WORKING PAPER

Methodology for Assessing Adoption, Efficiency and Impacts of Mechanized Raised Bed Technology

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AMMAN, DECEMBER 2017

SUGGESTED CITATION:

Le, Q.B., Dhehibi, B., 2017. Methodology for Assessing Adoptions, Efficiencies and Impacts of Mechanized Raised Bed Technology. Working Paper. International Center for Agricultural Research in Dry Areas (ICARDA), Amman, Jordan, 27 pp.

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List of Acronyms

ALS	Agricultural Livelihood System
ANOVA	Analysis of Variance
CA	Cluster analysis
CRP-DS	CGIAR Research Program on Dryland Systems
ICARDA	International Center for Agricultural Research in Dry Areas
MRBT	Mechanized Raised Bed Technology
PCA	Principal Factor Analysis
SLF	Sustainable Livelihoods Framework
SOCF	System-based Options by Context Framework

KEY MESSAGES

Abstract

Mechanized raised bed technology (MRBT) has been recognized as an important component of integrated water management to achieve higher productivity in intensive irrigated systems such as in the Nile delta. Effective management and policy for spreading the technology at scale toward achieving system-level outcome requires adequate understanding on drivers of farmers' MRBT adoption, insightful assessment of the technology efficiency regarding system performance and impacts. Related research efforts on these issues are challenged by both the complex nature of the task, and the diversity of socio-ecological context that shapes farming systems' performance. This paper concisely reviews and re-introduces a system-based option-by-context approach for guiding concrete analytical steps and operational methods for addressing the research issues in coping with the challenges of system complexity and contextual diversity. The paper elaborates methodologies, ranging from concepts to operational methods, that would needs for obtaining the following objectives: (1) Identify and characterize main livelihood types of smallholders in terms of their farms' biophysical and socioeconomic characteristics, (2) identify determinants, both common and livelihood type-specific, of farmers' adoptions of MRBT, (3) delineate the ceiling line of water use efficiency the MRBT can bring about (i.e. the efficiency frontier) and use it as a reference for assessing crop production efficiency of MRBT farms with respect to water and other resources uses, and evaluate impacts of MRBT on whole farm productivity and profit, household livelihoods, irrigated community-landscape (multi-scale impacts).

Keywords

Irrigated system, Egypt, Nile Delta, context, drivers, efficiency, impact, complexity, mechanized raised bed technology, option by context, livelihood typology, technical efficiency, production frontier, participatory Multi-Criteria Assessment

Highlights

- We concisely reviewed and re-introduced a system-based option by context as a general concept guiding concrete analytical steps and operational methods
- We described conceptual framework and econometric methods for identifying main livelihood types of smallholders in terms of their farms' biophysical and socioeconomic characteristics
- We described econometric method for identify determinants, both common and livelihood type-specific, of farmers' adoptions of MRBT and technology efficiency
- We analyzed the technology efficiency concept and the challenges in measuring it, and described economic methods for comparative evaluation of MRBT efficiency in coping with multiple inputs and shifting in production potential (i.e. the efficiency frontier),
- We argued for a multi-scale strategy in evaluating impacts of MRBT, discussed relevant impact criteria, indicators at each scale, and described participatory Multi-Criteria Assessment method.

1. INTRODUCTION

1.1. Background

Water scarcity for agriculture in Egypt has been, and will continue to be, a profound problem. The water scarcity has crossed the threshold value of 1,000 m3/capita/yr, and tend to be down to 500 m3/capita/yr in 2025 if there is no significant improvement in management (Swelam, 2016). Moreover, negative effects of climate change on agricultural production further asserts problems associated with water allocation for agriculture. According to a 2013 report by the United Nations Development Programme (UNDP) in association with the Egyptian Government and various other UN agencies, agricultural production could decrease by 8-47% by 2060, with employment losses of up to 39% (Swelam, 2016). Thus, the current and future challenge in Egypt is how to produce more food with less water resources. The benefits of each drop applied could be maximized by adopting appropriate irrigation scheduling and adapted irrigation practices.

Research on water management to achieve higher productivity in irrigated agriculture has identified mechanized raised bed technology (MRBT) as an important component of improved crop production package (Karrou *et al.*, 2011; Swelam, 2016). MRBT is an improved surface irrigation strategy, which enhances water productivity and makes the application of water in irrigated systems more efficient. In this technology, irrigation water is applied to the bottom of furrows among cropping beds, instead spread over the whole surface of the cropping area. Because there is less wetted area than in the traditional surface irrigation methods, water can be saved. Raised bed fields have wider furrows, as well as wider cropping beds, than those in the traditional ones, in way that the same number of crops could be irrigated with half of the amount of water. Raise bed machines are applied to ensure the raised bed design, as well as substitute to the labor demand required.

Raised bed technology has been proven to increase crop yields in both winter and summer crops and improve water use efficiency through decreasing irrigated areas, shortening the time needed for irrigation, and reducing water volume needed for a same amount of crops. Applying this practice can help to spend less money for irrigation, while achieving higher yields and increasing the farm income. The technology has been technically tested and validated by ICARDA projects over the last 10 years in Egypt. In the experimental farms, the application of this technique with the main winter crops has shown that up to 25% of water could be saved, while crop production increased by 10%. Net benefits increased by 40% in, and additionally, it reduced variable costs by 30% (Karrou *et al.*, 2011). This technology was disseminated for promoting sustainable agricultural intensification in 22 Egyptian governorates, as part of a nation-wide campaign by the Egyptian Government on self-sufficiency in wheat production (Swelam, 2016).

1.2. Research problems

Although a great deal of knowledge on the proven role of MRBT in improving water use efficiency given by irrigation, agronomic and economic studies, too few studies seek to understand (1) drivers affecting farmers' adoption of MRBT, (2) multi-aspects efficiency of MRBT (technically, economically and ecologically/environmentally), (3) impacts of MRBT on whole farms' performance and households' livelihoods. Proven knowledge on these issues will be essential for informing policies and development practices that aim disseminating the technology towards achieving food security, water resources saving, and thereby better resilience to climate change.

Drivers of farmers' MRBT adoption: So far, there has been a few studies on raised bed adoption in Egypt, such as the study of Dessalegn et al. (2016) conducted in Sharkia Governorate. As many other adoption analyses, the drivers of raised bed adoption was inferred from the analysis of one household/farm sample selected for the study area, hence the revealed cause-effect relationships are also applied uniformly over the study area. Indeed, the causal relationships defined in that way (one sample for the study area) is validly applied for an 'average household/farm' of the area (located in the centroid of the multi-variate sample). The more diversity in livelihood context/setting in the area would lead to the less representativeness of this average household/farm, thus weakening the plausibility of applying the causal relationship over the whole area. An improved method would be the stratification the studied population in according to functional livelihood contextual types, and then conduct multi-variate adoption analysis for each strata, then inferring adoption drivers in specific to the livelihood context type (Thiombiano and Le, 2016a). Adoption analysis in this way requires the identification of plausible livelihood contextual types beforehand. The livelihood contextual typology is also important as it can shape the efficiency assessment of the considered technology/intervention (Thiombiano and Le, 2015; Thiombiano and Le, 2016b).

Efficiency assessment of MRBT: So far, most of efficiency assessments for raised bed technology in Egypt have done in a straightforward way, which were about the partial agronomic efficiency – with respect to crop output, i.e. water productivity index (water volume needed / unit of crop yield), or to water input (crop yield response / unit of water input) - and irrigation cost (cost of irrigation / unit of cropping area, or cost of irrigation / unit of crop yield). However, at the same time crop yield is also influenced by other side conditions (e.g. soil quality) and other inputs (e.g. fertilizers and labor). Variation of these factors can make the comparison of the above indicators over the studied population inadequate. Moreover, it is important to know the ceiling of water use efficiency the MRBT can bring about (i.e. the efficiency frontier) as a reference for setting realistic goals and pathway towards to achieve the goals. Next, it would be useful to understand how MRBT shape the productivity-risk relationship. The meaningful hypothesis would be the implementation of MRBT can improve water productivity and yield while reduce, or not to increase risk for crop production. All of these issues have remained a gap in knowledge.

Impact assessment of MRBT: In current literature, effects of MRBT on what beyond crop yields, such as performance of whole farm, community livelihoods and irrigated agricultural landscape in Egypt have been speculative anticipations or hopes rather than scientific proofs or science-based projections. Efforts on filling this gap is important to realize impact pathways from interventions in MRBT toward achieving development goals in national and international programs and policies.

1.3. Research objectives

In line with the knowledge gaps above-justified, the following objectives are proposed to be considered:

(i) Identify and characterize main livelihood types of smallholders in terms of their farms' biophysical and socioeconomic characteristics
(ii) Identify determinants, both common and livelihood type-specific, of farmers' adoptions of MRBT over ICARDA's studied area in Egypt
(iii) Delineate the ceiling line of water use efficiency the MRBT can bring about (i.e. the efficiency frontier) and use it as a reference for assessing crop production efficiency of MRBT farms with

respect to water and other resources uses; evaluate the role of MRBT on crop productivity and the level of production risk,

(iv) Evaluate impacts of MRBT on whole farm productivity and profit, household livelihoods, irrigated community-landscape (multi-scale impacts)

2. APPROACH

2.1. System-based options by context approach

The thrust of conceptual framework for this study is a systems-based clarification of the relationship between context (including drivers) and management options as the basis for guiding data integration, selection of objective-oriented indicators and analysis/assessment of the diversity of land use systems and related contexts over space (Figure 1). The framework draws on insights of current frameworks for social-ecological systems in transitions (Ashley and Carney, 1999; Reynolds *et al.*, 2007; Pahl-Wostl *et al.*, 2010; Scholz *et al.*, 2011), but is kept simpler for operational implementation.

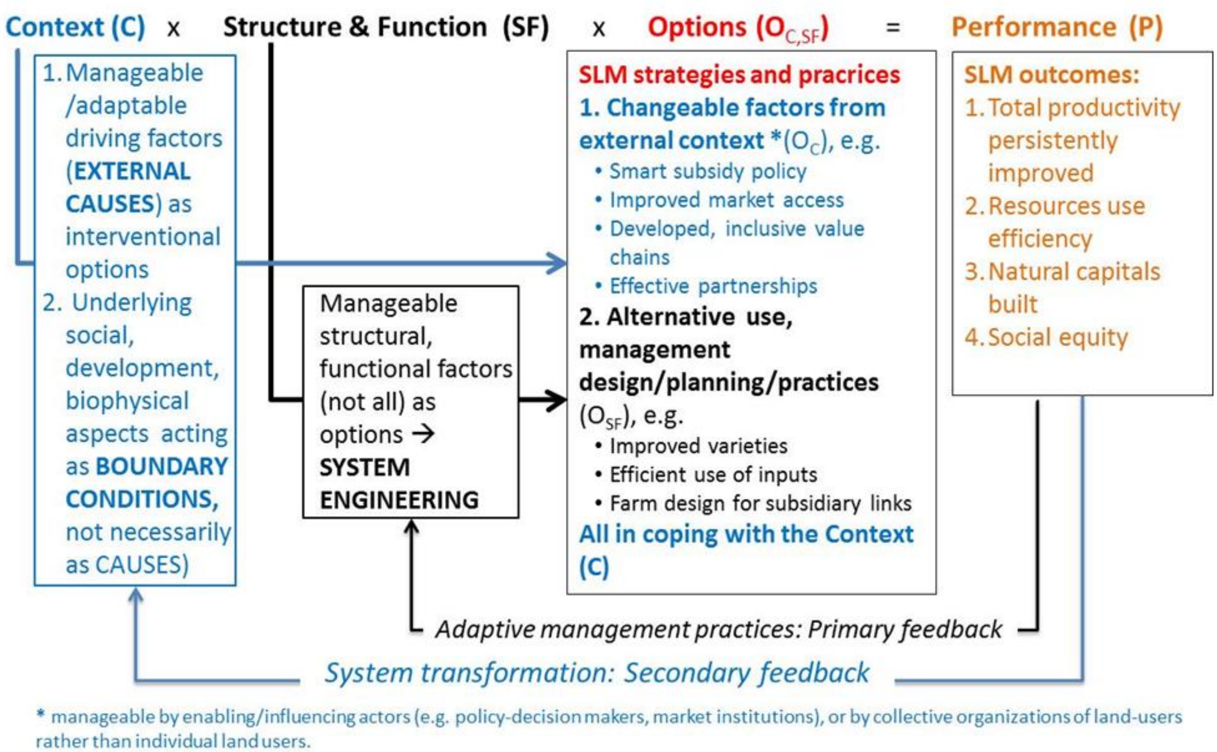

Figure 1: Relationship between management/technical options, structure and function of farming systems and context with a system-in-transition thinking. Sources: *(Le et al., 2016; Le et al., in prep)*

2.2. Analytical steps

Figure 2 is a proposal analytical diagram that includes sequential steps of empirical researches toward achieving the stated objectives. This procedure should apply for a sizable study area - such as an area covering several governorates with MRBT practiced – rather than a small site.

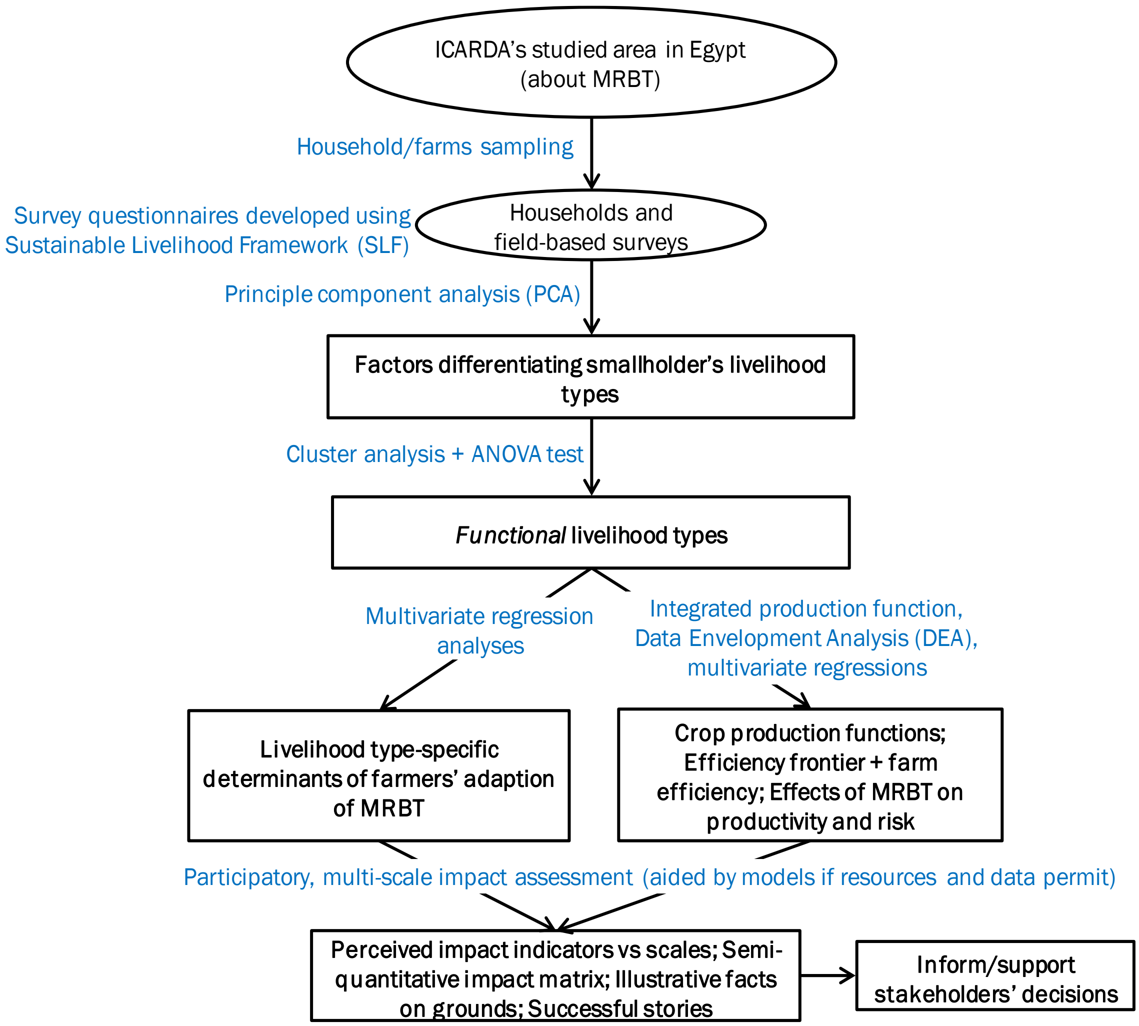

Figure 2: Analytical diagram showing empirical research steps towards obtaining the research objectives. Note: Boxes indicate the expected research outputs; blue texts indicate names of empirical research methods.

3. METHOD AND DATA

3.1. Method for identifying livelihood typology of smallholder farm-household systems

It is important to clarify the terms of types and typology. A 'type' is an abstract generic model which define the characteristic features of a series of objects. The term 'typology' designates both aspects: (1) the science of type elaboration, designed to help analyze a complex reality and order objects which, and (2) the system of types resulting from this procedure (Landais, 1998).

Selecting method: There are different methods for identifying livelihood typology, including expert opinions, participatory rankings (e.g. well-ranking), statistical analyses (non-parametric method such as tree-like step-wise analysis, or parametric method such as the combination of principal and cluster analysis). Each method has particular advantages and limitations as showed in Table 1. As the typology analysis here are embedded in a project targeting to sizable area, aims to collect sizable quantitative data and have a strong perspective for operational modelling research in later years, the parametric multivariate methods is proposed to be used.

Table 1. Advantages and limitations of different methods for defining livelihood typology

Method	Advantage	Limitation
Expert opinions	• Fast, cost-effective	• Risk of bias
Participatory rankings	• Fast, cost-effective • Participatory potential	• Difficult to include multi-criteria • Difficult to model type change
Step-wise/decision-tree classification	• Combine qualitative and quantitative criteria • Work with small sample size • Participatory potential • Easy to implement in simulation	• Difficult to know 'key' discriminates among many criteria • May be low contextual robustness
Parametric multivariate statistics	• Capture key discriminates • Easy to implement in simulation	• Less capable to capture many qualitative criteria • Not work well with small sample size

Source: Le and Feitosa (2012); Le (2015)

Basis for designing contents of data collection: The study is built on the concept of household/farm livelihood sustainability, including its adaptability and resilience in the vulnerability context (Fig. 3a). The Sustainable Livelihood Framework (SLF) describes the essential resources at household/farm disposal and livelihood strategies built from these resources in copying with the vulnerability context (DFID, 1999) (see Fig. 3a). These resources comprise five types of livelihood assets that are used to achieve households' or community's livelihood outcomes:

- human assets: labor, health, education and capabilities
- natural assets: lands (amount and quality), livestock and water resources,
- financial assets: incomes and savings from different sources,
- physical assets: housing conditions, access to infrastructure and equipment for agricultural production, and
- social assets: supports and advantages from social network, positions and projects/programs

In addition, from the resilience approach, the five livelihood assets are interactively determining the buffering capacity of the livelihood systems. Furthermore, the adaptability and transformability of household livelihoods will be determined by its and community's self-organizing and capacities and learning capacities (Speranza et al., 2014). The essential elements for household's and community's self-organizing and learning capacities in relation with livelihood assets are showed in Figure 3b. This livelihood framework should be used to guide the development of the contents of questionnaires for livelihood surveys, and indicators for analyses and assessments. Annex 1 is an example for how quantitative variables can be specified using sustainable livelihood framework (SLF).

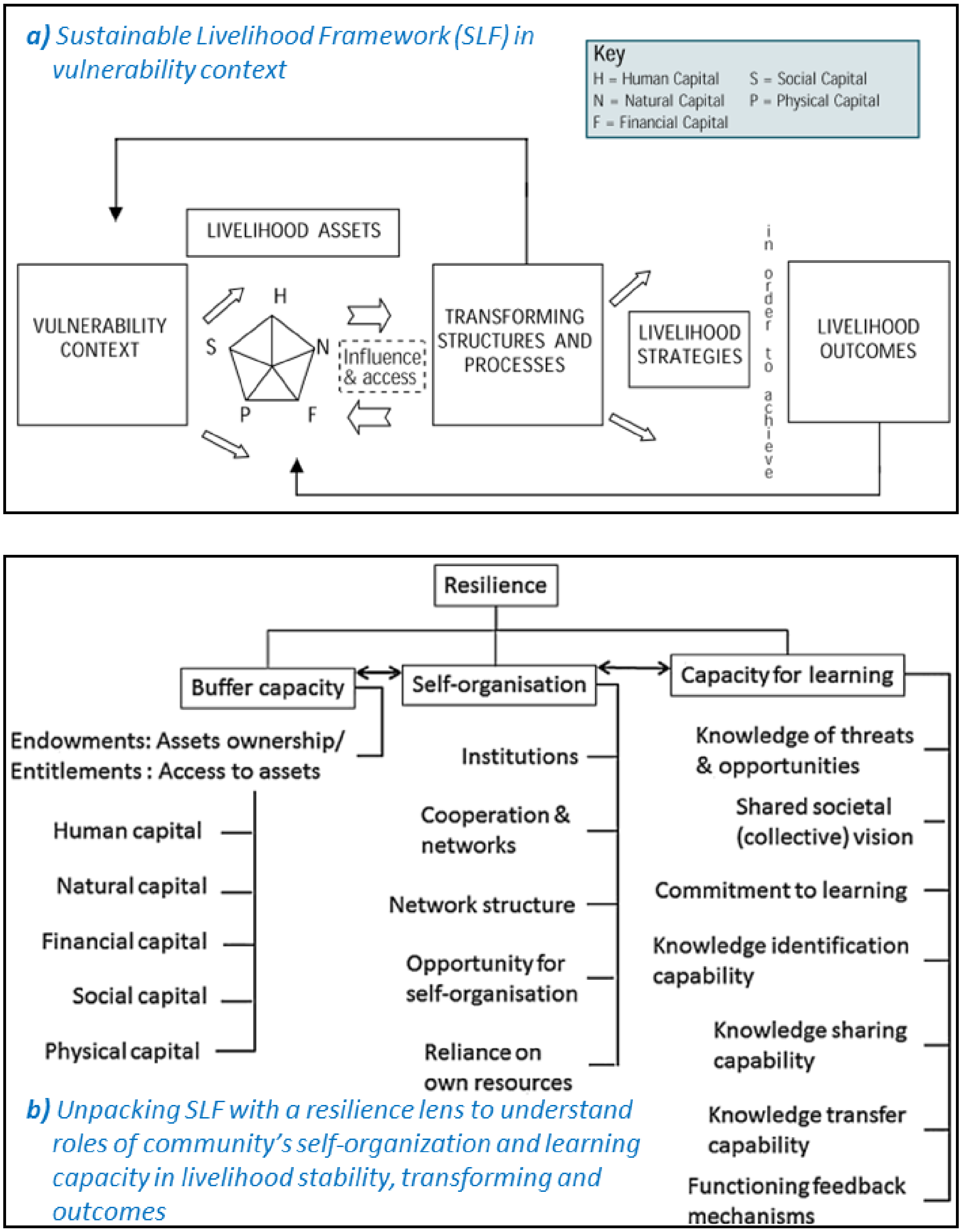

Figure 3. Conceptual framework of the study being based on Sustainable Livelihood Framework (Ashley and Carney, 1999) (Figure 3a), and livelihood resilience (Speranza *et al.*, 2014) (Figure 3b).

Principal Component Analysis (PCA) and subsequent Cluster Analysis (CA) and Analysis of Variance (ANOVA): <u>Principle Component Analysis (PCA)</u> will be used for discovering key factors explaining the majority of variation in the multi-variate livelihood data, as well as reducing the dimensionality of the data. The technique condenses a large number of original variables into a smaller set of new composite dimensions with a minimal loss of information (McGarigal *et al.*, 2000). The meaning of each principle component is interpreted in terms of the original variables with higher weights/loadings. Because the extracted principle components are independent from each other, the use of component scores for subsequent analysis will avoid multi-collinearity problem.

K-Mean Cluster Analysis (K-CA) will be used for deriving typical household/farm groups defined by livelihood criteria. Unlike hierarchical methods, K-CA methods avoid problems of chaining and artificial boundaries and work on the original input data rather than on a similarity matrix. For large dataset (e.g. hundreds of cases), K-CA should be chosen because it would be difficult to interpret grouping results using hierarchical cluster analysis. Data entered to K-CA can be:

- the scores of principal components (PCs) extracted by the earlier PCA, or
- the original livelihood variables being highly correlative with the extracted PCs

To determine the number of clusters, the procedure described in Robinson et al. (2006) can be used. The optimal cluster number is defined as the minimal cluster number with the highest cluster homogeneity. First, K-CAs are run with the number of clusters set to all values between 2 and 10. For each K-CA (with a concrete k value), we calculated the mean distance of cases to their assigned cluster centers. These mean distance values were then plotted against the increasing cluster number (k = 2, 3 …, 10). The optimal cluster number was chosen by examining the “elbow” of the curve— the point from which the overall cluster quality, i.e., the reduction of the mean distance from cases to their cluster centers, or the overall cluster homogeneity (Rakhlin and Caponnetto, 2006), is not substantially improved when k increases.

The livelihood groups of households/farms defined at this stage are just potentially functional livelihood types.

Unbalanced ANOVA will be done for testing if key dependent variables – such as MRBT adoption and efficiency, being not included in the PCA and K-CA – response differently among the classified livelihood groups. If the responses are statistically significant, the livelihood groups/types will be proven to be functional to indicators of the research objectives.

Functional livelihood types are useful for not only the follow-up adoption analyses and efficiency/impact assessments, but also directly policy and management practices. The functional types can help agricultural development projects/programs and scientists to improve their targeting. For example given limited resource and aims, we can know approximately where efforts should be focused by managing, or coping with what drivers. The result can also be used as an extrapolation domain: given a successful outcomes in a limited number of project sites, we can identify where similar intervention options have a potential of success based on livelihood contextual similarity.

3.2. Method for adoption analysis

Inferential statistical model: As the dependent variable (adoption variable) is in dummy scale (1 if the household adopts MRBT, 0 otherwise), binary logistic regression (bi-logit) is proposed to be used to identify factors determining MRBT adoption. As site-specific constraints and potentials for MRBT outcome, the unit of MRBT adoption analysis recommended being a field rather than household.

The effect of the hypothesized socio-ecological variables on the adoption of manure by a household can be modeled as equation (2):

$$P(MRBT) = 1 / (1 + exp\ (\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + ... + \beta_n X_n + \mu)) \qquad (1)$$

where P(MRBT) is the probability of MRBT adoption. X_i and β_i (i = 1, 2, 3, ..., n) are explanatory variables and their weight coefficients, respectively. μ is a random error term.

Performance evaluation of binary logistic regressions included:

- a chi-squared test for the overall statistical significance of the regression model,
- the probability of correct prediction, and
- Receiver Operating Characteristic (ROC) statistics. Although some pseudo-R^2 in bi-logit mimics the widely used R^2 in linear regression, there are no agreed benchmark values of the pseudo-R^2 parameters for answering if the model performance is acceptable. Alternatively, the goodness-of-fit of the model uses Receiver Operating Characteristic (ROC) statistics, as recommended by several experts in binary logistic regressions (Hosmer and Lemeshow, 2000; LaValley, 2008; Pepe et al., 2004). The ROC curve depicts the model sensitivity (True Positive Fraction) and model specificity (True Negative Fraction) over all possible cut-off points. The area under the ROC curve (theoretically ranging from 0.5 and 1.0) was used as the basis for evaluating model performance. If the area value is significantly ($p < 0.05$) higher than 0.5, then the model predicts the output better than chance. Area values of 0.7 to 0.8 show acceptable model performance, values of 0.8 to 0.9 demonstrate excellent performance, and values greater than 0.9 indicate an outstanding performance (Hosmer and Lemeshow, 2000).

Explanatory variables: The vector of explanatory variables [X_i] (i = 1, 2, 3, ... n) are from the indicators of livelihood assets of the household who own or operate the land. Vector [X_i] can have some overlap with the variables in the earlier PCA, but not be necessary. In general, the inclusion of livelihood variables in [X_i] should be based on understanding (either through literature or common sense) about the rationales of their effects on the adoption of MRBT. Different from variables in PCA, [X_i] in MRBT adoption analysis additionally include fields' attributes reflecting site's potentials and constraints for implementing MRBT, such as:

- Field's proximities (distance) to road and water supplier
- Land form or hydrological status
- Field size
- Soil fertility
- Tenure status

Annex 2 gives an example of a vector of explanatory variables in adoption analysis combining both household's and field's attributes.

Livelihood type-specific vs. combining adoption analyses: It is recommended to conduct both type of adoption analyses: analyses in specific to livelihood groups and analysis for combined/whole sample. The benefits for this strategy can be:

- Understand the added values of livelihood type-specific adoption analysis. E.g. The type-specific analyses reveal more informative determining roles of 'Age', 'Education' and 'Distance to road' (see related rows in Table 2)

- Reveal common determinants of adoption. E.g. The common positive effect of 'Field size' across livelihood types (Table 2)
- Limitation of data deficit in livelihood type-specific adoption analysis. E,g. In Table 2, for the case of 'Tenure security', it seems there are not enough variations in this variable within livelihood groups (resulting non-significant effects), but it is not the case with the combined sample (still significant likely due to enough variation in data). Thus, the adaption analysis for the whole sample complimentarily helps not to ignore the effect of the tenure factor.

Table 2. Example synthesis table show bi-logit results for livelihood groups and whole sample

Explanatory variable (X_i)	*Effect on MBRT adoption* (Note: + and – indicate significantly positive and negative effects, respectively; ns = non-significant)			
	Livelihood type A	*Livelihood type C*	*Livelihood type C*	*Whole population*
Age	+	*ns*	-	*ns*
Education	+	+	-	ns
Field size	+	+	+	+
Distance to main road	ns	+	-	ns
Tenure security	ns	ns	ns	+
Etc.	Etc.	Etc.	Etc.	Etc.

3.3. Methods for Comparative Assessment of Technical Efficiency

Production Frontier and Technical Efficiency

To compare how well the application of MRBT brings about efficient crop production, the efficiency evaluation should be *referenced* to the *production frontier* that presents the maximum output attainable from each input level given the potential of the MRBT regime. Figure 4 describes the production process of one input ***x*** (e.g. water, or fertilizer, or labor) into output ***y*** (e.g. crop yield) of a farm (Coelli, 1996a; Nguyen *et al.*, 2014). Curve ***F*** represents the production frontier being the production potential determined by MRBT. As F is of production potential, it is impossible to have any farm operating at a point above curve F. If farms operate on curve F, they will be efficient. For example, farms B and C are technically efficient at two different levels of inputs. If a farm operates below the frontier, if it will be technically inefficient. For instance, farm A is an inefficient compared to either farm B (having a higher yield given the same input), or farm C (having the same year but with lower input).

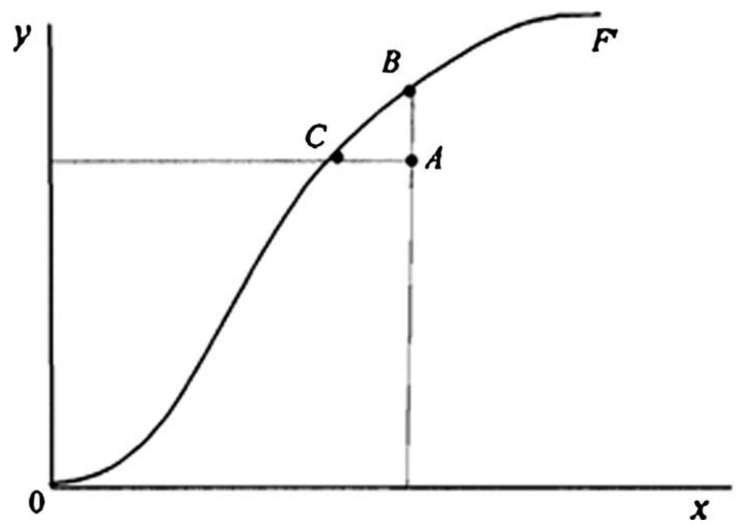

Figure 4. Production frontier (curve F) as a reference for evaluating technical efficiency (TE). Note: ***y***: output (e.g. crop yield), ***x***: input (e.g. water, or fertilizer, or labor). ***F***: production frontier curve reflecting the production potential of the considered technology; A: inefficient farm, B and C: efficient farms. Source: Nguyen et al. (2014).

Data Envelopment Analysis (DEA) or Stochastic Frontiers for evaluating TE, Testing Hypotheses

By definition TE can be calculated as simple ratios with respect to the unit of an input or output. For example, technical efficiency of MRBT regarding water use efficiency can be an input-oriented ratio such as yield/m^3 of water, or output-oriented index such as water volume needed for producing a unit of crop grains. However, in practice it is difficult to conduct comparative evaluation of TE among farms using those simple ratios. There are two problems:

- Observed yield is normally determined by multiple inputs, such as not only water, but also fertilizers, pesticides, labor and machineries and possible interactions among them. Therefore, evaluating technical efficiency of MRBT with respect to one input needs to control the other inputs. This can be done through field experiments in research stations, but the experiment fields cannot cover a wide range of non-experiment factors that meet actual contextual variation over a large research area such as a governorate.
- At community or landscape levels, efficiency measures can relate two or more system outputs, such as not only crop yield, but also energy use efficiency, greenhouse gas emissions from farm operation, and/or social outcomes (e.g. gender fairness). Broadly, at community or landscape scales efficiency can cover the interrelationships and trade-offs among a host of production, conservation, economic, and social values (Hein *et al.*, 2006; Keating *et al.*, 2010).

While methodological discussion for addressing the later problem would be rather the subject of impact assessment that will be elaborated in section 3.5, this section describes the method for coping with the former problem. The curve/function of production frontier can be used as a reference to calculate input-orientated TE in the way that addresses the question of the proportional reduction of input quantities while producing a given level of output quantities. TE is defined as:

$$TE = \frac{xTE}{x} \quad (1)$$

where *xTE* is the vector of inputs at the technically efficient point (on the production frontier *F* in Figure 4) and *x* is the vector of currently used inputs (Nguyen et al. 2014). In evaluation of MRBT's efficiency, the input vector would include major inputs for irrigated intensive crop production system, such as:

- water (m^3),
- fertilizers (cost),
- pesticides (cost),
- machinery and energy (costs), and
- labor (working days).

Obviously, the approach in equation (1) requires the estimation of the production frontier function. There are two principal methods for this task (Coelli, 1996a), which are:

- Data Envelopment Analysis (DEA) and
- Stochastic Frontiers (FRONTIER).

The former method involves mathematical programming, while the later is based on econometric analyses. The methodological details and computer software for DEA can be found in Coelli (1996a) (http://www.uq.edu.au/economics/cepa/deap.php), while those for FRONTIER is described by Coelli (1996b) (http://www.uq.edu.au/economics/cepa/frontier.php).

Given TE calculated for every sampled farm/household, comparisons about TE between the group of households who adopted MRBT and the group did not adopted MRBT are recommended. There will be two main comparisons with the following testing hypotheses:

Hypothesis 1: TE of farms with MRBT is higher than TE of farms without MRBT.

To control the variation of livelihood context, the comparison should be done within each livelihood group identified from section 3.2. The layout for TE comparison is showed in Table 3, in which the comparison will be done between rows of the same column. T-test will be used to test this hypothesis.

Table 3. Comparison of TE between MRBT and non-MRBT farms in different livelihood contexts/conditions. Hypothesis: $TE_{MRBT,\,k} > TE_{non\text{-}MRBT,\,k}$

	Livelihood context			
	Livelihood group 1	Livelihood group 2	...	Livelihood group k
Non-MRBT farms	$TE_{non\text{-}MRBT,\,1}$	$TE_{non\text{-}MRBT,\,2}$	...	$TE_{non\text{-}MRBT,\,k}$
MRBT farms	$TE_{MRBT,\,1}$	$TE_{MRBT,\,2}$	...	$TE_{MRBT,\,k}$

Hypothesis 2: The efficiency frontier of MRBT farms is higher than those of non-MRBT farms.

This hypothesis refers to qualitative improvement (new and higher equilibrium) induced by MRBT. Graphics comparison will be used to test this hypothesis. The upper ceiling of the MRBT farms cloud (i.e. curve F_{MRBT} in Figure 5) is hypothesized to be above the ceiling of non-MRBT farm clouds (i.e. curve $F_{non\text{-}MRBT}$ in Figure 5).

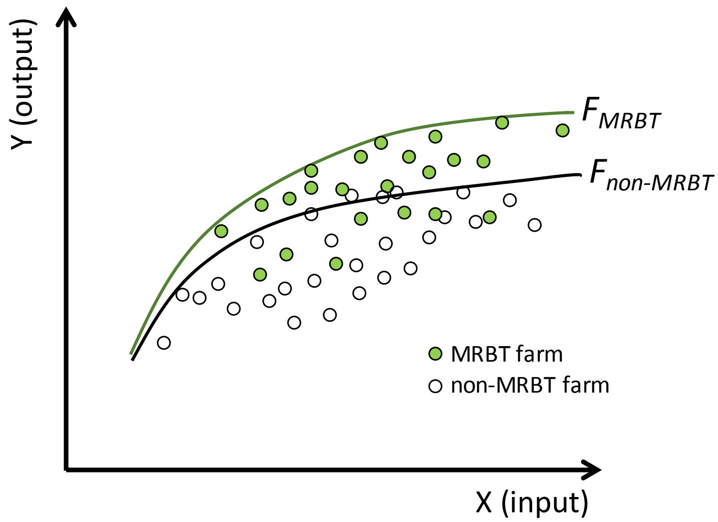

Figure 5. Hypotheses that MRBT improves farms' TE and production frontier.

3.4. Methods for Identifying Determinants of MRBT Efficiency in different livelihood contexts

Given data on household livelihood, farm characterization and farm TE, econometric analyses will be done to identify significant determinants of MRBT efficiency in specific to livelihood context.

Inferential statistical model: The dependent variable is farm TE. Depending actual distribution of TE coefficient there can be two optional scales of this variable that would lead to different statistical analyses.

If the dependent variable is the TE coefficient, i.e. a floating value between 0 and 1 where 1 presents efficient technology, the inferential statistical model can be multiple linear regression, or probit regression. Performance evaluation of these statistical model will be:

- a chi-squared test for the overall statistical significance of the regression model,
- The adjusted coefficient of determinant (R^2)

If the dependent variable is in a dummy scale: technical efficiency (e.g. TE is between 0.8[1] and 1) and inefficiency (e.g. TE < 0.8[1]), bi-logit model should be used (see section 3.2 for methodological details).

It is recommended to try both options of inferential statistical model and select the most statistically robust one.

Explanatory variables: The vector of explanatory variables [X_i] (i = 1, 2, 3, ... n) can be similar to those in the adoption analysis (see section 3.2).

Context-specific and common determinants: Similar to MRBT adoption analyses, it is recommended to conduct both type of analyses for identifying determinants of MRBT efficiency: analyses in specific

[1] This threshold can be adjusted based on the actual distribution of farm TE data. In general, a TE value above this threshold should indicate the efficient or near-efficient implementation of the technology.

to livelihood groups and analysis for combined/whole sample. The details of benefits provided by this approach is described in section 3.2.

3.5. Methods for Impact Assessment

Multi-scale indicators for impact assessment

Some recent reviews of impact assessment of agricultural technology innovation have acknowledged the role of multi-dimensional and multi-scale perspectives (e.g. Keating et al., 2010; Lauwers, 2009). However, it remains unclear from these reviews whether assessors can subjectively retain disciplinary options regarding the dimensions and system levels considered. Here, we argue that multidimensional and multi-scale perspectives are inherent in the environmental impacts caused by farming and are therefore inherent properties of the concept of eco-efficiency. In short, a genuine eco-efficiency assessment must always include a multidimensional and multi-scale perspective. However, based on an actual farming system and its social-ecological context, it is possible to focus on a number of dimensions and levels that are objectively of greatest importance and relevance.

To systematize the selection of indicators for comprehensive assessment of eco-efficiency, it is important to identify typical dimensions and system boundaries in the realization of agricultural eco-efficiency. These include the following.

(i) *Material resource use efficiency* (Giller *et al.*, 2006; Mueller *et al.*, 2012; Tuomisto *et al.*, 2012): Efficiencies of nutrient, water, and energy use in intensified farming;

(ii) *Minimization of negative environmental impacts* (environmental externalities) (Cassman, 1999; Foley *et al.*, 2003; Keating *et al.*, 2010; Picazo-Tadeo *et al.*, 2012; Tscharntke *et al.*, 2012; Tuomisto *et al.*, 2012): Typical environmental impacts of agricultural intensification include soil degradation (nutrient leaching, mining, and soil erosion); water pollution (both surface and ground water); GHG emissions; and biodiversity losses.

(iii) *Economic performance* (Den Bosch *et al.*, 1998; Hoang and Nguyen, 2013; Nguyen *et al.*, 2013): This includes crop returns to inputs (i.e., land use, nutrients, water, and labor); farm net income and net cash flow.

(iv) *Social acceptance and equity* (Rosenström and Mickwitz, 2004): This includes indicators of willingness-to-adopt and -to-pay for intensification options, as well as the social equity in sharing the benefits and costs of intensification.

Both expected outcomes and unwanted environmental impacts induced by MRBT inevitably occur at different system levels, ranging from production unit (e.g. crop field) to whole farm and agrarian landscapes that include different farm/household types and non-farm areas, connected by environmental flows and social relationships. Crop yield at production unit level is measured as either crop or livestock gain but includes both at farm level. At landscape level, food yield can include fishery outputs. Intensification targets food yield gauged at all of these levels. The environmental footprint of intensification on biogeochemical cycles, for example, occurs in routing through the farm soil sub-system to the whole farm system and the entire landscape. Scale-sensitive indicator sets are proposed in Table 4, in which minimal and optional indicators at each scale are suggested. In Table 4, the measurement of many bio-physical and economic indicators would need sophisticated methods such as system modelling; while social indicators would be rather done through participatory, yet semi-quantitative methods.

Table 4. Multi-dimensional and multi-system boundary indicators for ideally comprehensive assessment of impacts induced by MRBT in intensive irrigated systems.

Dimension (criteria)	*Relevant system levels (* indicates minimal requirement)*		
	Production unit (field)	*Whole farm*	*Agrarian landscape*
Material use efficiency			
• *Nutrients*	Crop nutrient-use efficiency* (absorption/uptake efficiency, partial nutrient productivity, agronomic efficiency)	Farm nutrient balance (consider within-farm nutrient recycling and/or reuse) and use efficiency*	Landscape nutrient balance (including specialized recycling, human-induced nutrient exchanges between farms, and soil redistribution over the landscape)*
• *Water*	Crop water-use efficiency*	Farm water-use efficiency (include water reuse)*	Landscape water-use efficiency*
• *Energy*	Crop fossil energy-use efficiency* (option: labor included or excluded)	Farm fossil energy-use efficiency* (option: labor included or excluded)	Landscape energy-use efficiency* (option: labor included or excluded)
Impact-minimization efficiency			
• *Minimize soil degradation* - *Soil nutrients*	Soil sub-system nutrient balance*		
	Soil organic carbon*		
• *Minimize water pollution*	Nitrate leaching*	Nitrate in ground water*	Phosphorus, nitrate loads to water bodies*, pesticide content in water*
• *Minimize GHG emissions*	GHG emissions*	GHG emissions from exposed dunghill*	Reduced GHG emissions due to spared vegetation conversion*
• *Minimize biodiversity losses*	Soil biodiversity		Landscape species and genetic pools*
Economic efficiency	Crop returns to inputs* = gross margin crops / input (inputs = cultivated land, applied nutrients, water and labor)	Net farm income* Farm net cash flow*	Average net farm income and farm net cash flow*
Social efficiency			

• *Fairness of benefit-sharing (social equity)*		Women's workload*	Gini index of net farm income*
• *Social acceptance*		Willingness-to-adopt re. intensification options* (Likert scale)	Adoption rates (%) of intensification options*
• *Social incentive*		Willingness-to-pay for intensification options* (Likert scale)	Rates (%) of willingness-to-pay for intensification options*

Farmer perception and Participatory Multi-Criteria Assessment (pMCA)

While scientific and data-driven methods are useful as an objective way to discover impacts in beyond of normal human mentality, assessment approach based on farmer perceptions has its own merit, being helpful regarding the following aspects:

- Help "scan" important dimensions and indicators for rapid and in-depth assessments
- Fairly meet the requirement of small or short-term projects
- Highly relevant to the social context of the study area, as well as to the measurement of social indicators.

Multi-Criteria Impact Assessment (MCA) is a decision-making method used to evaluate problems, when one is faced with a number of different alternatives and expectations and wants to find the 'preferred' solution with regard to different, and often conflicting, objectives. The ability of MCA to deal with complex impact assessment problems, which involve a number of conflicting ecological, environmental, societal and economic objectives and multiple interests groups, is widely acknowledged (Scholz and Tietje, 2002; Antunes *et al.*, 2011).

A typical multi-criteria problem (e.g. a discrete number of impact dimensions/criteria/indicators) is described in the following way: considering that A is a finite set of *n* alternatives and G is a set of *m* evaluation criteria, it is possible to build an $n \times m$ matrix (P) called the impact matrix, whose elements $p_{i,j} = g_j(a_i)$ ($i = 1, 2, \ldots n; j = 1, 2, \ldots, m$) represent the evaluation of alternative *i* by means of criterion *j*. An alternative a_1 is evaluated to be better than alternative a_2 (both belonging to the set A) according to the j^{th} criterion if $g_j(a_1) > g_j(a_2)$.

Participatory MCA in water management technologies would involves the following steps (Antunes *et al.*, 2011):

a) *Institutional analysis:* actors identification, characterization of the legal and institutional framework;
b) *Framing the decision*: reaching a commonly agreed problem statement;
c) *Defining key objectives and criteria*: identifying what values matter most to the participants in this particular situation;
d) *Establishing alternatives* and considering the relevant constraints. There may be a limited set of actual packages to implement MRBT;

e) *Identifying consequences*: that is the most important impacts that can affect the stated objectives and associated uncertainties. Table 4 can be used as suggestive structure for further discussion on consequences of MRBT;
f) *Evaluating the desirability of the consequences* according to the proposed criteria. Participatory scoring exercises can be applied.
g) *Ranking of alternatives* applying an aggregation procedure;
h) *Social impact analysis*, discussing the implications of each alternative for the main actor groups.

The participatory activities includes (see Figure 6):

- *preparatory interviews*: actors selection, understanding the decision context,
- *workshops*: alternatives and criteria identification, results discussion, and
- *a second round of interviews*: criteria weighting and alternatives evaluation

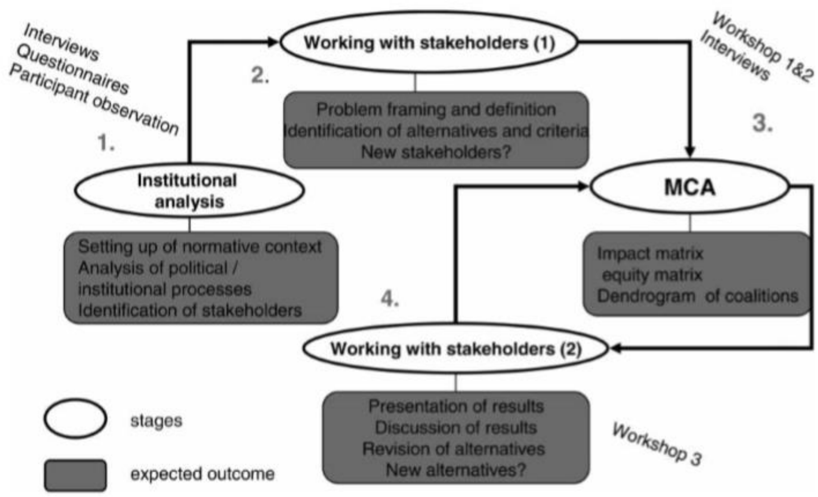

Figure 6. Flow chart of steps and activities for conducting participatory MCA. Source: Antunes et al. (2011)

4. CONCLUSIONS

Mechanized raised bed technology (MRBT) has been recognized as an important component of integrated water management to achieve higher productivity in intensive irrigated systems such as in the Nile delta. Effective management and policy for spreading the technology at scale toward achieving system-level outcome requires adequate understanding on drivers of farmers' MRBT adoption, insightful assessment of the technology efficiency regarding system performance and impacts. Related research efforts on these issues are challenged by both the complex nature of the task, and the diversity of socio-ecological context that shapes farming systems' performance. This paper concisely reviews and re-introduces a system-based option-by-context approach for guiding concrete analytical steps and operational methods for addressing the research issues in coping with the challenges of system complexity and contextual diversity. We described conceptual framework and econometric methods for identifying main livelihood types of smallholders in terms of their farms' biophysical and socioeconomic characteristics. We explained econometric method for identify determinants, both common and livelihood type-specific, of farmers' adoptions of MRBT and technology efficiency over ICARDA's studied area in Egypt. We analyzed the technology efficiency concept and the challenges in measuring it, and described economic methods for comparative evaluation of MRBT efficiency in coping with multiple inputs and shifting in production potential (i.e. the efficiency frontier). Finally, we argued for a multi-scale strategy in evaluating impacts of MRBT (production unit, whole farm, and community-landscape scales), discussed relevant impact criteria, indicators at each scale, and described participatory Multi-Criteria Assessment method for assessing MRBT's impacts.

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Annexes

Annex 1. Household variables for Principal Component Analysis. The main variables representing the livelihood assets of households based on the SLF were extracted from a multi-dimensional dataset and used to run the PCA. It allowed identifying key variables discriminating farms in Pontieba, Burkina Faso.

Livelihood asset	*Variable*	*Variable definition*	*Source[a]*
Human	$H_{HEADAGE}$	Household head age (year-old)	D
	$H_{MEANAGE}$	Average age of the household members	C
	H_{LABAGE}	Average age of the household labour	C
	H_{HEDUYR}	Number of years of classic education of household head	C
	H_{NBEDUC}	Number of educated members in the household	C
	H_{SIZE}	Household size (no. of people in the household)	D
	H_{LABOUR}	Number of workers of the household (labour)	C
	H_{DEPEND}	Dependency ratio of the household	C
Physical	$H_{DMARKET}$	Distance to important market (Main town) from household house	D
	H_{DROAD}	Distance to permanent road from household house (m)	R
	$H_{VEHICLE}$	Number of transportation means (bicycle and motorbike) possessed by the household	C
	$H_{BULLOCK}$	Number of bullock possessed by the farm	D
Natural	$H_{HOLDINGS}$	Farm land holdings (ha)	D
	$H_{HOLDINGCP}$	Farm land holdings per capita (ha/person)	C
	$H_{FALLOWCP}$	Farm fallow land per capita (ha/person)	C
	$H_{CULTLANDCP}$	Farm cultivated land per capita (ha/person)	C
	$H_{SHFALLOW}$	Share of fallow area in land holdings (%)	C
	$H_{SHCOTTON}$	Share of cotton area in land holdings (%)	C
	$H_{SHCEREAL}$	Share of cereals area in land holdings (%)	C
	$H_{SHMFCRP}$	Share of marketable food crops area in land holdings (%)	C
	H_{TLUCP}	Tropical livestock unit per capita (TLU/capita)	C
	H_{TLUHA}	Tropical livestock unit per ha of cultivated land (TLU/ha)	C
Financial	$H_{GROSSINC}$	Household annual gross income (FCFA)	C
	$H_{GROSSINCCP}$	Household annual gross income per capita (FCFA/capita)	C
	$H_{SHREMITINC}$	Share of remittance income in household annual gross income (%)	C
	$H_{SHNFINC}$	Share of Off-farm income in household annual gross income (%)	C
	$H_{SHLIVESTINC}$	Share of livestock income in household annual gross income (%)	C
	$H_{SHCOTINC}$	Share of cotton income in household annual gross income (%)	C
	$H_{SHCERINC}$	Share of cereals income in household annual gross income (%)	C
	$H_{SHMFCRPINC}$	Share of marketable food crops income in household annual gross income (%)	C

Note: [a] D = Direct extracted from the questionnaire; C = Compound information calculated based on information coded in the questionnaire; R = Extracted from map reading.

Annex 2: Description of hypothesized explanatory variables for crop choice and nutrient uses adoption analysis

Variable	Definition	Considered (x) in		Data source
		Crop choice analysis	*Nutrient use adoption analysis*	
Dependent/choice variables				
P_{CROP}	Crop choices on the plot (=1 if sorghum or millet, =2 if groundnuts, =3 if rice, =4 if maize and =5 if cotton)	x		On-farm interview
P_{MIN}	Adoption of mineral fertilizer use on the plot (= 1 if yes, = 0 if no)		x	On-farm interview
P_{ORG}	Adoption of organic fertilizer use on the plot (=1 if yes, = 0 if no)		x	On-farm interview
P_{MINORG}	Adoption of combined mineral-organic fertilizer use on the plot (=1 if yes, =0 if no)		x	On-farm interview
Household characteristics				
$H^{HEADAGE}$	Age of household head (year-old)	x	x	On-farm interview
H_{HEDUYR}	Number of school years the household head passed	x	x	On-farm interview
H_{SIZE}	Number of farm members	x	x	On-farm interview
H_{LABOR}	Number of workers	x	x	On-farm interview
H_{DEPEND}	Dependency ratio (= no. of dependents / no. of workers)	x	x	On-farm interview
H_{TLUCP}	Number of Tropical Livestock Units (TLU) of the household	x	x	On-farm interview
$H_{GROSSINCCP}$	Household annual gross income per capita (F CFA/person)	x	x	On-farm interview
$H_{HOLDINGS}$	Total holding land possessed by the farm (ha)	x	x	GPS and GIS-based measure
Plot/field characteristics				

P_{DHOUSE}	Distance from plot to homestead (m)	x	x	GIS recordings
$P_{PLOTSIZE}$	Plot size (ha)	x	x	GPS measurement
$P_{CROPTYPE}$	Type of current crop grown on the plot (= 1 if fertilizer-demanded crops (maize, rice or cotton); =0 if other crops)		x	On-farm interview
$P_{CROPHIST}$	Type of previous crops grown on the plot (= 1 if the previous crops are fertilizer-demanded ones (maize, rice or cotton); =0 if other crops)	x		On-farm interview
$P_{UPSLOPE}$	The upslope contributing area (m^2) at the plot location, indicating sedimentation accumulation potential in the plot	x	x	Terrain analysis from DEM
$P_{WETNESS}$	Topographical wetness index (= *ln* ($P_{UPSLOPE}$/surface slope)), indicating potential water saturation in the plot	x	x	Terrain analysis from DEM
PLS	The slope length (LS) factor at the plot location, indicating soil erosion potential.	x	x	Terrain analysis from DEM
Household access to enabling policy				
P_{CREDIT}	Plot's owner access to credit (= 0 if no, =1 if yes)	x	x	On-farm interview