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Genotype × environment × agronomic management interaction to enhance wheat yield in the Mediterranean rainfed environments of Morocco: II. Process based modeling

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ABSTRACT

Durum wheat (Triticum turgidum subsp. durum) is the oldest and most cultivated cereal crop in Middle East and North Africa (MENA) region and under Mediterranean climatic conditions. Morocco is one of the largest producer of durum wheat in MENA region, cultivated in more than 1 million ha area produced 2.5 million tons in 2020, which accounts for 17% of the total production in the region. In the region, rainfed production system is predominant, and with declining rainfall amounts with high variability, increasing water scarcity, and suboptimal input application, its productivity growth is low and needs to be increased to fulfill the growing demand. Developing context-specific management advisory is needed to improve productivity and resilience under such variable rainfed production environments. Agricultural Production Systems sIMulator (APSIM) model was calibrated and evaluated using four years (2015–2019) of on-station experimental data from genotype × seeding time × water management experiment conducted at International Center for Agricultural Research in the Dry Areas (ICARDA) research station, Morocco. Long-term (1984–2021) simulation was carried out to determine the contribution of Genotype × Environment × Management components for sustainably improving crop productivity. The results showed rainfall or supplementary irrigation (23–36%) followed by N fertilizer (28–38%), cultivar (9–14%), and seeding date (7–14%) have the largest contribution to the yield variance of durum wheat in Merchouch, Meknes, and Sidi El Aidi regions of Morocco. Under rainfed conditions, wheat yield was highest in Merchouch (4.5 t ha^{-1}) and lowest (1.8 t ha^{-1}) in Sidi El Aidi. Due to significant rainfall variability, the seeding date varies across year and location; however, generally, it is between 2nd week of November to 1st week of December. Under rainfed conditions, seeding after 1st week of December caused the average yield reduction of 120, 81, and 31 kg ha^{-1} d^{-1} in Merchouch, Meknes, and Sidi El Aidi, respectively. In all locations, short-duration varieties provided higher averaged yields with better resilience than medium and long-duration varieties. Decomposing yield variance caused by Genotype × Environment × Management provides the opportunity for risk reduction, improvement of wheat yield and resilience, and designing climate-smart adaptation strategies in rainfed Mediterranean conditions. Our findings highlight one-size-fits-all approach is inadequate and context-specific tailored agronomic practices and suitable genotypes is crucial for achieving sustainability and resilience of wheat production in variable climatic condition in Morocco and similar production environment.

1. Introduction

Crop simulation models have become increasingly important in agriculture, as they can provide valuable insights into crop productivity, input use, and yield gap analysis. The Agricultural Production Systems sIMulator (APSIM) model (Holzworth et al., 2014; Keating et al., 2003) can simulate a wide range of crops and cropping systems. It can simulate crop growth and development considering climate, soil, and management practices. The APSIM model considers the long-term effects of genotype × management × environment on growth, yield, and soil parameters for different soil types and climatic conditions.

For exploring options for sustainable intensification, APSIM model has been used to quantify the effect of variety × management on sorghum (Ojeda et al., 2022), develop climate-smart adaptation strategies of wheat in semi-arid Central Region of Morocco (Briak and Kebede, 2021), assess the impact of crop management and environment at

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regional scale in potato (Ojeda et al., 2021), assess the contribution of genotype × fertilizer × irrigation to explore the site and climate specific agronomic solution in wheat cultivation in Nepal (Devkota et al., n.d.). It was used to determine the effect of sowing date × variety (three maturity duration) in rainfed Mediterranean region of Italy (Bassu et al., 2009). Hochman and Horan (2018) used APSIM to explore 'best management practice' in wheat to higher production frontier levels in the water-limited environment of Australia. It is capable of simulating wheat grain yields analyzing the effect of soil type (soil water-holding capacity), nitrogen rate and application time, soil moisture storage, cultivars, sowing dates and density, and supplemental irrigation (SI) in rainfed environments of Central and West Asia and North Africa region (Heng et al., 2007), in Tunisia (Bahri et al., 2019) and particularly in Morocco (Briak and Kebede, 2021; Moussadek et al., 2015).

In rainfed Mediterranean conditions, it is well recognized that wheat yield is affected by genotype, environment, and management practices and their interactions (Devkota et al., 2022b; Devkota and Yigezu, 2020; Haq et al., 2017; Padovan et al., 2020). However, earlier studies lack systematic quantification of the contribution of genotype, management practices, and climatic conditions, which helps to develop bundled customized agronomic solutions for improving crop yield and resilience. Particularly under changing climatic conditions, appropriate genotypes and customized integrated management practices are paramount (Beres et al., 2020). Modeling studies can better extrapolate research findings over time and space, identify climate-smart integrated best management practices, and assess crop performance under varying soil and climatic conditions. Thus, the objectives of this study were to quantify the contribution of genotype, management practices, and climatic conditions and identify the appropriate genotype and context-specific management practices for sustainably closing the yield gap in diverse soil and climatic conditions of the Mediterranean environments of Morocco and similar environments.

2. Materials and methods

2.1. Calibration and validation of APSIM-Wheat model

2.1.1. Climate and soil dataset

The climate of the experimental study site (used for model calibration) is typically Mediterranean with hot and dry summers and cold and wet winters and highly variable annual rainfall across years. The long-term (1985–2021) annual rainfall in the experimental site Merchouch was 440 mm, and in two simulation sites, Meknes and Sidi El Aidi were 560 and 320 mm, respectively (NASA POWER, 2023). The mean annual air temperatures were 19.2 °C in Merchouch (maximum 22.7 °C and minimum 15.85 °C), 19.7 °C in Meknes (26.46 °C and 12.9 °C), and 19.49 °C in Sidi El Aidi (26.43 °C and 12.5 °C) (Fig. 1). The soil in the experimental site is classified as a gray Vertisol of clay-loam texture (47.6% clay and 41% loam content) with large cracks appearing during the dry season. The soil is low in organic carbon content (1.65%) and available K_2O (105 mg kg^{-1}) and high in assimilable P_2O_5. Additional soil characters across horizons are presented in Table 1.

2.1.2. Experimental detail and measurements

APSIM-wheat model was calibrated and validated using four years (2015/2016, 2016/2017, 2017/2018, and 2018/2019) of field experiment data conducted at ICARDA research field in Merchouch (33°36′41″N, 6°42′45″W, 390 m a.s.l.), Morocco. Each year, those field experiments were conducted from November–June. Detail has been explained in (Devkota et al., 2023), Part-I. Days to emergence, anthesis, and maturity were recorded each year for each treatment based on whole plot observation. For yield estimation, the crop was harvested (from 6 m × 2.2 m area) using a plot combine harvester. Total above-ground biomass yield and yield attributes were estimated from two rows (rows 9 and 10) with 1 m length from two points in each plot were harvested manually.

2.1.3. Model parameterization, calibration, and validation

The APSIM-Wheat model was parameterized, calibrated, and validated as the procedure described in (Gaydon et al., 2017). The model was parameterized using input parameters directly recorded or

Table 1
Soil input data used for model calibration and validation from Merchouch; and scenario analysis in Merchouch, Meknes, and Sidi El Aidi, Morocco.

Soil depth (cm)	CLL (cm^3 cm^{-3})	DUL (cm^3 cm^{-3})	SAT (cm^3 cm^{-3})	Bulk density (g cm^{-3})	SOC (%)	Texture (%)	
						Clay	Silt
Merchouch[1]							
10	0.40	0.54	0.59	1.12	1.65	47.6	41.4
40	0.40	0.53	0.58	1.12	1.25	47.6	41.3
70	0.35	0.54	0.59	1.11	0.81	47.6	42.9
95	0.35	0.54	0.58	1.11	0.81	47.6	41.1
Meknes[2]							
5	0.23	0.36	0.45	1.32	2.65	38.0	34.5
15	0.24	0.37	0.45	1.41	1.59	39.4	33.7
30	0.22	0.36	0.44	1.47	0.98	37.4	33.6
60	0.24	0.37	0.45	1.52	0.61	39.3	32.4
100	0.22	0.36	0.44	1.56	0.44	37.7	33.7
Sidi El Aidi[2]							
5	0.21	0.33	0.42	1.49	2.11	35.6	20.9
15	0.22	0.38	0.42	1.57	1.35	36.5	20.9
30	0.23	0.35	0.43	1.60	1.04	39.0	19.8
60	0.24	0.36	0.43	1.61	0.96	39.7	19.7
100	0.24	0.35	0.43	1.63	0.41	39.6	19.3

Note: CLL= Crop lower limit (or wilting point); DUL= Drained upper limit; SAT= Soil moisture content at saturation; SOC= Soil organic carbon.
Source: 1=Measured experimental station; 2=ISRIC World Soil data.

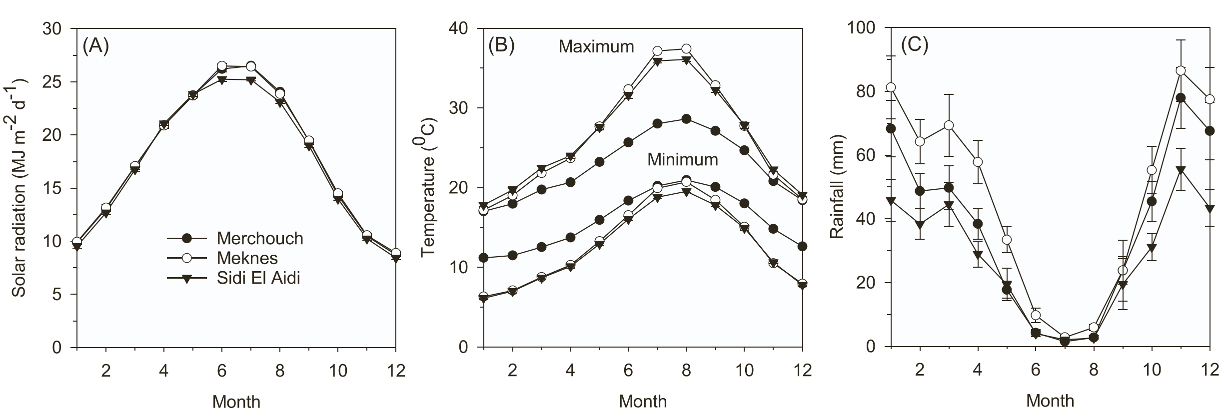

Fig. 1. Long-term (1985 –2022) solar radiation (A), maximum and minimum temperatures (B), monthly rainfall (C) in simulation sites Merchouch, Meknes, and Sidi El Aidi. Vertical lines in the figure are the standard errors.

measured (climate variables, soil physical and chemical properties, crop management practices, and inputs applied). Other model parameters unable to measure directly, such as variety-specific coefficients were calibrated by iterative adjustment. The parameterized model was run for the most favorable year (2018) using irrigated treatments to derive variety-specific coefficients for three maturity duration varieties (short-, medium- and long-duration; SDV, MDV, and LDV) (Table 2). Simulated outputs were compared with observed and the discrepancies in cultivar coefficients were re-adjusted. Three years of independent experimental data (2016, 2017, and 2019) were used for model validation. Model evaluation include growth and development parameters such as days to anthesis, maturity, grain yield, and total aboveground biomass weight used for timely and late seeding under supplementary irrigated and rainfed conditions (i.e., four treatments). Among 10 cultivars evaluated, based on the days to maturity, they were categorized into three categories, i.e., 152, 160, and 168 days as SDV, MDV and LDV, respectively and cultivar coefficients were derived accordingly (Table 2). As wheat-fallow is the major cropping system in the rainfed drylands of the MENA region, exploration of adaptation strategy using MDV and LDV is advantageous. Thus, three category cultivars were parameterized and used for the long-term simulation.

2.1.4. *Model performance statistics*

The model findings were assessed based on the mean, standard deviation, the ratio between simulated and measured, mean difference, absolute root mean square errors (RMSEa), mean absolute error (MAE), and normalized root mean square errors (RMSEn%) for the growth and yield parameters. It was assumed that the model reproduced experimental data best when the ratios between simulated and measured R^2 and D-stat were close to 1.0 (Timsina and Humphreys, 2006; Yang et al., 2014).

$$\text{Absolute root mean square } error\ (\mathrm{RMSE_a}) = \left(\frac{1}{n}\sum(\mathrm{Y_i}-\mathrm{X_i})^2\right)0.5 \quad (1)$$

$$\text{Mean absolute } error(\mathrm{MAE}) = \frac{\sum|\mathrm{X_i}-\mathrm{Y_i}|}{\mathrm{n}} \quad (2)$$

$$\text{Normalized root mean square errors } (\mathrm{RMSE_n}) = 100 \times \frac{((1/\mathrm{n})\sum(\mathrm{Y_i}-\mathrm{X_i})2)0.5}{\sum \mathrm{Xi}/\mathrm{n}} \quad (3)$$

Where, Y_i and X_i are simulated and measured values, respectively, X_i is the mean of all measured values (usually 3 replicates), and n is the number of measurements.

Table 2
Cultivar coefficients optimized for short- (SDV), medium- (MDV), and long- (LDV) maturity duration wheat varieties in Merchouch, Morocco.

Model specific parameters calibrated	Short (SDV)	Medium (MDV)	Long (LDV)
HeadEmergencePpSensitivity.FixedValue	1.0	1.0	0.0
Phyllochron.BasePhyllochron.FixedValue	80	90.10	99.37
ExtinctionCoeff.VegetativePhase.FixedValue	0.5	-	-
NumberFunction.GrainNumber. GrainsPerGramOfStem.FixedValue	35	-	-
PhyllochronPpSensitivity.FixedValue	-	0.349	0.205
CAMP.FLNparams.MinLN	9.0	6.5	7.0
CAMP.FLNparams.PpLN	0.0	1.0	4.0
CAMP.FLNparams.VrnLN	0.0	1.5	1.5
CAMP.FLNparams.VxPLN	0.0	-1.0	-0.5
HeadEmergenceLongDayBase.FixedValue	100	210	190
CAMP.EnvData.VrnTreatTemp	6.0	5.8	5.8
CAMP.EnvData.VrnTreatDuration	60	60	60

2.2. *Long-term simulation of genotype × environment × management*

2.2.1. *Initial condition and crop management data*

In all treatments, initial root biomass of 500 kg ha^{-1} was used to initialize the APSIM-Wheat model. Cultivar-specific parameters, planting date, emergence date, planting method, density, distribution, seeding depth and row spacing, fertilizer types and application rates, irrigation amount and date of application, and harvesting dates were recorded during the experimental period in all years. Those recorded parameters were used as input data for model calibration and validation.

2.2.2. *Soil profile and daily climate data*

Initial soil physical properties used for model calibration, validation, and scenario analysis are presented in Table 1. The model was calibrated and validated using the measured data from Merchouch experimental station. For the scenario analysis, respective soil profile data from Merchouch, Meknes, and Sidi El Aidi were used (Table 1). The long-term (1984–2021) daily weather data (rainfall, minimum and maximum air temperature, solar radiation, relative humidity, and wind speed) required for running APSIM-Wheat, were downloaded from the NASA POWER project (NASA POWER, 2023) for all three sites.

2.2.3. *Model application*

Simulations were created in APSIM-Wheat model in APSIM Next Generation to quantify the wheat yield gap and explore possible entry points for narrowing the gap in Morocco. After the satisfactory calibration and validation, the model was run for 37 years (1985–2021) for the weather and soil of Merchouch, Meknes, and Sidi El Aidi, the major wheat-growing regions in Morocco to explore:

2.2.3.1. Attainable yield and irrigation scheduling. We run the model for 37 years (1984–2021) under three water management scenarios:

i. Rainfed (only seasonal rainfall)
ii. Rainfed (seasonal rainfall) with initial high stored soil moisture (HSSM)
iii. Seasonal rainfall with initial HSSM and supplementary irrigation (SI) (HSSM + SI)

All three maturity duration varieties (short; medium, and long) were run for the long-term under all three water management conditions. Under rainfed conditions, the initial plant available water content (PAWC) was 112.6 mm in the top 40 cm soil profile (as in the normal rainfed conditions in the farmers field), while under HSSM, total initial PAWC in the top four soil profiles (0–95 cm depth) was 249 mm. HSSM mimics the water stored in the soil during the fallow period (as soil mulch), which is common practice in Morocco as a way to in-situ water harvesting. In 3rd scenario (HSSM+SI), SI was applied turning-on the automatic irrigation module of APSIM. SI was applied to the crop when PAWC dropped to 50% and irrigated up to 95% of the PAWC with maximum irrigation application of 30 mm in each irrigation and minimum 3 days for irrigation to return from 1st of September to 30th of March. In Morocco, irrigated wheat is grown in more than 0.85 million ha and needs to understand irrigation scheduling and explore the opportunity for sustainable intensification of wheat production through optimizing irrigation amount in SI.

2.2.3.2. Optimal seeding dates × N rate and yield gap. The optimal seeding date of wheat for three different climates (Merchouch, Meknes, and Sidi El Aidi) with 160-day (SDV, most common) variety was explored. Also, the optimal N rate for different seeding dates for three locations and the irrigation water required on different seeding dates in those locations was explored.

2.3. Statistical analysis

Mean, standard deviation, coefficient of variation, and percentage difference were calculated wherever applicable. Further, using the experimental data, APSIM-wheat model was calibrated and validated. The model ran for 37 years in three locations in the northern region of Morocco to explore the potential for closing the yield gap using genotype × environment × management. The main effect (ME) and total/interaction effect (TE) of rainfall, N fertilizer rate, variety, sowing date, and seed rate on yield variability were computed using equations (Eqs. 4 and 5). ME explains the share of the components to model output variability without interactions, i.e., if ME= 1, the assessed factors explain the entire proportion of model output variability, but if M< 1, residuals exist, which means additional factors are required to explain this variability. TE represents the interaction of a given factor with other factors, i.e., high TE values for a given factor denotes high interactions of that factor with other factors; therefore, TE does not include residuals (Ojeda et al., 2022, 2021).

$$\textit{Main effect}\ (\mathrm{MEi}) = \frac{\mathrm{Variance}\ (\mathrm{E[Yield\ Xi]})}{\mathrm{Variance}\ (\mathrm{Y})}\ldots.. \tag{4}$$

$$\textit{Total}\Big/\mathrm{Interaction\ effect\ (TEi)} = 1 - \frac{\mathrm{Variance(E[Yield\ X\_i])}}{\mathrm{Variance(Y)}}\ldots.. \tag{5}$$

Where, E[Yield Xi] denotes the expected value of crop yield across all sources Xi (soil type, mean temperature, rainfall, global solar radiation, planting date and irrigation strategy), while E [Yield X_i] is the expected value of crop yield across all sources except Xi. Nitrogen use efficiency (Eq. 6) and attainable yield gaps (Eqs. 7,8) were presented as essential.

$$\mathrm{Nitrogen\ use}\ \textit{efficiency}\mathrm{(NUE)} = \frac{\mathrm{Yield\ under\ applied}\ \textit{Nrate}(\mathrm{ha}^{-1}) - \mathrm{Yield}\ \textit{under}0\ \mathrm{kg\ N\ (ha}^{-1})}{\mathrm{Amount\ of\ \ N}\ \textit{applied}(\mathrm{ha}^{-1})}\ldots.. \tag{6}$$

$$\mathrm{Attainable\ water\ limited\ yield}\ \textit{gap}(\%) = \frac{(\mathrm{Yield\ under}\ \textit{HSSM} + \mathrm{SI}) - (\mathrm{Yield\ under\ rainfed})}{(\mathrm{Yield\ under}\ \textit{HSSM} + \mathrm{SI})}\mathrm{x}100\ldots. \tag{7}$$

$$\mathrm{Attainable\ rainfed\ yield}\ \textit{gap}(\%) = \frac{(\mathrm{Yield\ under}\ \textit{HSSM}) - (\mathrm{Yield\ under\ rainfed})}{(\mathrm{Yield\ under}\ \textit{HSSM})}\mathrm{x}\ 100\ldots.. \tag{8}$$

3. Results

3.1. Model calibration and validation

There was a good agreement between measured and simulated grain yield, total aboveground biomass production, days to anthesis and maturity for all seeding date × water management experiments in all four years in both calibration and validation data sets (Fig. 2, Table 3). Less than 25% RMSEn, fairly low MAE, fairly low mean difference between simulated and observed, and close to 1 ratio of simulated to observed (Table 3) indicate that the model was well parameterized.

3.2. Model scenario analysis

3.2.1. Attainable yield and yield variability

On average, short duration variety (152 DAS) produced the highest yield (+17% than LDV and + 9% than MDV) followed by MDV and the lowest by the LDV (Fig. 4 A). Averaged across the location (with SDV), compared to the rainfed (3.5 t ha^{-1}), HSSM increased yield by 48% (1.6 t ha^{-1}) and HSSM+SI by 106% (3.7 t ha^{-1}). Averaged across varieties, under rainfed conditions, wheat yield was highest in Merchouch (4.5 t ha^{-1}) and lowest (1.8 t ha^{-1}) in Sidi El Aidi, while with HSSM+SI, yield was highest in Sidi El Aidi (7.6 t ha^{-1}). Results of the long-term simulation showed yield variability across the year was highest under rainfed (coefficient of variation of 43%) followed by HSSM (35%) and the lowest (21%) under HSSM+SI (Figs. 4B,4 C,4D). Similarly, under rainfed conditions, yield variability of all three varieties was non-significant (42–43%), while under HSSM, it was 32%, 36%, and 36% for SDV, MDV and LDV; and under HSSM+SI, it was 19%, 22%, and 23% for SDV, MDV and LDV, respectively.

3.2.2. Optimal seeding dates and yield gap

The long-term simulated yield under favorable environment (HSSM+SI and application of 200 kg N ha^{-1}) showed the highest attainable yield obtained when seeded in 1st week of December (highest mean yield) in Sidi El Aidi (8.36 ± 0.56 t ha^{-1}) compared to corresponding values for Meknes (8.3 ± 0.62 t ha^{-1}) and Merchouch (7.49 ± 0.90 t ha^{-1}) (Fig. 5). In all three sites, attainable yield was higher with low variation for early seeding (before 1st December), than late seeding (after 1st of December). After 1st week of December, attainable yield decreased by 99, 130 and 215 kg ha^{-1} d^{-1} in Merchouch, Meknes and Sidi El Aidi, respectively.

Similarly, under rainfed conditions, the average attainable yield was highest in Merchouch (5.04 ± 1.69 t ha^{-1}) followed by 4.51 ± 1.97 t ha^{-1} in Meknes and the lowest 1.75 ± 0.79 t ha^{-1} in Sidi El Aidi when

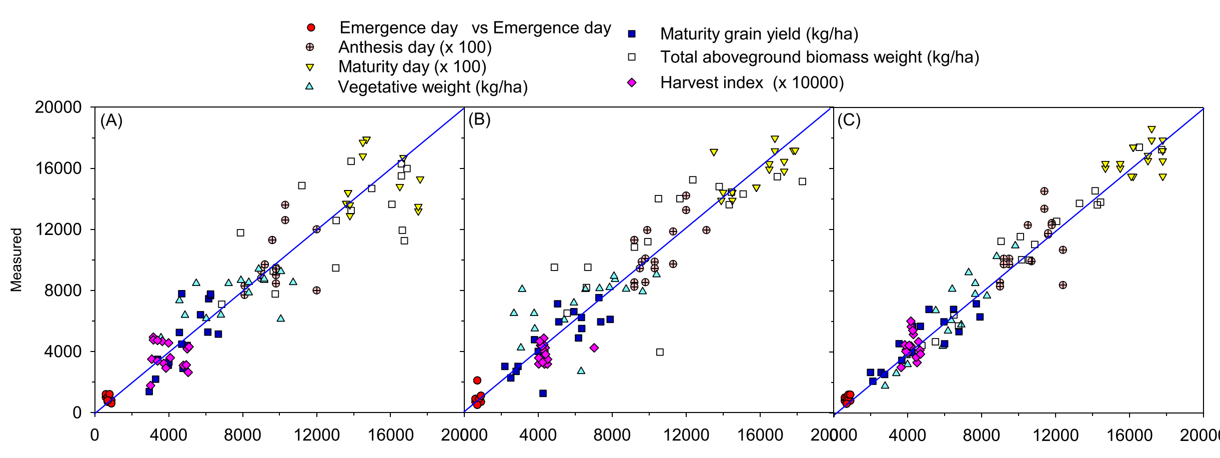

Fig. 2. Simulated and measured calibration and validation parameters of three maturity, i.e., short (A), medium (B) and long (C) duration varieties from the dataset from seeding dates x water management experiment from 2016 to 2019 at Merchouch, Morocco. The solid line is 1:1 line.

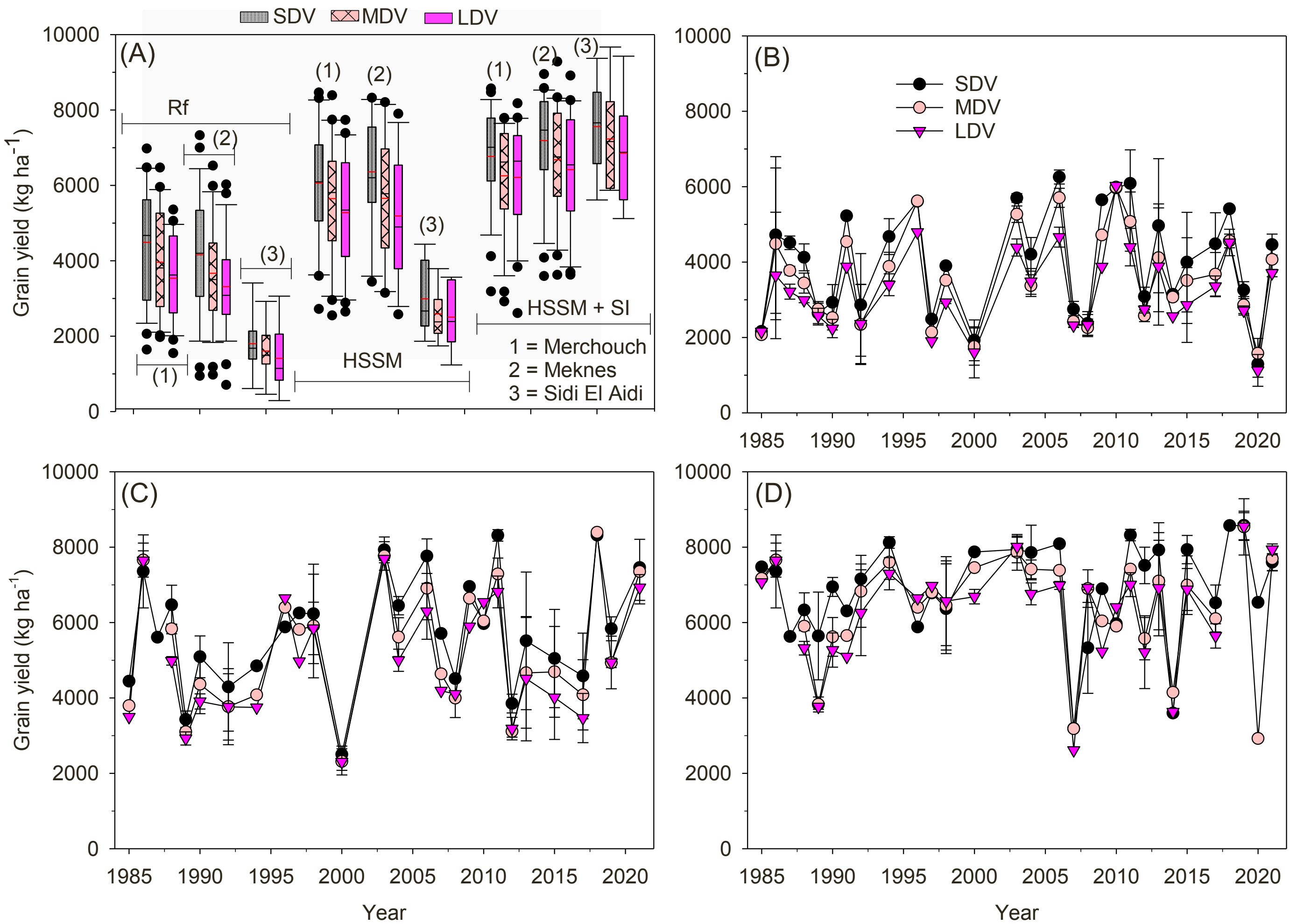

Fig. 3. Simulated attainable yield of short (SDV), medium (MDV), and long-duration (LDV) varieties under three water management conditions (Rf = rainfed; HSSM = high stored soil moisture; HSSM+SI = high stored soil moisture with supplementary irrigation) in three locations of Morocco (A), yearly simulated yield variation of three category wheat varieties under rainfed (B), HSSM (C), and HSSM+SI (D). Values in all figures are averaged across 100, 150 and 200 kg N ha^{-1} under November 15th and 1st December seeding dates.

seeded on 1st week of December (highest mean yield). The long-term simulation showed that seeding between 15th of November and 1st December is optimum for maximum potential yield under rainfed conditions. The average attainable yield decreased by 120, 81, and 31 kg ha^{-1} d^{-1} in Merchouch, Meknes and Sidi El Aidi, respectively when seeded after 1st week of December. There is 20% probability of getting > 7.5 t ha^{-1} under a favorable production environment (HSSM+SI with 200 kg N ha^{-1}) and more than 4.0 t ha^{-1} yield under rainfed conditions even under late seeding (up to 15th of January) but with high risk (CV of 33–60%) (Figs. 5C, 5D). In optimal sowing time (15 Nov to 01 Dec), the water-limited yield gap was highest in Sidi El Aidi (6.2 t ha^{-1}, 76%) followed by Meknes (3.8 t ha^{-1}, 46%) and lowest in Merchouch (2.6 t ha^{-1}, 35%). During the same time, rainfed attainable yield gap was 1.5, 2.1 and 1.1 t ha^{-1} (24%, 33% and 37%) in Merchouch, Meknes, and Sidi El Aidi, respectively.

3.2.3. *Yield gap decomposition and contribution of different Genotype × Environment × Management factors*

Variance decomposition of grain yield in terms of Genotype × Environment × Management to identify the major factors associated with grain yield showed the components vary across location and water management. Under rainfed conditions, for the main effect (Fig. 5, left), the major contribution was from rainfall (34–39%; mean 36%) followed by fertilizer (23–32%; mean 28%), variety (7–11%; mean 7%), and sowing date (5–8%; mean 7%) with residual of 16–24% (mean 20%). With supplementary irrigation (under both conditions), the contribution of rainfall and residual decreased, while the contribution of fertilizer, variety, and seeding time increased. Similarly, under HSSM, the contributions for the main effect were fertilizer (28–37%; 33%) followed by rainfall (26–37%; 31%), variety (8–13%; 11%), and seeding time (10–12%; 11%) with residual of 11–16% (mean 13%). Under HSSM+SI fertilizer (32–42%; 38%) followed by rainfall (18–30%; 23%), variety (11–18%; 14%), sowing date (13–16%; 14%), and residual (10–12%; 11%) were the major contributors for yield. Sidi El Aidi had highest contribution of rainfall than the other two sites. Similarly, the total or interaction effect (Fig. 5, right) varied across sites and the water management. Regarding the interaction effect, rainfall followed by fertilizer, seeding time, and variety (in descending order) are the major interacting factors under rainfed conditions. Under HSSM, N fertilizer followed by rainfall, sowing date, and variety; and under HSSM+SI, fertilizer rate followed by sowing date, rainfall, and variety are the major interacting factors.

3.2.4. *Optimal N fertilizer rate across sites and seeding date*

Nitrogen fertilizer rate varied across the site, water management and seeding date (Fig. 6). Under optimal seeding (15 November to 01 December), nitrogen use efficiency (NUE) was highest in Merchouch followed by Meknes and the lowest in Sidi El Aidi under rainfed

Table 3
Validation results for APSIM simulation of two seeding dates and water management practices in durum wheat in Merchouch, Morocco during 2015-2018.

Variable	Mean		Ratio	Standard deviation		Mean Diff.	RMSEa	MAE	RMSEn	N
	Observed	Simulated		Observed	Simulated					
Short duration variety (SDV)										
Emergence day	9	7	0.81	2.2	1.1	-2	3.32	2.75	36	16
Anthesis day	99	97	0.98	17.4	10.9	-2	16.11	11.22	16	16
Maturity day	152	152	1.00	18	15.8	0	22.43	16.81	15	16
Vegetative weight (kg ha^{-1})	7.74	7.58	0.98	1.34	2.16	-0.17	1.67	1.26	22	16
Maturity grain yield (kg ha^{-1})	4.87	4.00	0.82	2.08	1.19	-0.87	0.88	1.12	18	16
Total aboveground biomass (kg ha^{-1})	12.62	13.35	1.06	3.02	3.36	0.74	2.66	2.03	21	16
Harvest index	37	40	1.07	9.1	7.7	3.0	8.76	10.90	24	16
Medium duration variety (MDV)										
Emergence day	9	7	0.79	5	1.1	-2	2.96	3.25	32	16
Anthesis day	106	104	0.98	17	12.2	-2	13.4	11.11	12	16
Maturity day	159	158	0.99	14	15.67	-1	14.64	10.21	9	16
Vegetative weight (kg ha^{-1})	4.81	5.00	1.04	1884	1.85	0.19	0.93	1.72	19	16
Maturity grain yield (kg ha^{-1})	7.12	6.31	0.89	1780	2.47	-0.81	1.25	0.91	18	16
Total aboveground biomass (kg ha^{-1})	11.93	11.30	0.95	3519	4.05	-0.62	2.26	2.21	19	16
Harvest index	39	44	1.14	6	7.04	5	8.08	7.50	21	16
Long duration variety (LDV)										
Emergence day	9	7	0.83	2	1	-2	1.68	2.06	19	16
Anthesis day	109	107	0.98	18	13	-2	15.74	11.41	14	16
Maturity day	167	165	0.99	9	11	-2	10.97	9.39	7	16
Vegetative weight (kg ha^{-1})	4.75	4.74	1.00	1697	2	-0.01	0.95	0.97	20	16
Maturity grain yield (kg ha^{-1})	6.37	6.31	0.99	2750	2	-0.07	1.09	0.74	17	16
Total aboveground biomass (kg ha^{-1})	11.12	11.05	0.99	4099	4	-0.08	0.85	0.67	8	16
Harvest index	44	42	0.96	8	3	-2	8.52	6.83	19	16

condition. In Merchouch (Fig. 6A), the highest NUE was at 1st December seeding, where NUE was 25 kg grain kg^{-1} N at 100 kg N ha^{-1} in rainfed; NUE of 29 kg grain kg^{-1} N at 100 kg N ha^{-1} under HSSM; and NUE of 27 kg grain kg^{-1} N at 150 kg N ha^{-1} under HSSM+SI, indicated those could be the optimal N rate for Merchouch. A similar N rate can be applied for seeding between 15 November and 01 December. While seeding after 15 December, N rate should be lowered for maximizing NUE (~50 kg N ha^{-1} for rainfed, ~100 kg N ha^{-1} under HSSM, and < 150 kg N ha^{-1} under HSSM+SI). Similar to Merchouch, in Meknes (Fig. 6B), the highest NUE was under 1st December seeding, where the highest NUE (22 kg grain kg^{-1} N) was under 100 kg N ha^{-1} in rainfed; NUE of 33 at 100 kg N ha^{-1} under HSSM; and NUE of 31 at 150 kg N ha^{-1} under HSSM+SI, indicated those could be the optimal N rate for Meknes. However, in Sidi El Aidi (Fig. 6C), there was no need for more than 50 kg N ha^{-1} at all seeding dates under rainfed and HSSM conditions. However, under HSSM+SI, the optimal N rate can be up to 150 kg N ha^{-1} under optimal seeding dates, where NUE was 20 and 22 kg grain kg^{-1} N, respectively.

3.2.5. *Water requirement for different seeding dates*

Under HSSM+SI scheduling, Sidi El Aidi required the highest irrigation (204 mm) followed by equal amount (53 mm) in Meknes and Merchouch at optimal seeding date 15 November to 01 December (Fig. 7). There was a yield difference of 2.2 t ha^{-1} under the condition of below and above long-term median rainfall (244.2 mm) (Fig. 7B).

4. Discussion

Simulation models provide decision support to generate context-specific tailored selection of genotypes and agronomic management practices to diverse environmental conditions. In Morocco, wheat production area has increased but steadily over the years (FAOSTAT, 2023), where it has been challenged mostly due to declining water resources for supplemental irrigation, adverse effects of drought, heat stress, soil degradation, and low input use (Haddad et al., 2011; Karrou et al., 2016; Verner et al., 2018). In rainfed conditions, a yield gap of 1.2 t ha^{-1} (Karrou et al., 2016; Silva et al., 2023), 1.6–2.5 t ha^{-1} (Pala et al., 2011), and 0.57 t ha^{-1} (Devkota and Yigezu, 2020) are reported. Our study showed a water-limited yield gap of 2.6–6.2 t ha^{-1} (35–76%) and an attainable yield gap of 1.1–2.1 t ha^{-1} (24–37%) under timely planting with optimal fertilizer application (Fig. 4). This study comprehensively decomposed the variance contribution of genotype × environment × management practices for closing the yield gap (Fig. 4) and found the contribution of different factors varies across the production environments and water management practices. Previous studies have assessed genotype × management × environment effects on yield variation of different crops. Variance decomposition is a sensitivity analysis that allows the decomposition of variance contribution of each production factor to the model output (Monod et al., 2006), and the approach has been applied to potato in Tasmania, Australia (Ojeda et al., 2021), sorghum across US environments (Ojeda et al., 2022), cereal grain crops in European environment (Webber et al., 2018), maize in New Zealand (Teixeira et al., 2017), and maize in US corn belt (Baum et al., 2020). Additional variance decomposition studies in wheat production as affected by variety, sowing date, supplemental irrigation, nutrient management, and integrated good agronomic management practices are required in the water-stressed production environments (Briak and Kebede, 2021). Our study showed the proportional variation of the contribution of individual factors as main and/or total effects, where rainfall and/or supplemental irrigation, N fertilizer, sowing date, and variety are the major yield-limiting factors for durum wheat production in Morocco. Those practices can be considered as a set of adaptive ‘integrated good agronomic practices’ for increasing resilience of wheat production in the rainfed production systems of Morocco and similar climatic conditions of the Mediterranean region.

4.1. *Supplemental irrigation*

Application of supplemental irrigation (SI) during the water stress period increased yield by 35–76% in HSSM+SI (249 mm stored soil moisture at seeding + 53 mm SI) and by 24–37% in HSSM (249 mm stored soil moisture) compared to the rainfed condition (Fig. 4). Well distributed and > 300 mm rainfall amounts are crucial for higher yield, which is evidenced by the 38% years (probability) in Merchouch and 24% probability in Meknes having yield more than 5 t ha^{-1} under rainfed condition of the timely sown wheat (15th November and 1st of December) (Fig. 4). With increasing rainfall variability and decreasing rainfall amount, supplemental irrigation plays a crucial role for

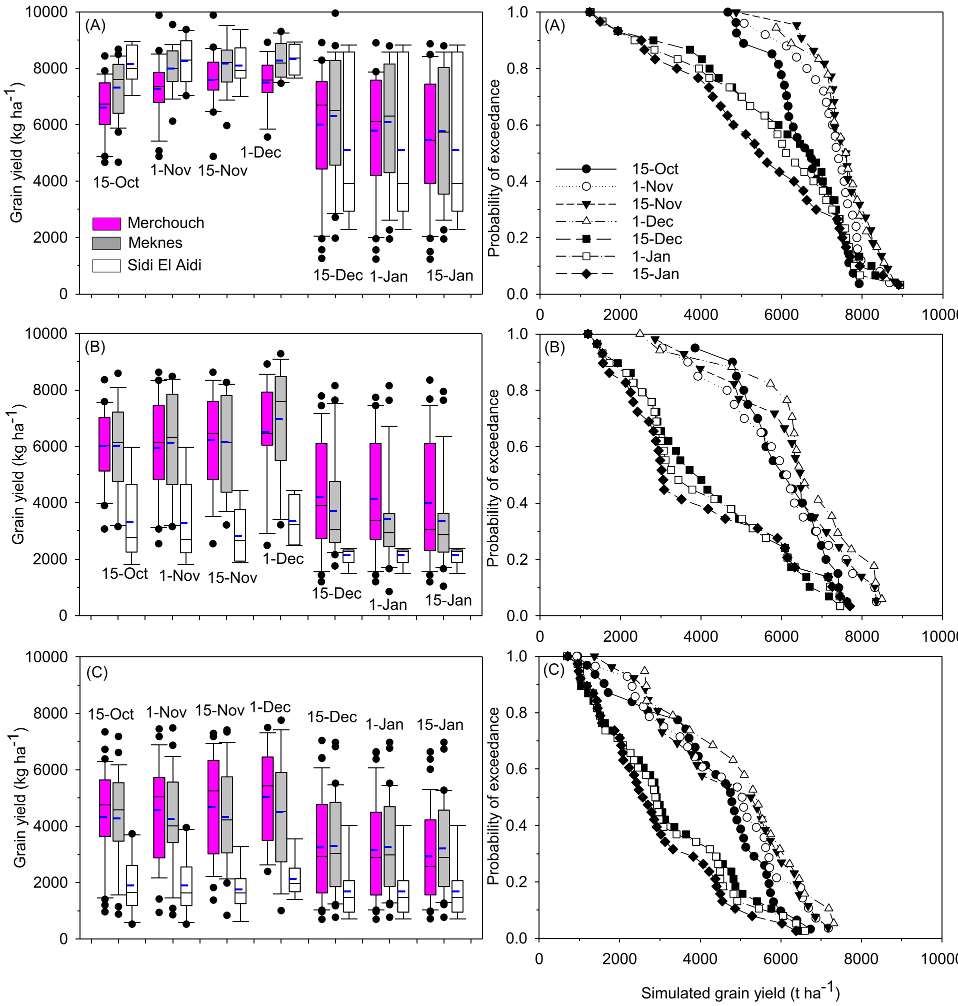

Fig. 4. (*Left*) Long-term simulated yield and (*right*) probability of exceedance for grain yield and under high stored soil moisture + supplementary irrigation (HSSM+SI) (A), yield under HSSM (B), and yield under rainfed (Rf) conditions (C) with N rate of 200 kg ha^{-1} and short-duration (152 days) as affected by seeding dates in Morocco. The probability of exceedance figure (*right*) is only for Merchouch. Black solid lines in the boxplot are the median and the blue dotted line is the mean.

narrowing the water-limited yield gap. In Merchouch and Meknes, on top of HSSM, 53 mm supplemental irrigation increased wheat yield to more than 6 t ha^{-1}. However, yield increment due to supplemental irrigation varies across planting dates, such with supplemtal irrigation increased durum wheat productivity from 2.8 to 5.4 t ha^{-1} in early planting and from 0.3 to 5.3 t ha^{-1} in late planting in Central Morocco (Karrou et al., 2016). Despite narrowing the yield gap during the dry years, supplemental irrigation provides resilience to climate change and yield stability under such climate crises (Nangia and Oweis, 2016). Supplemental irrigation with 60 mm at 59 zadok stage increased wheat yield by 91% in rainfed Sais region of Morocco (Abderrazzak et al., 2013). The mean grain yield from rainfed to 1/3rd SI, 2/3rd SI, and full supplemental irrigation were 1.36, 3.82 (+181%), 5.18 (+281%), and 5.70 (+319%) t ha^{-1} for bread wheat; and 1.24, 3.80 (+206%), 5.10 (+311%), and 5.75 (+364%) t ha^{-1} for durum wheat, respectively in Hadya, Syria (Karrou and Oweis, 2012). Despite several advantages such as yield increment, improving resilience to variable weather conditions, yield stability, risk reduction, improving grain quality; in the context of declining water availability, applying supplemental irrigation for rainfed wheat may not be a feasible option in the future in Morocco and also in the MENA region. However, deficit supplemtal irrigation can be adopted for saving water, improving grain yield and quality, and improving water productivity in the irrigated production systems, such as Tadla perimeter (covers more than 100,000 ha of irrigated wheat (Kselik et al., 2008) of Morocco, and similar production environment in irrigated drylands. The lowest water-limited attainable yield gap (highest yield under rainfed) in Merchouch, followed by Meknes was mainly related to the heavy clay texture soil of Merchouch and the higher amount of rainfall received in Meknes (Fig. 1). There were inherent differences in soil properties (Table 1) and agroclimatic conditions (Fig. 1) such as temperature and growing season across those locations. Similarly, higher yield in Sidi El Aidi under HSSM+SI was readily available water under light soil texture (Table 1) with optimal fertilization. Similar results have been reported by (Lembaid et al., 2021; Nouri et al., 2016).

4.2. *Rainfall amount and distribution*

Rainfall has a significant contribution on yield, highest main and the total or interaction effects in the rainfed (36%) followed by HSSM (31%) and 23% contribution under HSSM+SI conditions (Fig. 5). In rainfed wheat production system, where the total seasonal rainfall is the proxy of crop yield (Balaghi et al., 2008), total seasonal and rainfall during critical growth stages of wheat are critical (Latiri et al., 2010), rainfall accounts 75–88% of the total yield variation for barley, chickpea, wheat, and lentil (Devkota et al., 2022a), and Morocco's wheat production heavily dependents on large fluctuations in rainfall intensities (Berdai et al., 2011). Karrou and Oweis (2014) assessed the effect of rainfall

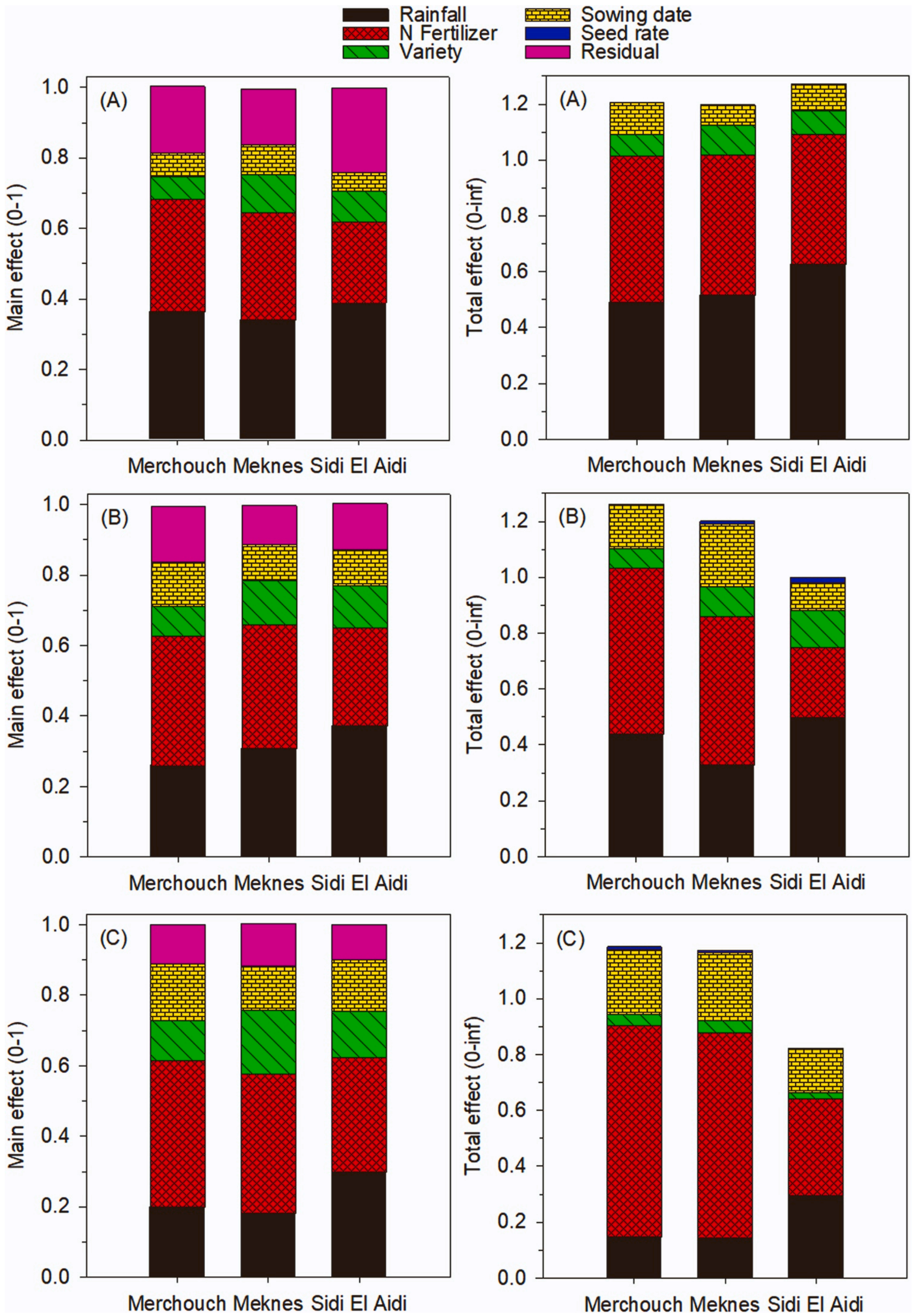

Fig. 5. Main effect (*left*) and total (interaction) effect (*right*) contribution of simulated yield variability as explained by sowing date, fertilizer, cultivar, rain, and seed rate in three sites of Morocco as affected by water management, i.e., rainfed (A), HSSM (B), and HSSM+SI (C).

variability in the major cereal production areas of Morocco and that for the period 1988–2008, yields fluctuated from 150 to 3000 kg ha^{-1} with a coefficient of variation ranging between 30% and 50% in the Northern and 60–70% in the Southern region of the country. With global warming, Moroccan climate is becoming drier and hotter (Filahi et al., 2017). In this context, a reliable seasonal forecasting system may help to reduce the vulnerability of such weather risks by timely enabling adoption practices as reported by (Lehmann et al., 2020).

4.3. Nitrogen fertilizer rate

Nitrogen fertilizer has a significant main effect, i.e., 28% under rainfed, 33% under HSSM, and 38% contribution under favorable environment, i.e., HSSM+SI in durum wheat yield variability in Morocco (Fig. 5). Also, there is significant interaction (total effect) of fertilizer with other factors such as variety, site, and seeding date (Fig. 5), and optimal N rate varies across seeding date and sites (Fig. 6). The general recommended nitrogen rate in Morocco is 84, 140, 210 and 280 kg N ha^{-1} respectively for rainfed, favorable rainfed, supplementary irrigation, and irrigated production system (INRA, 2022). In the rainfed areas of the south-central region (Chaouia area) of Morocco, grain and biomass yield of wheat increase significantly up to 90 kg N ha^{-1} (Ryan et al., 1997). However, these rates vary based on the PAWC, site, year (climate) and require field-specific adjustments and

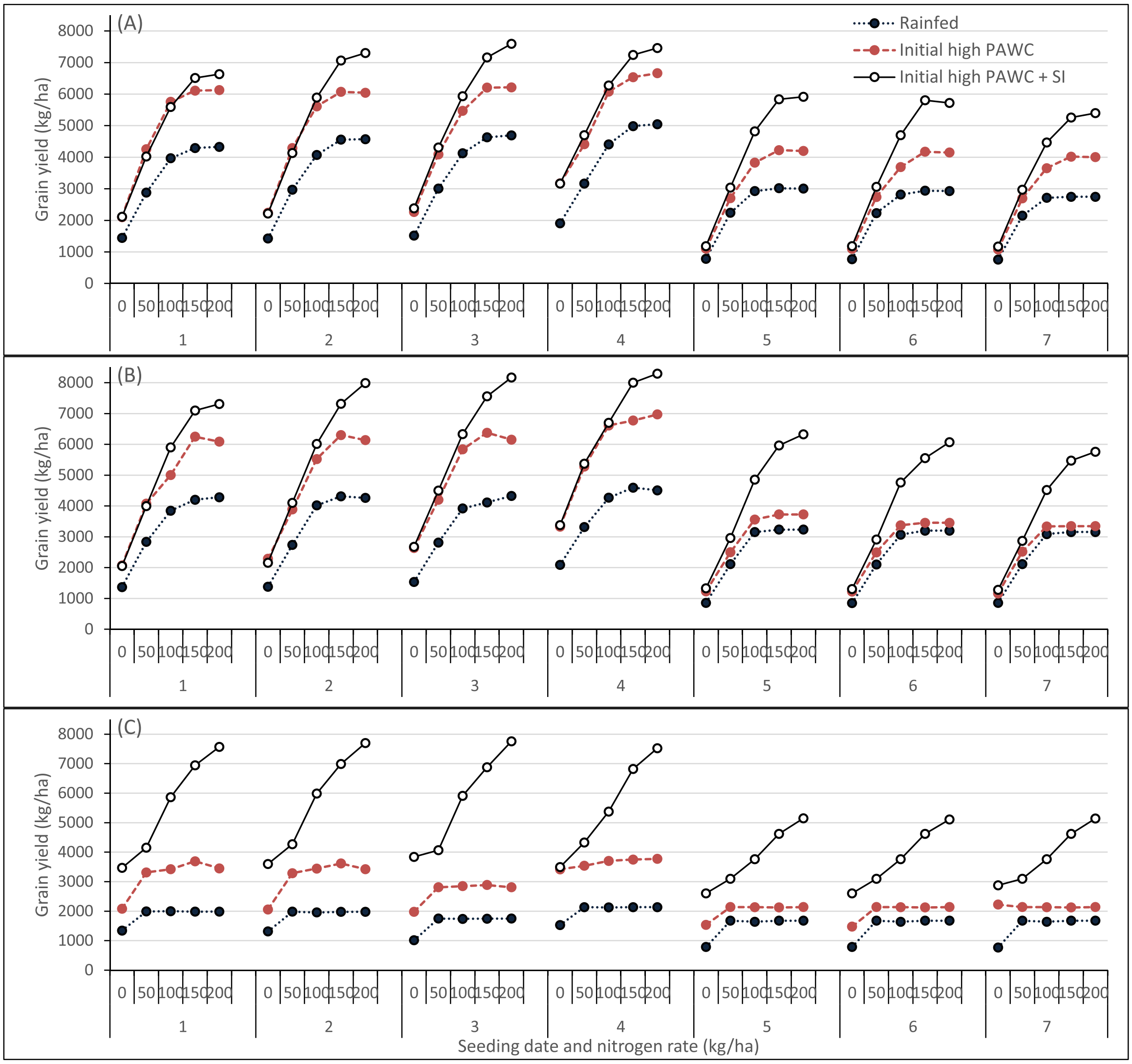

Fig. 6. Optimal N rate under long-term (1985 –2021) simulated wheat yield under seven different seeding dates as affected by soil moisture and supplementary irrigation in Merchouch (A), Meknes (B) and Sidi El Aidi (C), Morocco. Short duration variety (160 days seed to seed). 1 = October-15, 2 = November-1, 3 = November-15, 4 = December-1, 5 = December-15, 6 = January-1, 7 = January-15.

'one-size-fits-all' approach is inadequate. In the Mediterranean region of Australia, N management is viable when plant available water content before seeding increases (higher than 130 mm) and above median rainfall (Moeller et al., 2009). Even in rainfed conditions, nitrogen is one of the most yield-limiting factors; however, due to uncertainty of the climatic conditions, farmers are reluctant to apply. In this case, an optimal rate is required considering the economic profitability as chronic under-fertilization may mine soil nutrients. At the same time, over-fertilization may cause nutrient loss and reduce fertilizer use efficiency, although low or no nutrient loss or nutrient storage is reported from the wheat fields in semi-arid Mediterranean climatic conditions (Savin et al., 2022).

4.4. Seeding time

Seeding time is one of the major factors contributing to yield variability in different locations and water management, where the contribution of seeding time even increases under HSSM+SI (Fig. 5). The significant location × year × seeding date effect ($p < 0.001$) for the simulated grain yield indicated that seeding time varies with location and growing season. This variation was caused mostly by the variation of rainfall across the year ($p < 0.001$), where the yield difference was > 2.1 t ha^{-1} due to rainfall (above and below median) (Fig. 7B) and seeding time mostly affected by rainfall amount and distribution. Wheat is sensitive to water deficit and temperature fluctuation during the reproductive and grain-filling period (Alghabari et al., 2014; Farooq et al., 2011; John and Megan, 1999). If irrigation is available, early seeding can provide a more stable yield, which holds true for rainfed conditions and provides an opportunity to store more than 50 mm of seasonal rainfall. Thus, in rainfed drylands, generally early seeding can be suggested, however customized seeding time based on weather forecasting (considering rainfall amount, rainfall frequency, and temperature) can maximize the effective use of available water, which leads to improved crop productivity and resilience.

The more stable yield (low coefficient of variation) in the earlier seeding (37–44% in 15 October to 30 November, compared to seeding after 15 December (>55% CV under rainfed; and >37% CV under HSSM) indicates if sufficient soil moisture is available, advancing seeding time can narrow the yield gap especially as this can also benefit from the whole season rainfall. Even with late planting, irrigation improved grain yield by increasing available soil moisture and reducing canopy temperature (Amani et al., 1996). The physiological stages (anthesis, leaf area development, photosynthesis, and biomass accumulation) are more favored with early seeding because reduced rainfall and higher temperature coincide with the anthesis period under the late seeding conditions (Padovan et al., 2020). However, advancing the

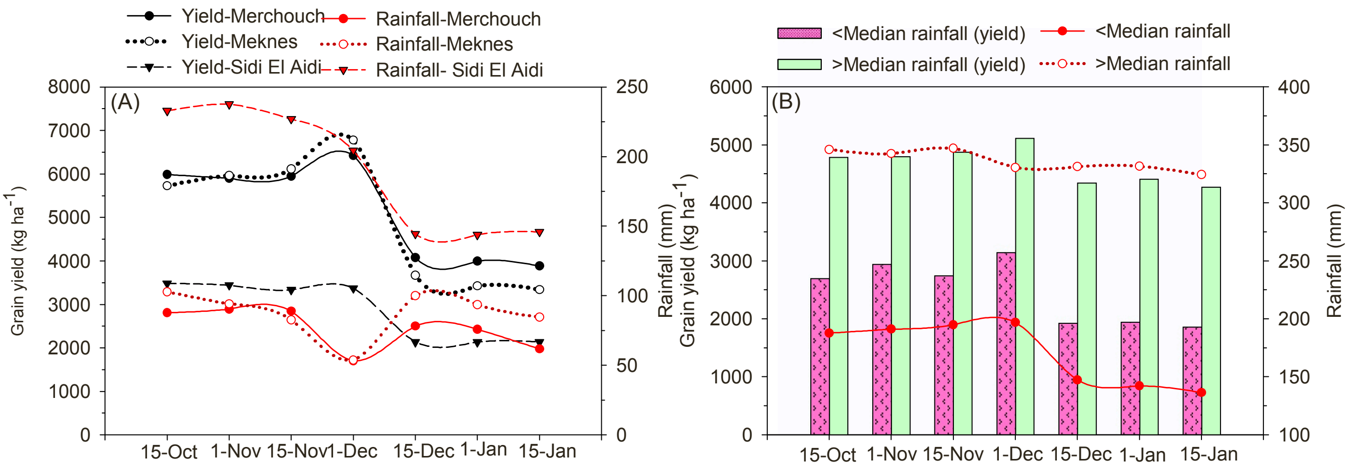

Fig. 7. Simulated grain yield and irrigation applied under HSSM+SI (A) and long-term simulated wheat yield and seasonal rainfall amount at below and above median long-term rainfall (B) under short duration variety (160 days) and N fertilizer rate of 100–200 kg ha^{-1}.

seeding date (earlier than optimal) requires an increased irrigation water supply (Fig. 7A). In the Mediterranean region, considering the rainfed dryland production systems with high rainfall variability, seeding time needs to be customized, and the optimal seeding date might be the one which demands low irrigation water without compromising the yield. The highest simulated yield in Merchouch for all seeding dates, compared to Meknes and Sidi El Aidi, was mainly due to low maximum temperature and difference between minimum and maximum with higher rainfall (greater difference between maximum and minimum temperature in Meknes and Sidi El Aidi) (Fig. 1).

4.5. Variety

The beneficial effect of best agronomic practices can be limited without using suitable varieties and adopting appropriate varieties is a critical factor in achieving higher yields and better-quality grains (Kirkegaard and Hunt, 2010; El Mourid and Gharous, 2008). In drylands, environment × management explains the most yield variance, however the contribution of genotype cannot be underestimated as its potential is suppressed by climate, soil, water, and management practices. Our study showed 9%, 11% and 14% contribution of genotype in wheat yield variability under rainfed, HSSM, and HSSM+SI conditions of Morocco (Fig. 5). It indicated that tested varieties are more responsive for the irrigated and favorable conditions and much higher level of drought tolerant varieties are required for the rainfed conditions with highly variable rainfall. Under irrigated conditions, varieties can express their full potential (Ojeda et al., 2022, 2021). Yield of short duration (<155 days maturity) variety was more stable across the years under the optimal seeding date and fertilizer rates, where SDV, MDV and LDV had CV of 28%, 29% and 32%; and yield of 5.2, 4.8 and 4.5 t ha^{-1}, respectively (Fig. 3). Grain yield of wheat varieties (comparing major varieties, e.g., Potam, Cocorit, Keyperounda) increased with the degree of earliness despite the similar amount of water used by the different cultivars (ElMourid, 1988; Mourid and Gharous, 2008). Moroccan wheat varieties have differences in adaptation; varieties released after 2003 have drought tolerance, while varieties released before 2003 possess a better ability to exploit favorable environments, and the earlier released varieties are widely adapted but do not possess high yield potential (Nsarellah et al., 2011).

5. Conclusions

APSIM-Wheat model is capable of and can be used as decision support to determine the contribution of Genotype × Environment × Management components for sustainably closing the yield gap and developing climate-smart adaptation strategies. Rainfall or supplementary irrigation (23–36%), N fertilizer (28–38%), cultivar (9–14%), and seeding date (7–14%) have the largest contribution to the yield variance of durum wheat in Merchouch, Meknes, and Sidi El Aidi region of Morocco. Under rainfed conditions, wheat yield was highest in Merchouch (4.5 t ha^{-1}) and lowest (1.8 t ha^{-1}) in Sidi El Aidi. Due to large rainfall variability, the seeding date varies across year and location; however, generally, it is between 15 to 30 November. Under rainfed conditions, seeding after 1st week of December caused yield reduction of 120, 81, and 31 kg ha^{-1} d^{-1} in Merchouch, Meknes, and Sidi El Aidi, respectively. Short-duration varieties provided higher yields with better resilience than medium (170) and long (180) duration varieties. Decomposing yield variance caused by Genotype × Environment × Management approach provides the opportunity for risk reduction and improvement of wheat yield and resilience in rainfed Mediterranean drylands.

Credit authorship contribution statement

Krishna Prasad Devkota: Conceptualization, Methodology, Formal analysis, Simulation modelling, Visualization, Writing original draft, Editing. **Mina Devkota**: Data Management, Writing original draft, Editing, Reviewing. **Rachid Moussadek**: Editing, Reviewing. **Vinay Nangia**: Editing, Reviewing.

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.

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