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Can Retention of Crop Residues on the Field Be Justified on Socioeconomic Grounds? A Case Study from the Mixed Crop-Livestock Production Systems of the Moroccan Drylands

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Abstract: Conservation agriculture (CA) involving zero tillage, crop diversification, and residue retention is considered a panacea for several interrelated problems in agricultural production. However, in the mixed crop-livestock production systems of the drylands, crop residues have great significance as sources of animal feed, posing a major challenge in the promotion of CA. While the economic benefits and the drivers of adoption of zero tillage and rotation have been well documented, the literature on the economics of residue retention (RR), especially in the drylands, is scanty. By applying the endogenous switching regression model to a case study of 2296 wheat fields in Morocco, this paper provides evidence on the socio-economic impacts of residue retention. Between 30% and 60% and above 60% of crop residues were retained respectively on 35% and 14% of wheat fields. These levels of residue retention led to 22% and 29% more yields, 25% and 32% higher gross margins and 22% and 25% more consumption of wheat, respectively. Retention of above 60% residue reduces both downside risk and variability of yield while lower levels of residue retention have mixed effects. Residue retention is economically and biophysically beneficial even for owners of livestock as the monetary value of the additional grain yield more than offsets the cost of purchasing an equivalent amount of feed from the market—all providing good economic justification for residue retention. Our findings show that economic reasons are not barriers for adoption of residue retention, but risk factors and absence of alternative feed sources might. The policy implication of our results is that there are high incentives for Morocco and other similar countries in North Africa and West Asia to invest in the development and/or import of alternative feed sources, introducing crop insurance, and raising the awareness of the economic, biophysical and environmental benefits of residue retention among farmers.

Keywords: residue retention; mixed crop-livestock systems; downside risk exposure; adoption and impact; drylands; Morocco

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1. Introduction

Conservation agriculture (CA) has received special attention and is being widely promoted throughout Africa under the assumption that it can help revert soil degradation [1–4]. CA involves three complementary practices, namely, zero or reduced tillage, crop diversification in the form of legume-based rotation or intercropping, and residue retention. Residue retention (RR) is defined as the act of not removing and preventing on-site grazing of the remains of field crops after the valuable parts (mostly grains) have been harvested. As one of the three pillars of CA, RR enhances the biological processes above and below the soil surface [5].

Residue retention is strongly recommended for reducing surface run-offs, improving rainwater infiltration, and suppressing and controlling the growth of weeds [5–7]. Soil covered with residue has better weed control with alachlor than uncovered soil [8]. RR also increases the fertilizer use efficiency of crops and enhances soil nutrient restoration processes [9]. When coupled with Zero tillage, residue retention increases infiltration of rainwater—an important benefit in the dry areas where moisture stress is the major limiting factor [10,11]. In this paper, we argue, and provide empirical evidence, that all these benefits of RR to the soil, and to the crop would also increase yield, gross margins, and household wheat consumption from own production while also enhancing yield stability and reducing the risk of obtaining low yields. Given the importance of crop residue as feed in the drylands, we also carried out a cost–benefit analysis of RR for livestock owners.

The trade-offs and synergies involved in the use of crop residues for feed or soil mulch represent one of the major interactions between crops and livestock in mixed crop-livestock production systems [12,13]. Given the importance of livestock production in the drylands of North Africa and West Asia where, in some cases, cereal (particularly of barley) production is carried mainly for animal feed, the trade-off is highly pronounced. This poses a major challenge in the promotion of CA in general, but particularly the residue retention component.

There is some documentation of the adoption, impacts, and challenges of promoting zero or reduced tillage and crop diversification in a CA setting in the literature [14–19]. However, the literature on the third pillar of CA (residue retention), especially in the context of the drylands, is either non-existent or at best very thin. Moreover, whether CA fits mixed crop-livestock systems is still debated [1,20]. The debate mainly arises from the potential trade-offs in the allocation of resources [1,21] and the socioeconomic setups influencing resource use in the mixed crop-livestock systems [22].

This paper aims at providing credible evidence for the adoption and economic viability of retention of different levels of crop residues. Specifically, we estimate impacts of varying levels of residue retention on yield, gross margins, and wheat consumption. These goals are achieved by applying the endogenous switching regression (ESR) model to data from a large representative sample of 2296 wheat fields cultivated by 1230 farm households which were drawn from the wheat-based production systems in Morocco. The paper also drew a comparison between the gain in gross margins and the cost of purchased feed needed to compensate for the residue that is retained in the field. Using a combination of downside risk analysis in the ESR and the stochastic dominance criterion, our paper analyzes the role of residue retention in managing production risk and yield variability. The findings of our paper will be useful to researchers, development practitioners, policy makers and donors in their effort to enhance the sustainability of dryland agriculture in Morocco and many other similar countries in North Africa and West Asia with mixed crop-livestock production systems.

2. Trade-Offs and Synergies between Crop and Livestock Production in Morocco

Agriculture plays an important role in the Moroccan economy. In terms of area coverage, cereals constitute about 43% of total arable land where, with a total area of 2.8 million ha (66% of total cereal area) and a total production of 7.3 million tones, wheat is the single most dominant crop in the country [23]. In 2010, the contribution of all cereals to agricultural value added was about US $1.8 billion, out of which the share of wheat was about US $ 850 million (47%)—making it the second most important crop next to olives [24]. Considering the rapid population growth and shifts in consumption habits, wheat, and particularly bread consumption, has over the years become central in Morocco's food security agenda.

As a dryland country, wheat production in Morocco also supports the livestock sector, being an important source of feed. Moroccan farmers use wheat as a dual-purpose crop where they harvest the grain for human consumption, and the straw for animal feed. When an adequate amount of rainfall is received, farmers can graze their sheep flocks on their wheat fields during its green stage, and still be able to harvest a good amount of grain and crop residue. This is practiced, for example, in some parts of Syria and Turkey, but it is not common in Morocco.

In Morocco, land use and management-related problems including overgrazing have led to pronounced land degradation [25]. The country suffers from high erosion rates ranging between 2.1 and 20 t/ha/year, thereby costing it over US $2.34 billion per year. Water and wind erosion affect 53% and 17% of the total area in the country, respectively, which are aggravated by several factors. With a contribution of 49% to total soil erosion, overgrazing is the single most important factor followed by malpractices in agricultural production (24%), deforestation (14%), and over-exploitation of vegetation cover (13%), respectively. Zero tillage with mulching was also found to be more effective in increasing infiltration and the efficiency of utilization of rainfall compared to both the conventional tillage system and zero tillage with complete stubble removal in the semi-arid areas of the Chaouia region, Morocco [11,25,26]. They cite [27] to explain these results where residue retention under zero tillage may have helped managing rainfall and retaining soil moisture throughout the growth and development period of wheat. All these studies clearly show the benefits of residue retention on moisture retention and hence crop yields.

There may be trade-offs between the value of crop residues for livestock feed and the value for soil protection and fertility maintenance, especially in dryland agriculture [28]. They suggest that the relative values for different purposes and in a variety of situations require further elucidation of the impact of residue retention on soil water storage, organic matter content, grain yield increases, and reduction of soil erosion in relation to the potential gains from animal production and survival. In a study carried out in Morocco, the author of [21] also concluded that farmers do not intentionally retain crop residues on the field for the purpose of soil improvement. Instead, short-term benefits of residues as livestock feed and as source of secondary income from sale override the biophysical rationale. Trade-offs encompass exchanges that occur as compromises, and they are more acute when resources are constrained [29]. The relationship between crops and livestock and the trade-offs around residues are determined by their agroecological potential and their socio-ecological contexts.

Farmers often face conflicting choices between short-term needs (e.g., feeding livestock, possibly at the expense of the productivity of crops and soil health) and desirable long-term changes such as enhancing productivity, land availability, and farming systems [30]. They argue that the challenge related to biomass use lies in the fact that crops and livestock combine different social, economic, and environmental benefits and costs that accrue across time. However, a strong argument in favor of RR is that short-term competition between soil amendment and livestock feed may turn into synergies in the longer term, especially when soil amendment improves feed production. Therefore, enhancing the sustainable development of the mixed crop-livestock production systems in dry areas requires optimization of the system in such a way that short-term trade-offs between crop and livestock production are minimized and their long-term synergies maximized. We argue that short-term economic advantages/disadvantages might be critical in farmers' decisions on whether to adopt crop residue retention and hence, providing empirical evidence is useful in informing the overall effort to promote conservation agriculture in the drylands.

Promotion of conservation agriculture (CA) comprising the three main pillars of zero or reduced tillage, crop diversification mainly using legume-based rotations, and crop residue retention began in Morocco in the 1990s. Field tests by the National Institute of Agronomic Research (INRA) and development organizations have successfully demonstrated that the introduction of CA brings more stable yields and involves lower production costs, reduced soil erosion, greater soil water conservation, improved soil quality, stable and higher crop yields, and lower production costs [25,31]. For Central Morocco, the authors of [31] estimated a gain in gross margins of about 60% for large farmers and 200% for small farmers. Despite such high returns, the adoption of CA in general and residue retention in particular is low. Moroccan farmers are reluctant to change grazing practices because they tend to consider animal husbandry as a first priority [32]. Furthermore, the tension around crop residues is exacerbated by the lack of alternative sources of feed, due to small capacity for growing rain-fed fodder species, reduction in the area and quality of pastures due to competition from food and cash crops, and reduction of vegetative cover (grasses, shrubs) caused by land degradation in the grazing perimeters surrounding the villages.

In view of the challenges of convincing farmers to leave the stubble on the field, analysis using data from the program "Adapting conservation agriculture for rapid adoption by smallholder farmers in North Africa" (CANA) funded by Australian Centre for International Agricultural Research (ACIAR), and implemented by International Canter for Agricultural Research in the Dry Areas (ICARDA) along with INRA between 2012 and 2015 concluded that zero tillage even without retention of crop residues offers tangible agroecological advantages (soil health, crop productivity) compared to conventional tillage. Currently, the issue of proposing a CA package without crop residue retention is being debated in Morocco and other countries in North Africa and West Asia. Given the importance of residues for feed in certain farming systems, it is important to analyze if the yield improvement recorded from zero tillage with residue retention over zero tillage without residue retention, justifies the dissemination of this technology. This paper therefore tries to provide empirical evidence for the economic value of residue retention and shed more light on whether residue retention passes the first test of economic viability for its dissemination among Moroccan crop-livestock producers.

3. Materials and Methods

3.1. Household Survey Data

Data for this study came from a large representative household survey conducted in 2013 covering twenty-one major wheat-producing provinces in Morocco. These provinces account for about 79% of the total number of wheat-growing farmers and 81% of the total wheat area in the country. The survey covered all four agroecological zones in the country where wheat is currently produced, namely, the favorable zone, intermediate zone, unfavorable south and the mountains zone. Provinces in the remaining two agroecological zones in Morocco (the Saharan Zone and the Unfavorable Oriental Zone) are excluded from the survey as wheat production in these zones is either non-existent or minimal.

A of 1230 farm households was drawn for this study using a stratified sampling approach where provinces, districts and villages were used as strata. The total sample was distributed proportionally across 292 villages drawn randomly from 56 districts that were also drawn randomly from the 21 study provinces (Table 1). Structured survey questionnaires were used to collect demographic, economic, social and consumption data from each sample household. Detailed production and utilization-related data were also collected for each of the 2296 wheat fields cultivated by all the 1230 sample households.

The exact amount of residue that needs to be retained for sustainable soil management is not well understood or agreed upon. Earlier studies in the United States of America suggested that 30% could be sustainably removed [33], while it has generally been believed in the EU that two-thirds of straw could be removed [34].

In conservation agriculture, 30% residue retention is set as a minimum requirement because several studies showed that such level of residue retention can reduce soil erosion by up to 80% [7,35,36]. Looking at the distribution of the reported proportion of wheat residue retained by the sample households, we grouped the proportionate residue use in three categories (greater than zero but below 30%, between 30% and 60%—both inclusive, and above 60%). Survey results showed that more than 60% of wheat residues are retained as soil mulch only on 14% of Moroccan wheat fields. The rate of retention of between 30% and 60% of wheat residue however is 33.6% of total wheat fields—indicating that at least 30% of the residue is retained on only 47.6% of all Moroccan wheat fields, which can be considered low.

Table 1. Statistics on Wheat Area and Number of Farmers and Distribution of Sample Households across the 21 Provinces.

Region	Province	Wheat Area (in 1000 ha), Average for 2002–2011			Total Number of Wheat Growers in 2011 (in 1000)	Sample Statistics				
						No. of Districts	No of Villages	Number of Households		
		Bread Wheat	Durum Wheat	Total				Male Headed	Female Headed	Total
Chaouia-Ouardigha	Benslimane	54.96	25.41	80.37	13.92	3	10	26	1	27
	Berrechid	131.96	133.9	90.39	20.70	2	13	40	3	43
	Settat			175.47	40.19	3	33	80	2	82
Doukkala-Abda	El Jadida	95.98	79.46	92.98	64.08	3	16	70	6	76
	Sidi Bennour			82.46	56.82	2	17	63	5	68
	Safi	74.74	73.59	148.33	63.25	3	19	128	2	130
Fes-Boulemane	Fes	69.79	29.72	12.94	3.64	1	1	8	0	8
	Moulay Yacoub			86.57	24.34	2	7	52	0	52
Gharb-Chrarda-Bni Hces	Kenitra	94.03	13.36	85.97	30.66	3	17	49	10	59
	Sidi Slimane			21.42	7.67	1	8	17	1	18
	Sidi Kacem	144.94	32.59	177.53	44.40	5	22	63	4	67
Marrakech-Tensift-Alhaouz	El Kelaa	155.36	67.91	73.68	20.33	2	12	36	2	38
	Rehamna			149.59	41.27	2	12	75	2	77
Meknès-Tafilalet	El Hajeb	48.95	9.88	58.83	9.02	3	7	22	0	22
	Khenifra	67.09	37.25	104.34	28.05	2	11	58	0	58
	Meknes	71.78	4.49	76.27	13.73	1	11	29	0	29
Rabat-Salé	Khemisset	127.62	29.58	157.2	32.67	4	25	61	6	67
Tadla-Azilal	Beni Mellal	153.68	37	190.68	46.06	3	7	89	1	90
Taza-Alhoceima-Taounate	Taounate	103.26	80	183.26	61.16	4	24	117	7	124
	Taza	32.83	70.34	82.54	39.24	5	14	75	0	75
	Guercif			20.63	9.81	2	6	20	0	20
Total Sample		1426.97	724.48	2151.45	671.01	56	292	1178	52	1230
Total National		1930.07	979.90	2909.97	Not available					
Sample as % National Total				73.9%						

While up to 30% of residue is retained on another 14.3% of wheat fields, no residue is retained on the vast majority (38.12%) of the wheat fields. This is consistent with the theoretical expectation as a sizeable number (30%) of Moroccan wheat growers also rear livestock with competing needs for crop residues as animal feed. Moreover, there is market for crop residue which would offer short-term benefits to farmers without livestock thereby reducing their propensity to retain crop residues for soil mulch.

3.2. Modelling Adoption and Impacts

In this study, we employed the endogenous switching regression (ESR) primarily because it readily provides estimates of the counterfactual outcomes, especially for the non-adopters. ESR provides estimates of the average treatment effect for the untreated (ATU) which, we believe, are useful in the decision for further promotion of residue retention.

We must disclose from the outset that finding a suitable instrumental variable for residue retention has proved to be particularly challenging for us. In this study, we used the total number of livestock owned in tropical livestock units per ha of land owned (TLU/ha) as an instrument for residue retention. Generally, in the absence of market for crop residues, TLU/ha would qualify as a good instrument because, the residue would be fully utilized as feed for the farmers' own livestock. In this Moroccan case study also, we argue that TLU/ha could be a valid instrument because in the rainfed areas of Morocco, which constitute over 83% of the total agricultural area in the country and other similar countries in North Africa and West Asia, exclusion of others' livestock from grazing on one's own field is a cultural taboo. Once crop is harvested and grain and straw are removed, all livestock in the area can graze what is left on the field. Moreover, given the scarcity of feed resources in the rainfed areas, prohibiting grazing on one's own field after harvest is easier for those who do not have livestock than those who do because they will be reciprocated by others if they want to graze their livestock on others' fields too.

In Morocco, transporting manure from stalls to crop fields is often not common and those who do it give priority to high-value crops such as fruits. The question is then about its effect on wheat yields and hence the potential for endogeneity problem. Given that communal grazing of crop fields after harvest is the norm (rather than the exception) in the rainfed areas, the number of livestock grazing and hence dropping their dung on the field is generally the same on all fields except those on which the owners decided to keep residue by prohibiting grazing of their own (if they have any) and others' livestock. Therefore, the positive impact of manure on yield will be evident only on those fields which are grazed publicly and not on the fields on which their owners prohibited grazing of their own or others' livestock. However, among the fields which are publicly grazed (and hence residue is not retained), no significant yield difference arising from manure is expected because the amount of manure per unit area among these fields is homogenous. However, the contribution of manure to yield, ceteris paribus, would be lesser among fields on which grazing is prohibited (i.e., fields where residue is retained) than the fields on which grazing is allowed and hence residue is not retained. This means that the treatment effects that we get from using TLU/ha as an instrument will underestimate the true treatment effect and hence, we can only consider them as the minimum effect that one can expect from residue retention. Given that the purpose of this paper is to provide evidence of there being no economic loss or at best some economic benefits to residue retention, the results of this analysis (even with its underestimation) will still be useful. We also carried out further investigation of the validity of TLU/ha as an instrument and the findings are discussed in the results section. In the worst-case scenario, unlike the IV model, even if the instrument is weak, the ESR model can be identified by construction through the assumed non-linearities of the distribution of the error terms [37].

3.2.1. Endogenous Switching Regression

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 [38,39], the ESR can be formulated as follows with the adoption decision (selection equation) modelled as:

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

where Z represents a matrix of the explanatory variables, β is a vector of parameters to be estimated and ε is a vector representing the normally distributed error term with mean zero and variance $\sigma^2{}_\varepsilon$. The outcome equations can also be formulated as:

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

$$y_0 = X_0\omega_0 + \epsilon_0\ if\ D = 0 \tag{3}$$

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, 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 the following covariance matrix:

$$cov(\varepsilon, \epsilon_1, \epsilon_0) = \begin{bmatrix} \sigma^2_{\epsilon 0} & \sigma_{\epsilon 1 \epsilon 0} & \sigma_{\epsilon 0 \varepsilon} \\ \sigma_{\epsilon 1 \epsilon 0} & \sigma^2_{\epsilon 1} & \sigma_{\epsilon 1 \varepsilon} \\ \sigma_{\epsilon 0 \varepsilon} & \sigma_{\epsilon 1 \varepsilon} & \sigma^2_{\varepsilon} \end{bmatrix} \tag{4}$$

where σ^2_ε is the variance of the selection equation (Equation (1)), $\sigma^2_{\epsilon 0}$ and $\sigma^2_{\epsilon 1}$ are the variances of the outcome equations for non-adopters and adopters while $\sigma_{\epsilon 0 \varepsilon}$ and $\sigma_{\epsilon 1 \varepsilon}$ represent the covariances between ϵ_1 and ϵ_0. 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:

$$E(\epsilon_1 | D = 1) = \sigma_{\epsilon 1 \varepsilon} \frac{\phi(Z_i\omega_i)}{\Phi(Z_i\omega_i)} = \sigma_{\epsilon 1 \varepsilon}\lambda_1 \tag{5}$$

$$E(\epsilon_0 | D = 0) = \sigma_{\epsilon 0 \varepsilon} \frac{-\phi(Z_i\omega_i)}{1 - \Phi(Z_i\omega_i)} = \sigma_{\epsilon 0 \varepsilon}\lambda_0 \tag{6}$$

where ϕ and Φ are the probability density and the cumulative distribution function of the standard normal distribution, respectively. If $\sigma_{\epsilon 1 \varepsilon}$ and $\sigma_{\epsilon 0 \varepsilon}$ 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 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 (7) and non-adopters (8), and the counterfactual hypothetical cases that the non-adopters did adopt (9) and the adopters did not adopt (10) can be analyzed as follows:

$$E(y_1 | D = 1) = X_1\omega_1 + \sigma_{\epsilon 1 \varepsilon}\lambda_1 \tag{7}$$

$$E(y_0 | D = 0) = X_0\omega_0 + \sigma_{\epsilon 0 \varepsilon}\lambda_0 \tag{8}$$

$$E(y_0 | D = 1) = X_1\omega_0 + \sigma_{\epsilon 0 \varepsilon}\lambda_1 \tag{9}$$

$$E(y_1 | D = 0) = X_0\omega_1 + \sigma_{\epsilon 1 \varepsilon}\lambda_0. \tag{10}$$

Finally, we calculate the average treatment effect on the treated (ATT) as the difference between (7) and (10) and the average treatment effect on the non-adopters (ATU) as the difference between (9) and (8) [40–43]. We also compute the effect of base heterogeneity for the group of adopters (BH1) as the difference between (7) and (9), and for the group of non-adopters (BH2) as the difference between (10) and (8). While three of the outcome indicators, namely, yield, gross margins, and wheat consumption, are obtained directly from the data, we used a moment-based specification of the stochastic frontier production function [44–46] to generate the downside risk exposure and yield variance. This is a flexible approach that has been largely used in agricultural economics to model the implication of risk and risk management [47–50].

Two alternative treatments, namely, retention of above 30 but below 60% residue and retention of above 60% residue on the field, are considered in this analysis. We estimate the impacts of the different levels of residue retention on three outcome indicators, namely, yield, gross margins, and consumption from the subsequent wheat crop. A number of factors, such as varieties used and the quantities of fertilizers, seed, labor, herbicides, and pesticides, are important in determining yield, which in turn will affect gross margins and consumption. Moreover, for farmers to adopt residue retention, the number of livestock owned by the farmer relative to the total land owned is one of the major variables that would influence whether farmers want to retain crop residue on their field. Therefore, the number of livestock per ha of land owned is used as an instrument. The list and descriptive statistics for all variables included in the regression models are provided in Table 2.

To create a more homogeneous dataset, all the continuous variables (such as yield, gross margins, consumption, farmer age, wheat area, and all quantities of inputs) are converted into their natural logarithm equivalents. Version 15 of the Stata software (StataCorp LP, College Station, TX, USA) [51] was used for all econometric estimation in this study.

3.2.2. Stochastic Frontier Production Function

Consider a risk-averse farm household that produces output y using inputs $\mathbf{x}$ under risk through a production technology represented by a well-behaved stochastic frontier production function $y = g\ (x,\ v)$, where v is a vector of random variables representing risk. These may include factors outside the control of the farmer that affect output such as temperature, rainfall, and insect and pest infestation. To account for such factors, we can employ a moment-based approach [45] to assess the probability distribution of the stochastic production function $g\ (x,\ v)$ where risk exposure is represented by the moments of the production function. We consider the following econometric specification for $g\ (x,\ v)$:

$$g(x,\ v) = f_1(x,\ \beta_1) + \mathrm{u}$$

where $f_1(x,\ \beta_1) = E\ g(x,\ v)$is the mean of $g(x,\ v)$, that is the first central moment, and $\mathrm{u} = g(x,\ v) - f_1(x,\ \beta_1)$ is a random variable with mean zero whose distribution is exogenous to farmers' actions. The higher moments of $g(x,\ v)$ are given by

$$E\ g(x,\ v) - f_1(x,\ \beta_1)^K \Big| \mathrm{x}\ = f_k(x,\ \beta_k)$$

where a value of $k = 2$ represents the second central moment (which is the variance) and $k = 3$ represents the third central moment, that is the skewness.

In this study, we go beyond standard mean-variance analysis, and we focus on the effects of variance and skewness and downside risk exposure. An increase in skewness implies a reduction in downside risk exposure, which in our application also indicates a reduction in the probability of crop failure. Reducing downside risk means decreasing the asymmetry (or skewness) of the risk distribution toward high outcome, keeping both means and variance constant [52].

Table 2. Summary statistics for selected variables.

Variable Name	Variable	Residue = 0%		Residue = 0.1–30%		Residue = 30.01–60%		Residue > 60%		Entire Sample		
		Mean Values or Count	Std. Dev.	Mean Values or Count	Std. Dev.	Mean Values or Count	Std. Dev.	Mean Values or Count	Std. Dev.	*n* ^	Mean value	Std. Dev.
	Variables derived from household-level data (*n* = 1230)											
Age	Age of household head (years)	59.44	14.02	59.77	13.42	59.40	13.09	59.77	14.93		59.52	13.75
Educ	Education of household head (years)	1.92	0.85	1.80 *	0.77	1.90	0.88	1.97	0.92		1.90	0.86
WArea	Wheat area (ha)	5.56	11.72	4.74	3.11	6.26	21.27	5.76	5.49		5.72	14.64
TArea	Total cropped area (ha)	10.50	17.88	9.03	13.29	12.56	1.79	10.51	17.46		11.02	25.85
WDist	Walking distance from home to seed sources (km)	17.40	13.33	17.36	12.24	18.32	14.71	15.54 **	13.08		17.45	13.67
Cons	Wheat consumption from own production (kg/capita/year)	55.64	30.17	59.99	31.97	68.28 ***	32.19	72.12 ***	35.20		63.07	32.52
Sex	Household head is female (0 = No, 1 = Yes)	***16***	***0.18***	***5***	***0.17***	18	0.20	10	0.23	49	0.04	0.20
OffFarmemp	Off-farm employment (0 = No, 1 = Yes)	***80***	***0.39***	***30***	***0.38***	69	0.37	37	0.40	216	0.18	0.38
TLU/ha	Number of livestock in tropical livestock units per ha owned	***0.61***	***0.05***	***0.45*** ***	***0.05***	0.46 **	1.03	0.35 ***	0.10		0.49	1.09
	Variables derived from field-level data (*n* = 2296)											
Fieldsize	Area of the field (or plot) in ha	5.77	9.51	4.95 *	5.24	6.21	17.52	6.28	7.92		5.87	12.26
Labor	Total amount of labor used (person days/ha)	55.03	34.48	51.36 **	33.81	56.94	37.03	60.14 **	40.56		55.85	36.21
RF	Rainfall (mm/year)	361.94	92.68	351.29 *	121.21	344.97 ***	98.98	376.56 *	96.09		356.75	100.31
QN	Quantity of nitrogen fertilizer used (kg/ha)	39.57	45.52	36.24	44.13	45.74 ***	52.14	44.27	50.27		41.82	48.42
QDAP	Quantity of DAP fertilizer used (kg/ha)	30.18	24.08	26.25 ***	25.62	31.44	29.91	32.60	24.89		30.38	26.55
QSeed	Quantity of seed used (kg/ha)	173.08	55.73	164.84 **	58.09	176.39	57.96	174	52.57		173.20	56.49
QPesti	Quantity of pesticides (kg/ha)	0.20	0.46	0.33 ***	0.58	0.20	0.48	0.25 **	0.49		0.23	0.49
QHerbi	Quantity of herbicides (kg/ha)	0.93	0.59	0.89	0.63	0.88 *	0.60	0.91	0.61		0.91	0.60
Yield	Yield (kg/ha)	1356.45	1017.81	1195.30 **	1204.50	1514.61 ***	1418.71	1666.43 ***	1445.31		1429.47	1260.10
FavZone	Farm in favorable zone? (1 = Yes, 0 = No)	330	0.48	84 ***	0.44	287	0.37	150 ***	0.50	851	0.37	0.48
ItermZone	Farm in intermediate zone (1 = Yes, 0 = No)	266	0.46	100	0.46	233	0.46	75 **	0.42	674	0.29	0.46
GM	Gross margins (MAD/ha) [#]	3332.76	2964.02	2941.03 **	3526	3742.27 **	4024.03	4171.69 ***	3885.74		3530.53	3576.87
ZT	Was ZT practiced on the field? (0 = No, 1 = Yes)	139	0.37	26 ***	0.27	94 **	0.33	41	0.34	300	0.13	0.34
Rot	Rotation practiced? (0 = No, 1 = Yes)	310	0.48	91 **	0.45	256	0.47	158 ***	0.50	815	0.35	0.48
ImpVar	Planted to improved wheat varieties? (0 = No, 1 = Yes)	***307***	***0.48***	***69*** ***	***0.41***	232 **	0.46	137 **	0.50	745	0.32	0.47
[#] of fields	Number of fields on this category	***876***		***330***		771		319		2296		
Irrig	Is the field irrigated? (0 = No, 1 = Yes)	***133***	***0.36***	***45***	0.34	165 ***	0.41	52	0.37	395	0.17	0.38

^ n indicates the number of cases with a "Yes" answer and ***bold-italic*** figures represent count values; [#] The exchange rate in 2012 was 1US \$ = 8.62 Moroccan Dirhams (MAD); ***, **, * represent significant difference between adopters of the specific level of residue retention and the counterfactual (0% residue retention) at 0.01, 0.05, and 0.1 levels, respectively.

4. Results

The coefficient estimates on the variable representing the predicted residuals from a probit model that regressed the adoption of residue retention on all the explanatory variables included in both the selection and outcome equations is significant at 0.01 level, showing that endogeneity is indeed a problem, thereby justifying our use of a model that corrects for it. Post-estimation ESR model diagnostics including the likelihood ratio test for the joint independence of the three equations presented in Table 3 also confirm that the three equations are interdependent of each other. The statistically significant correlation coefficients (rho_1 and rho_2) also suggest the existence of endogeneity. In other words, the decision to adopt and the impact of retention on yield, gross margins, and wheat consumption given the adoption decision, are influenced by both observed and unobserved factors. In the yield equations, for example, the negative and significant correlation coefficient estimates for both adopters and non-adopters indicate that there is positive selection bias such that farmers with above average yield have greater propensity to retain residue.

The instrument used in this paper is the number of livestock owned in tropical livestock units per ha of land owned (TLU/ha). Given the issues discussed in the methods section, we followed [40] to carry out a falsification test and the results showed that the instrument has a negative and significant effect on the adoption decision (i.e., farmers with higher TLU/ha tend to have lower propensity to retain residue) but has no significant effect on the yield, gross margins and wheat consumption of the non-adopters, thereby giving us confidence on the validity of the instrument [37].

4.1. Impacts on Yield

The coefficients of the key explanatory variables in the ESR model carry important information. However, as the main objective of this study is to measure the impacts of residue retention, results on factors affecting the adoption decision and factors affecting the impacts from the full information maximum likelihood (FIML) estimation of the ESR model are discussed below only briefly. The difference in the coefficients of the explanatory variables in the outcome equations of residue retention for fields on which residue retention is adopted and not adopted illustrates the presence of heterogeneity in the sample [40]. Consistent with agronomic science, quantities of inputs such as DAP fertilizer, seed, irrigation, rainfall, and labor had strong association with the productivity of the fields regardless of whether residue was retained or not (Table 3). The use of improved varieties and certified seeds also led to higher yields relative to the use of local (and old improved) varieties and uncertified seeds for both fields on which residue retention was adopted and not adopted—showing clear advantage of the use of both improved varieties and certified seeds.

The expected wheat yield under actual and counterfactual conditions from the ESR model are presented in Table 4. Farmers who retained above 0 but below 30% of residues obtained 88.5 kg/ha (7%) lesser yield than those who did not retain any residue. However, farmers who retained above 60% and between 30% and 60% of their residues, respectively, obtained on the average 388 kg/ha (31%) and 299 kg/ha (24.78%) more yield than those who did not retain any residue, respectively. Similarly, comparing the expected wheat productivity in the counterfactual case (d) and observed outcome (b), those who are not retaining any residue are forgoing 149 kg/ha (11%) of wheat yield relative to what they would if they retained more than 60% of their residues on the field.

The total wheat area in the country (average for 2002–2011) was 2.91 million hectares. At the current national average adoption levels of 14.86% and 35.53%, the adoption rates of above 60% and between 30% and 60% residue retention have led to increases in the national wheat production by 0.16 million and 0.31 million tons per year, respectively, which account for only small portions (3.82% and 7.03%) of the total domestic supply of wheat in the country. On the other hand, adoption of between 0.1% and 30% residues led to loss in total production amounting to 0.03 million tons (0.78%) per year.

4.2. Impacts on Gross Margins

Results of the FIML estimation of the ESR model for measuring the impacts of different levels of residue on gross margins are presented in Table 5. These results show that amount of rainfall, quantities of DAP fertilizer, quantity of herbicides, seed, rainfall, irrigation, and adoption of zero tillage and rotation have positive and significant effects on gross margins from the subsequent wheat crop.

Table 3. Results of the endogenous switching regression models for measuring impacts of retaining different levels of residue on wheat yield (kg/ha).

Independent Variables	Adoption and Yield Equations for Retention of between 0.1% and 30% Residue (Counterfactual: No Residue Retained at all)						Yield Equation for Retention of 30–60% Residue (Counterfactual: No Residue Retained at all) ^				Yield Equation for Retention of 60% or Above Residues (Counterfactual: No Residue Retained at all) ^			
	Yes = 1, No = 0		Yield for Adopters		Non-Adopters		Yield for Adopters		Non-Adopters		Yield for Adopters		Non-Adopters	
	Coef.	Std. Er	Coef.	Std. Er	Coef.	Std. Er	Coef.	Std. Er	Coef.	Std. Er	Coef.	Std. Er	Coef.	Std. Er
Age (years)	0.071	0.138	0.003	0.019	0.043	0.046	0.002	0.022	0.001	0.024	0.014	0.034	0.008	0.021
Education (years)	0.083	0.096	−0.012	0.014	−0.016	0.031	−0.017	0.016	0.019	0.016	0.034	0.027	−0.007	0.015
Sex (1 = male, 0 = female)	0.101	0.145	0.016	0.021	0.008	0.066	0.010	0.024	0.032	0.024	0.011	0.040	0.026	0.023
Improved Variety (No = 0, Yes = 1)	−0.132	0.098	0.335	0.014 ***	0.403	0.035 ***	0.349	0.016 ***	0.385	0.017 ***	0.285	0.026 ***	0.332	0.015 ***
Quantity of *n*-fertilizer used	0.046	0.046	0.005	0.007	0.006	0.013	−0.004	0.008	−0.005	0.008	0.039	0.014 ***	0.004	0.008
Quantity of DAP fertilizer	−0.170	0.035 ***	0.048	0.005 ***	0.037	0.010 ***	0.062	0.006 ***	0.037	0.007 ***	0.059	0.012 ***	0.046	0.006 ***
Amount of seed used (kg/ha)	−0.096	0.098	0.051	0.014 ***	0.088	0.028 ***	0.054	0.016 ***	0.017	0.017	0.065	0.027 **	0.054	0.015 ***
Labor	−0.089	0.101	0.044	0.014 ***	0.010	0.030	0.062	0.016 ***	0.037	0.017	0.008	0.025	0.047	0.015 ***
Wheat area (ha)	−0.012	0.058	0.011	0.008	0.048	0.024 **	0.014	0.010	0.013	0.010	0.005	0.015	0.008	0.009
Cultivated area (ha)	−0.009	0.014	0.002	0.002	0.002	0.004	0.003	0.002	0.000	0.002	0.001	0.003	0.002	0.002
Quantity of herbicides (kg/ha)	−0.161	0.086 *	−0.028	0.012 ***	0.004	0.026	−0.017	0.014	0.001	0.015	0.003	0.022	−0.026	0.013 **
Quantity of pesticides (kg/ha)	0.238	0.110 ***	0.088	0.015 ***	−0.032	0.030	0.074	0.018 ***	−0.007	0.019	0.042	0.027	0.081	0.017 ***
Rainfall	−0.581	0.114 ***	0.118	0.018 ***	0.059	0.030 **	0.146	0.019 ***	0.019	0.023	0.324	0.032 ***	0.107	0.019 ***
Zero tillage	−0.965	0.260 ***	0.180	0.023 ***	0.316	0.044 ***	0.238	0.027 ***	0.113	0.071	0.112	0.031 ***	0.146	0.023 ***
Rotation	−0.072	0.073	0.062	0.010 ***	0.136	0.026 ***	0.062	0.012 ***	0.039	0.012 ***	0.101	0.020 ***	0.050	0.012 ***
Irrigation	0.777	0.132 ***	1.250	0.018 ***	1.462	0.044 ***	1.208	0.021 ***	1.495	0.029 ***	1.320	0.035 ***	1.252	0.020 ***
Favorable zone	0.050	0.086	−0.010	0.014	0.020	0.031	−0.018	0.014	−0.016	0.015	−0.022	0.024	−0.016	0.013
Intermediate zone	−0.054	0.081	0.022	0.012 ***	0.000	0.026	0.024	0.013 *	0.030	0.014 **	0.031	0.024	0.027	0.012 **
TLU/ha	−0.035	0.008 ***												
Constant	4.278	1.031 ***	5.391	0.161	5.147	0.300 ***	5.019	0.169 ***	6.102	0.194 ***	4.098	0.278 ***	5.384	0.155 ***
Rho			0.551	0.443	0.041	0.359	0.017	0.251	−0.824	0.035 ***	0.056	0.291	−0.671	0.096 ***
Sigma			0.198	0.007 ***	0.198	0.007 ***	0.144	0.004 ***	0.169	0.007 ***	0.142	0.006 ***	0.147	0.007 ***
Wald test x2	1377.5 ***						1916.4 ***				1208.890 ***			
Log likelihood	−446.4						−523.5				54.399			

*, **, *** respectively represent significance at 0.1, 0.05 and 0.01 levels; ^ In the interest of space, the results of the selection equations for retention of between 30% and 60% and, above 60% are omitted.

Table 4. Average Expected Treatment and Heterogeneity Effects on Yield, Gross Margin, and Consumption from Endogenous Switching Regression.

Treatments		Yield ^				Gross Margins (MAD/ha) ^				Consumption kg/capita/year ^			
	Subsamples Effects	**To Adopt**	**Not to Adopt**	**Treatment**	**% Change**	**To Adopt**	**Not to Adopt**	**Treatment**	**% Change**	**To Adopt**	**Not to Adopt**	**Treatment**	**% Change**
Retention of between 0.1% and 30% residues (counterfactual: no residue retained at all) (Yes = 330)	Farm households that adopted	1173.56 (64.79)	1262.08 (56.19)	−88.52 (11.68) ***	−7.01%	2830.62 (191.09)	3100.12 (285.10)	−269.50 (10.68) ***	−8.69%	55.18 (1.70)	60.20 (2.56)	−5.02 (0.92) ***	−8.34%
	Farm households that did not adopt	1163.82 (32.06)	1347.30 (33.88)	−183.48 (4.95) ***	−13.62%	2748.84 (122.48)	3111.50 (89.88)	−362.66 (40.95) ***	−11.66%	60.73 (1.85)	57.24 (1.49)	3.49 (0.44) ***	6.10%
	Heterogeneity effects	9.73 (5.64)	−85.22 (65.09)	94.95 (10.79) ***		81.78 (13.45)	−11.38 (7.32)	93.16 (11.45) ***		−5.54 (3.19)	2.96 (0.33)	−8.51 (0.91) ***	
Retention of between 30% and 60% residues (counterfactual: no residue retained at all) (Yes = 771)	Farm households that adopted	1504.89 (50.59)	1206.08 (36.40)	298.82 (14.41) ***	24.78%	3642.02 (142.81)	3009.76 (112.73)	632.25 (34.23) ***	25.17%	62.73 (0.92)	51.42 (0.99)	11.31 (0.18) ***	22.00%
	Farm households that did not adopt	1366.69 (38.21)	1351.20 (34.35)	15.51 (4.81) **	1.15%	3266.06 (112.47)	3225.89 (98.73)	40.21 (20.60) **	1.25%	61.67 (1.13)	51.94 (1.05)	9.73 (0.16) ***	18.73%
	Heterogeneity effects	138.21 (62.54) ***	−145.12 (50.06)***	283.33 (14.46) ***		375.96 (179.78) ***	−216.10 (149.19)***	592.09 (38.91) ***		1.06 (1.39)	−0.52 (0.44)	1.57 (0.24) **	
Retention of 60% or above residues (counterfactual: no residue retained at all) (Yes = 319)	Farm households that adopted	1656.88 (80.99)	1268.79 (55.82)	388.09 (26.23) ***	30.59%	4074.06 (216.48)	3151.08 (152.49)	922.98 (69.11) ***	32.46%	80.91 (1.77)	64.58 (1.63)	16.33 (0.43) ***	25.29%
	Farm households that did not adopt	1496.85 (43.88)	1348.39 (34.05)	148.47 (10.56) ***	11.01%	3751.71 (139.91)	3225.90 (98.73)	525.81 (44.16) ***	16.30%	69.74 (1.01)	57.57 (0.92)	12.17 (0.24) ***	21.14%
	Heterogeneity effects	160.03 (87.62) **	−79.60 (65.71)	239.63 (23.60) ***		422.34 (266.12) ***	−74.83 (187.71)	197.17 (84.22) ***		11.17 (1.98) ***	7.01 (1.81) ***	4.16 (0.48) ***	

*, **, *** respectively represent significance at 0.1, 0.05, and 0.01 levels; (x) Values in brackets are standard errors; ^ While logarithmic transformations were made on all continuous variables, the treatment effects were recovered by taking antilogarithms.

Table 5. Full information on maximum likelihood estimates of the endogenous switching regression models for measuring impacts of retaining different levels of residue on gross margins (MAD/ha).

Independent Variables	Gross Margins Equation for Retention of Between 0.1% and 30% Residues (Counterfactual: No Residue Retained at all)						Gross Margins Equation for Retention of 30–60% Residues (Counterfactual: No Residue Retained at all)				Gross Margins Equation for Retention of 60% or Above Residues (Counterfactual: No Residue Retained at all)			
	Yes = 1, No = 0		Adopters		Non-Adopters		Adopters		Non-Adopters		Adopters		Non-Adopters	
	Coef.	Std. Er	Coef.	Std. Er	Coef.	Std. Er	Coef.	Std. Er	Coef.	Std. Er	Coef.	Std. Er	Coef.	Std. Er
Age (years)	−0.078	0.169	0.051	0.111	0.012	0.060	−0.020	0.061	0.009	0.052	0.007	0.070	0.013	0.052
Education (years)	−0.099	0.128	−0.048	0.065	0.010	0.043	−0.008	0.041	0.002	0.037	0.081	0.056	0.007	0.037
Sex (1 = male, 0 = female)	−0.209	0.192	0.057	0.241	−0.105	0.068	0.032	0.061	−0.068	0.056	0.054	0.083	−0.059	0.056
Improved Variety (No = 0, Yes = 1)	0.073	0.125	0.245	0.111	0.030	0.043	0.218	0.043 ***	0.099	0.037 ***	−0.024	0.054	0.092	0.037 ***
Quantity of *n*-fertilizer used	0.015	0.067	−0.018	0.028	0.012	0.018	−0.014	0.020	−0.007	0.019	0.080	0.030 ***	−0.005	0.019
Quantity of DAP fertilizer	0.047	0.052	0.077	0.022 ***	0.067	0.014 ***	0.062	0.017 ***	0.077	0.015 ***	0.099	0.024 ***	0.069	0.014 ***
Amount of seed used(kg/ha)	−0.079	0.126	0.047	0.063	0.113	0.034 ***	0.042	0.043	0.116	0.037 ***	0.087	0.056	0.116	0.037 ***
Labor	−0.025	0.123	0.017	0.068	0.040	0.033	−0.021	0.044	0.069	0.038 *	−0.023	0.052	0.064	0.038 ***
Wheat area (ha)	0.087	0.074	0.062	0.055	0.008	0.027	0.047	0.024 **	0.020	0.023	0.032	0.032	0.016	0.023
Cultivated area (ha)	−0.001	0.018	0.001	0.010	0.005	0.005	−0.007	0.006	0.008	0.005	0.005	0.007	0.008	0.005
Quantity of herbicides (kg/ha)	−0.075	0.110	−0.321	0.058 ***	−0.246	0.032 ***	−0.305	0.037 ***	−0.310	0.033 ***	−0.198	0.046 ***	−0.314	0.033 ***
Quantity of pesticides (kg/ha)	0.217	0.135	−0.444	0.067 ***	−0.028	0.038	−0.267	0.048 ***	−0.004	0.042	−0.110	0.056 **	−0.003	0.042
Rainfall	0.208	0.150	0.104	0.204	0.152	0.050 ***	−0.016	0.054	0.219	0.047 ***	0.427	0.067 ***	0.198	0.045 ***
Zero tillage	0.588	0.149 ***	0.561	0.256 **	0.331	0.064 ***	0.284	0.179	0.286	0.061 ***	0.176	0.065 ***	0.243	0.059 ***
Rotation	0.239	0.092 ***	0.167	0.091 *	0.073	0.033 **	0.012	0.032	0.086	0.028 ***	0.092	0.043 **	0.078	0.028 ***
Irrigation	0.062	0.163	1.729	0.162 ***	1.316	0.051 ***	1.792	0.068 ***	1.339	0.053 ***	1.368	0.073 ***	1.360	0.049 ***
Favorable zone	0.169	0.112	0.084	0.126	−0.078	0.039 **	−0.027	0.037	−0.019	0.033	−0.051	0.049	−0.021	0.033
Intermediate zone	−0.118	0.110	0.013	0.087	−0.018	0.035	0.049	0.035	0.017	0.031	0.051	0.050	0.019	0.031
TLU/ha	−0.060	0.014 ***												
Constant	−1.389	1.294	6.130	0.668 ***	6.008	0.415 ***	7.402	0.477 ***	5.263	0.413 ***	4.321	0.586 ***	5.428	0.385 ***
Rho			−0.084	1.901	0.929	0.016 ***	0.011	0.236	−0.168	0.041 ***	−0.008	0.300	−0.164	0.029 ***
Sigma			0.390	0.048 ***	0.445	0.014	0.368	0.009 ***	0.351	0.010 ***	0.296	0.012 ***	0.350	0.009 ***
Wald test x2	1848.76 ***						1725.52 ***				774.58 ***			
Log likelihood	−1117.52						2639.79				1560			

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

The ESR estimates of treatment effects of residue retention on gross margins are also presented in Table 4. The results show that farmers who retained more than 60% of residue obtained on the average 922.98 MAD/ha, i.e., US $107.07/ha (32.46%) higher gross margins than what they would have obtained had they not retained any residue. Likewise, farmers who retained above 30 but below 60% residue obtained 632.25 MAD/ha or US $73.35/ha (25.17%) greater gross margins than what they would have had they not retained any. Were non-adopters to retain more than 60% residue on their fields, they would have, on average, earned 525.81 MAD/ha or US $61.00/ha (16.30%) greater gross margins.

Based on data from [21], we calculated that the total gross revenue that a farmer can obtain from selling all crop residue (average of 77 bales/ha) after wheat harvest is MAD 468.26/ha. Assuming that price does not change based on the volume of sales by a single farmer (an assumption which is not too far from reality), we calculated that the gross margins farmers forgo by deciding to retain 45% (the average of 30% and 60%) and 60% of their wheat crop residue in the field are MAD210.72/ha and MAD280.96/ha, respectively. Considering the additional income from yield gains and the forgone income from residue sale (or cost incurred in the purchase of feed with equivalent nutritional values), our results show that by retaining 60% and 45% of residue on the field, farmers can obtain MAD 642.02/ha, i.e., US $ 78/ha (19%) and MAD 421/ha or US $51/ha (12%) higher gross margins than what they would if they did not retain any—indicating that retention of at least 30% residue leads to gains in gross margins where retention of more than 60% residue leads to the highest benefit.

4.3. Impacts on Wheat Consumption from Own Production

Total area devoted to wheat production (wheat area), rotation, irrigation, and the use of improved varieties—all have positive and significant effects on wheat consumption. The estimates of treatment effects from ESR (Table 4) show that adopters of more than 60% residues retention on the average consume about 16.33 kg/capita/year (25.29%) more wheat than what they would had they not retained any residue on the field. Adopters of between 30% and 60% residue retention also consume on average about 11.31 kg/capita/year (22%) more wheat than what they would if they had not retained any residue on the field.

4.4. Impacts on Downside Risk and Variability of Yields

We generated the second central moment as an indicator of the variance of yield and the third moment as an indicator of downside risk exposure. The results of the ESR regressions for both yield variance and downside risk are presented in Table 5. The treatment effects from ESR (Table 6) show that adoption of above 60% residue retention leads to 149% and 267% lower probabilities of obtaining below average levels of yields for adopters and non-adopters (had they adopted), respectively. It also reduces the variability of yield by 39% and 16% for adopters and non-adopters, respectively. These benefits are of extremely high importance for rainfed wheat production in drylands where erratic weather is often associated with variable yields and high risk of obtaining crop loss. However, retention of between 30% and 60% residues leads to mixed results—reducing the probability of obtaining low levels of yields for those who have already adopted by 89% while it would potentially increase the variability of yields by 39% were non-adopters to adopt it. Though different in magnitudes, the impacts on downside risk and variability of yield for retention of between 0.1% and 30% residues are similar to those of retention of between 30% and 60%.

Table 6. Average expected treatment and heterogeneity effects on average expected downside risk exposure and variance of yield—ESR results.

Treatments	Subsample Effects	Downside Risk Exposure				Variance			
		To Adopt	Not to Adopt	Treatment	% Change	To Adopt	Not to Adopt	Treatment	% Change
Retention of between 0.1% and 30% residues (counterfactual: no residue retained at all)	Farm households that adopted	−0.0040 −0.0004	−0.0177 −0.0006	0.0137 (0.0007) ***	+77%	0.0341 −0.0016	−0.0451 −0.0003	0.0782 (0.0015) ***	+173%
	Farm households that did not adopt	−0.0586 −0.0004	0.0300 −0.0003	−0.0617 (0.0004) ***	−206%	0.0379 −0.0002	0.0576 −0.0002	−0.0197 (0.0009) ***	−34%
	Heterogeneity effects	0.0547 (0.0006) ***	−0.0207 (0.0007) ***	0.0137 (0.0008) ***	+66%	−0.0038 (0.0018) **	−0.1027 (0.0004) ***	0.0989 (0.0017) ***	+96%
Retention of between 30% and 60% residues (counterfactual: no residue retained at all)	Farm households that adopted	−0.0033 −0.0001	−0.0287 −0.0002	0.0255 (0.0003) ***	+89%	0.0208 −0.0004	−0.0482 −0.0003	0.0691 (0.0003) ***	+143%
	Farm households that did not adopt	−0.0035 −0.0001	0.0077 −0.0001	−0.0113 (0.0003) ***	−147%	0.0219 −0.0004	0.0429 −0.0003	−0.0210 (0.0003) ***	−49%
	Heterogeneity effects	0.0002 (0.0001) *	−0.0365 (0.0002) ***	0.0367 (0.0003) ***	+101%	−0.0011 (0.0005) **	−0.0912 (0.0004) ***	0.0901 (0.0004) ***	+99%
Retention of 60% or above residues (counterfactual: no residue retained at all)	Farm households that adopted	0.0022 −0.0001	−0.0045 −0.0004	0.0067 (0.0004) ***	+149%	0.0203 −0.0007	0.0330 −0.0010	−0.0128 (0.0013) ***	−39%
	Farm households that did not adopt	0.0035 −0.0001	−0.0021 −0.0002	0.0056 (0.0002) ***	+267%	0.0259 −0.0004	0.0307 −0.0007	−0.0049 (0.0009) ***	−16%
	Heterogeneity effects	−0.0013 (0.0001) ***	−0.0024 −0.0005	0.0011 (0.0005) **	+46%	−0.0056 (0.0008) ***	0.0023 (0.0013) *	−0.0079 (0.0017) ***	−343%

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

5. Discussion

Our model shows positive gains in yield and gross margins from the use of improved varieties and certified seeds over the use of local (and old improved) varieties and uncertified seeds for both fields in which residue retention was adopted and not adopted. These results are consistent with the theoretical expectation because the goal of dissemination of improved varieties and certified seeds are to enhance productivity and increase income of smallholders and are comparable with the results of a past study from Morocco [53]. Likewise, the positive effects of rotation and zero tillage on yields and gross margins of the subsequent wheat crops validate the theory behind the CA principles. Our model results also show that adoption of the practice of retaining above 60% residue has not only significantly increased the productivity and gross margins of wheat farmers who have already adopted but also carries substantial potential for those who are yet to adopt it. These results are generally consistent with many studies from Morocco [54,55] and other parts of the world [56–59] which found that residue retention is associated with significant productivity and gross margin gains.

The negative yield impact of the retention of less than 30% of residues, however, is counterintuitive. A possible explanation is that the gain from low levels of residue used as mulch may be more than offset by the negative effect of retention of residue. This might be an indication of a non-linear relationship between the amount of residue retained for soil mulching and the nutrient availability for the subsequent crop. Moreover, retention of lower levels of residue may be a barrier to the early growth and development of the crop and have some possible allelopathic effects that counter the positive effects. Providing full explanation for this counterintuitive result will, however, require further research on experimental stations with proper control on other confounding factors.

Despite the high average gains per unit area of 245 kg/ha, the relatively small level of adoption of residue retention undermines its national impact. If Morocco invests in the promotion of the retention of above 60% residue to attain coverage of 75% and 100% of total wheat area in the country, it will be able to increase wheat supply from domestic production by at least 19% and 26%, respectively—sizeable increases which are worthy of the investment. The benefits are expected to be even higher if the farmers were to adopt residue retention along with the other two components of CA (zero or reduced tillage and crop diversification) as there are synergies that can be tapped into. Therefore, Morocco, and other similar countries in North Africa and West Asia have high incentives to promote CA. Given the complexity and knowledge intensity of the CA technology, it is necessary to provide farmers with the needed extension service support as well as the flexibility to gradually adopt the different components at their own pace [60].

Retention of at least 30% of the residues is economically and biophysically advantageous even to farmers who own livestock. This is because the sale of the additional grain yield obtained due to residue retention will more than offset the cost of purchasing equivalent amount from the market to feed their own flock. At the current national adoption levels of 14.86%, 35.53%, and 12.12%, retention rates of above 60%, between 30% and 60%, and between 0.01% and 30% residues have led to total national gains of about US $ 50.36 and 92.67 million dollars and a loss of 9.37 million dollars per year, respectively. While the low adoption levels of larger amounts (>30%) of residue have undermined the aggregate macro-level benefits, wider adoption of the technology (particularly retention of above 60% residue) has high potential to generate sizeable economic benefits to the country. These benefits are expected to be even much higher in the long run when the full benefits of residue retention in terms of rehabilitation of soil nutrients and soil health start to accrue.

The yield gains and possibly the higher gross margins from retention of residues have led to increased wheat consumption by the adopters. Available estimates [23] show that the average energy consumption during 2006–2008 for Morocco was 3260 kilocalories per capita per day. The projection for the average energy consumption in 2015 in the Near East and North Africa was about 3090 kilocalories per capita per day [61]. Taking the average energy per kilogram of wheat of 3390 kilocalories, the additional 16.33 kg/capita/year of wheat consumed by adopting more than 60% residue retention in Morocco translates to a gain of 153.77 kilocalories/capita/day.

The fact that there is a non-linear relationship between the quantity of residue retained and yield [62,63] provides the explanation for the mixed results on yield risk and variability. In low-rainfall areas, residue retention as mulch, through its positive effect on moisture retention and improvement in soil organic matter, has a positive effect on yield while it can lead to slightly lower yields in high-rainfall areas. Given that the study covers 21 provinces with different agro-ecologies and precipitation levels, the mixed results are understandable. The allelopathic effects of different levels of residue retention might also have contributed to these results. In CA, residue retention is supposed to be accompanied with zero-tillage and crop rotation. As most of the farmers in the sample have not adopted ZT and/or rotation along with residue retention [60], this might have also contributed to the mixed results on the downside risk and variability of yield.

Overall, our model results show that there are sizeable benefits to retention of larger amounts of residue. The findings of our study will provide additional evidence to support the efforts to promote residue retention for mulching, which has seen major resistance, especially in the mixed crop-livestock production systems of the drylands. With these results in place, the next discussion will have to focus on the development of strategies for the dissemination of the evidence among policy makers, development practitioners, extension personnel, and farmers to enhance its adoption and to find alternative feed sources without which it will be impossible to convince farmers, particularly those who own livestock.

6. Conclusions

There are clear yield, yield stability, and yield risk management advantages to the retention of above 60% residue. The results on the impacts of retaining below 60% of the residues on the downside risk and variability of yields are, however, mixed, which, along the trade-offs with feed demand, might provide part of the explanation for the low adoption levels. If Morocco promotes the retention of more than 60% residues to cover 75% and 100% of total wheat area in the country, it will be able to increase wheat supply from domestic production by at least 19.28% and 25.71%, respectively. We found that the gains from grain yields are high enough to more than offset the costs of alternative feed sources that provide equivalent amounts of calories and proteins for the livestock. All these results show that retention of at least 30% of the residues from wheat crop can be justified on economic grounds. The challenge in the dissemination of this technology might come from the absence of alternative sources of feed and the associated possible increases in feed prices, as well as the mixed results in terms of downside risk and variability of yields, especially for those who retain below 60% of the residues on the field.

The policy implication of our results is that Morocco and other similar countries in North Africa and West Asia will benefit from investing on the development and/or import of alternative feed sources and the introduction of crop insurance. Raising awareness of the economic, bio-physical, and environmental benefits of residue retention among farmers would also be essential in the overall promotion not only of residue retention but also of conservation agriculture as a sustainable production system.

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