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Socioeconomic, biophysical, and environmental impacts of raised beds in irrigated wheat: A case study from Egypt

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ABSTRACT

Raised beds (RB) are hailed as means to mitigate the problem of excessive irrigation. However, their adoption and impacts in Egypt are not well-documented. This paper is based on survey data collected from a sample of 691 wheat fields drawn from three major wheat-producing provinces of Egypt. Using area-weights for upward aggregation, we estimated that 19.3% of total wheat area in the three provinces is cultivated with raised beds. We applied the endogenous switching regression model to analyze the socioeconomic, biophysical, and environmental impacts of RB. Model results showed that the adoption of RB led to a 937 kg/ha (12.79%) increase in yield, a US$77.60/ha (9.47%) increase in gross margins, an 824.63 m^3/ha (15.05%) reduction in irrigation water application, 16.7% reduction in seeding rate, 5.56% increase in water productivity, and an 11.80% reduction in downside yield risk. Adoption of RB didn't have significant effect on soil salinity and quantities of fertilizer and labor inputs. These results show that RB can provide panacea to several interrelated socioeconomic, biophysical, and environmental problems associated with irrigation. The policy implication of our findings is that Egypt and other similar countries can benefit from embracing RB as part of the technology packages promoted by their national agricultural extension systems. The benefits to these countries will increase if they invest more on research for adapting and perfecting the RB technology including its mechanization and its efficacy in soil salinity management.

1. Introduction

In the late 2000s, irrigated lands constituted about 20% of total global cultivated land (Thenkabail et al., 2009a), 40% of total food production (Thenkabail et al., 2009b), and 65% of total ground and surface water exploited by humans (Thenkabail, 2010). After a decade, the share of irrigation in total croplands and in total food production have reduced to 20% and 40%, respectively, while the share in total ground and surface water exploited by humans has increased to 70% (World Bank, 2020) - indicating that irrigation has sizeable role not only in determining the sustainability of water resources but also on the ability of the human race to produce sufficient food. Over time, several challenges associated with irrigation including ground water depletion, water conflicts, soil salinization and hence yield loss are emerging. Some of these problems are aggravated by farmers' mismanagement. This paper provides field-level empirical evidence from Egypt on whether the use of raised beds in irrigated wheat production helps mitigate some of these challenges.

Ground water is being depleted at a faster pace and competition among countries and communities sharing the same water sources is increasing due to growing demand for water and large regional variations in the distribution of the endowments (Wada et al., 2010). The increased competition for water along with the increasing scarcity of surface water resources are in some cases leading to water conflicts (Levy and Sidel, 2011). Another challenge facing our world is soil salinity, which results from the accumulation of salt above levels that adversely affect plant growth (Shrivastava and Kumar, 2015). Regardless of the irrigation method, poor water management practices including insufficient leaching and poor drainage are bound to accumulate salts at and beyond the rooting zone causing soil salinity (Shahid, 2013). Salinized areas are steadily growing at a rate of 10% per year currently costing the world about US$27 billion per year (Zaman et al.,

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2018). Left unchecked, by 2050, salinity is expected to affect more than 50% of croplands worldwide (Jamil et al., 2011).

All the challenges discussed above show the very high importance of irrigation in food, water and soil security (Koch et al., 2012; Thenkabail et al., 2010) and hence the due attention that it deserves. Therefore, introduction of effective ways of sustainably conserving water and timely recognition of salinity symptoms in irrigated fields and use of appropriate soil and water management practices may save further degradation of water and soil resources and costly reclamation efforts (Shahid, 2013).

The different irrigation methods that are currently used by farmers can be broadly classified into five categories, namely: flood, furrow, sprinkler, subsurface, and localized irrigation methods (Kandiah, 1994). Historically, flood irrigation (also known as traditional surface irrigation) has been the most dominant irrigation method (Bilibio et al., 2011; Yigezu et al., 2014). This method is characterized by poor control over water distribution and hence associated with low water use efficiency (Yigezu et al., 2013; Irmak et al., 2011). Poor water management under flood irrigation is also often associated with soil salinity problems (Shahid, 2013). With surface irrigation, applying an optimal (equivalent to the leaching requirement) amount of water to leach the salt down through the soil profile is the desired method for maintaining suitable soil salinity (Thompson et al., 2010). However, there are tradeoffs between the two goals of increasing water use efficiency and reducing salinity. For example, in the face of scarcity of water and the associated growth in the use of low-quality water, the tendency to increase the water use efficiency in irrigation can lead to the accumulation of salts in the soil as the leaching fraction is reduced, and the salts contained in the irrigation water are not leached enough (Machado and Serralheiro, 2017).

In Egypt, the main source of irrigation is fresh water from the Nile and flood irrigation is the most common irrigation method. Therefore, the main cause of salinity in the country is capillary effect due to excessive application of irrigation water in areas where the ground water table is shallow, especially in lower Egypt. The main strategy used in the country for mitigating salinity problems has been developing drainage structures for the crop lands. Subsurface drainage system is widely applied in the Nile Delta to withdraw the excessive irrigation water from the root zone and lower the groundwater level. The drainage water is officially reused after mixing with canal fresh water to adjust the salinity. Farmers also unofficially reuse drainage water. Moreover, farming in the Nile delta is highly intensified and diversified because farm sizes are very small (an average of 0.5 acre per family). As a result, farmers apply excessive amount of fertilizers in order to maximize their farm income. In the absence of proper leaching and soil management, such practices also increase the salinity level in the soil. Therefore, all efforts aimed at identifying appropriate irrigation methods should be driven not only by water use efficiency considerations but also their implications on salinity.

The other methods of irrigation are less common, especially in the production of cereals but play important roles in fruit and vegetable production. Drip irrigation is perhaps the best irrigation technology because it ensures uniformity in water application and hence enhances plant growth, saves water by minimizing evaporation, reduces nutrient leaching, and requires lower labor input, especially for land leveling. However, it may not work when irrigation water has high iron content as it can create clogging. Maintenance cost can also be high, and tubes can be easily damaged by rodents and insects causing leakages. Sprinkler irrigation is efficient on soils with medium and coarse texture and water can be applied at low rates. However, frequent application may be needed to recharge soil moisture depleted by the crop. While furrow irrigation requires low initial investment on equipment and involves lower pumping costs, it involves higher labor costs and lower application efficiency compared to sprinkler and subsurface drip irrigation. For example, Albaji et al. (2010) found that drip and sprinkler irrigation methods are more effective and efficient than surface irrigation. However, soil texture, salinity, and slope can be major limiting factors for sprinkler irrigation. For drip irrigation, the calcium carbonate content can be an additional limiting factor.

By reducing the amount of water application while also allowing excess water to drain into open collector which discharges it off the field, raised beds are effective in enhancing yield, water productivity and soil structural and chemical properties including reducing soil salinity (McDonald, 2019; Soomro et al., 2017; Devkota et al., 2015; Amer et al., 2011; Velmurugan et al., 2016; Acuña et al., 2011; Bakker et al., 2005; Ahmad and Mahmood, 2005). Planting on beds can also lead to the reduction in fungal and other diseases with improved radiation interception, acquisitive temperature and reduced humidity in the canopy enabling farmers to reduce their pesticide applications (Alwang et al., 2018). However, while raised beds have several advantages, their suitability in mixed crop-livestock systems is yet to be established (Manik et al., 2019).

Raised beds have long history in Egypt where several farmers apply it for several crops including vegetables. The adoption of raised bed technology in Egypt is increasing due to its multiple benefits (Alwang et al., 2018; Swelam, 2016). However, the types and extents of benefits from raised beds depend on the dimensions of beds and its associated farrows and the method of implementation (manual or mechanized), sowing method (rows vs. broadcasting) and seeding rates. In recognition of the benefits of the raised bed technology, the shortcomings of traditional designs, and the threats that continue to constrain agricultural production in the North African and West Asia regions, the International Center for Agricultural Research in the Dry Areas (ICARDA) and its national and international partners have carried intensive research between 2004 and 2008 (proof of concept) which led to the design and testing of a raised bed machin between 2009 and 2012. Ultimately, ICARDA in collaboration with the Agricultural Research Center (ARC) of Egypt developed prototypes for raised bed machines that are adapted and suitable to the local socio-economic and agroecological conditions in the country.

Since 2012, there have been concerted efforts to out-scale the raised bed technology in general and the mechanized raised bed (MRB) technology in particular in Egypt, through at least five different projects. While good progress was made during the implementation of the projects, a breakthrough was not made until after the policy makers in Egypt got convinced by the appropriateness and advantages of the MRB technology in 2016 as a result of which MRB has been included as one component of the wheat technology package that is widely being popularized through the National Wheat Campaign of the government. If the use of the MRB continues to expand at its current pace, an estimated 800 thousand ha of land is projected to be under the technology by 2023 (Alwang et al., 2018). However, it is important to note that an inappropriate implementation of raised beds can lead to yield reduction if the bed width is too large and furrow depth is too shallow due to water stress on the middle rows because water does not reach the effective root zone. The design and introduction of raised beds should carefully factor the soil type and salinity level. Raised beds should also be packaged with other appropriate technology components such as crop variety and fertilizer and seed rates because different varieties perform differently depending on the specifications of the beds and whether the soils are salt-affected, sandy or clay. Therefore, using raised beds without proper advisory services can lead to negative effects on yield and soil health. Maintaining the delicate balance between the specifications of the raised beds and identification of the other complementary technology components can be complicated which may in many cases affect the adoption of the technology, especially by mostly uneducated smallholders.

National research partners from many other countries including Morocco, Tunisia, Algeria, Nigeria, and Sudan have also shown interest to introduce the technology into their respective countries. As a result, the project called Enhancing Food Security in Arab Countries (EFSAC) implemented jointly by ICARDA and ARC which promoted the raised bed technology in Egypt also carried adaptation and testing activities in all these countries (EFSAC, 2018). This indeed is an exciting moment for ICARDA and its partners which invested a lot of time, efforts and resources into developing and perfecting the MRB technology as it has great potential to transform agriculture in irrigated areas of many countries in the North African and West Asian regions and more other regions with similar biophysical conditions. However, it remains unanswered whether the technology can be a panacea for several agricultural problems in irrigated agriculture and providing the expected social, economic, biophysical and environmental benefits to the farmers who are using it and their surroundings.

Using data collected to measure the impacts of a technology package that was introduced to enhance wheat productivity in Egypt, this paper attempts to shed some light on the levels of adoption and impacts of the raised bed (RB) technology on wheat fields in three major wheat-growing provinces namely, Al-Sharkia, Al-Dakahlia and Kafr Al Sheikh in the Nile Delta region. Specifically, the paper provides estimates of: 1) economic benefits in terms of yield and net returns; 2) social benefits in terms of the amount of labor needed and the reduction of downside yield risk in wheat production; and 3) biophysical/environmental benefits in terms of reducing the quantity of irrigation water applied per unit of area (m^3/ha), increasing water productivity (kg/m^3), and reducing salinity (dS/m). Unfortunately, the data that was collected did not make distinction between different types of raised beds (mechanically or manually constructed; width and height of beds; width and depth of furrows between beds; seeding methods – row planting vs. broadcasting, and seeding rate). The traditional manually constructed raised beds are still common in Egypt, especially in vegetable cultivation while they are starting to be replaced by mechanized raised beds in cereal cultivation. As a result, about 40–50% of all raised beds in wheat fields in the study governorates are estimated to be constructed manually or semi-mechanically using chisel plow. Therefore, despite our earnest desire to measure the impacts of the mechanized raised beds, the results of our study cannot be explicitly attributed to mechanized raised beds nor to the manually constructed raised beds. Hence, we report the impacts of raised beds in general regardless of their type. The findings of our study are believed to be useful to inform future research and extension and guide policy and development efforts in Egypt and many similar countries facing the challenges associated with irrigated agriculture.

2. The raised bed technology in Egypt

Egypt has a total of 3.69 million ha (8.8 million feddan) of agricultural land out of which an estimated 3.61 million ha (97.7%) is irrigated with the remaining 84,000 ha rainfed. The Nile River is the main source of water in the country. Therefore, agriculture heavily depends on the Nile River from which it obtains about 55.5 billion m^3/year of water. Due to the highly fertile alluvial soils and availability of water for irrigation, wheat productivity in Egypt is the highest in Africa. For example, average wheat yields in the country stands at about 6.7 ton/ha which is much higher than the African average of 2.6 t/ha (FAOSTAT, 2019). However, because of rapid population growth, the country is under pressure to open new lands for cultivation thereby increasing the pressure on the limited water supply. Moreover, available water resources have reduced by over 80% in the last century (FAO, 2016). New upstream initiatives might also potentially compromise the amount of water Egypt will get in the future. Another domestic challenge Egypt is currently facing is that because of the accumulation of salts, mostly at the soil surface, 35% of the agricultural land is suffering from salinity reducing the yield potential of the agricultural lands.

Raised beds have been considered by some farmers as a good practice for irrigated land and have been used in Egypt since long time (Alwang et al., 2018). However, given the high labor demand for their construction, their adoption has been limited. In view of the current and potential future challenges for agriculture in Egypt, the International Center for Agricultural Research in the Dry Areas (ICARDA) and its national partners including the Agricultural Research Center (ARC) of Egypt have carried long term research to improve the efficacy of raised beds for the conservation not only of water and soil but also of agricultural labor. To this effect, they designed a raised bed machine (RBM) for which a prototype has been developed and validated. The machine has been tested in various parts of the country and demonstrated clear advantages in terms of enhancing yield and in saving irrigation water and labor for land cultivation relative to both the traditional surface irrigation and the traditional raised beds.

In the last decade, yields of some field crops have increased while water consumption, otherwise known as evapotranspiration (ET), has slightly decreased due to wide adoption of new agronomic practices that reduce ET. These practices were introduced through different large research-for-development projects to improve the productivity of irrigated farming systems using surface irrigation. These practices include raised bed, soil salinity amendment packages (including gypsum application, biofertilizer, leaching fraction, etc.), lining irrigation canals, gated pipe surface irrigation, deficit-irrigation as an optional practice to cope with water shortage condition and alternate furrow irrigation. Crop lands in Egypt are generally flat with maximum slope of 5%. However, laser-based land leveling is practiced in some crop lands to enhance irrigation efficiency. Currently, in addition to the dissemination of raised bed technology, the government of Egypt is implementing a nation-wide irrigation modernization initiative that mainly focuses on switching from surface flood irrigation to pressurized irrigation systems (drip and sprinkler) to reduce irrigation application. In this connection, the agriculture research center of Egypt has recently developed and disseminated high yielding, drought tolerant and water efficient crop varieties mainly of wheat, barley, and maize.

The scientists who developed the mechanized raised bed (MRB) technology argue that when accompanied with good practices it has the potential to reduce salinity, increase photosynthesis and reduce diseases and pest prevalence. In short, MRB will provide a panacea for most of the irrigation-related problems Egyptian farmers are currently facing and may face in the future. Several initiatives and projects have tried to disseminate the MRB technology into six provinces. Between 2011 and 2014, a project funded by the International Fund for Agricultural Development (IFAD) and the project "Enhancing Food Security in the Arab Countries (EFSAC)" funded by multiple donors in the Arab world introduced the technology as part of a wheat technology package involving six other components in Al-Sharkia governorate. The same projects also promoted the technology in Al-Dakahlia governorate between 2015 and 2018. Since 2018, the EFSAC project popularized the technology in Al-Behera governorate.

The MRB technology was also introduced in Al-Assuit since 2015 by a project funded by the Food and Agriculture Organization of the United Nations (FAO). A development program funded by the European Union (EU) has also introduced the technology in Al-Fayoum and Al-Minia provinces since 2018. Based on the evidence demonstrated by these projects, policy makers in Egypt were convinced on the appropriateness and advantages of the technology for which they have decided to include MRB as one component of the wheat technology package that is being widely popularized through the government's national wheat campaign (NWC). NWC has much larger coverage than all the projects mentioned above not only in terms of number of districts and villages covered but also in terms of number of farmers included in the popularization effort from each district and village as it is disseminating the MRB in 22 governorates across the country. ARC plans to increase the total cultivated area using RB from 1,000,000 acre in 2019/2020 to 1,037,843 acre in 2020/2021 (FAS, 2020).

Several project reports showed that based on bivariate data analysis, the adoption of the mechanized raised bed (MRB) technology was associated with 15–25% increase in yields, 50% lower seed costs, a 25% reduction in irrigation water, and lower labor costs (ICARDA, 2017; Swelam, 2016; Swelam and Atta, 2012; Karrou et al., 2012). Since its dissemination in 2011, the mechanized raised bed technology has expanded in various parts of the country. The raised beds constructed using the ICARDA-ARC raised bed machine are 130 cm wide and 50 m long. The associated furrows are 20–40 cm wide and 20–30 cm deep. The machine plants the seeds in straight rows and can be calibrated to the desired seeding rate (optimally at 107 kg/ha). For wheat, the recommended spacing for planting is 7 rows on each bed which are 15 cm apart. At the same time, a large number of farmers have been constructing permanent raised beds either semi-mechanically or manually with their own modifications to the bed sizes, farrow depths and widths. For semi-mechanical raised beds, farmers first plant using broadcasting at a high seeding rate of above 145 kg/ha and then prepare the raised beds using chisel plows. While there is huge variation in the dimensions of the semi-mechanically constructed raised beds, they generally have much narrower beds than MRBs. The traditional manually constructed raised beds on the other hand are much wider than the semi-mechanically constructed beds but still slightly narrower than the fully mechanized. Similar to the semi-mechanized raised beds, farmers using the traditional manually constructed raised beds use broadcasting with high seeding rate of over 145 kg/ha. All types of raised beds are believed to have advantages in terms of irrigation water saving and yield over the traditional furrow and flood irrigation (Fig. 1).

Experts estimate that up to 200 thousand ha of crop land is under raised beds out of which, about 100 thousand ha are estimated to be under wheat. The experts also estimate that some 40–50% of the raised bed in wheat lands is manually or semi-mechanically constructed and more than half (up to 60 thousand ha) is estimated to be fully mechanized as the expansion of raised beds in wheat fields intensified mainly after the introduction of the raised bed machines. Unavailability of the RB machine is the main reason given for why some farmers are cultivating their wheat fields with semi-mechanical or manually constructed raised beds. Non-adopters of raised beds consider the land used as farrows between beds to be too much in the face of their small landholding. While the benefits of raised beds regardless of the levels of mechanization seem to be widely agreed, experts warn that some specifications followed in the construction of manual and semi-mechanized raised beds might not deliver some or all of the benefits, and in the extreme case may be harmful.

3. Data

As described above, between 2011 and 2018, the EFSAC project introduced a wheat technology package with a total of 10 components (variety, raised beds, seed and fertilizer rates, herbicide and pesticide rates, planting and harvesting dates, rotation, and irrigation scheduling). As part of the conclusion of the 2nd phase of the project, there was a need to measure the adoption and impacts of the technology package. To this effect, the research team purposively included Al-Sharkia and Al-Dakahlia, the only two governorates where the project introduced the technology package, into the sample. To see if the technology was expanding outside the project areas and also to make sure that the socio-economic and environmental changes happening in Al-Sharkia and Al-Dakahlia are not also happening elsewhere, one governorate (Kafr Al Sheikh) was included into the survey as a control. Afterwards, a multi-stage stratified random sampling procedure was used to draw samples.

Using power analysis, the minimum sample size needed to ensure a confidence level of 95% and a precision level of at least 3% for estimates of adoption was determined to be 602. To account for missing values and for balancing of the samples across all sampling units, the sample size was increased to 615. The sample households were then distributed across all three governorates, proportional to their farmer populations. To do this, first districts and villages were stratified into project and non-project districts and villages. Then, random samples of project and non-project districts and villages were selected for inclusion into the sample. Then, at the level of villages (the primary sampling units), farm households were randomly drawn using the master file containing all wheat growers of each village as sampling frames. Given that the main objective of this study is to draw lessons from the project interventions, there was concern that by taking random samples of farmers at the village levels, we may run the risk of not having sufficient number of farmers in the sample who have adopted one or more of the technologies promoted by the project. To overcome this potential problem, the research team decided to first take a random sample of 426 households (70% of the total sample size) using a random sampling procedure and then randomly select the remaining 189 households (30% of the total sample) only from among those who were project participants. By so

a) Cultivation using traditional farrow and flood irrigation

b) Cultivation using semi-mechanized raised beds

c) Cultivation using manually constructed raised beds

d) Cultivation using mechanized raised beds

Fig. 1. Cultivation using the traditional furrow and different types of raised beds.

doing, the team ensured having sufficient number of farmers who used each technology component in the sample. Descriptive statistics for selected variables are presented in Table 1.

4. Methods

One of the main challenges in the estimation of average treatment effects is related to establishing counterfactuals as selection bias is often inherent in program participation. Egyptian wheat farmers may self-select into or out of the adoption of the raised bed technology for various reasons. Some farmers may adopt it because they believe that they have the right soil, tractor(s), manpower and special knowledge, skills, abilities and expertise and as a result, have stronger motivation to adopt the technology. Other farmers may have reasons including lack of manpower, shallow soil and confidence and negative attitude to believe that the technology will not work for them. Moreover, some important explanatory variables are very difficult to measure and hence despite all efforts, remain missing in the data and hence are omitted from the regression. As a result, the problem of endogeneity is likely to be present during estimation which, left unaddressed, might lead to erroneous inferences.

Depending on the source of bias, several econometric approaches can be used to address the problem of selection bias in program evaluation using quasi-experimental and observational data. Imbens and Wooldridge (2009) provide a good review of the literature and the developments in causal inference and impact assessment. Propensity score matching (PSM) due to Rosenbaum and Rubin (1983) is by far the most widely used for improving causal inference and estimation of average treatment effects (El-Shater et al., 2016; Morgan and Winship, 2014; Henderson and Chatfield, 2011; Jalan and Ravallion, 2003). Propensity Score Matching (PSM) helps in correcting biases introduced only by observable covariates (Heckman and Vytlacil, 2007). Therefore, results from PSM can sometimes be misleading since unobservable factors such as skills and motivation can influence not only the outcome but also the program participation decision thereby leading to confounding errors (See Austin, (2008) for critical review of PMS). To overcome this problem, two other methods, namely the instrumental variables (IV) regression (Angrist and Pischke, 2009) and endogenous switching regression (Maddala and Nelson, 1975) methods have been proposed. In this paper, we employ the Endogenous switching regression (ESR) approach for estimating treatment effects of the adoption of raised bed (RB) among Egyptian wheat farmers.

4.1. Endogenous switching regression (ESR)

The difference in the outcomes of interest between adopters and non-adopters may not only be due to observable heterogeneity but also due to unobserved heterogeneity (Bidzakin et al., 2019; Paltasingh and Goyari, 2018; Khonje et al., 2015; Malikov and Kumbhakar, 2014). Therefore, we use an endogenous switching regression (ESR) to account for both observable and unobservable endogeneity of the adoption decision by simultaneously estimating the adoption function (Eq. (1)) and the outcome equation of interest for each group (Eq. (2) or (3)).

Theoretically, farmers decide to adopt a technology when the expected utility received from adoption (D_1^*) is greater than the utility received from non-adoption (D_0^*). While utility is not observable, adoption is observable and is treated as a dichotomous choice: D = 1 if $D_1^* > D_0^*$ and D = 0 if $D_1^* < D_0^*$. Thus, following Bidzakin et al. (2019), Shiferaw et al. (2014) and Lokshin and Sajaia (2011) the ESR can be formulated as follows with the adoption decision (selection equation) modeled as:

$$D_i^* = Z_i\beta + \varepsilon_i \text{with} D_i = 1 \quad if D_i^* > D_0^*, \text{otherwise} D_i = 0 \tag{1}$$

where Z represents a matrix of the explanatory variables, ß is a vector of parameters to be estimated and ε a vector representing normally distributed error term with mean zero and variance σ_ε^2..

The outcome equations can also be formulated as:

$$y_1 = X_1\omega_1 + \epsilon_1 if D = 1 \tag{2}$$

Table1

Summary statistics for variables included in the models.

Variable	N^	Min	Average	Max	Standard deviation	For RB=		
						Yes	No	% of Yes
The household is part of the random sample (0 = No, 1 = Yes)	426^	0	0.70	1	0.46	74	352	17%
The household is part of the purposive sample (0 = No, 1 = Yes)	189^	0	0.30	1	1.46	147	15	91%
The field is part of the random sample (0 = No, 1 = Yes)	459^	0	0.66	1	0.47	83	376	18%
The field is part of the purposive sample (0 = No, 1 = Yes)	232^	0	0.33	1	0.47	199	33	86%
The farm is in Al-Sharkia {1 = yes, 0 = No}	370^	0	0.44	1	0.78	159	111	59%
The farm is in Al-Dakahlia {1 = yes, 0 = No}	207^	0	0.34	1	0.78	89	118	43%
The farm is in Kafr Al-Sheikh {1 = yes, 0 = No}	138^	0	0.22	1	0.78	0	138	0%
Sex of household head is Male (0 = No, 1 = Yes)	592^	0	0.96	1	0.18	255	337	43%
Sex of household head is Female (0 = No, 1 = Yes)	23^	0	0.04	1	0.18	4	19	17%
Age of household head (Years)	615	21	56.01	28	10.47	55.09	55.28	
Family size (number of persons)	615	2	5.31	18	1.89	5.61	5.11	
Total labor used (Persons/season)	615	0	1.81	9	1.15	1.72	1.88	
Area cultivated with wheat in 2016 (Ha)	615	0.10	0.84	22.68	1.32	1.08	0.83	
Total cropped area in 2016 (Ha)	615	0.42	2.61	46.27	3.79	3.37	2.09	
Size of a wheat field – for the entire sample (ha)	691	0.05	0.73	12.18	0.95	0.91	0.64	
Size of a field only for the random sample (ha)	459	0.07	0.61	4.62	0.49	0.65	0.60	
Soil in this field is medium or deep {1 = yes, 0 = No}	525^	0	0.76	1	0.43	227	298	43%
Soil in this field/plot is shallow {1 = yes, 0 = No}	166^	0	0.76	1	0.43	55	111	33%
Quantity of nitrogen fertilizer used (kg/ha)	691	150	174.60	200	23.19	159.71	184.87	
Quantity of TSP fertilizer used (kg/ha)	691	0	148.65	200	57.71	149.64	147.97	
Quantity of seed used (kg/ha)	691	107.14	139.74	190.47		120.90	152.73	
Yield (ton/ha)	691	6.43	7.33	10.74	0.88	7.84	6.96	
Gross margins (in thousand EGP/ha)[a]	691	2.10	14.56	24.32	3.1	15.96	13.60	
Number of RB-machines per 10,000 ha of wheat area in each district	8	0	3.56	12.54	4.00			
Total number of sample households	615							
Total number of sample wheat fields (plots)	691							

Notes:

^ - N stands for total sample size and N^ stands for number of cases with a "1 = Yes" value.

[a] - The exchange rate in 2017 was 1US$ = 17.77 Egyptian Pounds (EGP).

$$y_0 = X_0\omega_0 + \epsilon_0 if D = 0 \quad (3)$$

where y_i is a vector of dependent variables representing outcomes for adopters (y_1) and non-adopters (y_0), X_i is a matrix of explanatory variables some of which may be in Z where for proper identification of the model, Z contains at least one explanatory variable which is not in X; ω_i is a vector of parameters to be estimated, and ϵ_1, and ϵ_0 are error terms.

The error terms from the three equations ε, ϵ_1, and ϵ_0 are assumed to have a trivariate normal distribution with mean vector zero and a symmetric covariance matrix as shown in Lokshin and Sajaia (2011).

If ε is correlated with ϵ_1, and ϵ_0, the expected values of ϵ_1, and ϵ_0 conditional on the sample selection are non-zero.

If $\sigma_{\epsilon1\varepsilon}$ and $\sigma_{\epsilon0\varepsilon}$ are statistically significant, this would indicate that the decision to adopt and the outcome variable of interest are correlated suggesting evidence of sample selection bias. Therefore, estimating the outcome equations using ordinary least square (OLS) would lead to biased and inconsistent results and Heckman procedures (Heckman, 1979) are normally used. In the face of heteroscedastic error terms, the full information maximum likelihood (FILM) estimator can be used to fit an endogenous switching regression that simultaneously estimates the selection and outcome equations to yield consistent estimates. The ESR can be estimated where the actual expected outcomes of adopters (4) and non-adopters (5), and the counterfactual hypothetical cases that the non-adopters did adopt (6) and the adopters did not adopt (7) can be analyzed as follows:

$$E(y_1|D = 1) = X_1\omega_1 + \sigma_{\epsilon1\varepsilon}\lambda_1 \quad (4)$$

$$E(y_0|D = 0) = X_0\omega_0 + \sigma_{\epsilon0\varepsilon}\lambda_0 \quad (5)$$

$$E(y_0|D = 1) = X_1\omega_0 + \sigma_{\epsilon0\varepsilon}\lambda_1 \quad (6)$$

$$E(y_1|D = 0) = X_0\omega_1 + \sigma_{\epsilon1\varepsilon}\lambda_0. \quad (7)$$

Finally, we calculate the average treatment effect on the treated (ATT) as the difference between (4) and (7) and the average treatment effect on the non-adopters (ATU) as the difference between (6) and (5) (Di Falco et al., 2011; Lokshin and Sajaia, 2011; Lokshin and Glinskaya, 2009; Miranda and Rabe-Hesketh, 2006; Carter and Milon, 2005). We also compute the effect of base heterogeneity for the group of adopters (BH1) as the difference between (4) and (6), and for the group of non-adopters (BH2) as the difference between (7) and (5).

A number of factors such as varieties used and the amounts of fertilizers, seed, labor, quantity of irrigation water are important in determining yield, which in turn will affect the gross margins and water productivity. Moreover, for farmers to adopt the mechanized raised bed (MRB) – by far the dominant type accounting for 70–80% of total raised beds, it is necessary that they have access to rented or privately-owned raised bed machine (RBM). Therefore, we use availability of the raised bed machine as instrument in the estimation of the ESR. Version 15 of the Stata software (StataCorp, 2017) was used for all the data analysis carried in this study.

5. Results and discussion

5.1. Model diagnostics

The Durbin-Wu-Hausman test (Hausman, 1978) was carried to examine if endogeneity is a problem for the estimation of impacts of the adoption of the raised bed technology on yield, downside risk on yield, per-capital wheat consumption, gross margins, water productivity, quantity of irrigation water applied and soil salinity. The test results showed that endogeneity was indeed a problem in the yield and downside risk equations for which we used the endogenous switching regression (ESR) for estimation of the treatment effects. However, for the rest of the equations, the test results showed that endogeneity was not a problem and hence we used the ordinary least squares (OLS) regression which is efficient.

An exogenous variable which is excluded from the list of covariates is needed to serve as an instrumental variable for identification during the simultaneous estimation of the selection and outcome equations. For an excluded exogenous variable to be a valid instrument, it must be sufficiently correlated with the included endogenous regressors but uncorrelated with the error term (Angrist and Pischke, 2009; Stock et al., 2002). We believe that the adoption of the raised bed technology is correlated with the availability of raised bed machines and hence we use the number of raised bed machines per 10,000 ha of wheat area in each district (RBM_10k_ha) as an instrument. A falsification test (Di Falco et al., 2011) showed that RBM_10k_ha does not have a direct effect on the outcome variables (yield and downside risk on yield) except through its effect on adoption of the raised bed technology. Further justification for the use of RB_10k_ha as an instrument is that since 2012, different projects have purchased and distributed about 120 of the ICARDA-ARC raised bed machines to promote the mechanized raised bed technology, especially in the Al-Sharkia and Al-Dakahlia provinces. Village-level data on the availability of raised bed machines would be a much better instrument but the data that we were able to obtain is only at district level. We believe that the district-level figures will still be valid because most service providers both public and private are located in the district capitals where they serve all farmers who are interested and have the financial means to pay for the services within the district. The downside of this instrument is that about 40–50% of all raised beds in wheat fields are manually or semi-mechanically constructed and hence may make the instrument weak. For example, the correlation between the adoption of the raised bed technology and the instrument (RBM_10k_ha) is 0.36 making it not very strong. As a result, the use of the endogenous switching regression (ESR) which can also be identified through the assumed non-linearities is justified. Robustness checks were also carried comparing several alternative specifications of the models. The results from ESR were also compared with results of an OLS regression. The results show that the signs of coefficients of only few variables changed while the values of almost all parameter estimates showed slight changes. However, their significance levels remained stable. Likewise, the estimates of treatment effects from the ESR model were found to be stable in terms of all the sign, magnitude and statistical significance of the effects.

5.2. Determination of the level and explaining adoption of raised bed

Based only on the random sample of 426 households, the average farmer population-weighted adoption rate of the raised bed technology in the three sample provinces is 17.61%. Al-Sharkia province has the highest district level number of wheat growers-weighted adoption rate with 38.27% of farmers cultivating wheat using the raised bed technology followed by Al-Dakahlia at 10.32% while none of the farmers in the Kafr Al-Sheikh province are using the technology. The corresponding district wheat area-weighted adoption degrees in each province stand at 39.57%, 13.03% and 0.00%, respectively - leading to a wheat area-weighted adoption degree in all three provinces of 19.28%. The fact that the % of wheat area under RB cultivation is higher than the % of farmers using the technology shows that on the average, relatively larger farmers are using the technology.

Estimates of the full information maximum likelihood (FIML) estimation of the selection and outcome equations of the ESR models for yield and downside risk on yield are provided in Table 2. As the main objective of this paper is to measure impacts of RB, only a brief discussion of the results pertaining to the factors affecting the adoption of RB is provided here.

From column A in Table 2, we can see that several variables have statistically significant effects on farmers' decision on whether to adopt the raised bed technology. As expected, the number of raised bed machines per 10,000 ha of wheat land in each district (RBM_10k_ha), which is used as an instrument in the ESR model has a positive and significant

Table2
Full information maximum likelihood (FIML) estimates of the endogenous switching regression model for yield and downside risk on yield.

Independent variables	Adoption of raised bed (No = 0, Yes = 1)		Yield for				Downside risk on yield for			
			Adopters		Non-adopters		Adopters		Non-adopters	
	A		B		C		D		E	
	Coef.	Std.Er	Coef.	Std.Er	Coef.	Std.Er	Coef.	Std.Er	Coef.	Std.Er
Total amount of labor (persons per season)	-0.14	0.09	-0.51	38.06	-43.31	20.77**	0.00	0.00	0.00	0.00
Quantity of irrigation water (M3/ha)	0.01	0.00***	1.36	0.16***	-0.01	0.05	0.01	0.00***	0.01	0.00***
Quantity of TSP fertilizer used (kg/ha)	0.00	0.00	-1.81	0.78**	-0.19	0.46	0.00	0.00	0.00	0.00
Quantity of nitrogen fertilizer used (kg/ha)	0.00	0.01	-3.14	4.03	-0.79	1.39	0.00	0.00	0.00	0.00
Seed rate (kg/ha)	-0.03	0.01***	-2.75	3.47	-6.50	1.39***	0.01	0.00**	0.01	0.00***
Soil has above medium depth (No = 0; Yes = 1)	0.45	0.26*	-274.29	121.95**	-55.67	61.85	0.01	0.00*	0.01	0.00***
Crop rotation is used (No = 0; Yes = 1)	0.59	0.24**	-131.77	120.69	8.22	73.76	0.00	0.00	0.00	0.00
Improved wheat variety used (No = 0; Yes = 1)	-0.26	0.44	134.67	151.66	-114.85	96.30	0.00	0.00	0.01	0.00***
Used recommended sowing date (No = 0; Yes = 1)	1.05	0.29***	-180.61	257.61	250.02	67.70***	0.00	0.00	0.00	0.00
Used recommended harvest date (No = 0; Yes = 1)	1.00	0.40**	391.60	251.71	102.70	71.59	0.00	0.00	0.00	0.00
Past participation on wheat project (No = 0; Yes = 1)	1.00	0.30***	759.31	176.62***	500.78	77.00***	0.00	0.00	0.01	0.00***
Sex of household head (Female = 0, Male = 1)	-0.14	0.61								
Family size (number of persons)	0.05	0.06								
Total area cultivated (ha)	0.01	0.05								
Total area cultivated with wheat in 2016 (ha)	-0.02	0.05								
Farmer owns tractor (No = 0; Yes = 1)	-0.36	0.29								
RBM_10k_ha (RB machines/10,000 ha)	0.14	0.03***								
_cons	16.90	2.13***	1574.94	1225.01	8169.53	480.34***	-0.03	0.01***	0.00	0.00
Rho			-0.48	0.13***	0.36	0.14***	-0.22	0.14	0.27	0.12***
sigma			764.195	33.10***	509.24	18.28***	0.01	0.00**	.01	0.00***
Wald χ^2 test			195.03***				4.78**			
LR test of independence of equations			12.43***				17.81*			

*, **, *** respectively represent significance at 0.1, 0.05 and 0.01 levels.

effect on farmers adoption decision. Likewise, participation in past projects which promoted wheat technology packages including the raised bed machine also has a positive and significant effect on farmers' adoption decision. Farmers with medium to deep soils are also found to have a higher propensity to adopt raised beds. Farmers decisions to adopt the other technology packages including rotation and the recommended planting and harvesting dates have positive and significant effects on the adoption of the raised bed technology showing complementarity between the technology components. There is also an association (some positive and some negative) between the quantities of inputs such as the quantity of irrigation water applied, and seed rate used and the adoption of raised beds. Some of these could be the results of reverse causality where the adoption of raised bed may be the cause and the quantities of inputs may be the effects, but we believe that there are two-way causalities for which estimation of the pairs of the selection and outcome equations using ESR is appropriate.

5.3. Impact of the adoption of the raised bed technology

In this study, several indicators including yield, downside risk on yield - a proxy for changes in the likelihoods of obtaining low yield levels, gross margins, per-capita wheat consumption from own production, water productivity, quantity of irrigated water, and salinity were used to measure the impacts of adoption of RB. Based on the FIML estimation of the ESR model (Table 2), the average expected treatment and heterogeneity effects of the adoption of RB on yield and downside yield risk are presented in Table 3. The results of the OLS estimation of impacts of adoption of RB on gross margins, per-capita wheat consumption from own production, water productivity, quantity of irrigated water applied, and soil salinity are presented in Table 4.

5.4. Impacts on yield and downside yield risk

Model results show that adopters of the RB technology are on the average obtaining about 112.65 kg/ha (1.46%) yield gain which is much less than the 25% yield gain documented in past project reports for the mechanized raised bed (MRB) technology. The fact that this study does not make any distinction between types of raised beds (manual vs. mechanized; width and height of beds; width and depth of furrows and row vs. broadcast planting) may have contributed to the discrepancy. The developers of the RB machine argue that depending on how they are constructed, some traditional raised beds might even lead to reduced yields. But still, results of the downside risk analysis show that adopters of RB are enjoying 11.8% less risks of lower yields which, in the face of climate change and growing problem of soil and water salinity, is a great benefit. Had non-adopters used the technology, our results show that they would have obtained 1505 kg/ha (21.6%) higher yields than their current average which is closer to what was reported earlier for mechanized raised beds. These yield gains would also be accompanied by a very high level (over 540%) of risk reduction - showing that the benefits that will be enjoyed by those who are yet to adopt RB are far greater than what has been realized by those who have already adopted. Combining these results, we can conclude that a typical wheat farmer in the sample provinces can obtain on the average, 12.79% increase in yield.

Table3
Average expected treatment and heterogeneity effects of the adoption of the raised bed (RB) technology on yield and downside risk on yield.

Subsamples Effects	Decision stage		
	Yield		
	To adopt	Not to adopt	Treatment
Farm households that adopted RB	7847.19 (a)	7734.54 (c)	112.65***
Farm households that did not adopt RB	8474.53 (d)	6968.97 (b)	1505.56***
Heterogeneity effects			
	Downside risk on yield		
Subsamples Effects	To adopt	Not to adopt	Treatment
Farm households that adopted RB	0.00099 (a)	0.00087 (c)	0.00012***
Farm households that did not adopt RB	0.00404(d)	0.00005(b)	0.00398***
Heterogeneity effects	0.00099 (a)	0.00087 (c)	0.00012***

*** represents significance at 0.01 level.

Table4
Ordinary Least Squares (OLS) estimates of the impacts of the adoption of the raised bed technology on per-capital wheat consumption from own production, gross margins, water productivity, quantity of irrigation water applied, soil salinity and seed rate.

Independent Variables	Impacts on wheat consumption (kg/capita/year)		Impacts on gross margins (EGP/ha)		Impacts on water productivity (kg/m^3)		Impacts on quantity of irrigation water (m^3/ha)		Impacts on probability of having above average soil salinity		Impacts on seeding rate (kg/ha)	
	A		B		C		D		E		F	
	Coef.	Std.Er	Coef.	Std.Er		Std.Er	Coef.	Std.Er	Coef.	Std.Er	Coef.	Std.Er
Raised bed used on this field (No = 0; Yes = 1)	18.12	10.50*	1042.25	340.28***	0.08	0.02***	-804.89	53.99***	-0.25	0.26	-23.35	2.30***
Sex of household head (Female = 0, Male = 1)	12.97	15.40	-100.43	499.36	0.03	0.03	-114.42	91.26	0.10	0.05*	-12.61	3.59***
Family size (number of persons)	-11.91	1.76***	-260.63	56.91***	-0.01	0.00***	-21.91	10.38**	0.27	0.21	0.65	0.41
Total area cultivated (ha)	-1.60	1.13	-81.24	36.70**	0.00	0.00	-16.90	6.68**	0.01	0.00**	0.90	0.26***
Total area cultivated with wheat in 2016 (ha)	2.68	1.38*	-167.28	44.62***	0.00	0.00	17.29	8.14**	0.01	0.00*	-1.18	0.32***
Farmer owns tractor (No = 0; Yes = 1)	-5.70	9.46	143.35	306.66	0.01	0.02	35.50	56.09	-0.01	0.00*	-4.11	2.22*
Total amount of labor (persons per season)	8.70	2.76***	45.58	89.55	0.00	0.00	28.76	16.35*	-0.03	0.00***	-0.64	0.65
Quantity of irrigation water (M^3/ha)	0.00	0.01	0.85	0.21***	0.01	0.00***	-0.07	0.30	1.85	0.29***	-0.01	0.00***
Quantity of TSP fertilizer used (kg/ha)	0.03	0.05	-6.06	1.62***	0.00	0.00	1.14	1.06	-0.62	0.22***	0.27	0.04***
Quantity of nitrogen fertilizer used (kg/ha)	0.22	0.18	-2.35	5.78	0.00	0.00	-3.40	0.96***	0.40	0.28	-0.01	0.01
Seed rate (kg/ha)	-0.16	0.16	-12.50	5.31**	0.01	0.00***	43.63	42.75	-0.96	0.2***	-6.11	1.68***
Soil has above medium depth (No = 0; Yes = 1)	45.44	7.21***	-455.44	233.85*	-0.03	0.01**	-3.94	45.41	-0.71	0.2***	5.15	1.79***
Rotation was used (No = 0; Yes = 1)	8.65	7.65	248.48	248.18	-0.01	0.01	-71.94	60.27	-0.60	0.22***	3.60	2.39
Improved wheat variety used (No = 0; Yes = 1)	-1.73	10.17	80.05	329.75	0.01	0.02	65.34	51.17	1.17	1.35	-6.04	2.02***
Used recommended sowing date (No = 0; Yes = 1)	-18.01	8.64**	595.61	280.04**	0.03	0.01**	-79.47	56.60	-0.25	0.26	7.76	2.23***
Used recommended harvest date (No = 0; Yes = 1)	-6.25	9.56	842.34	309.79***	0.03	0.02	6.63	52.95	0.10	0.05*	-8.31	2.07***
Past participation on wheat project (No = 0; Yes = 1)	-26.61	8.93***	2167.09	289.39***	0.11	0.01***	6347.21	253.91***	0.27	0.21	142.79	12.84***
_cons	78.71	59.42	12,807.87	1926.55***	2.57	0.10***	-804.89	53.99***	0.01	0.00**	-23.35	2.30***
R-square or Pseudo R-square	0.1621		0.4077		0.7256		0.4136		0.4040		0.5373	
Joint significance (F-Statistic) or LR- χ2	7.66***		27.25***		104.67***		29.71***		314.22***		48.91***	

*, **, *** respectively represent significance at 0.1, 0.05 and 0.01 levels.

5.5. Impacts of adoption of raised beds on consumption, gross margin, input use and soil salinity

We have also analyzed the impacts of the adoption of the raised bed technology on several socio-economic and environmental indicators. While we found that adoption of RB led to significant benefits in some indicators, we also found that it does not have significant effects on some others. For example, as can be seen from column A in Table 4, the adoption of RB led to an increase in wheat consumption from own production by 18 kg/capita/year (21.87%). Results in column B also show that adoption of RB led to a 1042.25 EGP or US$58.25 per ha (7.5%) increase in gross margins. The fact that the percentage increase in gross margins for a typical wheat farmer in the sample provinces is lower than the percentage gain in yield shows that adoption of RB also led to a net increase in the costs of production. The additional labor cost for manually constructed raised beds can be a contributor. The data we have collected in the survey is only on broad cost items including "land preparation" which can include cost of land levelling, tillage, construction of raised beds, etc. for which we don't have data specifically on the cost of building raised beds. Therefore, the service fee farmers pay for having mechanized raised beds on their fields might also be higher to make the total cost of production to be higher to reduce the percentage gains in gross margins.

The results in columns C and D in Table 4 show that adoption of RB has the added benefit of reducing the amount of irrigation water applied by 804.89 m3/ha (15.05%) and the associated benefit of increasing water productivity by 0.08 kg/m3 (5.56%). These benefits have very high importance in Egypt not only because the magnitudes are high, and the country continues to face irrigation water shortages, but also because they can justify the RB technology from all the social, economic and environmental dimensions. Adoption of RB also has a clear impact on the reduction of the seeding rate (Column F) by 23.35 kg/ha (16.71%). We had also looked at the impacts of the adoption of the raised bed technology on the amounts of TSP and nitrogen fertilizers applied and the total amount of labor used. However, the results showed that it did not have significant impacts.

Adoption of RB is found to have no significant effect on soil salinity (column E) – a disappointing result as soil salinity is a growing concern in Egypt and almost all irrigated production systems of the world. The scientists who developed the raised bed machine (RBM) argue that if we looked at only the fields cultivated by the RBM or manually with careful adherence to the bed width and height and furrow width and depth specification can reduce the salinity problem as they are designed to enhance the efficiency of drainage and reduce the quantity of water to be applied. Our results might have been confounded by several factors. First, we have wide variation of raised beds which are bundled into one group as RB where some of the manually constructed RB might actually be counterproductive. Second, analysis of soil salinity is best done using carefully designed study based on actual measurement of soil salinity on the spot or based on analysis of carefully collected soil samples. Unfortunately, the only data we had for this analysis was farmers subjective assessment of the salinity level of their fields as "low", "moderate" or "high".

In general, though lower in magnitude, our results are consistent with findings of past research in other parts of the world. For example, in a study conducted in Pakistan, Soomro et al. (2017) found that the use of raised bed led to 24.65% higher yield, 50.73% water saving and 54.37% water productivity in wheat production relative to conventional flood irrigation system. In a study carried in Bangladesh, Mollah et al. (2015) found that grain yield on 70 cm wide beds was 0.5 t/ha (21%) higher than that of conventional tillage. Zhongming et al. (2005) reported that in wheat production in the Hexi Corridor of China, the use of raised beds led to the reduction of 750 m^3/ha of irrigation water.

6. Conclusions

This paper analyzed the social, economic, and environmental impacts of the raised bed technology (RB) in Egypt. RB has several benefits including significant gains in yield and gross margins, significant reductions in quantities of inputs including the amounts of irrigation water and seed, and the added advantage of higher water productivity. Adoption of RB however didn't have significant effects on soil salinity. To enhance the benefits of the RB technology, scientists from the International Center for Agricultural Research in the Dry Areas (ICARDA) and the Agricultural Research Center (ARC) of Egypt have developed a raised bed machine which helps the construction of the beds with the optimal specifications of the beds and furrows while at the same time reducing labor demand - thereby minimizing farmers' drudgery to construct the structures. While the benefits estimated in this study are high enough, the scientists who developped the technology believe that even higher benefits can be expected if the traditional raised beds were excluded from the analysis and the benefits of row planting included.

The main implication of our results is that it is important to invest in the dissemination of RB by enhancing farmers' awareness of the social, economic, and environmental benefits of the technology. Future studies in this topic should close the knowledge gap by making comparisons not only between traditional tillage and raised beds in general but also between the mechanized raised beds constructed with the optimal specifications and traditional raised beds that are constructed with suboptimal specifications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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