none	yield, cost, profitability
Torkamani and Shajari (2008)	Iran	Irrigation	farm survey (n = 187)	cross-sectional	none	mean yield and production risk

† Studies conducted by CIMMYT/ICARDA researcher(s).

the widening income inequality while promoting sustainable production practices in wheat.

Discrimination based on group attributes such as ethnicity and gender has long attracted the attention of socio-economists (Alesina et al., 1999; Jurajda, 2005; Banerjee et al., 2005a). In the field of political economy, social divisions undermining economic progress form one of the most relevant research hypotheses (Banerjee et al., 2005b). However, there exists only limited empirical evidence on social segregation shaping agrarian change and rural development. We are not implying that heterogeneous access to the technology and impact are completely neglected in wheat research. Gender is one of the most important element of social segregation and explicit integration of gender considerations is essential in many R4D activities including WHEAT (Badstue et al., 2017). Although women contribute critically to the food production, they face discrimination in terms of access to production resources and have more constraints in agricultural production than men (Theriault et al., 2017; WB, FAO, & IFAD, 2008). Taking lessons from the gender research, WHEAT FP1 aims to cover the livelihood impacts of technological interventions separately on socially and economically disadvantaged communities.

Establishing causality and other methodological challenges. The main challenge in the impact studies is establishing causality, and this hurdle appears in three different but interrelated forms. The first and most important challenge is establishing a viable counterfactual to predict outcomes had the intervention not happened. Second, attributing the impact completely to an intervention is difficult. Third, the outcomes often appear after a time lag. To mitigate these problems, a number of methods have been used in the impact evaluation literature including experimental approaches, longitudinal comparisons (or reflexive control) of participants, cross-sectional comparisons of participants versus nonparticipants, econometrics methods such as the instrumental variables approach, and quasi-experimental methods including propensity score matching and covariate matching, the double-difference estimator etc. (Khandker et al., 2009).

Analysis of empirical data on technological interventions in agriculture often rely on descriptive and regression analyses to establish association between the intervention and the outcome. However, the existence of an association does not necessarily imply causation. Unless technology dissemination takes place in a completely randomized experiment, farmers themselves decide whether to adopt the technology or not, making agricultural technology adoption a non-random process. Comparing the outcomes between adopting and non-adopting farm households may be misleading as these groups may differ systematically due to self-selection of subjects into or out of the treatment (non-random selection bias). That means the measure of association between intervention and outcome might be distorted due to a sample selection that does not accurately reflect the target population. Even a regression model that contains technology adoption as a treatment variable and controls for the use of other inputs and household attributes cannot completely rectify this bias as there could still be certain unobserved heterogeneity.

Experiments are the widely accepted method to address the problem of establishing as the counterfactual is artificially constructed by random selection of technology recipients. This approach ensures that both groups are statistically similar in observable as well as unobservable characteristics, thus avoiding program placement and self-selection biases. However, only a few studies have so far used an experimental design to elicit technology impacts in agriculture and some of them run into design problems. Particularly, the experimental approach is often not feasible in demand-driven programs in which participants make their own decisions of whether to participate or not. Random assignment also conflicts with the nature of community-driven development programs (Davis et al., 2012). There are also practical problems that can bias the estimates from experimental design. The implementation of the experiment itself alters the framework within which the program operates. This “randomization bias” can arise for a number of reasons. For instance, if random exclusion from a program decreases motivation of those left out, and they may perform poorly than they might otherwise have done, thus artificially boosting the apparent advantages of participation (Heckman and Smith, 1995). Furthermore, experiments are often costly to conduct and require close monitoring to ensure their effective administration. The potential for denying treatment can pose ethical questions that are politically and culturally sensitive.

The standard statistical procedure to deal with selection bias especially in observational data is the instrumental variables (IV) approach. Estimation using instrumental variables allows identification of the impact of exogenous changes on technology adoption, and eliminates the effect of reverse causation or simultaneity. However, suitable instrumental variables are not readily available. Because of this reason, many researchers argue that causality is nearly impossible task to establish. Among the studies listed in Table 2, none used randomized access to innovations to identify the causal effect. A few studies used propensity score matching, which to a certain extent controls for the observed heterogeneity. A couple of studies that used endogenous switching regression acknowledge that identification is still a problem and that caution should be exercised while interpreting the results and making policy recommendations based on the findings. Most of the studies use cross-section datasets, although use of panel data would have controlled for part of the unobserved heterogeneity that is time-invariant.

Finally, all of the existing impact studies focus the effect of interventions only on farming communities, albeit that there are certain interventions in other fields that are left unexamined. First, consumption effects of wheat price reduction in the output markets due to productivity enhancement are hardly examined, although its implications on poverty reduction is arguably significant. Second, the cultivable land and other factors of production saved due to productivity enhancement and the associated ecological effects are not widely examined. The third is the indirect effects of CIMMYT and ICARDA on farming communities through building communities of agricultural knowledge in less developed countries. The capacity building programs of CGIAR centers empowers research institutions (e.g. National Programs) and researchers (e.g. breeders within CIMMYT, ICARDA, or other institutions) to aid smallholder farmers. Nevertheless, these indirect effects are difficult to observe let alone measure. Documenting the capacity building activities in WHEAT and identification of its potential contributions is the first steps towards capturing these indirect effects (e.g. Huang et al (2014)). However, even if we decide to look only at contribution and account it qualitatively, we still need to obtain the viable counterfactual and this is not an easy task. Working groups of researchers will be formed in the coming years to develop a methodological frame for assessing the abovementioned indirect effects of WHEAT interventions, which will be included in the forthcoming versions of adoption-impact strategy reports.

6. Research priorities for 2019-2021 by the CRP flagships

Research activities in CRP WHEAT is managed under different flagships and cross cutting themes. Most of the WHEAT adoption and impact evaluation activities are organized under FP 1. The objective of this FP is stated as maximizing "the value-for-money for WHEAT as a whole by providing horizontal guidance to WHEAT, based on a solid understanding of its potential impact and comparative advantage in a dynamic and heterogeneous world" (CRP WHEAT, 2016). Intermediate development outcomes include increasing resilience of the poor to climate change and other shocks, increasing income and employment, increasing productivity, improving diets for poor and vulnerable people, enhancing benefits from ecosystem goods and services, and enhancing the cross-cutting issues of climate change, gender and youth, policies and institutions, and capacity building. More information on this and other FP objectives is available at wheat.org, and from related proposals and the other strategy reports (e.g., Badstue, 2013). To increase the effectiveness of adoption-impact studies in WHEAT, the present document suggests a number of strategies. A summary is provided in Appendix Table 1. For the next three years (2019-21), the following activities will be taken up – given there is adequate resources available – as the research priorities of the adoption-impact team.

- There are a number of emerging threats to wheat production / productivity (e.g., including the wheat blast, yield risks due to climate change etc.), which require immediate intervention. Detailed household surveys may not appropriate for the quick and robust measurement of the changes. Hence, **a rapid survey module** will be developed in 2019. This instruments will be similar to the limited/smart surveys developed by Elbers and colleagues (Elbers et al., 2003) and employed by World Bank researchers (SWIFT survey) to capture global poverty (World Bank, 2017), and the Rural Household Multi-Indicator Survey (RHoMIS) (Hammond et al., 2017). There are no similar instruments that facilitate the estimation of adoption and impacts of agricultural interventions in any of the cereal systems. The feasibility and usefulness of carrying out these surveys, both through remotely-supervised group-sourcing and the conventional data collection methods, will be thoroughly examined.

  Potential partners: International Livestock Research Institute; Vrije Universiteit Amsterdam; The World Bank.

Although most of the adoption/impact research activities in WHEAT are organized under FP1, they are having some indirect relevance in other flagships also. Below we describe the strategic priorities for adoption and impact studies, conducted under FP1, but in relation to other FPs.

In relation to FP2 ("Novel tools for improving genetic gains and breeding efficiency"):

- A major challenge in the varietal adoption and hence impact studies is precise identification of varieties grown on farm. Errors and mismatches are common in a research that relies either on farmer recall of varieties or on expert opinion. Adoption studies could benefit greatly from more precise characterization of germplasm in the farmers' field through **DNA fingerprinting**. The measure is also important to evaluate the changes in genetic diversity of crops, because a decline in genetic variability might reduce the plasticity of crops to respond to biotic and abiotic stresses, including drought and pest infestations (Manifesto et al., 2001). Although the technology is promising, the application of DNA fingerprinting for varietal identification has its own limitations, including high cost and technical problems related to sampling for DNA extraction (leaves vs. seeds), transportation of samples, and preservation of DNA material etc. Therefore, WHEAT will standardize the method in the coming years, building on learnings from successful applications in wheat in Ethiopia and Afghanistan (publications forthcoming).

  Potential partners: National Bureau of Plant Genetic Resources, India; National Institute of Plant Genome Research, India; DArT, Australia.

In relation to FP3 ("Better varieties reach farmer faster"):

- One the strategic priorities in CRP WHEAT is updating of Lantican et al. (2016) study, which documented the global use and effects of improved wheat germplasm for 1994-2014. This will be carried out through **systematically collecting the details on release of new varieties, estimating the adoption rate and economic benefits from adoption,** and attribute the technology the many wheat improvement program across the developing world. While the database on varietal release can be constantly updated, obtaining farmer adoption data is more difficult, which is required for national-level or sub-continental-level impact analysis. More research investment is required in this connection, especially if DNA fingerprinting is applied. However, if resources are available, this research will not only provide valuable details on the constraints and opportunities on ground for the wheat researchers and policy-makers but also subsequently generate datasets for the global impact assessment. We will be also able to document and quantify the effect of structural changes occurred in CGIAR and establishment of CRP WHEAT. Such a variety adoption database would also be ideal reference to make ex-post impact studies on other completed projects also. However, the frequency of reporting and depth of analysis depends on the financial resources available over time.

Potential partners: NARS of the key target countries (e.g., ICAR in India, EIAR in Ethiopia, BARI in Bangladesh, INIFAP in Mexico, CAS in China etc.)

In relation to FP4 ("Sustainable intensification of wheat-based farming systems"):

- Developing a technical report on the **methodological frame for macro-level impact evaluation of sustainable intensification practices** in wheat systems would be one of the priority areas. This document is expected to comprehensively address the issues associated with tracking adoption, establishing causality, attributing credit, and developing counterfactual scenarios for crop and resource management research in WHEAT. The data source will be farm household surveys, conducted across the key intervention areas.Enhancing the methodological rigor of micro-level impact assessments by (1) using multidimensional impact variables, (2) employing econometric methods and randomized trials to establish causation, and (3) explicitly accounting the socioeconomic and institutional heterogeneity, while framing the studies. The smart surveys, described above, will also be employed in this connection.

  Potential partners: NARS of the key target countries.

- **Establishing long-term data collection activities** in the key WHEAT intervention areas will be highly valuable for comprehensive and detailed data needed for rigorous assessment of technology diffusion patterns and impact pathways. Again, financial resources are to be found to carry out such long-term research activities.

  Potential partners: NARS of the key target countries.

- **Facilitating cross-country comparisons** by unifying parts of household and village survey questionnaires on adoption and impacts of sustainable intensification of wheat systems conducted by researchers of socio-economic programs. In particular, recommendations will be given to the scientists to include a set of generic variables that stand proxy for improvements in human health and welfare. The first publication, combining data from Pakistan, India, and Bangladesh, will be developed in 2019.

In relation to the cross-cutting themes:

- Empowerment of rural women is considered as a necessary pre-requisite to attain food security and alleviate poverty in developing countries (Diiro et al., 2018; Malapit and Quisumbing, 2015; Sraboni et al., 2014). While a number of studies address women empowerment as a developmental outcome (Akter et al., 2017), the deterministic role of rural women empowerment on agrarian development and gender transformative approaches have not received sufficient research focus. On one hand, the quantitative empirical studies addressing technological change often limit the gender dimension to a binary variable (sex of the household head). The key roles and responsibilities of women members of the farm household, who are directly or indirectly involved in crop and livestock production, are overlooked by doing so. On the other hand, the in-depth qualitative case studies are not sufficiently broad to allow for generalization, due to small sample size. Against this backdrop, more mixed-effect studies that use information from quantitative household surveys and qualitative case studies (e.g., GENNOVATE) are required for quickly and effectively capturing rural women involvement in agricultural activities and decision-making and its ramifications on technological change and farmer livelihoods.

  Potential partnerships: Royal Tropical Institute (KIT); University of Oxford, UK; Indian Institute of Technology Guwahati.

- Developing methodological frame on the indirect effects of WHEAT interventions is another priority area. Working groups are needed to be organized and procedures and guidelines of impact evaluation developed to capture the indirect effects of WHEAT interventions (e.g., estimate the land-saved through sustainable intensification of wheat cultivation).

  Potential partnerships: International universities (e.g., Institute of Development Studies, UK; University of California Davis).

- Scientist training programs for CIMMYT and ICARDA researchers and national partners to strengthen analytical skills in adoption and impact evaluations will be one of the major steps towards increasing impact rigor in WHEAT.

- Developing institutional capacity through technical reports and workshops on the potential of employing satellite imageries and UAVs for adoption-impact studies in the WHEAT. Use of these non-conventional methods of data collection could be complementing the conventional household surveys in some of the forthcoming research projects.

Potential partnerships: International universities (e.g., University of Goettingen, Germany; UC Louvain, Belgium; University of Maryland etc.).

- Enabling a learning experience by complementing the conventional quantitative studies with qualitative ones is essential to identify the patterns of technology dissemination in the society and the associated impact pathways. Qualitative studies and participatory approaches are important tools to provide effective feedback to the R4D system, so that the scaling out mechanisms can easily adapt to deliver technologies more efficiently in the complex systems. Mixed methods will be relevant also to capture the less-studied topics such as social exclusion.

  Potential partnerships: International universities (e.g., University of Guelph, Canada; University of Maryland, USA).

7. Conclusion

Over the last four decades, CGIAR research interventions in crop genetic improvement, pest management, and natural resource management have generated significant economic benefits, compared to the investments made (Renkow and Byerlee, 2010). Institutionalizing the impact assessment has become a research priority to address underinvestment in CGIAR R4D. In this connection, CRP WHEAT has developed this strategy document. Here we seek to advance practical understanding on the challenges faced by smallholder farmers to access the technologies and to benefit from them. This document is also expected ultimately to help practitioners frame effective and inclusive scaling out strategies in developing countries. Examining the existing review of literature in wheat over the last one-decade and the advancements made in the field, we have come up with a set of priority research areas for adoption-impact studies in wheat systems. By systematically addressing these priorities, we expect that the coherence between the various fragmented studies can be improved significantly within CRP WHEAT.

Appendix Table 1: Challenges and Potential Solutions

Challenges	*Potential solutions*
[1] The number of studies on varietal adoption is limited.	a) More systematic studies on varietal diffusion with a more comprehensive definition of technological change. b) Wider use of data collection methods other than conventional household surveys (e.g., village surveys, secondary datasets etc.).
[2] Farm-household surveys are inadequate for varietal identification.	Use of DNA Fingerprinting technique to identify varieties.
[3] Definition of technology adoption is too narrow and measurement is binary.	a) A system perspective of technological change warranted. b) Focus on less-studied, socially relevant aspects of diffusion process (e.g., social inclusion).
[4] Monitoring of sustainable intensification technologies is time-consuming.	Use of rapid/limited survey instruments, possibly supplemented by satellite imageries.
[5] Limited investigation on relevance of inherent technology attributes in determining the scaling out patterns.	a) Compilation and analysis of cross-country data (possibly from different time-periods) where reasons for farmer adoption, dis-adoption and non-adoption are clearly indicated. b) Investment in developing longitudinal datasets. c) A meta-analysis of technological change in wheat systems.
[6] The number of studies is inadequate to cover the ongoing R4D efforts in wheat in the developing world.	a) More systematic studies, focusing particularly on less-studied, socially relevant aspects of technological change (e.g., economic equality, environmental effects etc.). b) Investment to develop longitudinal datasets in selected countries. c) Explicitly accounting for socioeconomic and institutional heterogeneity while framing the studies. d) Examining the impacts on non-farming communities.
[7] Establishing a causal relationship between adoption and outcomes is challenging.	a) Developing and refining the methodological framework (e.g., impact assessment of sustainable intensification practices) and providing a clearer guidance on identification strategies for socioeconomists working in WHEAT. b) Randomized control trials.
[8] Many studies do not provide a learning experience.	a) Complementing the conventional quantitative studies with qualitative ones. b) Explicitly accounting the socioeconomic and institutional heterogeneity, while framing the studies. c) A meta-analysis of technological impacts in wheat.

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