Agronomy for Sustainable Development (2019) 39:58
https://doi.org/10.1007/s13593-019-0602-2

RESEARCH ARTICLE

Legume-based rotations have clear economic advantages over cereal monocropping in dry areas

Yigezu A. Yigezu[1] · Tamer El-Shater[2] · Mohamed Boughlala[3] · Zewdie Bishaw[4] · Abdul Aziz Niane[5] · Fouad Maalouf[5] · Wuletaw Tadesse Degu[6] · Jacques Wery[1] · Mohamed Boutfiras[3] · Aden Aw-Hassan[1]

Accepted: 31 October 2019

Abstract

Current land use trends show an increasing preference for monocropping – mostly a consequence of policies and incentives aimed at enhancing the intensification of cereals. This shift has caused some to question whether legume–cereal rotations can remain economically viable options for farmers, particularly in the dry areas. In this paper, we present the results of an endogenous switching regression model which suggests, for the first time, that legume–cereal rotations have clear economic advantages over cereal monocropping. Rotations provide higher yields, gross margins, and consumption of wheat and faba beans. Most past economic analyses on rotation used data from experimental stations or small-sized farmer surveys covering only one season and variety. This study makes an important improvement by employing two-year data from a large sample of 1230 farm households and their 2643 fields cultivated with different varieties of wheat and faba beans in the wheat-based production system of Morocco. Assuming a biennial rotation – the fastest cycle possible in a rainfed dryland system, this paper is also the first to demonstrate that joint adoption of rotations and improved faba bean varieties leads to a two-year average gross margin that is US$537/ha (48%) higher than wheat monocropping. This is the highest economic benefit of all available cropping options. A striking result of the study is that, contrary to common expectations, adopters of rotation did not use lesser amounts of nitrogen fertilizer than those monocropping wheat, thereby undermining the ecological benefits of faba bean–wheat rotations. Given that current average applications are below marginal product-maximizing levels, higher marginal yields of nitrogen fertilizers after rotation help explain farmers' current behavior. Our results suggest that: 1) promoting improved legume varieties may enhance adoption of rotation; and 2) an economic rationale should be used as the main driver of the rotation agenda in the dry areas.

Keywords Rotation · faba bean · wheat · improved variety · ecology · economic benefit · impact

1 Introduction

Cultivation of faba bean as a rotation crop has great ecological benefits in various cropping systems. It is used as a break crop for cereals (Lopez-Bellido et al. 2006) and has the potential to enhance soil nitrogen for subsequent cereal crops (Nuruzzaman et al. 2005). Faba bean can also improve the economic value of subsequent cereal crops by enhancing their yields and protein content (Ruisi et al. 2017). They provide a range of other benefits that are not directly related to nitrogen (N), such as

- Enhanced phosphorus (P) availability (Pypers et al. 2007; Nuruzzaman et al. 2005)
- Favorable microbial community in the rhizosphere (Yusuf et al. 2009)
- Breaking soil-borne disease cycles (Jensen et al. 2010).

✉ Yigezu A. Yigezu
y.yigezu@cgiar.org

[1] International Centre for Agricultural Research in the Dry Areas (ICARDA), 2 Port Said, Victoria Sq, Ismail El-Shaaer Building, Maadi, P.O. Box 11711, Cairo, Egypt

[2] International Centre for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria

[3] Settat Regional Dryland Agricultural Research Centre, INRA, Meknes, Morocco

[4] International Centre for Agricultural Research in the Dry Areas (ICARDA), Addis Ababa, Ethiopia

[5] International Centre for Agricultural Research in the Dry Areas (ICARDA), Beirut, Lebanon

[6] International Centre for Agricultural Research in the Dry Areas (ICARDA), Rabat, Morocco

As faba beans grow, a large amount of nitrogen (N_2) is fixed, resulting in a positive N balance when crop residues are incorporated into the soil after harvest (Amanuel et al. 2000). Several studies reported savings of between 100 and 200 kg/ha in the amount of N fertilizers applied to cereals following faba bean (Preissel et al. 2015; Nuruzzaman et al. 2005). Kirkegaard et al. (2008) also found wheat yield increases from 20 to 36% in a faba bean–wheat rotation compared to a barley–wheat rotation. Legume–cereal rotations are also known to reduce the demand for labor for weed control in subsequent cereal crops (Vereijken and Kloen 1994). In addition, legumes reduce soil erosion (Lawson et al. 2007) and enhance stability and resilience (Suso and Maalouf 2010).

Faba bean is among the most important legumes with high nutritional values, including protein, carbohydrates, vitamin B, antioxidants, and mineral contents, when used for human food and animal feed (Crepona et al. 2010). They are also rich in their micro-element content, including iron, manganese, copper, and zinc—indicating the possibility of faba bean bio-fortification (Baloch et al. 2014). Faba bean also provides an excellent dietary source of natural antioxidants for chronic disease prevention and health promotion (Oomah et al. 2006). They play a key role in conserving the biodiversity of insect pollinators as they are entomogamous/partially allogamous crops, which attract and maintain wild bees, honeybees, and bumblebees (Köpke and Nemecek 2010).

Despite all these benefits, cereal monocropping is a growing phenomenon with implications not only for agro-biodiversity, but also for food and nutrition (Jacques and Jacques 2015). This is especially so in the drylands of the North Africa and West Asia (NAWA) region, where the total area under legumes has been reduced from about 2.6 million ha in 1990 to about 1.2 million ha in 2016 (FAOSTAT 2018). Yield, food security, financial returns, and reduced investment because of specialized machinery and a predictable calendar of activities that can be accomplished with casual labor are the main arguments in favor of monocropping (Cook and Weller 2004).

Land-use decisions involving many crops and varieties are largely influenced by trade-offs/synergies related to resource use, input demand, livestock feed, and other costs and benefits inherent in those decisions. Farmers may decide to adopt only one or both varieties depending on the existence of competition or synergies in the use of productive resources among the varieties (Yigezu et al. 2018b). The crop and varietal choices are also determined by farmers' perceptions, preferences, and attitudes. These are shaped by many factors, including economic incentives or disincentives as well as market and production risks (Pannell et al. 2006). These factors, together with the pressure to maximize profits, are compelling farmers in many parts of the world to monocrop or use longer rotations, leading to declining soil qualities and yields of subsequent cereal crops, and biodiversity (Fig. 1). If the current momentum in monocropping is to change, economic justifications for rotations are needed.

Some work has been done on the economic impacts of cereal–legume rotations, mostly focusing on the developed world (see the review by Preissel et al. 2015) and based on data from experimental stations. However, little is known about their economic and nutritional impacts in the context of smallholders. Even less is known about the economic and ecological benefits being realized in farmers' fields. The Schilizzi and Pannell (2001) case study from Australia may be of some relevance to Mediterranean dryland countries, but the sizes of the landholdings and economic conditions of farmers in Australia and the Mediterranean countries in the NAWA regions are very different. Moreover, none of the previous studies assessed the combined economic impacts of the adoption of rotations and improved varieties, especially within a multi-year context.

Therefore, the objective of this study is to document the effects of the individual and simultaneous adoptions of a faba bean–wheat rotation and the use of improved faba bean varieties on yields, farm incomes, and food and nutrition security. The study involves actual 2-year production and utilization data from a large sample of smallholder farmers and their wheat and faba bean fields in Morocco. This paper also seeks to identify the determinants of adoption and estimate current and potential national benefits from the adoption of rotations and improved faba bean varieties. The findings of this research are expected to be useful for policy makers, extension personnel, development practitioners, and donors in Morocco and other similar countries.

The remainder of this paper is organized as follows. Section 2 addresses the materials and methods. Subsection 2.1 describes the role of faba bean in the wheat-based production systems in Morocco, Subsection 2.2 presents the data, and Subsection 2.3 details the methods used. Results and

Fig. 1 Increasing trend in monocropping is threatening agricultural biodiversity

discussion are presented in Sect. 3, with conclusions being drawn in Sect. 4.

2 Materials and methods

2.1 Faba bean in the wheat-based production systems of Morocco

Faba bean is an important crop in Morocco, providing nutritional, biological, and economic benefits to smallholder farmers in the wheat-based production systems. In the late 1970s, a collaborative program—Station Centrale des Légumineuses Alimentaires—between Institut National de la Recherche Agronomique (INRA) and the Food Legume Improvement Program of the International Centre for Agricultural Research in the Dry Areas (ICARDA) was established. Since 1982, the collaborative program has registered several faba bean varieties in the national catalog. Among these are three small-seeded faba bean varieties—Alfia5, Alfia17, and Alfia21—and three large-seeded faba bean varieties—Defes, Karabiga, and Loubab.

Of the 13 faba bean cultivars found in Moroccan farmers' hands, only three are improved. Even these three improved varieties are over 25 years old. However, the new cultivars are gaining popularity. In 2011, they were grown on about 29,000 ha (15.62% of the total national faba bean area). Alfia17, which was released in 1986, is the second most popular variety, covering about 8% of the total national faba bean area.

The cereal area in Morocco increased by 19% from an average of 4.4 million ha in the period 1961–1979 to an average of 5.2 million ha in the period 2001–2014. However, the area under grain legumes dropped by 13% in the same period—from an average of about 458,000 ha to about 400,000 ha (FAOSTAT 2018). In particular, the area dedicated to faba bean has dwindled, declining from an average of about 200,000 ha between the late 1980s and early 1990s to an average of about 120,000 ha in the mid-1990s. More recently, although it has exhibited some fluctuations, it has rebounded to an average of about 190,000 ha between 2010 and 2013 (Fig. 2). This recent expansion of the faba bean area is primarily at the expense of oilseeds because faba bean, which competes with oilseed as a break crop in rotation with cereals, enjoyed price support via tariff protection. As a result, in the domestic market, faba bean have traded at 18% above the world (European Union) market price equivalent (Jackson et al. 2014). The marketing of faba bean is also much easier because legumes are sold or used on-farm for direct consumption by local livestock, whereas sunflower seeds must be processed.

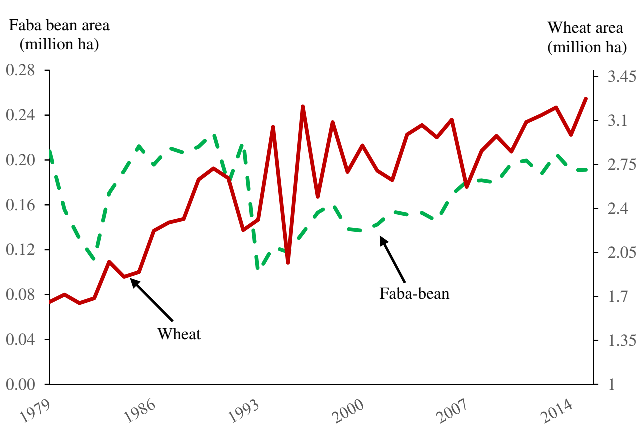

Fig. 2 Areas under faba bean and wheat 1979–2015. Note: Since 1993 with some fluctuations, the area under wheat in Morocco has remained almost the same for about 20 years while that under faba bean has almost doubled in the same period. Source: Wheat: Department of Strategies and Statistics Ministry of Agriculture. Faba beans: FAOSTAT

In Morocco, more than 60% of faba bean cultivation takes place in the northern parts of the country, where the annual average rainfall is above 400 mm. Over the years, the area under faba bean has dwindled because of drought, *Orobanche*, *Botrytis*, stem nematodes, and insect damage. While the adoption of improved varieties of cereals showed modest increases, the adoption of improved varieties of legumes in general, and faba bean in particular (which have resistance to many of the prevalent diseases and pests) remains very low (Yigezu et al. 2019). This is consistent with the findings of other studies in developing countries (see for example Walker et al. 2015). Average faba bean yields in Morocco remained at about 0.71 t/ha during the period 2001–2014, which is 58% lower than the world average of 1.7 t/ha (FAOSTAT 2018).

2.2 Data

Data for this study came from a large sample, household survey conducted in 2013 covering 21 major wheat-producing provinces in Morocco. These provinces account for about 81% of the national wheat area in the country. Power analysis was used to determine the minimum sample size (1061) that would ensure 95% confidence and 3% precision levels for our adoption estimates. To account for possible attrition, missing data, and errors, we increased the sample size by 15%. Consequently, a sample of 1230 wheat-growing farm households, cultivating 2296 plots of wheat, was drawn for this study. A stratified sampling approach was used in which provinces, districts, and villages were used as strata. The sample was distributed in proportion to the population sizes across 292 villages in 56 districts that were randomly drawn from the 21 study provinces (for more details on the data, see Yigezu et al. 2019).

While the primary purpose of the survey was to determine the adoption and impacts of improved wheat varieties in Morocco, the study team was also interested to analyze the economic viability of legume–cereal rotations in the wheat-based production system. Therefore, the 1230 wheat producers included in the sample were asked if they have more plots, other than the 2292 planted to faba bean in 2012. A total of 326 farmers (26%) responded "yes". Then, the study team collected additional field-level production and utilization data from a total of 347 faba bean fields cultivated by the 326 households in 2012. As a result, the total number of fields included in the sample increased to 2643. Of the 347 fields cultivated with

Table 1 Descriptive statistics for selected variables some of which are included in the endogenous switching regression (ESR) models

Variable	For plots cultivated with faba bean (FB) in 2012			For plots which were cultivated with wheat in 2012		
	Non-adopters of improved varieties of FB	Adopters of improved varieties of FB	Total	Not cultivated (with) FB in the previous season[a]	Cultivated (with) FB in the previous season[a]	Total
Number of households	284	42	326[c]	755	475	1230
Number of plots	295	52	347[c]	1481	815 (83)[d]	2296
Average area of the plots (ha)	1.75	2.11	1.8	2.8	6	3.94
Farmers who adopted improved varieties of faba beans	0	42	42	15	33	48
Plots planted to improved varieties of faba bean[f]	0	52	52	20	42	62
Farmers who adopted improved varieties of wheat	38	26	64	175	249	424
Plots planted to improved varieties of wheat[e]	39	33	72	326	419	745
Number of plots that are irrigated[g]	0	0	0	203	192	395
Average age (years)[g]	59.2	58.5	59.1	59.9	58.6	59.4
Average number of years of education[g]	1.6	2.3***	1.7	1.7	2.1***	1.9
Average amount of family labor (person days/ha)[g]	4.0	3.9	4.0	4.2	4.5	4.3
Average faba bean area (ha)[b]	1.8	3.6***	2.0	0.72	2.5***	1.6
Average wheat area (ha)	2.1	5.3***	3.6	2.6	6.2***	3.9
Average total cropped area (ha)[g]	8.9	10.8	9.2	10.9	15.4***	12.5
Average walking distance from seed sources (km)[g]	21.1	19.4	20.8	19.3	13.4***	17.2
Average price paid for seed (MAD/kg)[g]	9.8	7.5	9.4	2.3	2.2	2.3
Average quantity of DAP fertilizer used (kg/ha)[g]	98.7	144.2***	105.5	27.2	33.4***	29.4
Average quantity of nitrogen fertilizer used (kg/ha)[g]	3.5	17.6***	5.6	35.5	50.4***	40.8
Average amount of seed used(kg/ha)[g]	100.5	106.1***	101.4	168.0	179.9***	172.2
Average amount of pesticides used(kg/ha)[g]	0.4	0.27**	0.37	0.24	0.20	0.23
Average amount of herbicides used(kg/ha)[g]	0.84	1.1**	0.88	0.9	0.92	0.904
Average faba bean consumption (kg/capita/year)[f]	56.7	77.6***	59.8	57.1	77.2***	66.3
Average wheat consumption (kg/capita/year)[e]	51	84***	66.1	50.5	84.7***	62.6
Average gross margin from faba bean production (US$/ha)[f]	940.9	1084.3***	962.4	958.8	1056.3***	993.4
Average gross margin from wheat production (US$/ha)[e]	606.6	723.5***	624.1	464.9	667.67***	536.88
Average faba bean yield (kg/ha)[f]	1,155.3	1,407.2***	1,193.1	1170	1348.3***	1252
Average wheat yield (kg/ha)[e]	1202	1,860***	1,503.6	1190.6	1863.6***	1429.5
Was the seed you used certified? {1 = yes, 0 = no}[g]	3.7	44.2***	9.8	43.1	60.5***	49.3
Farm is in favorable zone {1 = yes, 0 = no} (% of yes)[g]	48.1	34.6**	46.1	30.3	49.3***	37.1
Farm is in intermediate zone {1 = yes, 0 = no} (% of yes)[g]	25.4	61.5***	30.8	31.5	25.5***	29.4
Did you get credit from banks {1 = yes, 0 = no} (% of yes)[g]	35.9	44.2	37.2	40.2	60***	47.3
Do you have off-farm employment {1 = yes, 0 = no} (% of yes)[g]	14.6	23.1*	15.9	16.6	17.9	17.1

***, **, *A statistically significant difference from the corresponding value in the immediately preceding column at 0.1, 0.05, and 0.01 levels, respectively

[a] For each field under wheat in 2012, we asked if it was planted with faba beans (FB) in the previous (2011) season and if yes, we asked if they used improved variety of FB

[b] Average faba bean area (ha) for adopters does not necessarily represent area under improved varieties as improved varieties covered only part of total faba bean area

[c] Of the total sample of 1230, only 326 had cultivated faba beans on a total of 347 additional fields in 2012, which along with the 2296 wheat fields makes a total of 2643 fields

[d] Values between parentheses represent the frequency of fields on which rotation and improved varieties of faba beans were simultaneously adopted

[e,f, g] The variable is included as explanatory or dependent variable in the ESR models for measuring the impacts on the subsequent wheat crop, the first year faba bean crop and in both, respectively

faba bean, only 52 (15%) were cultivated with improved varieties; the remaining 295 (85%) were cultivated with local varieties. To capture the effects of legume–cereal rotations over 2 years, data were also collected on the crops planted on each of the 2643 wheat and faba bean fields planted in the preceding (2011) season. All the 347 fields under faba bean in 2012 had been planted to wheat in the preceding season. Of the 2292 fields cultivated with wheat in 2012, 815 (36%) had been cultivated with faba bean in 2011. Of these 815, just 83 (10%) were under improved varieties of faba bean. Wheat and faba bean consumption-related data were also collected from the entire sample of 1230 households. The summary statistics for variables of interest are provided in Table 1.

2.3 Methods

Estimation of local average treatment effects was the focus in the program evaluation literature. The main challenges in this search were related to selection bias in establishing counterfactuals. Several econometric approaches can be used to address the problem of selection bias in program evaluation using 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) is by far the most widely used tool for improving causal inference and estimating local average treatment effects. PSM helps in correcting biases introduced only by observable covariates. Results from PSM can sometimes be difficult to justify because, while it can help in correcting biases introduced only by observable covariates, unobservable factors, such as skills and motivation, can influence not only the outcome, but also the program participation decision (in our case the decision to adopt rotation and/or improved faba bean varieties). This leads to confounding errors (see Austin 2008 for a critical review of PSM).

More recently, there has been a major shift towards the use of two other methods, the endogenous switching regression (ESR) and instrumental variables (IV). Both account for the endogeneity of the participation decision and are potent to correct for selection bias introduced by both observable and unobservable factors. While IV is arguably the best evaluation method for observational data, it may perform poorly, especially if all the necessary conditions for its implementation are not fulfilled. In contrast, the requirements for the implementation of ESR are less stringent, but it has a drawback as it implicitly assumes that covariate effects may not be the same across the two different states (or regimes) of which only one is observed (Powers 1993).

In our case, we have no compelling reason to assume that the effects of the different explanatory variables are the same for adopters and non-adopters. In the face of these trade-offs, choosing between the two models becomes difficult. In our case, rotation and improved legume varieties have a long history in Morocco, making it difficult to find good instruments for an IV regression model. Moreover, the adoption of rotation and/or improved faba bean varieties might help farmers with certain characteristics to further exploit their benefits or suffer the adverse effects. For example, given the lack of mechanization for legume harvesting—harvesting being done mainly by women in Morocco—women adopters of improved faba bean varieties might invest more time in learning about the characteristics of the varieties and make them work better for themselves than male adopters and all non-adopters. Therefore, the implicit assumption of the same coefficients for the covariates across regimes may not necessarily be relevant. After careful evaluation of the pros and cons of available methods, we decided to use the ESR in this study.

Endogenous switching regression (ESR) The main rationale for the use of ESR is that the difference in the outcomes of the variable of interest (e.g., income) between adopters and non-adopters may be due not only to observable heterogeneity, but also to unobserved heterogeneity (Abdulai and Huffman 2014). ESR attempts to overcome this problem by simultaneously estimating the equation for the adoption decision and the outcome equation for the variable of interest for each group.

Assume that i represents a single decision maker (in our case a farmer), d_i and d_i^*, respectively, represent the observable and unobservable (latent) adoption decision variables, $\boldsymbol{Z}_i$is a matrix of observed farm and non-farm characteristics which are believed to explain variations in adoption, and ϵ_i is the error term associated with the adoption decision. The adoption decision (also called the selection) equation can then be described as

$$d_i = \begin{cases} 1 \; if \; d_i^* > 0 \\ 0, otherwise \end{cases} \qquad d_i^* = \boldsymbol{Z}_i\beta + \epsilon_i \tag{1}$$

Assume also that $\boldsymbol{y}_i$ is a vector of dependent variables representing the outcomes of the farmers' adoption decisions, where y_1 represents the outcome for adoption and y_0 that for non-adoption, $\boldsymbol{X_i}$ is a matrix of explanatory variables that are expected to affect the outcome variable, $\boldsymbol{\omega}_i$ is a vector of parameters to be estimated, and $\epsilon_1$and ϵ_0 are error terms associated with the outcome equations corresponding to the adoption and non-adoption decisions, respectively. Then, the two outcome equations can be described as

$$y_1 = \boldsymbol{X}_1\boldsymbol{\omega}_1 + \boldsymbol{\epsilon}_{1i} \; if \; d = 1 \tag{2}$$

$$y_0 = \boldsymbol{X}_0\boldsymbol{\omega}_0 + \boldsymbol{\epsilon}_{0i} \; if \; d = 0 \tag{3}$$

Simultaneous estimation of equations (1) to (3) represents the ESR, where the model assumes that the error terms from the three equations—ε, ϵ_1, and ϵ_0—have a tri-variate normal distribution with mean vector of 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_{ε}^2 is the variance of the selection equation (equation 1) and $\sigma_{\epsilon 0}^2$ and $\sigma_{\epsilon 1}^2$ are the variances of the outcome equations for non-adoption and adoption, respectively, with $\sigma_{\epsilon 0\varepsilon}$ and $\sigma_{\epsilon 1\varepsilon}$ representing the covariance between ϵ_1 and ϵ_0.

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

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

where ϕ and Φ are the probability density and the cumulative distribution functions of the standard normal distribution, respectively. If $\sigma_{\epsilon 1\varepsilon}$ and $\sigma_{\epsilon 0\varepsilon}$ are statistically significant (i.e., they are heteroscedastic), this would indicate that the decision to adopt and the outcome variable of interest are correlated, suggesting evidence of sample selection bias. In the face of heteroscedastic error terms, the full information maximum likelihood (FIML) estimator can be used to fit an ESR that simultaneously estimates the selection and outcome equations to yield consistent estimates. The ESR can be used to compare the actual expected outcomes of adopters (equation 7) and non-adopters (equation 8) and to investigate the counterfactual hypothetical cases that the non-adopters did adopt (equation 9) and the adopters did not adopt (equation 10) as follows:

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

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

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

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

The choice of variables and specification of the models were made based on theory, the literature, and the authors' knowledge of the Moroccan wheat-based production system. To make sure that the covariates selected for inclusion in the models are appropriate (i.e., to test the goodness of fit), we evaluated estimates of the conditional density of adoption. Also, we used the Wald χ^2 test statistic to determine the joint significance of all covariates included in the pair of selection and outcome equations. The correlation coefficient (rho) that is generated during estimation of the ESR model has also been checked to determine if the switch is indeed endogenous. Hence, the selection of ESR to estimate impacts is justified.

Finally, following El-Shater et al. (2016), 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). We also compute the effect of base heterogeneity for the group of adopters (BH_1) as the difference between (7) and (9) and for the group of non-adopters (BH_2) as the difference between (10) and (8).

This paper estimates the impacts of two treatments: adoption of rotation and the adoption of improved faba bean varieties. To this effect, three separate ESR models were estimated: one for the impacts of adoption on yield, gross margin, and consumption of the subsequent wheat crop. The second was estimated to measure the impacts of adoption of rotation on the amounts of nitrogen (N) fertilizer, diammonium phosphate (DAP) fertilizer, pesticides, and herbicides applied to the subsequent wheat crop. Both are based on the data from the 2296 fields that were planted with wheat in 2012. The third ESR model was estimated to measure the effects of the adoption of improved faba bean varieties on yield, gross margin, and consumption of faba bean. This is based on data from the 347 fields that were planted with faba bean in 2012. To ensure a better approximation to a normal distribution, a logarithmic transformation was carried out for all continuous variables. The logarithmic dependent and explanatory variables, along with the linear specification of the outcome equation in the ESR model, make the yield function a variant of the Cobb-Douglas production function. As a result, the coefficient estimates of the FIML estimation of the ESR model for yield would have to be interpreted as elasticities (or percentage changes), which can be converted into marginal values by evaluating them at the mean values of the physical input and output quantities. Version 15 of the Stata software was used for all econometric analysis.

Diagnostic results of the choice and specification of the ESR model Several variables described in Table 1 are used as covariates (i. e. , $\boldsymbol{Z}$ and $\boldsymbol{X}$, respectively, in the selection and outcome equations of the ESR model described in the subsection 2.3). Following the FIML estimation of the ESR model (table of results not presented here), tests of goodness of fit for the pairs of selection and outcome equations estimated for each of the outcome variables—yield, gross margin (computed as the difference between total revenue and total costs excluding cost or rental value of land), and wheat consumption—show that the model is well specified. All the covariates included in the model together provide a good estimate of the conditional density of adoption of rotation and the joint significance of the explanatory variables with high and significant (at 1% level) Wald χ^2 test statistic values. The correlation coefficient (rho) values in the wheat yield and wheat consumption equations are positive, but not statistically significant for the adopters. This showed that, in the absence of the treatment (i.e., in the absence of rotation), the wheat yield that typical adopters of rotation would have obtained and the level of wheat they would have consumed would not be statistically significantly different from the yield and consumption of any individual randomly drawn from the whole sample. This suggests that the switch is not endogenous. The rho value in the gross margin equation for adopters, however, is negative and significant. This shows that in the absence of the treatment, the adopters of rotation would have obtained statistically significant lower gross margins than those of any randomly drawn individuals. This indicates that the switch is endogenous. For non-adopters, the rho values of the yield and gross margin equations are both negative and statistically significant, showing that, in the absence of the treatment, they would have obtained lower yields and gross margins than any individuals randomly drawn from the whole sample. The shift is endogenous and hence justifies the use of ESR to estimate the treatment effects. For the wheat consumption equation, the rho value is also not significant for non-adopters, signaling that, in the absence of the treatment, non-adopters of rotation would have consumed the same amount of wheat as any individual randomly drawn from the whole sample. This shows that in principle, estimation of the treatment effects using ordinary least squares and ESR would lead to the same results. Given the mixed results, the decision to estimate the models using ESR is justified.

In the ESR model for the adoption and impacts of improved faba bean varieties, the conditional density of adoption and the joint significance of explanatory variables showed that the fit is good, with a Wald χ^2 test statistic that is significant at 0.01%. The correlation coefficients (rho) are not significantly different from zero in all cases except for adopters in the gross margin equation. This implies that the switch is endogenous for adopters in the gross margin equation and, hence, the use of ESR for estimating the effects of adoption of improved faba bean varieties is justified.

3 Results and discussions

3.1 Impacts of the faba bean–wheat rotation

The indicators used to assess the effects of adopting rotation are yields, gross margin, and consumption of faba beans and the subsequent wheat crop. Based on the FIML estimation of the ESR model, the average expected treatment and heterogeneity effects of the adoption of a faba bean–wheat rotation on yield and gross margin of the subsequent wheat crop and per capita wheat consumption by household members are provided in the rows represented by group A of Table 2. Adopters of a rotation of wheat with faba bean obtained 459 kg/ha (48%) higher yields than what they would have obtained had they continued with wheat monocropping. A faba bean–wheat rotation also increased their gross margin from the subsequent wheat production by MAD1258/ha or US$146/ha (24%). Model results also show that adopters of a faba bean–wheat rotation consumed 27.7 kg/capita/year (53.2%) more wheat, showing that adopting a rotation not only increases income, but also enhances food security at the household level. These results are novel, as they demonstrate that legume–cereal rotations lead to higher yields, gross margins, and consumption of wheat even under biennial rotation, which is the fastest cycle possible in rainfed dryland areas. These results have not been documented elsewhere in the literature.

While the positive effects on yield and gross margin are reasonable, the lower percentage increase in gross margin than that of yields seems to be counterintuitive. Theoretically, we would expect a higher proportional increase in gross margin relative to the increase in yields on at least two grounds. First, we expect farmers are aware of the nitrogen fixing qualities of faba beans, which is why they reduce the amount of nitrogen fertilizers that they apply to their subsequent wheat crops. This reduces their costs while maintaining or even increasing their yield levels. Moreover, rotations have the potential to break diseases and pest cycles and, hence, farmers are expected to apply less pesticides, thereby also reducing costs.

Other than rotation, the quantities of nitrogen (N) and diammonium phosphate (DAP) fertilizers, the use of certified seeds of improved varieties, and irrigation all have positive and significant effects on yields and gross margins from the subsequent wheat crop for both adopters and non-adopters of rotation. These are consistent with theoretical expectation. The quantity of pesticide used, however, also has positive and significant (at the 0.1 level) effects on the yields of both adopters and non-adopters and the gross margin for non-adopters, while its impact on consumption is not significant. The quantities of herbicides have negative effects on the wheat yields of adopters of rotation, indicating that the typical adopter of rotation is applying more than the marginal product-maximizing level. Farmers in the intermediate agro-ecological zone who adopted rotation are found to have higher yields than those who adopted rotation, but who are in the unfavorable zone. In contrast, monocropping farmers in the favorable zone are obtaining lower yields than monocropping farmers in the unfavorable zone. These results show the benefits of rotation are especially very high in the favorable and intermediate zones. These results provide possible explanations for the higher propensity for the adoption of rotation among farmers in the favorable and intermediate zones, as we found above.

Effects of rotation on the use of chemical inputs Reduction in the amount of N fertilizer needed for a subsequent cereal crop because of the nitrogen fixing characteristic of legumes and the breaking of disease and pest cycles are often cited as being among the main benefits of legume–cereal rotations. Therefore, we tried to see if Moroccan farmers and the physical ecology are indeed benefitting from the reduction in N fertilizer, insecticide, and herbicide inputs. The descriptive statistics provided in Table 1 show that adopters of rotation had higher application rates of N fertilizers (23%), DAP fertilizers (42%), and herbicides (2%). Their application rate for insecticides was 17% less than those who practiced wheat monocropping. Given the confounding errors inherent in univariate analysis (such as the averages presented in Table 1), we estimated an ESR model in Table 2 to see the effects of rotation on input application levels. (FIML estimation results are not reported here, but the associated treatment effects are reported in the lower part, group C). After controlling for important confounding factors identified in Table 1, the ESR model results show that the decision to rotate led the current adopters of rotation to use 12.6 kg/ha more N fertilizer, 0.02 kg/ha more herbicides, 151 kg/ha less DAP, and 0.06 kg/ha less insecticides than they would have if they had not adopted rotation. Likewise, were non-adopters of rotation to

Table 2 Results from endogenous switching regression (ESR) showing average treatment effects of faba bean–wheat rotation and adoption of improved faba bean varieties on yield, gross margin, and consumption of faba bean and wheat and average chemical inputs for the subsequent wheat crop

Group	Crop	Sub-sample effects	Yield (kg/ha)[a]			Gross margin (i.e., total revenue-total cost other than cost of land) (MAD/ha)[a]			Consumption (kg/capita/year)[a]		
			Decision state		Treatment	Decision state		Treatment	Decision state		Treatment
			To adopt	To not adopt		To adopt	To not adopt		To adopt	To not adopt	
A	Subsequent wheat crop (second year)	Farm households that adopted rotation	1422	963	459***	6414	5156	1258***	79.8	52.1	27.7***
		Farm households that did not adopt rotation	1086	973	113***	5638	4468	1170***	58.5	49.3	9.2***
		Heterogeneity effects	336	− 10	346	776	688	88	21.3	2.8	18.5
B	Faba bean(first year)	Adopters of improved faba bean varieties	1380	1249	131***	9045	8184	861***	76.7	53.5	23.2***
		Non-adopters of improved faba bean varieties	1152	1071	81***	8103	7332	771***	55.1	36.6	18.5***
		Heterogeneity effects	229	178	51	942	852	90	21.6	16.9	4.7

Group	Crop	Sub-sample effects	N fertilizer used (kg/ha)			DAP fertilizer used (kg/ha)			Pesticides used (kg/ha)			Herbicides used (kg/ha)		
			Decision state		Average treatment effect (ATE)	Decision state		ATE	Decision state		ATE	Decision state		ATE
			To adopt	Not to adopt		To adopt	Not to adopt		To adopt	Not to adopt		To adopt	Not to adopt	
C	Subsequent wheat crop (second year)	Farm households that adopted rotation	25.0	12.4	12.6***	21.1	172.4	− 151.3***	1.14	1.20	− 0.06***	1.72	1.70	0.02***
		Farm households that did not adopt rotation	77.5	17.6	59.9***	14.3	14.7	− 0.4	1.23	1.16	0.07***	4.39	1.79	2.60***
		Heterogeneity effects	− 52.5	− 5.2	− 47.3	6.8	157.7	− 150.9	− 0.09	0.04	− 0.13	− 2.68	− 0.09	− 2.59

***Significant effect at 0.01 level of adoption on the impact variable for those identified by the column headers to be at the decision stage ‘To adopt’

[a] The treatment and heterogeneity effects on yield gross margin and consumption reported in the upper part of the table correspond to the crops identified in the first column

DAP: diammonium phosphate

adopt legume-based rotation, they would have used about 60 kg/ha more N fertilizer, 0.07 kg/ha more pesticides, 2.61 kg/ha more herbicides, and 0.44 kg/ha more DAP than their current application rates. These results show that the higher gross margin from rotation is derived from a combination of the yield gains and the substantial reduction in costs of DAP fertilizers and pesticides, which offset the additional costs of the higher N fertilizer and herbicide rates. As explained in the introduction section, rotation enhances nutrient availability (in this case, DAP) and creates favorable microbial communities in the rhizosphere. At the current application levels of pesticides, wheat planted after faba bean might be less affected by insects and diseases than plants in mono-cropped wheat.

The coefficient estimates of both the quantities of N and DAP fertilizers in the yield function estimated using ESR are positive and significant. This implies that typical Moroccan farmers (both adopters and non-adopters of rotation) are applying fertilizer in quantities that are below the marginal product-maximizing levels for the subsequent wheat crop. The results showed that for adopters of a faba bean–wheat rotation, holding the quantities of other inputs and all other things constant, the marginal product of N fertilizer is 0.81 kg/ha. That is, an additional 1 kg of N fertilizer above the current average application level of 50.4 kg/ha would lead to a 0.811 kg (0.04%) higher wheat yield. The marginal product for DAP is 3.12 kg/ha (a 0.17% increase in yield). Given the current average yields of N and DAP fertilizers of 37 kg/ha and 58 kg/ha, the lower marginal yields indicate that Moroccan farmers are producing wheat using application levels that are above the marginal product-maximizing levels, but below the total product-maximizing levels of these fertilizers. For farmers who are currently monocropping wheat, the marginal products of N and DAP fertilizers are 0.34 kg/ha and 1.4 kg/ha, which are lower than those of the adopters of rotation. Given the current N and DAP fertilizer application rates by adopters and non-adopters of rotation (after controlling for other confounding factors), the larger marginal products of N and DAP fertilizers for adopters of rotation than non-adopters are, as previous studies documented, indications of

- Enhanced nutrient use (Pypers et al. 2007; Nuruzzaman et al. 2005)
- The creation of a favorable microbial community in the rhizosphere (Yusuf et al. 2009)
- The breaking of soil-borne disease cycles (Jensen et al. 2010)

They indicate higher wheat yield responses to N and DAP fertilizers after rotation than for wheat monocropping.

Looking at the area-weighted averages in Table 1, adopters of rotation are using more herbicides and less pesticides than those who are not rotating. A pairwise *t* test, however, showed that the differences are not statistically significant, indicating that adopters of rotation are not using any less or more amounts of pesticides and herbicides on their subsequent wheat crop than farmers practicing wheat monocropping. This is undermining the ecological benefits from following faba bean–wheat rotations that are being realized in Morocco. It is an interesting finding because, theoretically, we would expect adopters of rotation to use lesser amounts of pesticides and herbicides, but they are not. This is a result not shown by any other study. Determining whether the current application levels of N and DAP fertilizers in Moroccan wheat fields are environmentally optimal and whether the negative environmental effects of the additional amount of N fertilizer (which is more soluble) is higher than the reduced application levels of DAP (which is less soluble) with rotation, is beyond the scope of this paper. Finding the explanation(s) for the higher marginal products after rotation and the environmental implications of the current application levels and developing a better understanding of the rationale behind current farmer application levels are also interesting subjects for future research.

3.2 Effects of using improved varieties of faba bean

An analysis of the distributions of the quantities of N and DAP fertilizers applied in faba bean production (Table 1) shows that it is bimodal. Most farmers are either not applying fertilizers or applying at low rates of less than 25 kg/ha, while a sizeable number of farmers are applying at a rate above 100 kg/ha. On average, farmers are applying about 100 kg/ha DAP and only 6 kg/ha of N fertilizer on faba bean crops. Results from the ESR model (group A in Table 2) show that the quantity of DAP fertilizer applied has positive and significant impacts on the yield and gross margin of faba bean. These findings are in line with other studies, which showed that the application of phosphorus to leguminous food crops and the subsequent cereals increases grain yields (El-Kalla et al. 1999; Bolland et al. 2000). Though weakly significant (at the 0.01 level), the quantity of N fertilizer applied has a positive effect on the yields of adopters of improved varieties of faba beans. This is consistent with the literature. Although faba beans can fix N, the application of nitrogen fertilizers at a rate of 20 kg/ha at planting time has been shown to be beneficial for faba bean to enhance biological fixing (R'kiek 1994).

For those who did not adopt improved varieties of faba bean, application of N fertilizer has negative and significant effects on faba bean yield and gross margin. While the positive and significant effects of N fertilizer on faba bean yield are generally intuitive, the negative and significant effects among non-adopters of the improved varieties are puzzling. Unpublished data from Morocco show that some improved faba bean varieties, which have not yet been released, have higher responses to N fertilizer than the local checks. Hence, the low response of local faba bean varieties to N fertilizer could provide a possible explanation for our results. The quantity of seed is found to have a positive, but weakly significant effect (at the 0.1 level), on faba bean yields regardless of the adoption of improved varieties of faba beans. This indicates that typical faba bean farmers are applying slightly lower seeding rates than optimal.

To assess if improved faba bean varieties would provide additional economic incentives for farmers to adopt rotation, we used the same livelihood indicators as those for rotation and adapted them to the case of adoption of improved varieties of faba bean. We estimated the ESR for faba bean yield, gross margin, and consumption by the household. The FIML estimation results are not presented here, but the associated treatment effects are presented in Table 2. Model results show that adoption of improved faba bean varieties led to 131.3 kg/ha (11%) more yield and MAD852 (US$ 99/ha) (11%) higher income. The consumption of faba bean increased 23.2 kg/capita/year (43%) over what would have been consumed if they had not adopted. This result is consistent with the finding of Asfaw et al. (2012). These authors found that adoption of improved legume technologies had a significant positive impact on consumption expenditure. However, it remains to be proved whether the higher incomes from the adoption of improved faba bean varieties and other agricultural technologies help farmers to consume more diverse and nutritious foods. These results show that improved faba bean varieties indeed have economic benefits that could possibly provide additional incentives for the adoption of rotation.

3.3 Results of the simultaneous adoption of rotation and improved varieties of faba bean

We calculated the effects on gross margins of the adoption of faba bean–wheat rotations (the calculations assume a 2-year planning horizon and significant differences in the biophysical and socio-economic production conditions, including rainfall, input quantities, and other agronomic practices of farmers across the two years). First, we computed the total 2-year gross margin of a typical farmer who is practicing wheat monocropping (TYNRMC) at twice the average wheat income of a typical farmer—US$1123/ha (this figure is the weighted average of the actual gross margin of non-adopters and what adopters would have obtained if they had not adopted—both taken from group A of Table 2). Then, we computed the 2-year gross margin resulting from adoption of a faba bean–wheat rotation (TYNRAR)—US$1525/ha (this figure is the sum of the average gross margin from the cultivation of faba bean by a typical farmer and the gross margin from the cultivation of wheat after faba beans. The average gross margin is the weighted average of the actual gross margin of adopters and the gross margin that would have been realized if non-adopters had actually adopted. These values are taken from group A of Table 2. The gross margin for the subsequent cultivation of wheat is taken from group B of Table 2). The result of adopting rotation on the 2-year gross margin (TYIMNRAR) is computed as the difference between TYNRAR and TYNRMC. Accordingly, the adoption of faba bean–wheat rotations led to a 2-year total additional gross margin of US$403/ha (36% higher than what would have earned if farmers had practiced wheat monocropping).

If farmers were to simultaneously adopt faba bean–wheat rotations and improved faba bean varieties, then they would have obtained a total 2-year gross margin of US$1619/ha. This implies that the simultaneous adoption of rotation and improved varieties of faba bean leads to a US$497/ha (44%) higher gross margin. The simultaneous adoptions will also lead to higher consumption of faba bean in the first year and higher consumption of wheat in the second year. These results clearly show that the simultaneous adoption of rotation and improved faba bean varieties has a higher impact on the 2-year gross margin and consumption of faba bean and wheat in the first and second years, respectively. This is yet another set of novel results, as no other study has shown the added advantage of improved faba bean varieties in increasing the benefits of rotation. Given such very high economic benefits, the total wheat area in Morocco on which both rotation and improved varieties of faba bean are adopted currently stands at 23.6%. While the degree to which rotation is adopted is relatively high (over 50%), the low adoption level of improved faba bean varieties (16%) is responsible for the low level of simultaneous adoption.

3.4 Explaining the low individual and joint adoption of improved varieties of faba beans and rotation

In 2012, the total area under faba bean in Morocco was estimated at 187,000 ha, with only 15.62% covered by improved varieties. Assuming that, on average, the adoption levels and yield impacts in the faba bean growing areas not covered by our survey are the same, aggregation using area weights, then the per ha yield gains at the national level showed that Morocco has been producing a total of 3838 t (1.8%) more faba bean because of the adoption of improved varieties. Likewise, the introduction of improved faba bean varieties has led to a gain in the national gross margin of about US$25 million/year. These results show that Morocco is already benefitting from the introduction of improved varieties of faba bean. However, the low adoption levels, given the higher economic advantages of the improved varieties, indicate that the country can reap more benefits if it invests in promoting adoption of improved varieties and achieving a wider acceptance.

All the above results provide adequate household and national level economic and food security justifications for the adoption of faba bean–wheat rotations and improved varieties of faba bean. The fact that 39% of Moroccan wheat growers have adopted faba bean–wheat rotations on 35% of their wheat plots during the survey year also reflects farmers' approval of rotations. The total area under rotations is, however, 54% which, assuming the typical farmer uses a fixed rotation cycle, indicates that the average rotation cycle is about once in every 2 years. Given the lower proportion of farmers adopting rotation, the higher adoption in terms of area covered suggests that relatively larger-scale farmers are the main adopters of rotation. An analysis of national yield figures also showed that since the early 1990s, while the variability of yields of both wheat and faba bean showed similar patterns, wheat yields have generally stagnated and faba bean yields have generally increased. This has resulted in reducing the yield difference between the two crops. Given that the relative prices have not changed much, the increasing faba bean yields might make faba bean economically more attractive. Therefore, these trends also provided further justification for increasing the adoption of faba bean–wheat rotations after the early 1990s. This is consistent with the national area figures where, with some fluctuations, wheat acreage has stagnated at about 2.75 million ha while the faba bean acreage has doubled from 0.1 to 0.2 million ha in about 20 years (Fig. 2). Survey results also showed that most farmers have started rotation after 2000 (Fig. 3a, b).

Both the area and number of farmer-based adoption rates for improved faba bean varieties are low, but comparable (16% and 15%, respectively). This shows that adoption of improved faba bean varieties is uniform across all farm sizes. Given the high economic benefits, the low adoption level of improved faba bean varieties is puzzling. In pursuit of an explanation for this dilemma, we first analyzed the yields of the top five varieties based on production data from the one-shot survey in 2013 (which was an average rainfall year in Morocco). Descriptive statistics of the yields showed that each of the three improved faba bean varieties found on farmers' lands had higher average yields than the single most important local variety. This local variety, *Sbaai*, covers 62% of the total national faba bean area in Morocco—making the situation more complicated. We then asked a leading faba bean breeder to evaluate the top five faba bean varieties in Morocco in terms of their different traits. The breeder rank ordered the traits of *Sbaai* to be very good in terms of its marketing (consumption) traits, grain and straw yields, and frost tolerance. We then analyzed the data on farmers' rankings of the traits in terms of their importance in faba bean variety selection. The analysis was done using the results of the household survey. This showed that grain yield, grain yield stability, grain color, grain size, and grain shape were ranked as the top five most important factors that farmers consider during varietal choice.

Except for grain yield stability (on which the variety *Sbaai* is rated as poor and which farmers considered as the second most important trait), farmers' ratings of desirable traits and those found in *Sbaai* are consistent. Based on farmers' ratings, in addition to yield stability which ranked second, guaranteed minimum yield and drought tolerance ranked eighth and tenth of a total of 22 traits. These results clearly show that market and weather risks are important factors in farmers' varietal selections, and, despite their clear yield and financial advantages, the improved varieties are not meeting the marketing (consumption) trait preferences of farmers. This provides an explanation for the low adoption level of the improved faba bean varieties. Even then, our survey data showed that there is a 0.55 correlation between the adoption of rotation and the adoption of improved faba bean varieties. Such a correlation value provides an indication that the introduction of improved faba bean varieties is enhancing the adoption of rotation. A closer look at the patterns shows that most of the farmers cultivating the improved faba bean varieties adopted them after 2000. This shows that despite their limitations, the importance of improved varieties is becoming more evident among Moroccan farmers and hence we can expect this trend to continue. This will be even more significant if new varieties with farmers' preferred traits are introduced.

Beside the inherent traits of rotation and improved varieties of faba beans, other factors can also explain the low adoption. These factors can be broadly classified into three categories:

- The farm: whether the field is in a favorable and intermediate agro-ecology; if the plot is irrigated; if an improved variety is used on the plot; if the seed used on this field is certified; and how far this field is from the market
- The farmer: age; education; number of family members working on this farm; access to credit; and land holding
- Institutional: access to extension services; participation in hosting demonstration trials; and visiting field days.

These variables were used in the selection equation of the ESR model as determinants of farmers' adoption decisions on rotation and improved faba bean varieties. The choice of the explanatory variables was based on basic agronomic and socio-economic principles and the literature (Yigezu et al. 2018a; El-Shater et al. 2016).

Our ESR model results (a detailed presentation of the results is omitted here) showed that the use of certified seeds and improved varieties of wheat have positive and significant (at the 0.01 level) effects on the farmers' propensity to adopt rotation. Likewise, having access to irrigation and being in the favorable and intermediate zones increases the likelihood of a field to be under rotation. Participation in field days and hosting demonstration trials on improved crop cultivation practices and access to credit also have positive effects on the propensity to adopt rotation, but at the 0.05 and 0.1 levels, respectively. The benefits from rotation are expected to be highest in areas of higher agricultural potential with better water availability. There is also evidence that the absolute pre-crop effects tend to be similar across different soil fertility levels—confirming that our results are consistent with theoretical expectation. The negative and significant coefficients of distance from seed source and seed price are also consistent

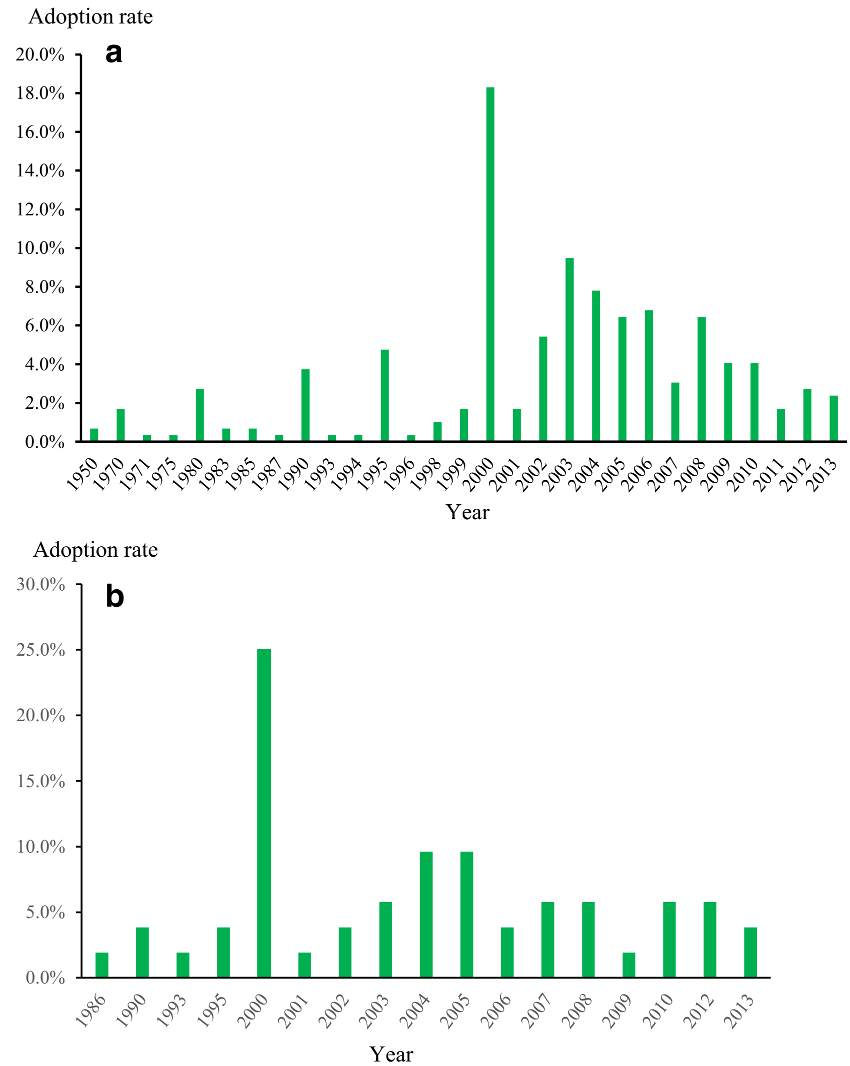

Fig. 3 **a** Starting year of cultivation for faba bean varieties currently in use (for all sample farmers). Note: The chart shows that most of the farmers adopted the new varieties after the year 2000. Source: Farm survey. **b** Year of adoption of improved faba bean varieties (for adopters only). Note: Except for 2000, the annual number of additional adopters of improved faba bean varieties has been almost uniform since 1986. Source: Farm survey

with theory. Poor access to seeds and high upfront costs of production are expected to reduce farmers' ability to adopt rotation. In the absence of seeds of improved varieties, farmers would have to plant local varieties of faba bean that are susceptible to pests and diseases—leading to higher production risks and thereby discouraging farmers from adopting rotation. Farms which use family labor are also found to have lesser tendencies to adopt rotation. The possible explanation for this result is that legume production, especially harvesting, is not yet mechanized in Morocco and hence the drudgery of producing faba beans would disincentivize farmers from using their own family labor to adopt rotation.

Likewise, adoption of improved varieties of faba bean is positively affected by the number of years of education, the use of certified seeds, and being in the favorable and intermediate zones. Farmers with a larger faba bean area and total cropped land are also found to have higher propensities to adopt. These results are reasonable, as the larger-scale farmers and those who are in relatively better rainfall areas have higher incentives to use improved varieties.

4 Conclusions

We carried out economic analyses of the adoption of legume-based rotations and improved varieties using an endogenous switching regression (ESR) applied to 2-year data on production and utilization of wheat and faba bean crops from a large sample of 1230 farm households in the wheat-based production system of Morocco. We are the first to document that legume–cereal rotations have economic advantages and make clear contributions to national food and nutrition security even under the fastest (biennial) rotation cycle possible in rainfed dry areas. Along with other benefits documented elsewhere, this finding shows that rotation is one of the few agricultural practices with joint economic, biophysical, and ecological benefits. Reduction in the amount of N fertilizer needed for a subsequent cereal crop is one of the known benefits of rotation. Against common expectation, we find that Moroccan farmers are using more N fertilizer with rotations; this undermines the ecological benefits of rotation. This, however, does not rule out the possibility that Morocco is still reaping other ecological benefits of rotation, such as improved soil health and structure, enhanced nutrient use, and broken disease cycles. The absence of new improved faba bean varieties that exhibit more of the important farmer-preferred traits, particularly those related to consumption and marketing, explains the low adoption of improved faba bean varieties and hence rotation. In addition to measures aimed at encouraging domestic production of faba bean, these findings point to the need for policy and extension interventions to strengthen the national and international research system for the development of new improved faba bean varieties with farmer-desired traits. It is also essential to raise farmers' awareness of the economic and ecological benefits of faba bean–wheat rotations in dry areas. The findings also imply that in areas where N fertilizer application rates are lower than the marginal product-maximizing levels, an economic rationale should be used to drive the rotation agenda.

Funding information Funding for this research was obtained from CGIAR Research Program on Wheat (CRP-WHEAT) (Agreement No. 200077), the EU-IFAD project entitled "Enhanced Smallholder Wheat Cropping Systems to Improve Food Security under Changing Climate in the Drylands of West Asia and North Africa" (Agreement No. 100127), and the 2nd phase of the project on Enhancing Food Security in Arab Countries (EFSAC)—Agreement No. 200021, 200001, 200052, and 200070.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Abdulai A, Huffman W (2014) The adoption and impact of soil and water conservation technology: an endogenous switching regression application. Land Econ. 90:26. https://doi.org/10.3368/le.90.1.26

Amanuel G, Kuhne RF, Tanner DG, Vlek PLG (2000) Biological nitrogen fixation in faba-beans (Vicia faba L.) in the Ethiopian highlands as affected by P fertilization and inoculation. Biology and Fertility of Soils 32:353–359. https://doi.org/10.1007/s003740000

Asfaw S, Shiferaw B, Simtowe F, Lipper L (2012) Impact of modern agricultural technologies on smallholder welfare: evidence from Tanzania and Ethiopia. Food Policy 37:283–295. https://doi.org/10.1016/j.foodpol.2012.02.013

Austin P (2008) A critical appraisal of propensity-score matching in the medical literature between 1996 and 2003. Stat Med 27(12):2037. https://doi.org/10.1002/sim.3150

Baloch FS, Karaköy T, Demirbaş A, Toklu F, Őzkan H, Hatipoğlu R (2014) Variation of some seed mineral contents in open pollinated faba bean (*Vicia faba* L.) landraces from Turkey. Turk J Agric For 38(5):591. https://doi.org/10.3906/tar-1311-31

Bolland MDA, Siddique KHM, Brennan RF (2000) Grain yield responses of faba-beans (Vicia faba L.) to applications of fertilizer phosphorus and zinc. Aust J Exp Agric 40:849. https://doi.org/10.1071/EA99164

Cook RJ, Weller DM (2004) In defense of crop monoculture: new directions for a diverse planet. Proceedings of the 4th International Crop Science Congress, 26 Sep–1 Oct 2004, Brisbane, Australia. Published on CDROM. Web site www.cropscience.org.au [Accessed on May 28, 2018]

Crepona K, Marget P, Peyronnet C, Carrouéea B, Arese P, Duc G (2010) Nutritional value of faba-beans (*Vicia faba* L.) seeds for feed and food. Field Crop Res 115:329. https://doi.org/10.1016/j.fcr.2009.09.016

El-Kalla SE, Mostafa AK, Leilah AA, Rokia AA (1999) Mineral and bio-phosphatic fertilization for intercropped faba-beans and onion. Egypt J Agric Res 77:253–271

El-Shater T, Yigezu YA, Mugera A, Piggin C, Haddad A, Khalil Y et al (2016) Does zero tillage improve the livelihoods of smallholder cropping farmers? J Agr Econ 67(1):154. https://doi.org/10.1111/1477-9552.12133

FAOSTAT (2018) FAO online database. http://faostat3.fao.org/home/E. [Accessed on 15 July 2018]

Imbens GW, Wooldridge JM (2009) Recent developments in the econometrics of program evaluation. J Econ Lit 47(1):5. https://doi.org/10.1257/jel.47.1.5

Jackson D, Cherrou Y, Santos N (2014) Morocco oilseeds sector review, country highlights, Investment Centre, Food and Agriculture Organization of The United Nations (FAO), Rome, 2014. http://www.fao.org/3/a-i3922e.pdf [accessed on July 9, 2019]

Jacques PJ, Jacques JR (2015) Monocropping cultures into ruin: the loss of food varieties and cultural diversity. Sustainability 4:2970. https://doi.org/10.3390/su4112970

Jensen ES, Peoples MB, Hauggaard-Nielsen H (2010) Faba-beans in cropping systems. Field Crop Res 115:203. https://doi.org/10.1016/j.fcr.2009.10.008

Kirkegaard J, Christen O, Krupinsky J, Layzell D (2008) Break crop benefits in temperate wheat production. Field Crop Res 107:185. https://doi.org/10.1016/j.fcr.2008.02.010

Köpke U, Nemecek T (2010) Ecological services of faba bean. Field Crop Res 115(3):217. https://doi.org/10.1016/j.fcr.2009.10.012

Lawson YD, Dzomeku I, Drisah Y (2007) Time of planting *Mucuna* and *Canavalia* in an intercrop system with maize. J Agronomy 6:534. https://doi.org/10.3923/ja.2007.534.540

Lopez-Bellido L, Lopez-Bellido RJ, Redondo R, Benitez J (2006) Faba-beans nitrogen fixation in a wheat-based rotation under rain fed Mediterranean conditions: effect of tillage system. Field Crop Res 98:253. https://doi.org/10.1016/j.fcr.2006.03.001

Nuruzzaman M, Lambers H, Bolland MDA, Veneklaas EJ (2005) Phosphorus benefits of different legume crops to subsequent wheat grown in different soils of Western Australia. Plant Soil 271:175–187. https://doi.org/10.1007/s11104-004-2386-6

Oomah B, Tiger N, Olson M (2006) Balasubramanian P. Phenolics and antioxidatives activities in narrow-leafed lupins (*Lupinus angustifolius* L.). Plant Food Hum Nutr 61:91. https://doi.org/10.1007/s11130-006-0021-9

Pannell DJ, Marshall GR, Barr N, Gurtis A, Vanclay F, Wilkinson R (2006) Understanding and promoting adoption of conservation practices by rural landholders. Aust J Exp Agric 46:1407–1424. https://doi.org/10.1071/EA05037

Powers D (1993) Endogenous switching regression models with limited dependent variables. Sociol Method Res 22(2):248. https://doi.org/10.1177/0049124193022002004

Preissel S, Reckling M, Schläfke N, Zander P (2015) Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: A review. Field Crop Res 175:64. https://doi.org/10.1016/j.fcr.2015.01.012

Pypers P, Huybrighs M, Diels J, Abaidoo R, Smolders E, Merckx R (2007) Does the enhanced P acquisition by maize following legumes in a rotation result from improved soil P availability? Sil Biol Biochem 39:2555 https://hdl.handle.net/10568/92833

R'Kiek C (1994) Synthèse des travaux de recherche. Edts INRA, 10 p. http://om.ciheam.org/article.php?IDPDF=96605758

Ruisi P, Amato G, Badagliacca G, Frenda AS, Giambalvo D, Di Miceli G (2017) Agro-ecological benefits of faba-beans for rainfed Mediterranean cropping systems. Ital J Agron 12(3):223. https://doi.org/10.4081/ija.2017.865

Schilizzi S, Pannell DJ (2001) The economics of nitrogen fixation. Agronomie 21(6-7):527. https://doi.org/10.1051/agro:2001142

Suso MJ, Maalouf F (2010) Direct and correlated responses to upward and downward selection for outcrossing in *Vicia faba*. Field Crop Res 116(1-2):116. https://doi.org/10.1016/j.fcr.2009.12.001

Vereijken P, Kloen H (1994) Innovative Research with Iconological Pilot Farmers. In Plant Production on the Threshold of a New Century. Proceedings of the International Conference at the Occasion of the 7th Anniversary of the Wageningen Agricultural University, held between June 28 and July 1, 1993, Wageningen, The Netherlands

Walker TS, Alwang J, Alene A, Ndjuenga J, Labarta R, Yigezu YA, et al. (2015) Varietal Adoption, Outcomes and Impact. In Crop Improvement, Adoption, and Impact of Improved Varieties in Food Crops in Sub-Saharan Africa, CABI Wallingford. https://ispc.cgiar.org/sites/default/files/pdf/ISPC_DIIVA_synthesis_report_FINAL.pdf

Yigezu YA, El-Shater T, Mugera A, Aw-Hassan A, Piggin C, Haddad A et al (2018a) Enhancing adoption of agricultural technologies requiring high initial investment among smallholders. Technol Forecast Soc 134:199–206. https://doi.org/10.1016/j.techfore.2018.06.006

Yigezu YA, Yirga C, Kassie GT, Aw-Hassan A (2018b) Modelling land use decisions in production systems involving multiple crops and varieties. African J Agric Resour Econ 13(3):240 http://afjare.org/wp-content/uploads/2018/09/4.-Yigezu-et-al.pdf

Yigezu YA, Boughlala M, El-Shater T, Najjar D, Bentaibi A (2019). Analysis of the Adoption, Impacts, and Seed Demand of Improved Varieties. In Political Economy of the Wheat Sector in Morocco: Seed Systems, Varietal Adoption and Impacts. International Center for Agricultural Research in the Dry Areas, Beirut

Yusuf AA, Iwuafor ENO, Abaidoo RC, Olufajo OO, Sanginga N (2009) Grain legume rotation benefits to maize in the northern Guinea savanna of Nigeria: fixed-nitrogen versus other rotation effects. Nutr Cycl Agroecosyst 84:129. https://doi.org/10.1007/s10705-008-9232-9

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.