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Intensification options in cereal-legume production systems generate trade-offs between sustainability pillars for farm households in northern Morocco

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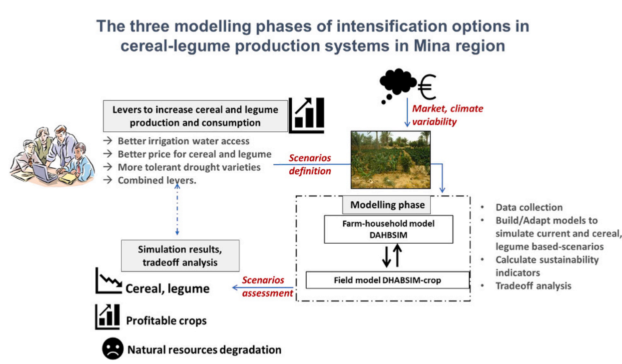
HIGHLIGHTS

- Higher prices and lower variability for grain crops have a modest effect on their production
- Current agricultural policies in MENA region only enable increased natural resources degradation.
- More land allocated to vegetables and not grains as access to irrigation water increases

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Farmers in the MENA (Middle East and North Africa) region face several interrelated challenges including natural resource depletion, low crop productivity, and food and nutrition insecurity. To address some of these challenges, governments are considering different incentives to increase crop production. However, incentives often entail trade-offs and may have diverging effects on economic, social, and environmental sustainability.

OBJECTIVES: This study assessed the *ex-ante* effects of incentives targeted towards increasing crop production on the production and consumption decisions of farm households on the Saïss plain of northern Morocco.

METHODS: The assessment was conducted with a dynamic, intertemporal farm household model that simulates farm production and food consumption decisions. The model was calibrated using survey data from 85 farm households for 2014. Four scenarios were codesigned with local stakeholders and then simulated over a continuous 15-year period to capture rainfall variability: (1) increased availability of annual groundwater for irrigated cropping from 31 m^3 ha^{-1} to 215 m^3 ha^{-1}, (2) a 15% increase in grain prices for cereals and legumes,

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(3) introduced drought tolerant crop varieties, and (4) a fourth scenario that combines all factors in the above three scenarios.
RESULTS AND DISCUSSION: Our results showed that regardless of the scenario, the area of cereals and legumes cultivated only slightly changed compared to the Baseline scenario. However, according to the scenarios tested, the total production of cereals increased by 10% to 21% and of legumes increased by 2% to 9%. This production increase is the direct consequence of increased crop yields due to an intensification of crop production methods. The incentives increased the consumption of cereals and legumes by up to 43%. This increase was mainly due to a shift from grain to vegetable production that increases cash income, resulting in more food purchases from the market while consumption from own production dropped by up to 53%. The average increase in crop income was 14% in scenarios 1–3 and 28% in scenario 4. However, increased income had ramifications for nature resource stocks, with irrigation water use from groundwater increasing by 593% in the Water scenario and 320% in the combined scenario, relative to the Baseline scenario. In the Water scenario, incomes increased by 15% and nitrogen leached increased by 36%, highlighting the trade-off between economic and environmental sustainability.
SIGNIFICANCE: These results show the challenges in obtaining acceptable compromises between the three sustainability pillars as the scenarios increased income but also led to increased groundwater extraction and nitrate leaching.

1. Introduction

Cereal and legume crops are important sources of food in the MENA (Middle East and North Africa) region (Billen et al., 2015; Sadok et al., 2019). Despite efforts to improve cereal and legume production, domestic production is typically insufficient to meet domestic demand, for example, more than 50% of cereal demand and 80% of legume demand in the MENA region is met from inter-region imports (Dernini et al., 2017; Marrou et al., 2021). This reliance on imports poses major challenges (Khoury et al., 2014), which are exacerbated by price volatility (Soffiantini, 2020), extreme weather, and geopolitical tensions that influence trade. Different price and production incentives can enhance the productivity and profitability of cereal-legume cropping systems (Yigezu et al., 2019). However, the effectiveness of these incentives is often plagued with environmental concerns related to the overextraction of finite groundwater resources, nitrate leaching, and soil fertility decline.

In the MENA region, agriculture is increasingly becoming specialised. While higher incomes from specialised agriculture provide an opportunity to increase market purchases of food, restricted market access, high transaction costs, and marketing risks compromise the ability of farm households to sustain a balanced diet through increasing market purchases of food alone (Hossard et al., 2021). Moreover, specialised agriculture has increased the extraction of groundwater resources to support irrigation activities (Ahmed et al., 2021), and this increased extraction can lead to a greater prevalence of conflicts over water resources (Li et al., 2021). Within this context, the conservation of soil and water resources, the improvement of farm income, and securing a stable and sustainable supply of diverse crops is important for public policy (Garnett et al., 2013; Struik and Kuyper, 2017). There are several price and productivity policies in the MENA region that have aimed to revitalise crop production, including in Tunisia (CEA-AN, 2012), Lebanon (Hadi and Heinrich, 2017), Egypt (Medany, 2016), and in the Pillar II of the Green Morocco Plan (Saoud, 2011). However, unanswered questions remain about how these policies may influence the performance of farm households.

Existing studies on farm household performance in the MENA region have mostly taken a qualitative approach to understand the production and income trajectory of farms (El Ansari et al., 2020). Some studies have examined *ex-ante* responses to policy incentives (Belhouchette et al., 2012; Jeder et al., 2019). To examine these responses requires considering the possible interactions between the biophysical characteristics of the farm and the socio-economic resources and strategies that determine their productive potential at field and farm scales (Souissi et al., 2017).

The objective of our study is to explore options for the intensification of cropping systems for farm households on the Saïss plain of northern Morocco. We ask the question: how production incentives relating to additional groundwater, increased crop prices, and more drought tolerant crop varieties affect the production and consumption decisions of a typical farm household. The incentives were designed and proposed by local stakeholders as being the main levers capable today of increasing farm production and income. To answer the question, we used a farm household model called "Dynamic Agricultural Household Bio-Economic Simulation Model - DAHBSIM" (Komarek et al., 2017), which was adapted to the conditions of the study region.

2. Methods

2.1. Study region context

The study region was the Saïss plain, which covers a land area of about 2200 km^2 in northern Morocco. A semi-arid climate characterises the Saïss plain. During the 1980–2010 period, annual average rainfall was 500 mm (range 207–677) (El Ansari et al., 2020). Most farms in the study region combine non-irrigated cereal crops with legume and vegetable crops. Cereals account for 50% of the total arable land and the region contributes 13% of the total cereal production in Morocco. On average, 14% of all arable land on the Saïss plain is irrigated (Berni et al., 2018). The production of cereals and vegetables is mainly market-oriented but with a sizeable quantity used for self-consumption (defined as consuming own-produced food). Crop yields vary greatly across farms and also across years. For example, the median yields for wheat and onions in 2014 were 3.5 t ha^{-1} and 28 t ha^{-1} with standard deviations of 1.4 t ha^{-1} and 13.6 t ha^{-1}, respectively (El Ansari et al., 2020). Farmers on the Saïss plain have historically used a range of crop sequences such as wheat-wheat (wheat monocropping), a wheat-barley rotation, or a wheat-legume rotation. However, in the past decade, rotating non-irrigated wheat with irrigated vegetables has become more common, due to vegetables profitability.

The crop income per farm in the study region is about 28,000 Moroccan Dirhams (MAD), which is 58% less than the national average (Vidic, 1978). Sales of cereal grain (mainly soft wheat: *Triticum aestivum*), barley (*Hordeum vulgare*), and vegetables (onion: *Allium cepa* and potato: *Solanum tuberosum*) are the major sources of cash income for farm households (Hossard et al., 2021).

Until the early 1980s, Morocco focused on promoting self-sufficiency in key crops such as cereals, and on exporting in an unstructured way a few crops such as tomatoes (Harbouze et al., 2019). This period was marked by a policy of direct support to farmers and a market price guaranteed for key crops. From the 1980s, state intervention in the Moroccan agricultural sector gradually reduced, although subsidies continued for agricultural inputs like certified seeds (Harbouze et al., 2019). This situation continued until the 2000s, by which stage endemic poverty was widespread among farm households, mainly caused by low crop productivity. In 2008, the Green Morocco Plan was launched with a 12-year horizon. One of the main objectives of this Plan (pillar II) was to increase farmers' incomes and employment by focusing on producing high value-added crops and providing improved access to inputs (mainly irrigation), while simultaneously improving food sovereignty (World-Bank, 2020). The Plan also proposed to increase cereal crop yields. In 2021, the Green Generation Plan was launched with the main objective to sustainably preserve natural resources, in addition to improving the livelihoods of farmers and strengthening their sovereignty of cereal production.

Since the launch of the Green Morocco Plan in 2008, the Saïss plain has seen a gradual intensification of agricultural production. This intensification has been also accompanied by specialization, mainly based on onion and potato production, which lead to an increase of about 15% in the area share of marketable vegetable crops in less than 10 years (Fadlaoui et al., 2013). A central part of the intensification has been through the irrigation of crops using groundwater, and this had led to, in some regions, an average decrease in the groundwater table of 90 m over the past 32 years (Fadlaoui et al., 2013).

2.2. Characteristics of the simulated farm household

The primary data used in this study were taken from a survey that included 85 farm households on the Saïss plain (El Ansari et al., 2020). The survey was conducted in 2014 by the International Centre for Agricultural Research in Dry Areas (ICARDA), the Institut National de la Recherche Agronomique (INRA)-Morocco, and the CIHEAM-IAMM Montpellier (El Ansari et al., 2020). Both purposive and stratified random sampling techniques were used to select the villages and households to survey within villages.

Interviews with the household heads were conducted using a set of three structured questionnaires. The first questionnaire investigated the socio-economic and nutritional characteristics of the household, such as questions on gender and age composition, farming activities, sources of income, consumption of different food products both from on-farm production and market purchases. The second questionnaire looked in more detail at each household's farming activities. It aimed at 1) understanding the impact of farming decisions on crop production, including water and fertilizer use and implications on soil fertility, and the share of self-consumption relative to the total production per crop; and 2) identifying the main tasks involved in growing crops as well as the division of labour (for men and women) for specific farm activities. The third questionnaire sought structural data to mainly describe crop production on the surveyed farm households including available arable land area, actual land use, the amount of time spent on agricultural activities, the proportion of each task performed per labour type (family vs. hired) and yields of crops from each plot within each surveyed farm by soil type and input quantity.

We simulated how different policy incentives alter indicators of farm household sustainability for a typically farm in the study region. The typical farm was based on a farm household typology analysis of 286 households that identified three distinct farm household types in the study region (El Ansari et al., 2020). We only conducted our simulations on one of the three farm household type that was the mixed cereal-legume farm household. This household type had a sample size of 85 farm households and reflected a common type of farm household in the study region and in the MENA region (Bazzi et al., 2021).

Mixed cereal-legume farm households mostly cultivate rainfed cereal crops (barley and soft wheat) in rotation with rainfed legume crops (chickpea and broad bean) and some irrigated potato and onion crops. Their production system is characterized by low levels of external inputs of 60 kg of nitrogen (N) per ha applied as mineral fertilizer, 31 m^3 ha^{-1} of irrigation (ground) water and an average of labour requirement of 11 person-days ha^{-1} month^{-1}. As a result, average grain yields of 3.3 t ha^{-1} for soft wheat and 3.5 t ha^{-1} for barley are low compared to their potential (Table 3), and hence low cash incomes of 6491 MAD ha^{-1} from cropping (Table 1, Table 2). Regardless of crop, the household mainly produces for the market (Table 2). The cereals and legumes consumed by farmers from their own production constitute less than 1% of the total production (Table 2). That said, the quantity of wheat consumed from on-farm production is around 160 kg person^{-1} year^{-1} (Table 2). This represents 80% of the Moroccan average of 200 kg person^{-1} year^{-1} (Fellahtrade, 2022).

2.3. Farm household model

2.3.1. Objective function

To simulate the scenarios, we adapted the Dynamic Agricultural Household Bioeconomic Simulation Model called DAHBSIM to the contexts in our study region. The DAHBSIM model is an optimization model for the simulation of scenarios related to policies and economic incentives, to improve the livelihoods of farm households where households consume varying levels of their own agricultural produce. The model was initially used in Malawi to assess fertilizer prices (Komarek et al., 2017) and crop productivity (Komarek and Msangi, 2019). In the current study, we adapted the model to the context of the semi-arid areas of Morocco. This adaptation was mostly related to adapting the water budget module, as a subcomponent of the DAHBSIM summary crop module, to better reflect drier climates (Supporting Information Section 2).

DAHBSIM is a mathematical programming model that optimises an inter-temporal objective function subject to several constraints, given historical data on market and weather conditions. The model is inter-temporal because equations are indexed over the 15-year simulation sequence and the decisions of farmers made to optimise the model's objective function (Eq. 1). DAHBSIM maximises the utility of the farm household by using the mean-standard deviation approach in Eq. 1 (Hazell and Norton, 1986):

$$U = \sum_{y=1}^{n} \left(\frac{CI_y + OI_y + VFC_y - (\varnothing \times \sigma_y)}{(1+i)^y} \right) \tag{1}$$

Where U is the objective function to be maximised over a simulation period of n individual years (y), CI_y is crop income, and OI_y is non-agricultural income. Crop income (CI_y) equals the summation of cash revenues from all farm products sold (multiplication of quantity sold by market price) minus the summation of the cost of all inputs used such as seeds, fertilizer, hired labour, irrigation water, and mechanisation. VFC_y is the implicit value of food self-consumption, with the quantity of self-consumption valued at market prices. Farm household income equals $CI_y + OI_y$ and farm household profit equals $CI_y + OI_y + VFC_y$. The annual discount rate (i) is set at 4%. Ø is the risk aversion coefficient, and σ is the annual standard deviation of the farm household income. Our study used a set of states of nature for crop prices and yields to calculate the

Table 1
Characteristics of the simulated farm household.

Variable	Average	Standard deviation
Cropped area (ha)	11.62	11
Irrigated area (%)	2.6	3.7
Crop income (MAD ha^{-1} year $^{-1}$)	6491	8795
Off-farm income (MAD year $^{-1}$)	2457	827
Total cattle (number)	3.3	4
Total sheep (number)	11.2	24
Irrigation water (m^3 ha^{-1} year $^{-1}$)	31	99
Total labour (person-days ha^{-1} month^{-1})	11	32
Mechanisation cost (MAD ha^{-1} year $^{-1}$)	586	312
Seed costs (MAD ha^{-1} year $^{-1}$)	519	310
Mineral fertilizer (kg N ha^{-1} year $^{-1}$)	60	51
Family size (number of people)	6	3

Notes: Data from a survey of 85 farms in the mixed cereal-legume farm household type (El Ansari et al., 2020). MAD is the Moroccan Dirham, 1 MAD = 0.098 $.

Table 2
Average crop production and self-consumption for the simulated farm household.

Variable	Cereals		Legumes		Vegetables	
	Wheat	Barley	Chickpea	Faba bean	Onion	Potato
Area planted (ha)	6.48	1.24	2.16	1.44	0.27	0.03
Irrigated area (ha)	0.0	0.0	0.0	0.0	0.27	0.03
Volume of irrigation water (m^3 ha^{-1})	0.0	0.0	0.0	0.0	1190	1254
Yield (t ha^{-1})	3.3	3.5	1.7	1.5	19	33
Total production (t)	21.4	4.4	3.4	2.2	5.13	0.99
Quantity sold (t)	15.12	2.28	2.24	1.75	5.1	0.98
Quantity used to feed animals (t)	0.07	0.91	0.00	0.39	0.00	0.00
Quantity retained for seeds (t)	4.85	1.05	1.12	0.01	0.01	0.00
Other uses (t)	0.34	0.05	0.00	0.02	0.01	0.00
Self-consumption (t $household^{-1}$ $year^{-1}$)	1.014	0.088	0.011	0.003	0.024	0.003
Self-consumption (kg $capita^{-1}$ $year^{-1}$)	159.5	13.18	1.68	0.43	3.83	0.36
Self-consumption (kcal $capita^{-1}$ day^{-1})	1503.3	44.1	7.9	1.6	4.5	5.0

Notes: Data from 85 farms in the mixed cereal-legume farm household type (El Ansari et al., 2020). The caloric content of each crop was obtained from Smith et al. (2016). Other use means quantity per product offered for family members and neighbours. Cereal and legume yields are expressed in dry weights. Vegetable yields are expressed fresh weights. All data (including crop yields) are from the farm survey (Section 2.2).

standard deviation of farm household income. Our standard deviation calculation is based on levels of simulated farm household income and historical variability in crop yields and prices (FAO, 2022) (Supporting Information Section 1). These variable yields and prices capture two sources of production and market risk encountered by farmers (Komarek et al., 2020).

The key model outputs (optimised variables) in DAHBSIM include area allocated to each crop, and associated input quantities for each crop, family labour time allocation, crop production, self-consumption, consumption through market purchases. Other indicators include environmental externalities from crop production such as volume of irrigation water used, and soil indicators related to nitrate leaching, organic matter content, and soil nitrate content.

2.3.2. Land, labour, and crop rotation constraints

For land, the household cannot allocate more land to crops than is available. For labour, the household must have enough labour available from family sources and from hiring in labour to meet monthly labour requirements for agricultural tasks. For agronomic rotational constraints, the household cannot grow the same crop type on the same plot of land, for a specific soil type, in two consecutive years. For example, the household cannot grow chickpea or faba bean on the same plot of land, for a specific soil type, in two consecutive years.

2.3.3. Cash constraint

Expenditure on agricultural inputs and food products from the market cannot exceed cash income ($CI_y + OI_y$) in any year (Eq. 2). The year subscript is dropped from Eq. 2 for presentation purposes Only.

$$CI + OI \geq \sum_{prd=1}^{PRD} QB_{prd}\, P_{prd} + \sum_{ipt=1}^{IPT} QB_{ipt}\, P_{ipt} \tag{2}$$

where QB is the quantity of a product purchased from the market (*prd*) or an input used in on-farm production (*ipt*), and P is the price. Non-agricultural income (*OI*) is assumed to be constant each year, based on its value reported during the household survey.

2.3.4. Product supply and demand constraints

For the simulated household in each year for each product (*prd*), the quantity of total consumption (*QC*) cannot exceed the sum of the quantity consumption from own production (self-consumption) (*QSC*), the quantity of that product purchased from the market (*QB*), and quantity saved as seed for the subsequent year (if any) (*QS*) (Eq.3).

$$QC \leq QSC + QB + QS \tag{3}$$

2.3.5. Recursive link across years within model

The model has a dynamic recursive structure that explicitly accounts for dynamic interactions across the years by using the end values of the previous year as the starting values for the current year. The model updates the soil water content, soil organic matter, and soil nitrogen content each year by considering the previous crop and its management. The soil conditions of nitrogen and organic matter are the key dynamic variables that are updated and re-initialised between years, as is the carryover of seed stocks. The yields obtained at the end of the first (inter-temporal) simulation year are multiplied by biophysical stress coefficients which increase or decrease the yields in the next (inter-temporal) simulation years depending on the preceding crop and next year's precipitation.

2.4. Data for model calibration and scenario simulation

2.4.1. Input date for crop module

A critical component of the database used in DAHBSIM is input data for the crop module. The parameters used in the crop module are as follows (as summarised in Table 3):

- Soil parameters: soil density (1.2 m^3 kg^{-1}), soil water holding capacity (133 mm m^{-1}), soil depth (1.2 m), organic matter (1%), mineralization rate (1.3), initial soil water (80 mm m^{-1}) and nitrate (10 kg N ha^{-1}) contents were obtained from the experimental INRA station in Meknes (Touhtouh et al., 2015)
- Rainfall and temperature: average monthly rainfall, as well as daily maximum and minimum temperatures and solar radiation were obtained from the nearest meteorological station of the Institute National de la Recherche Agronomique de Meknès (INRA-Meknès) to the study region. The potential evapotranspiration was calculated using the Priestley-Taylor method (De Bruin and Keijman, 1979).
- Agronomic practices: actual irrigation water and nitrogen fertilizer application rates for each crop were obtained from the farm survey.
- Crop growth and development: Phenological characteristics as well as growth parameters (e.g., maximum root depth) were determined for each crop using a range of data including published data and farmer data from the field surveys (Table 3).

2.4.2. Activity, farm household, consumption, and market database

The DAHBSIM database was divided into two main sections to capture household decisions: the first one describes the structure of the farm households including age and gender structure of the family, and agricultural input use; the second one describes the agricultural activity at plot level for each farm household. The agricultural activities in our study are defined based on the Hammouda et al. (2018) methodology, where activities are based on a combination of a crop, a cultivar (local or improved), a soil type (organic matter content), and an intensification level based on application rates for seed, fertilizer, labour, mechanisation cost, and irrigation water. There are two intensification levels for crop production in the current study: (1) extensive and (2) intensive. There are 198 activities possible for the simulated farm household to conduct, with activity details here https://cloud.iamm.fr/index.ph

Table 3
DAHBSIM crop module parameters.

Parameter	Data source	Crop					
		Wheat	Barley	Chickpea	Faba bean	Onion	Potato
Crop cycle (days)	Farmer survey	180	180	120	120	150	150
Potential yield (t ha^{-1})	Technical document INRA Meknes	6.5	5.5	2.5	4	55	45
Crop Coefficient (Kc)	Steduto et al. (2012)	1.15	1.15	1	1.05	1.05	1.15
Yield response factor to water stress (Ky)	Calibrated	1.05	1.05	1.05	1.15	1.10	1.10
ET0 (mm day^{-1})	Calculated	4.5	4.5	4.5	4.5	4.5	4.5
Maximum root depth (m)	Technical document INRA Meknes	0.9	0.9	0.8	0.6	0.9	0.9
Nitrogen to crop yield coefficient (KN) (kg N kg $grain^{-1}$ or $tuber^{-1}$)	Calibrated	0.03	0.025	0.03	0.03	0.008	0.007

Notes: Kc is growth phase dependent. The values of Kc presented here correspond to the maximum value of Kc at the flowering stage.

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2.4.3. *Crop module calibration and validation*

The calibration process of the model had two steps. First, calibration was done for the crop module. Second, calibration was done at the scale of the farm household. We evaluated the simulated crop yields against data from the farmer surveys, as suggested by Belhouchette et al. (2011) and Komarek et al. (2017). For each activity, we initially parameterised the model using only activities carried out with low inputs (intensification level: extensive). After which the model was validated for the same activities but under an intensive production setting.

To calibrate the crop module, we only adjusted the parameters to which the crop module is sensitive, as suggested by Belhouchette et al. (2012). We parameterised the conversion coefficients of nitrogen into biomass (*KN*), and the yield response factor to water stress (*Ky*) and then adjusted their values within a reasonable range of fluctuation as detected by previous research, and the authors' knowledge and experience (Donatelli et al., 1997). Simulated and observed yields were compared using the relative Root Mean Squared Error (rRMSE) (Loague and Green, 1991) in Eq. 4:

$$RRMSE = \frac{\sqrt{\sum_{1}^{n} \frac{(Oi-Si)^2}{n}}}{\overline{O}} \times 100 \quad (4)$$

where: S_i is simulated yield, O_i observed yield, $\bar{O}$ average observed yield, and n the number of observations.

2.4.4. *Farm household module calibration*

In the first step, the first simulation year is used as the base year to evaluate the performance of the model by comparing the simulated and observed data. The variables selected for the evaluation of the performance of the model included crop areas, crop income, and crop self-consumption. In this first step, the model was solved for several values of the risk aversion coefficient. The risk aversion coefficient retained was the one that produced the smallest difference between simulated and observed data using the percentage of average deviation (*PD*) (Hazell and Norton, 1986) (Eq. 5):

$$PD = \frac{(Xsim - Xobs)}{Xobs} \times 100 \quad (5)$$

Where: *Xsim* is the simulated value of the variable that requires calibration, *Xobs* is the observed value, and *PD* is percentage deviation. In the second step. Positive Mathematical Programming (PMP) (Howitt, 1995; Heckelei, 2003; Belhouchette et al., 2011) was used so that the simulated crop areas equalled the observed crop areas in the first simulation year.

2.5. *Scenario design*

The study team designed the simulation scenarios jointly with ten individuals from different professional backgrounds representing local stakeholders that focus on sustainably enhancing cereal (notably soft wheat) and legume production. A meeting with local stakeholders was set up in March 2016 to identify simulation scenarios and possible levers that may address policy relevant challenges. Table 4 presents the list of stakeholders present and their affiliation. The meeting was carried out in three stages: i) a presentation of the study context and goals, ii) a presentation of the production goals and socio-economic issues for the farmers surveyed via individual interviews, and iii) a general discussion that aimed to specify the key issues at stake in the study region, and the levers available to address the issues.

After considerable deliberations with the local stakeholders, a consensus was reached on four key issues:

First, the importation of soft wheat in Morocco is becoming increasingly expensive for the Moroccan government, costing 1.2 billion dirhams in 2015 (MIF, 2017). This policy of government importing wheat primarily aims to keep the purchase price of wheat flour affordable for consumers. However, this policy inadvertently turned out to be detrimental to domestic producers of soft wheat whose average cost of production is typically higher than farmers in exporting countries thereby making domestically produced wheat more expensive relative to its international price. This issue appears to be a real hurdle in the overall effort to increase local production of soft wheat. Questions remain if reducing the quantities imported would facilitate the diversion of resources to encourage greater domestic production of soft wheat. Today, 90% of soft wheat producers in Morocco sell their production to the Office National Interprofessionnel des Céréales et des Légumineuses (ONICL) with a producer support price set at 2800 MAD t^{-1}. Despite this support, production of soft wheat is struggling to prevail as it is faces serious competition from horticulture and arboriculture. With the development of irrigation, horticulture and arboriculture are often more profitable than soft wheat (Sayouti and Mekki, 2015).

Second, there is an absence of direct support for legume production despite their importance as a source of human food, livestock feed, and in maintaining soil fertility. The area of legumes planted is fast decreasing in Morocco because of their low and variable yield which is related to their sensitivity to biotic (pest and diseases) and abiotic (soil moisture) stresses, variable prices, and their substantial labour demand, notably for weeding.

Table 4
List of stakeholders consulted and their affiliations.

Affiliation	Skills
Farmers	Two cereal farmers and one vegetable farmer
Researchers from INRA Meknes	One agronomist specialised in cereal and legume-based agricultural systems. Two agricultural economists.
An advisor from the division of irrigation and farmland development of the Ministry of Agriculture	Water resource management
Two agricultural advisors from Office National du Conseil Agricole (ONCA)	Management of irrigation and agricultural practices
An agricultural advisor from the Regional Agriculture Department (DRA)	Incentive measures of production and strategic choices

Third, the intensification of cereal production will inevitably lead to an increase in the irrigation area dedicated to soft wheat and legumes, which currently are mostly grown in non-irrigated fields. Fourth, the introduction and cultivation of new certified varieties will make it possible (to a certain extent) to increase soft wheat and legume yields and decrease their variability. This will be possible by continuing the introduction of selected non-hybrid varieties that are free of viruses, but also more tolerant to spring moisture-stress.

Based on these past trends and projections, five scenarios were codesigned with the stakeholders: Baseline, Premium, Water, Variability, and Combined. In all five scenarios socio-economic, land use, yield per crop and intensification level, environmental and household food consumption indicators were calculated (Table 7 and Table 8). All scenarios were simulated over a 15-year period. A 15-year simulation period was chosen as it was deemed sufficiently long to cover a wide range of rainfall conditions. For the 15-year simulation period, average annual rainfall was 431 mm year^{-1}, the rainfall standard deviation was 136 mm year^{-1}, and the rainfall coefficient of variation was 32%.

A Baseline scenario in which economic conditions for the farm household remain the same over a 15-year simulation. The only exogenous factor that varies over the simulation period is annual precipitation, which causes endogenous changes in soil water and nitrogen dynamics. Results from the remaining four incentive scenarios are compared to results from this Baseline scenario.

A Water scenario that increases water available for cropping on the farm household. The local agency of irrigation water oversees the set-up, the maintenance, and the billing of irrigation water for farmers in the Saïss area. This agency divides the Saïss irrigation area into different sectors depending on the volume of irrigation water provided to farmers. The low input-farms dominated by cereals and legumes are typically located in a sector in which farmers are provided with a limited amount of irrigation water. To increase crop production through increasing the total volume of irrigation water, the agency has heavily invested in new water infrastructure over the past 5 years. In the Water scenario the simulated farm household has more irrigation water available each year (215 m^3 ha^{-1} instead of the current 31 m^3 ha^{-1}). For this scenario, the only modifications compared to the Baseline scenario are (a) the change in the volume of groundwater that is available for irrigation at farm level, (b) introducing the possibility to cultivate additional irrigated cereal and legume crops (data required to simulated the irrigated crops in DAHBSIM obtained from local experiments), and (c) an additional transaction cost to the farmer which was estimated in consultation with the local irrigation agency at 10% of the total irrigation cost (i.e., from 122 MAD ha^{-1} to 134 MAD ha^{-1}. The total irrigation cost represents almost 5% of the total production cost. In this scenario, the investment costs required to provide the infrastructure to increase water availability on farm are paid by the government, as is the currently reality.

A Premium scenario in which the farm household receives a 15% higher price of soft wheat and legumes compared to in the Baseline scenario. This scenario poses the question if grain price incentives can increase grain production given the existing profitability of other non-grain crops. An aim of this price support is to stabilise income for social reasons such as expressed in the previous (Green Morocco Plan, 2008–2018) and the more recent (Generation Green, 2020–2030) agricultural policies. For wheat this represents 3220 MAD t^{-1} instead of the current selling price of 2800 MAD t^{-1}. This scenario reflects current debates that insist on the need to increase the support for soft wheat production, which has evolved little since 2005, and to initiate support for legume production. Without this price support, Moroccan cereal farmers may decrease the land area dedicated to cereal crops in favour of more profitable vegetable crops.

A Variability scenario in which the farm household encounters lower variability in soft wheat and legume yields through changes in varieties. This scenario shows the current efforts of public research and development institutions which seek to extend the use of improved varieties and certified seeds. Only 10% of legume seeds across the Saïss plain are certified (Laamari et al., 2016). For this scenario, we did not simulate a yield increase linked to the use of certified seeds. We assumed that various other factors contribute to limiting production (e.g., water stress). For that reason, this scenario includes a 15% decrease in yield variability for soft wheat and legumes, and an increase in the seed cost for soft wheat and legumes. The seed cost (obtained during the meeting with local stakeholders) increased for soft wheat from 3280 MAD t^{-1} to 3770 MAD t^{-1}, for chickpea from 10,800 MAD t^{-1} to 12,420 MAD t^{-1} and for faba bean from 9300 MAD t^{-1} to 10,700 MAD t^{-1}.

A Combined scenario in which the farm household has the following three incentives: a 7.5% increase in the price of cereals and legumes (instead of the 15% considered in the Premium scenario), irrigation water availability of 129 m^3 ha^{-1} year^{-1} compared to the 215 m^3 ha^{-1} year^{-1} in the Water scenario, and access to the benefits of same improved varieties in the Variability scenario. This Combined scenario investigates how all three incentives alter production and consumption decisions.

3. Results

3.1. Model calibration

The comparison between the observed and simulated yields gave a rRMSE below 11% in the calibration step (Table 5). For the validation step, the simulated yields, except for chickpea, are comparable to the observed yields. The lowest rRMSE was obtained for vegetable crops and the highest rRMSE was for chickpea (Table 5).

A risk aversion coefficient of 1.6 was selected as a first step in the PMP calibration process because it gave the lowest deviation of simulated crop area from observed crop area (Table 6). For crop income, the average absolute deviation between simulated income and observed income was 8% when the risk aversion coefficient was 1.6 (Table 6). However, the total quantity of self-consumption of crops was underestimated (Table 6). Smallholder farmers often have a preference for consumption from their own production even at higher opportunity costs mainly for cultural and market risk aversion reasons (Yigezu and Sanders, 2012).

3.2. Scenario results: averages

The largest increase in average crop income over the 15-year simulation period was in the Combined scenario (from 7380 MAD to 9460 MAD), i.e., a 28% increase compared to the Baseline scenario (Table 7). For the other scenarios, the average increase was 14.5% compared to the Baseline scenario.

For all the four incentive scenarios, the area of cereals and legumes remained similar. This seems counterintuitive as the area dedicated to vegetables increased by 50% to 250% relative to the Baseline scenario (Table 7). Despite the high percentage increases, the absolute area of vegetables remained minor compared to cereals and legumes.

The area dedicated to cereals decreased by 5% in the Water scenario, 6% in the Variability scenario, and 11% in the Combined scenario. Cereals are less profitable than vegetables, which explains why with more irrigation water more vegetables are grown at the expense of cereals. The Premium scenario did not change cereal areas because the 15% price increase did not compensate for the difference in profitability of vegetables relative to cereals. That said, the incentives scenarios increased the area of legumes by 5% to 24% relative to the Baseline scenario, and specifically by 16% in the Premium scenario (Table 7). This increase in legumes was accompanied by an increased area of vegetables because a larger area was planted to the more profitable legume-vegetable rotation at the expense of the fallow area (Table 7).

In all incentive scenarios, irrigation water used, and nitrate leaching was at least equal to the Baseline scenario. For irrigation water, the largest increase was in the Water scenario (593%) followed by the Combined scenario which led to an increase of about 320% relative to

Table 5
Crop model calibration and validation.

Crops	Number of extensive activities	Model calibration results			Model validation results			
		Simulated yield (t ha^{-1})	Observed yield (t ha^{-1})	rRMSE (%)	Number of intensive activities	Simulated yield (t ha^{-1})	Observed yield (t ha^{-1})	rRMSE (%)
Wheat	153	3.19	3.23	1.95	74	4.2	3.47	13
Barley	25	3.01	2.96	1.49	38	2.3	3.33	15
Chickpea	20	1.22	1.53	11.0	5	1.5	1.74	22
Faba bean	74	1.9	1.79	1.53	20	1.65	2.05	12
Onion	17	21.90	22.12	4.00	34	33	33.4	8
Potato	22	25.32	24.32	3.5	18	28	26	10

Notes: Cereal and legume yields are expressed in dry weights. Vegetable yields are expressed fresh weights. Results through the comparison of simulated and observed yields and calculation of rRMSE for all the activities in the study region. Every value represents, per crop, an average value for all the activities. Observed yields based on observed activities across all 85 surveyed farm households are listed here: https://cloud.iamm.fr/index.php/s/6RRee2qLBFsebBr.

Table 6
Comparison of simulated and observed individual crop area, crop income, and self-consumption of crops.

Variable	Observed data	Change in variable in simulations under different risk aversion coefficients and PMP					
		1.5	1.55	1.6	1.67	1.7	PMP
Wheat area (ha)	6.48	2%	1%	1%	-1%	-1%	0%
Barley area (ha)	1.24	27%	25%	25%	25%	25%	0%
Potato area (ha)	0.03	833%	833%	0%	1433%	1800%	0%
Onion area (ha)	0.27	70%	63%	15%	96%	22%	0%
Faba bean area (ha)	1.44	−6%	24%	−3%	−3%	−3%	0%
Chickpea area (ha)	2.16	−39%	−48%	−17%	−41%	−43%	0%
Total cropped area (ha)	11.62	0%	1%	0%	0%	−1%	0%
Crop income (MAD ha^{-1})	6292	10%	8%	8%	11%	11%	- 6%
Self-consumption (kcal person^{-1} day^{-1})	1562	−32%	−32%	−34%	−33%	−33%	−14%

Notes: Change is calculated as $\frac{(X_{sim} - X_{obs})}{X_{obs}} \times 100$, where X is the variable in column 1, *sim* is simulated data, and *obs* is observed data. MAD is the Moroccan dirham, with 1 MAD = 0.098 \$. Self-consumption is consumption of own-produced food.

Table 7
Average socio-economic and environmental indicators for the 15-year simulation period.

Variable		Baseline Scenario variable level	Change in variable level in each scenario			
			Premium	Water	Variability	Combined
Crop income (MAD ha^{-1} year $^{-1}$)		7380	13%	15%	15%	28%
Utility (MAD ha^{-1})		30,054	19%	16%	9%	15%
Total consumption (kcal person^{-1} day^{-1})		1523	1%	8%	6%	22%
Self-consumption (kcal person^{-1} day^{-1})		1008	12%	−1%	−29%	−53%
Purchasing (kcal person^{-1} day^{-1})		515	−13%	32%	83%	174%
Total consumption (kcal person^{-1} day^{-1})	Cereals	928	0%	8%	7%	18%
Total consumption (kcal person^{-1} day^{-1})	Legumes	155	5%	19%	17%	43%
Total consumption (kcal person^{-1} day^{-1})	Vegetables	440	11%	12%	10%	27%
Self-consumption (kcal person^{-1} day^{-1})	Cereals	897	−10%	−28%	−55%	−87%
Self-consumption (kcal person^{-1} day^{-1})	Legumes	62	24%	2%	31%	−44%
Self-consumption (kcal person^{-1} day^{-1})	Vegetables	49	402%	500%	380%	539%
Total labour (person-days month^{-1})		7.9	1%	3%	11%	14%
Irrigation water use (m^3 ha^{-1} year $^{-1}$)		31	0%	593%	0%	320%
Nitrate leaching (kg N ha^{-1} year $^{-1}$)		14	21%	36%	−7%	7%
Crop pattern (ha^{-1} year $^{-1}$)	Cereals	6.4	0%	−5%	−6%	−11%
Crop pattern (ha^{-1} year $^{-1}$)	Legumes	3.7	16%	5%	17%	24%
Crop pattern (ha^{-1} year $^{-1}$)	Vegetables	0.2	50%	250%	50%	200%
Crop pattern (ha^{-1} year $^{-1}$)	Fallow	1.32	−53%	−30%	−24%	−47%

Notes: The change is calculated as $\frac{(X_{sim} - X_{obs})}{X_{obs}} \times 100$, where X is the level of the variable, *sim* is simulated data, and *obs* is observed data reported in first numerical column. MAD is the Moroccan Dirham, 1 MAD = 0.098 \$. Self-consumption is the consumption of own-produced food. Supporting Information Section 3 reports a sensitivity analysis of the simulation results.

the Baseline. The change in nitrate leaching was 36%, 21%, −7% and 7% for the Water, Premium, Variability and Combined scenarios, respectively relative to the Baseline scenario. For the Variability scenario, the decrease in nitrate leaching because of lower nitrogen fertilizer application rates. This decrease in fertilisation is linked to the increase in the area dedicated to legumes (Table 7), which consume little nitrogen, compared to cereals (150 kg N ha^{-1}). This change in fertilizer use strengthens the importance of evaluating the value of rotation by considering the entire rotation cycle (Yigezu et al., 2019).

The change in crop pattern under the four incentive scenarios resulted in a 1% to 14% increase in labour requirements compared to the Baseline scenario. In the Baseline scenario, the household cropping activities required on average across all months in the year 7.9 person-days ha^{-1} $month^{-1}$ labour (range 0–25). This increase is because vegetable farming is more labour-intensive than cereals and legumes with an average of 52 person-days ha^{-1} $month^{-1}$ for vegetables, 7.5 person-days ha^{-1} $month^{-1}$ for cereals, and 6 person-days ha^{-1} $month^{-1}$ for legumes.

Overall, food consumption increased in all scenarios compared to the Baseline (Table 7). The largest increase was in the Combined scenario (22%) compared to the Baseline. For the other scenarios, it was less than 7%. For all the scenarios, the increase in consumption was proportional to the increase in crop income and hence the increase in purchasing power (Table 7). The increase in consumption is different for each product. The increase in cereal and legume consumption in the incentive scenarios was up to 19% compared to the Baseline (Table 7). Vegetable consumption increased in all scenarios (10%– 27%).

Self-consumption showed substantial variability across the scenarios. However, the variation for each scenario relative to the Baseline was the opposite of that for total consumption. Indeed, a decrease in self-consumption of 53%, 29% and 1% was observed for Combined, Variability and Water scenarios compared to Baseline scenario, respectively. Only the Premium scenario resulted in an increase of 12% in self-consumption. For cereals, self-consumption results also show the opposite of those for total consumption. Indeed, self-consumption of cereals was 10% to 87% lower in the incentive scenarios compared to the Baseline scenario (897 kcal $person^{-1}$ day^{-1}). The result is different for legumes where self-consumption is much higher for the Variability (31%), Water (2%) and Premium (24%) scenarios compared to the Baseline scenario. Only the Combined scenario showed a decrease of 44% compared to Baseline scenario. For vegetables, all scenarios generated a substantial increase in average self-consumption of 450% compared to the Baseline scenario.

3.3. Scenario results: variability

For all scenarios, the analysis of the coefficient of variation for the 15-year weather sequence showed a relatively high and almost identical inter-annual variability in crop yields (Table 8), as well as, in crop income, utility (from Eq. 1), and total consumption. The coefficient of variation for all these variables and in all scenarios was between 9% and 47% (Fig. 1). Rainfall variability between seasons and years was the main driver of crop yield variability and consequently its related indicators.

Inter-annual variability in cereal and legume crop areas was both low and stable, regardless of the scenario (data not shown). The areas dedicated to these two crops were relatively stable and depended little on the weather in the year under consideration and the type of scenario. On the other hand, for vegetable farming, the coefficient of variation for the vegetable area between years and by scenario was high (data not shown). The Water and Variability scenarios present coefficients of variation of 43% and 28%, respectively, followed by Combined (67%) and Premium (68%) and finally Baseline (127%) scenarios.

The situation in terms of the pattern of crop choices is reflected in the nitrate leaching at farm level, where the coefficient of variation is high (at least 34%) for all scenarios (Fig. 1).

As mentioned above, the coefficient of variation for crop consumption is relatively high but it is almost identical for all scenarios. This result can be explained by an inter-annual readjustment through self-consumption and purchases of food–known as consumption-smoothing (Morduch, 1995). The coefficient of variation for self-consumption is higher for Variability (45%) than for Water (37%), Baseline (26%) and the Premium (22%) and Combined (25%) scenarios (Fig. 1). This result is different for purchases, where the coefficient of variation is higher for Water scenario than for all the other scenarios (data not shown).

The analysis of the results by scenario shows variable production levels depending on the crop types and their level of intensification (Table SI.1.). The variation in production is the result of a variation in the area dedicated to each crop and intensification level (Table SI.2), the yield per crop and intensification level (Table SI.3), or both yield and area at the same time. In all scenarios, there was a general increase in the yield of cereal crops (at the aggregated level across barley and wheat and both intensification levels) (Table 8) and there was a decrease or no change in the total area of cereal crops (Table 7). Given the magnitude and direction of the changes in cereal crop yield and area, the net result was that the incentives led to cereal crop production increasing between 10% and 21% across the scenarios. In all scenarios, there was a general decrease in the yield of legume crops (at the aggregated level across faba bean and chickpea and intensification level) (Table 8) and there was an increase in total area of legume crops. Given the magnitude and direction of the changes in legume crop yield and area, the net result was that the incentives saw legume crop production increase between 2% and 9% across the scenarios. Ultimately, yield and area are combined to determine total production, and this total production is what is available to sell or consume, which has implications for broader issues like food security and trade. Despite the incentives not leading to an increase in cereal area planted, the incentives did increase total cereal production through a positive yield effect.

Table 8
Average, standard deviation, and coefficient of variation of the crop yield for 15 years of simulations.

Crops	Scenarios				
	Baseline	Premium	Water	Variability	Combined
Barley					
Average (t ha^{-1})	2.62	2.67	2.52	2.96	2.93
Standard deviation (t ha^{-1})	0.50	0.70	0.68	0.28	0.32
Coefficient of variation (%)	19	26	27	9	11
Wheat					
Average (t ha^{-1})	3.11	3.85	3.93	3.95	4.13
Standard deviation (t ha^{-1})	0.59	0.18	0.18	0.20	0.37
Coefficient of variation (%)	14	5	5	5	9
Chickpea					
Average (t ha^{-1})	2.60	2.27	2.57	2.17	2.01
Standard deviation (t ha^{-1})	0.42	0.28	0.41	0.20	0.43
Coefficient of variation (%)	16	13	16	9	21
Faba bean					
Average (t ha^{-1})	2.22	2.25	2.07	2.06	2.20
Standard deviation (t ha^{-1})	0.24	0.30	0.29	0.26	0.26
Coefficient of variation (%)	11	13	14	13	12
Onion					
Average (t ha^{-1})	18.71	17.21	13.56	14	15.39
Standard deviation (t ha^{-1})	8.82	6.33	5.28	6.29	3.16
Coefficient of variation (%)	47	37	96	80	21
Potato					
Average (t ha^{-1})	30.92	27.57	31.04	25.36	32.44
Standard deviation (t ha^{-1})	11.65	2.35	2.29	2.00	2.00
Coefficient of variation (%)	47	9	7	8	6

Notes: The average simulated yield per crop is obtained by using the DAHBSIM cropping system model. Cereal and legume yields are expressed in dry weights. Vegetable yields are expressed fresh weights.

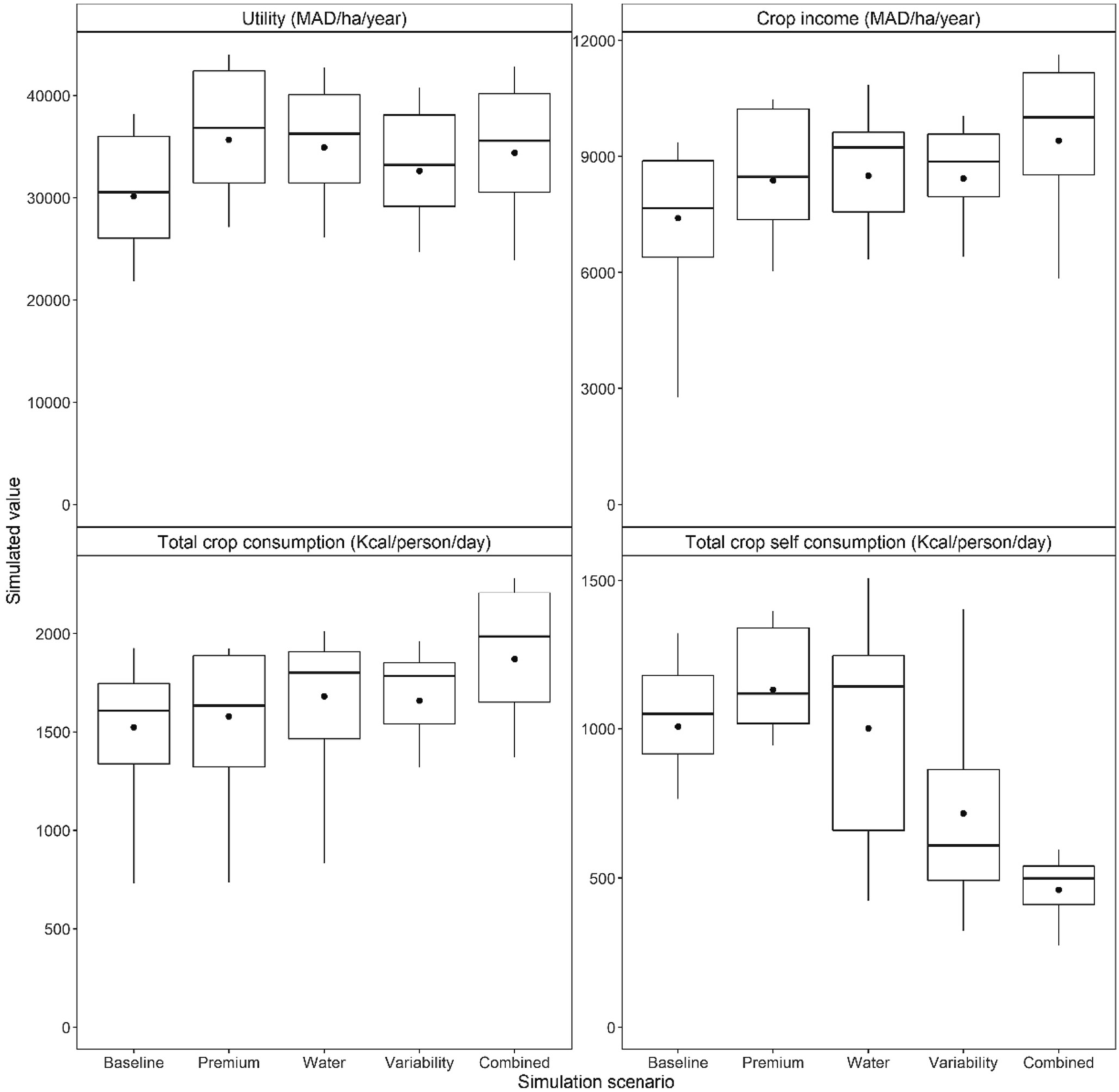

Fig. 1. Variability in utility, crop income and consumption on the simulated farm household over ethe 15-year simulation period. Boxes indicate the interquartile range (IQR). The upper whisker extends from the third quartile upper hinge of the box to the largest value no further than 1.5 × IQR from the upper hinge. The lower whisker extends from the first quartile lower hinge of the box to the smallest value at most 1.5 × IQR from the lower hinge. Outliers excluded for clarity. Black circle inside each box shows the average.

4. Discussion

4.1. Important but insufficient levers to increase cereal and legume production

For all scenarios, crop income for the farm household remains well below the national average in Morocco in 2020 (WorldBank, 2020). This result is consistent with recent studies that show only a slight improvement in farm income over the past 20 years, despite the policies introduced in several MENA countries (WorldBank, 2020). Nevertheless, this result must be put into perspective, as crop income is similar to the implicit value of self-consumption. This implicit (noncash) value of self-consumption is often not considered when studying farm production and food consumption choices (Janssen and van Ittersum, 2007; van Wijk et al., 2014), despite the importance of consuming own-production (Singh et al., 1986).

The scenarios increased the overall production of cereals (range across scenarios: 10% to 21%) and legumes (range across scenarios: 2% to 9%). The increase in total production can be explained mainly by the intensification of how these crops are produced, and the entailing increase in their yield. Indeed, the area dedicated to these crops remains the same or even dropped in some cases (Table SI.2). This intensification also resulted in a large increase in the total production of vegetables (mainly potatoes) (range across scenarios: 38% to 257%). This increase can be explained by both increases of yield and area dedicated to vegetable crops. Indeed, cereals and legumes are less profitable than vegetable farming. This may partly explain why growth in the land area of cereals and legumes has recently stagnated in the MENA region

(OECD, 2018; Kruseman et al., 2020).

For all scenarios, the incentives led to an increase in groundwater extraction and nitrate leaching. Current policies that support crops such as wheat and legumes are among the direct or indirect causes of environmental degradation and water depletion in the MENA region (Mubarak, 1998; Hossard et al., 2021).

4.2. Effects on calorie consumption

All scenarios resulted in a substantial increase in the total consumption of cereals, legumes, and vegetables. This result is relatively coherent since several studies show that the overall level of consumption for farm households in the MENA region is acceptable compared to FAO recommendations (Soffiantini, 2020). Nevertheless, this increase masks differences in decision-making by the farm households according to the type of scenario and crop.

For cereals, all the scenarios lead to a decline in cereal self-consumption, and thus to greater dependency on market purchases. This presents a major risk for the purchasing power of farm households in the MENA region, where the subsidies granted to strategic products (particularly wheat flour and semolina) are progressively declining (Babu and Gajanan, 2022). Purchased cereals are often of much lower quality than self-consumed cereals (Rastoin and Benabderrazik, 2014).

For legumes, the results of self-consumption are different. Indeed, a policy that advocates an incentive for legumes or the stabilisation of legume yields by using more drought tolerant varieties increased self-consumption compared to the other scenarios. This is related to three phenomena: higher legume production in these two scenarios, lower risk in relation to their production, and a less than 1% difference between crop selling prices and buying prices for market purchases.

The Combined scenario showed the greatest decline in the self-consumption of legumes and cereals compared to the other scenarios. This Combined scenario also generated the largest increase in overall consumption due mainly to the greatest increase of crop income implying that the household will rely mainly on purchases for its consumption needs. This type of scenario, which uses several levers, is recommended by most scientists to increase the production of cereals and legumes (Mahmood et al., 2017; Hammouda et al., 2018). The application of this type of scenario must be accompanied, however, by a policy that encourages healthier diets. It is likely that maintaining plant-based food consumption at an acceptable level will come at the expense of superior quality food in the Combined scenario.

4.3. Complex risk management

The analysis of the coefficients of variation shows high variability in the different indicators. This demonstrates the complexity of decision-making for farm households in dry areas. Three important findings were generated: i) the areas allocated to cereals and legumes are reasonably stable across years despite the weather variability. This result is consistent with existing studies (Nasrallah et al., 2018; OECD, 2018) which showed that the variation in terms of the production of cereals and legumes is mainly due to yield variation not variation in area planted, ii) a highly variable agricultural income depending on the climatic year. This situation is even more worrying as the average income per farm household member is much lower than the national per-capita average; and iii) variable overall consumption is dependent on the market. This situation is exacerbated by self-consumption, which is highly dependent on annual production, which is itself highly variable.

4.4. A challenging trade-off

A trade-off existed between the three dimensions of sustainability along the for socio-economic, food consumption, and environmental criteria (Fig. 2). The Baseline scenario had a lower level of cereal and vegetable production relative to the other scenarios. It also had the lowest environmental impact compared to the other scenarios. This implies that, not only will any public intervention in line with the scenarios have a limited effect on cereal and legume production, but it will also have a negative effect on the environment compared to the current situation, as represented by the Baseline scenario. This result is worrying because the negative effects of agriculture on the environment are already substantial in the MENA region (Nin-Pratt et al., 2018; Ouda et al., 2021).

The scenario that involves a higher use of water resources will not be beneficial for the promotion of strategic crops in addition to its negative impact on the environment (Fig. 2). When choosing between the different scenarios to boost cereal and legume production, the Combined scenario seems to be the most relevant as it allows an increase in farm household profit. However, this increase is similar to the increase in other scenarios (21% on average), but also has less of an environmental impact compared to the Water scenario. Across the MENA region, the scenario most supported by public authorities today is the one that relies on a greater use of irrigation water from groundwater as the main response for boosting the production of strategic crops (Seekell et al., 2017; Rosa et al., 2018). This type of scenario is unsustainable in terms

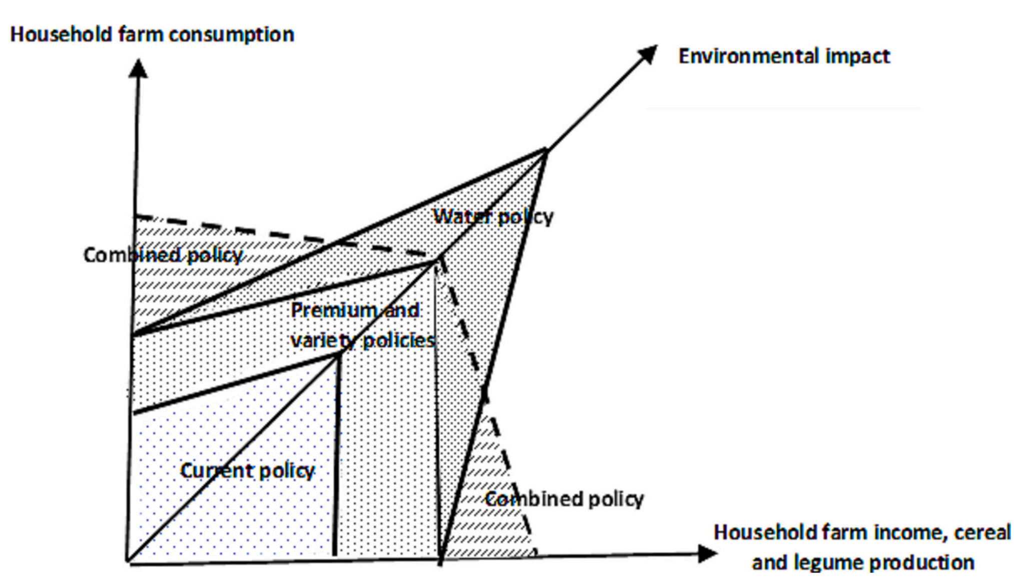

Fig. 2. Conceptual representation of the socio-economic, farm household food consumption, and the environment effects of current and tested policies in MENA.

of its negative impact on the water resources and its limited effect on improving consumption.

Moreover, no scenario tested led to better performance for all three sustainability indicators (food consumption, environmental, and socio-economics) (Fig. 2). Future research will therefore need to test alternative scenarios which may lead to better outcomes in terms of reducing the negative impacts on the environment while ensuring higher consumption, income, and cereal production. Scenarios based on greater public support conditional on transformative changes to promote cereals and legumes may be more relevant to improve all three pillars of sustainability. Scenarios based on greater public support with access to water conditional on transformative changes to promote the creation of more diverse cropping systems may be more relevant to improve performance indicators in each of the three pillars of sustainability. These transformative changes should be considered in a combined way and could take several forms: less soil tillage, land laser levelling for increased water-use efficiency, using more efficient irrigation systems, agroforestry, and switching from chemical to organic fertilizer. These transformative changes would all require testing under local contexts to assess if they meet two main objectives: (1) to improve the productivity and ecological performance of farms dominated by cereals and legumes, but (2) also to ensure that these farms remain competitive when less access to irrigation water occurs.

5. Conclusion

This study used a dynamic, intertemporal bio-economic model to simulate the socio-economic, food consumption, and environmental effects of different incentives for sustainably intensifying cereal, legume, and vegetable production. The results show that the policies aimed at enhancing cereal and legume production, as currently conceived by public authorities, may negatively impact crop consumption, farm income, or the environment. We draw three conclusions from our results. First, the simulated scenarios increased the production of cereals and legumes through a mixture of changes in yield and area. Second, all the scenarios led to a decline in consumption from own production, thus causing farm households to depend more on the increasingly unstable market which is characterized by price volatility, inflation, and civil unrest in the MENA region. Third, almost all the studied levers for boosting cereal and legume production led to the depletion soil and water resources.

Finally, as synergies among all the three pillars of sustainability were not found in the current study, future studies at farm level in the MENA region would be beneficial to explore alternative scenarios that encourage more diversity in production systems (such as varieties, crops, rotation types and cycles, agroforestry, and livestock enterprises). The modular, dynamic, and flexible DAHBSIM simulation model allows, in combination with participatory methods, for the *ex-ante* simulation of such scenarios.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgement

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103769.

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