



Dry sowing reduced durum wheat performance under irrigated conservation agriculture

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ABSTRACT

Permanent raised beds (PB) are a conservation agriculture option for irrigated conditions that can improve soil quality, increase soil moisture conservation and stabilize yields compared to conventional furrow irrigation. In irrigated wheat (*Triticum* sp.) production, wet sowing (i.e. applying irrigation before sowing) is most widely used. It allows pre-sowing weed control but reduces sowing time flexibility. Dry sowing, i.e. applying irrigation after sowing, reduces options for weed control but improves water use efficiency and sowing time flexibility. This study evaluated the performance of durum wheat (*Triticum durum* L.) under conventionally tilled (CTB) and PB with wet and dry sowing in northwestern Mexico. In those four tillage-sowing irrigation environments (ENV), five nitrogen (N) fertilization treatments were tested. Plant stand, grain yield, and grain quality were measured for ten years and fertilizer-based N use efficiency indices were assessed in three years. Plant stand, wheat yield and quality were significantly affected by ENV. The lowest plant stand and yield were found in PB-Dry sowing. On average, only 54 plants m⁻² emerged in PB-Dry whereas 159 plants m⁻² emerged in CTB-Wet. Plant stand showed high yearly fluctuations, with plant stand in dry sowing favored by lower reference evapotranspiration, with CTB-Dry favored more by high minimum temperature and PB-Dry by high maximum temperature. Yield ranged between 4.20 and 7.94 t ha⁻¹. Yield in PB-Dry was on average 0.35 to 0.50 t ha⁻¹ lower than in the remaining ENV, but positive interactions between year and dry sowing systems were associated with high minimum temperatures at germination and tillering. N fertilization management affected wheat quality, but not wheat yield, possibly due to high levels of soil mineral N available at sowing that were not measured in this study. Split application of N increased grain N content compared to basal N application. Research should address reduced plant stands with dry sowing in conservation agriculture to find management options that improve wheat emergence. Further efforts to optimize N fertilizer management in PB are required to improve grain quality components.

1. Introduction

Wheat (*Triticum* sp.) is the third most important cereal in the world by production, after maize (*Zea mays* L.) and rice (*Oryza sativa* L.) (FAOSTAT, 2018) and is a staple source of nutrients for around 40 % of the world's population (Giraldo et al., 2019). Mexico is the third-largest exporter worldwide of durum wheat (*Triticum durum* L.), selling 839,000 t annually (SIAP, 2019). Mexico's main wheat production area is the

Yaqui Valley in the state of Sonora. The valley has a semi-arid climate and crop production depends on irrigation water, mainly from dams. The agroecosystem conditions are representative of several major wheat-producing regions of the developing world, including the Indus Valley in Pakistan, the Gangetic Valley in India, and the Nile Valley in Egypt (Reynolds and Ortiz, 2000).

In 2017, more than 220,000 ha were sown to wheat, principally durum wheat, with an average yield of 6.5 t ha⁻¹ (SIAP, 2019). Crop

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production in the valley is limited by water supply. Reduced availability of irrigation water from poor rains and reservoir recharge, combined with other users' increased demands, resulted in a decline of summer crop production since 2002 (McCullough and Matson, 2016). Farmers and researchers are exploring cropping practices that reduce the use of irrigation water and simultaneously allow for greater flexibility of sowing date, since timely sowing is important to avoid terminal heat stress (Flores, 2020).

Conservation agriculture, an approach based on minimum tillage, crop residue retention, and economically viable crop rotations, has been mostly adopted in rainfed cropping and is now studied and promoted for sustainable intensification of irrigated farming systems in Latin America and South Asia (Derpsch et al., 2010; Erenstein et al., 2012). Permanent raised beds (PB) are a conservation agriculture option for irrigated conditions that can improve soil quality (Verhulst et al., 2011a) and increase soil moisture conservation (Grahmann et al., 2018a). In irrigated cropping, conservation agriculture can help to mitigate climate change by reducing greenhouse gas emissions (Abdalla et al., 2013) as well as improving and stabilizing wheat yields, compared to conventional furrow irrigation (Jat et al., 2020; Verhulst et al., 2011b). Reported drawbacks include reduced grain protein concentration (GPC; Grahmann et al., 2016, 2014) and overall reduced nitrogen use efficiency (NUE; Grahmann et al., 2019). Water availability is closely related to NUE (Cossani et al., 2010). Together they affect wheat quality parameters like grain protein, test weight or thousand kernel weight. Research is needed to identify best timing and mode of N application for improved grain yield and quality under irrigated CA.

The most widely adopted sowing practice in the Yaqui Valley is 'wet sowing'. A pre-sowing irrigation of around 100 mm is applied and sowing follows after two to three weeks, when the soil has dried sufficiently to be accessed with machinery. Weed control can be carried out pre-seeding; mechanically under conventional tillage (CT), or with a broad spectrum herbicide application (Lobell et al., 2005). A downside of the method is the unproductive loss of irrigation water. Additionally, rains may delay the drying of the soil, forcing farmers to postpone sowing and missing the optimum sowing window. In 'dry sowing', the crop is sown directly into the dry soil and irrigated soon afterward, causing weed and crop seeds to germinate at the same time, requiring selective herbicides for weed control. Dry sowing area has increased in the region in recent years. Alternating use of wet and dry sowing could be a practical solution for farmers to improve water use efficiency compared to continuous wet sowing, as well as avoiding the development of herbicide resistance in weeds by diversifying weed control options compared to continuous dry sowing (Marquez Berber et al., 2014).

In other countries with farming conditions similar to those of the Yaqui Valley, dry sowing under conservation agriculture was studied with various crops and showed yield benefits and water savings over conventional tillage and, in the case of rice, over the transplanting practice (Devkota et al., 2015; Sudhir-Yadav Humphreys et al., 2011). Irrigated PB with dry sown crops were evaluated in India ("double no-till" for rice-wheat or maize-wheat; Jat et al., 2019; Parihar et al., 2017; Singh et al., 2016), Bangladesh (maize; Gathala et al., 2016), Central Asia (rice-wheat; Devkota et al., 2015; wheat; Hemmat and Taki, 2001) and China (bread wheat; He et al., 2015). Few studies have compared tillage regimes and sowing practices or their interactions under irrigated conditions, and none was found for durum wheat.

The objectives of this study were to (1) determine the effects of dry and wet sowing on durum wheat yield, yield components, and grain quality traits under conservation agriculture and conventional tillage and (2) to assess the effect of different N fertilizer management approaches on yield and fertilizer-based NUE indices.

2. Materials and methods

2.1. Site description

The experiment was established in 2007 at the Norman E. Borlaug Experiment Station (CENEB) near Ciudad Obregón, Sonora, Mexico (lat. 27°22,010'N, long. 109°55,051'E, 38 m asl) and concluded in 2018. The site has an arid climate with average rainfall during 2009–2018 of 337 mm and annual maximum and minimum temperatures of 32 °C and 16 °C (Table S1). Average annual evapotranspiration is 1713 mm. Rainfall is concentrated during June to November. Monthly temperatures during November to May average a maximum of 29 °C and a minimum of 11 °C. Mean precipitation for the wheat growing period is 42 mm and evapotranspiration is 907 mm. The soil is a Hyposodic Vertisol (Calcaric, Chromic). All horizons in the soil profile to 2 m are slightly alkaline (pH 8) and low in organic matter (<1.2 %). At 0–70 cm depth, the soil texture is 33 % sand, 17 % silt and 50 % clay.

2.2. Experimental set-up and crop management

The experiment had a randomized complete block design for four environments that combined tillage and sowing irrigation practice: conventionally-tilled beds (CTB) with wet and dry sowing and PB with wet and dry sowing. The PB treatments had been under conservation agriculture for over ten years previously to the experiment. Plots were defined by N fertilizer management, with three replicates (Fig. S1) and were 3 m wide (4 beds of 0.75 m width) and 10 m long, a space of 30 m². The CTB were tilled after each crop with a disk harrow to 20 cm depth and new beds were formed. The PB were only reshaped in the furrow without disturbing the soil on the bed. In wet sowing, 100–120 mm irrigation was applied two-to-three weeks before sowing; in dry sowing, the field was irrigated one or two days after sowing with 100–120 mm, which provided higher soil moisture content during germination than wet sowing. Four auxiliary irrigations of 80–100 mm were applied to all plots each cycle. The N fertilizer treatments consisted of a control treatment with no N fertilizer and five treatments with different doses and divisions between first and second fertilization (Table 1), applied as urea. The basal N application was done on the same day as the pre-sowing (wet sowing) or sowing (dry sowing) irrigation, applying the fertilizer in the furrow and incorporating it through irrigation. The N application at first node was completed immediately prior to the first auxiliary irrigation. Nitrogen was applied either once (basal) or split between pre-sowing and first node (split). The highest total amount of tested N fertilizer was 240 kg ha⁻¹, which is below the average mineral fertilizer amount of 260 kg N ha⁻¹ applied by farmers (Lobell et al., 2005).

Untreated seed of durum wheat variety CIRNO C2008 was sown between end of November and mid-December at a seeding rate of 120 kg ha⁻¹ (approximately 240 seeds m⁻²). Except in 2014 and 2016, unfertilized maize was sown as a summer crop to ensure soil cover and straw residue production and to extract residual N. All plots received a banded basal application of 46 kg P₂O₅ ha⁻¹ as triple superphosphate. In most

Table 1

N fertilization treatments used during the study period (2008–09 to 2017–18). All treatments were applied in three replicates for each tillage-irrigation environment (permanent raised beds and conventionally tilled beds, both with wet and dry sowing).

N fertilization treatment	Total N dose (kg N ha ⁻¹)	Basal application before sowing	Application at first node
0 N	0	0	0
120S	120	36	84
180S	180	54	126
180B	180	180	0
240S	240	72	168
240B	240	240	0

Table 2

Yield-relevant co-variables assessed for each plot by averaging daily temperature data for a particular period. Note that sowing date, date of 50 % emerged plants and flowering date were recorded yearly at the plot scale.

Abbreviation	Description	Period
TminPQ	Average minimum temperature during photothermal period (°C)	Photothermal period: 20 days before to 10 days after flowering
TmaxPQ	Average maximum temperature during photothermal period (°C)	
TminGF	Average minimum temperature during grain filling period (°C)	Grain filling: 30 days after flowering
TminGerm	Average minimum temperature during germination (°C)	Emergence: 3 weeks after sowing
TminTill	Average minimum temperature during tillering (°C)	Tillering: 4 weeks after 50 % Emergence

years, one application of insecticide was needed to control aphids. In wet sowing, glyphosate was used at sowing to control weeds, whereas in dry sowing selective herbicides (mostly bromoxynil and fluroxypyr) and manual control were used.

2.3. Data collection

Soil temperature was recorded hourly at 5 cm soil depth with 6 sensors (12-Bit Temperature smart sensors combined with HOBO U12 Data logger) per tillage × irrigation treatment for several weeks after sowing in the 2011–12 and 2016–17 cropping cycles. Yearly meteorological data were obtained from a weather station located approximately 2 km from the experiment (Table S1).

For plant population after emergence, plants were counted in four 0.375 m² (0.50 m × 0.75 m) areas per plot before tillering (Zadoks 13–15) and the average plant population per plot was calculated. A GreenSeekerTM handheld optical sensor (Trimble, Inc., USA) was used to collect NDVI measurements 40 (NDVI1) and 100 (NDVI2) days after sowing. Measurements were taken in the two central beds of each plot between four to eight times during the cropping cycle. Detailed information about NDVI measurements can be found in Verhulst et al. (2011c). To quantify the heterogeneity of the plant cover, the coefficient of variation (CV) for each NDVI measurement sequence was analyzed for the NDVI readings at 40 and 100 days after sowing (Govaerts et al., 2007).

Durum wheat was harvested between end of April and beginning of May. Yield was measured according to CIMMYT (2013). The central area of each plot (two center beds of 10 m length) was combine harvested, grain weight and moisture content were measured, and grain yield was calculated at 12 % moisture content. Harvest index was calculated by dividing the dry grain weight from 50 stems by the dry weight of 50 stems and used to calculate biomass (CIMMYT, 2013). Straw was calculated as the difference between grain yield and harvest index-calculated biomass. Thousand kernel weight (TKW) was measured by counting a subsample of 200 grains and measuring the dry weight. Test weight is defined as wheat per unit volume and expressed in kilograms per hectoliter (kg hL⁻¹; Carson and Edwards, 2009). The grains were poured through a cone in a 1 L vessel and converted to the test weight of a hectoliter. Grain protein concentration was determined in 2011, 2012 and 2013 using near-infrared reflectance spectroscopy (AACC method 39–10, AACC International, 2010) with the Foss NIR Systems Feed and Forage 6500 instrument (Foss, Hillerød, Denmark), expressed at 12.5 % moisture by multiplying grain N with the factor 5.7 (Liu et al., 2018; Mariotti et al., 2008). Nitrogen in straw was determined for the same three years using the Kjeldahl method (Kjeltec 2200, Foss, Hillerød, Denmark) according to the AACC method 46–11A (AACC International, 2010).

2.4. Calculations

The following fertilizer-based NUE indices were calculated according to Congreves et al. (2021); Dobermann (2007) and Fixen et al. (2015):

$$N \text{ uptake in grain } [\text{kg N ha}^{-1}] : N_g = \%N_{\text{grain}} \times \text{grain yield} \quad (1)$$

$$N \text{ uptake in straw } [\text{kg N ha}^{-1}] : N_s = \%N_{\text{straw}} \times \text{straw yield} \quad (2)$$

$$\text{Total aboveground N uptake } [\text{kg N ha}^{-1}] : N_t = N_g + N_s \quad (3)$$

$$\text{Agronomic efficiency } [\text{kg kg}^{-1}] : \quad (4)$$

$$AE = \frac{\text{Grain yield in fertilized plots} - \text{Grain yield in unfertilized plots}}{N \text{ fertilizer rate in fertilized plots}}$$

$$\text{Partial factor productivity } \left[\frac{\%}{\%} \right] : PFP = \frac{N_t}{N \text{ fertilizer rate}} \times 100 \quad (5)$$

$$\text{Apparent recovery efficiency } [\text{kg kg}^{-1}] : \quad (6)$$

$$RE = \frac{N_t \text{ in fertilized plots} - N_t \text{ in unfertilized plots}}{N \text{ fertilizer rate in fertilized plots}}$$

2.5. Data analyses

The linear mixed model used in this study considered the interaction between tillage × irrigation as environment (ENV) that is replicated across years. Thus, the response variables are explained by the following model:

$$y_{jklm} = \mu + E_j + F(E)_{k(j)} + RF(E)_{lk(j)} + Y_m + YE_{jm} + YF(E)_{mk(j)} + e_{jklm}$$

Where the 3 fixed effect terms of the linear mixed model above are: μ , the overall mean, E_j the effect of the j th environment comprising the combination of the two irrigation levels with the two tillage levels ($j = 1, 2, \dots, 4$), and the $F(E)_{k(j)}$ that denotes the nested fixed effect of the k th fertilizer level ($k = 1, 2, \dots, 6$) within each of the j th environments. The 4 random effects of the above linear model are: $RF(E)_{lk(j)}$ the interaction of the l th replicate ($l = 1, 2, 3$) with the $F(E)_{k(j)}$ with identically and independent normal distribution (*iid*) $RF(E)_{lk(j)} \sim N(0, \sigma_{RF(E)}^2)$ where $\sigma_{RF(E)}^2$ is the variance of the replicate × fertilizer level nested within environment, Y_m denotes the random year effects assumed *iid* such that $Y_m \sim N(0, \sigma_y^2)$ where σ_y^2 is the variance of the year effects, the $YF(E)_{mk(j)}$ assumed to be *iid* such that $YF(E)_{mk(j)} \sim N(0, \sigma_{YF(E)}^2)$ where $\sigma_{YF(E)}^2$ is the variance of the year × fertilizer within environment and the residual term e_{jklm} that accounts for any variation not explained by the previous terms and is also assumed to have an *iid* $e_{jklm} \sim N(0, \sigma_e^2)$ where σ_e^2 is the residual variance.

The code for this paper was generated using SAS software, Version 9. If not stated differently, presented averages were calculated without the 0 N kg ha⁻¹ N fertilizer treatment (0 N) which was only considered to calculate fertilizer-based NUE indices.

2.5.1. The Partial Least Square regression and its biplot

Partial Least Squares (PLS) regression describes the treatment × environment interaction in terms of differential sensitivity of cultivars to environmental variables. In PLS the explanatory variables are hypothetical variables (linear combinations of the complete set of measured environmental variables) and there is no limit to the number of explanatory co-variables that can be used (Vargas et al., 1998). PLS regression has been used in agronomic studies to improve the prediction of grain yield and protein content in wheat and barley (Hansen et al., 2003), to reveal the factors that control wheat yield in China (Hu et al.,

2018) and to explain tillage–straw system \times year interaction for wheat yield by climatic co-variables (Verhulst et al., 2011b). In this study, the crop responses over years (Y) were modeled using environmental co-variables: for plant stand, daily minimum and maximum temperatures and reference evapotranspiration in the three weeks after sowing were used; co-variables for crop yield are listed in Table 2.

Therefore, the matrix Z contains the environmental co-variables that can be written as

$$Z = t_1p'_1 + t_2p'_2 + \dots + t_Mp'_M + E_M = TP' + E \quad (7)$$

Where matrix T contains the $t_1 \dots t_M$ vectors forming the Z -scores (indexed by years) and matrix P has the $p_1 \dots p_M$ vectors called Z -loadings (indexed by environmental variables) and E has the residuals.

The response variable matrix Y can be represented in a bilinear form as

$$Y = t_1q'_1 + t_2q'_2 + \dots + t_Mq'_M + F_M = TQ' + F \quad (8)$$

Where the matrix Q had the $q_1 \dots q_M$ vectors named Y -loadings (indexed by the crop response under different treatments) and F contains the residuals.

As can be observed, the relationship between Y and Z is transmitted through the latent variable T . Due to the fact that $T = ZW$; where W is a vector of weights, then the expectation of the response variables is

$$E(Y') = (TQ')' = QT' = Q(ZW)' = (QW)'Z' = Z'Z' \quad (9)$$

Similarly, for the X matrix of environmental co-variables, $T = XW$, and

$$E(Y) = TQ' = XWQ' = X\Xi' \quad (10)$$

The vectors of T , W , and Q can be depicted in the same biplot; including representations of treatment combinations, years and environmental co-variables. The distance between two treatment vectors (end points) indicates the amount of interaction between those. The

cosine of the angle between two treatment (or year) vectors approaches the correlation between the treatments (or years) with respect to their interaction. Acute angles indicate positive correlations, with parallel vectors (in the same directions) representing a correlation of 1. Obtuse angles represent negative correlations, with opposite directions indicating a correlation of -1. Perpendicularity of directions indicates a correlation of 0. The relative degrees of interaction for a treatment combination over years can be obtained from orthogonal projections of the year vectors on the line determined by the direction of the corresponding treatment vector. Year vectors having the same direction as the treatment vectors have positive interactions (that is, the treatments performed well in those years); however, vectors in the opposite direction have negative interactions.

3. Results

3.1. Crop establishment

In 2011–12, soil temperature decreased under dry sowing for both tillage environments one week after sowing and right before emergence. Both, PB-Dry and CTB-Dry showed on average three to four degrees lower soil temperature compared to the wet sown tillage treatments (Fig. 1A). Similarly, in the 2016–17 cropping cycle, both dry sown tillage treatments had one to two degrees lower soil temperatures six days after sowing (Fig. 1B). Emergence was three days later in dry sown environments than with wet sowing. Minimum air temperature during the two weeks after sowing averaged 4.2 °C in 2011 and 8.9 °C in 2016.

Tillage-sowing irrigation environment significantly affected plant stand (Table 3). Under dry sowing, plant stand under PB was only half of that for CTB. This difference between tillage systems was much smaller under wet sowing (Table 3). Plant emergence averaged over all fertilized treatments was variable among years with environment averages per year ranging from 16 to 203 plants m^{-2} . In most years, CTB had higher plant stand than PB (Fig. 2; most points below 1:1 line). Plant stands

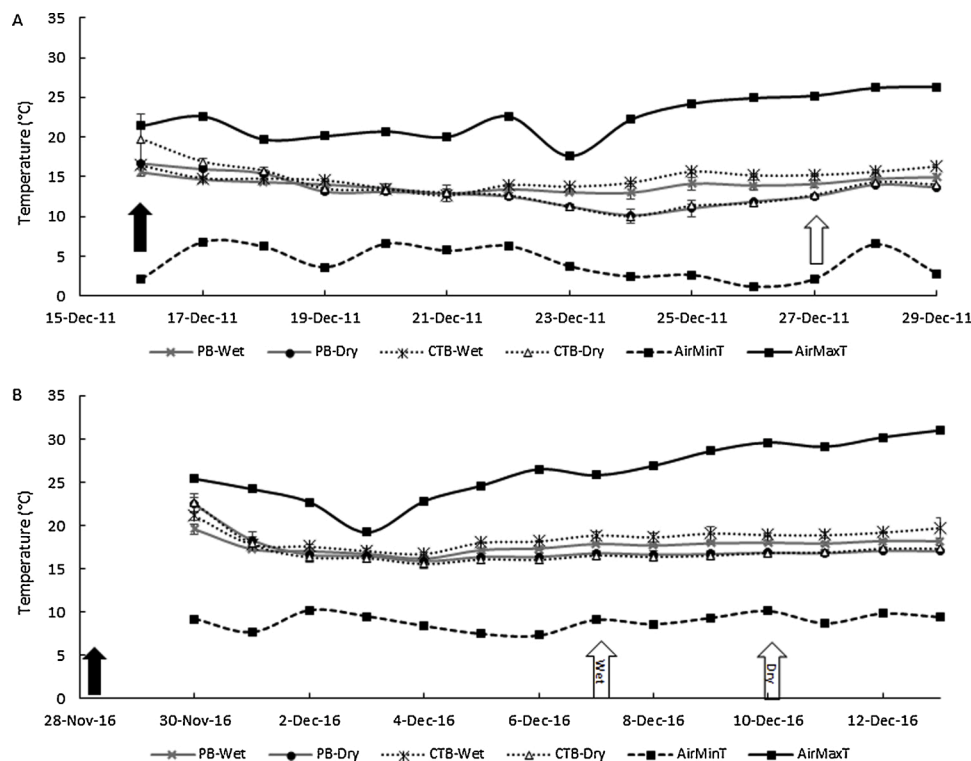


Fig. 1. Minimum (AirMinT) and maximum (AirMaxT) air temperature and soil temperature in 6 cm depth measured two weeks after sowing in the cropping cycles 2011-12 (A) and 2016-17 (B) for each environment (PB: permanent raised beds, CTB: conventionally tilled beds, Dry: dry sowing, Wet: wet sowing) at CENEB in Ciudad Obregón, Mexico. Error bars depict standard deviation of soil temperature ($n = 6$), black arrows indicate sowing and white arrows indicate emergence.

Table 3

Crop establishment traits averaged over 10 years without the 0 N control treatment (Mean, SD-standard deviation with $n = 150$) for each environment (tillage \times irrigation, PB: permanent raised beds, CTB: conventionally tilled beds, Dry: dry sowing, Wet: wet sowing) at CENEB in Ciudad Obregón, Mexico. Means with the same letter are not significantly different by the least square significant difference test at $P < 0.05$.

	PB-Dry			PB-Wet			CTB-Dry			CTB-Wet		
	Mean	SD		Mean	SD		Mean	SD		Mean	SD	
Plant stand (plants m^{-2})	54	36	C	138	28	B	106	70	B	159	28	A
NDVII	0.39	0.17	D	0.58	0.10	B	0.52	0.19	C	0.64	0.07	A
CV1 (%)	23.2	8.3	A	13.2	5.5	C	15.6	8.7	B	8.7	3	D

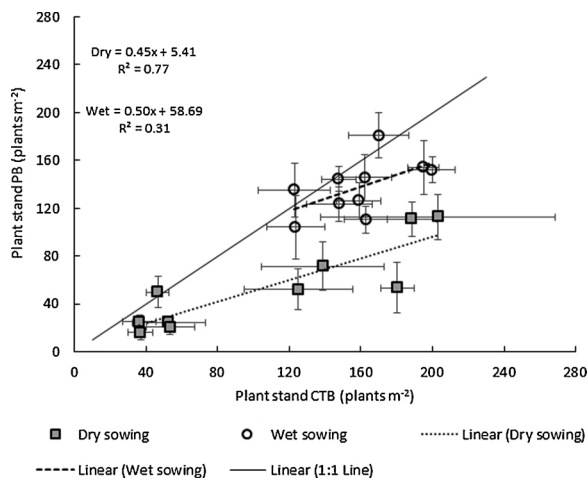


Fig. 2. Wheat plant stand (plants m^{-2}) averaged over ten years and five N fertilization treatments without 0 N control treatment for each tillage \times irrigation environment (PB: permanent raised beds, CTB: conventionally tilled beds) at CENEB in Ciudad Obregón, Mexico. Error bars depict standard deviation for CTB (horizontal lines) and PB (vertical lines).

under CTB and PB were correlated, with a stronger correlation for dry sowing ($R^2 = 0.77$) than wet sowing ($R^2 = 0.31$; Fig. 2). The slopes of the regression lines were similar for dry and wet sowing, but the intercept was lower for dry (5.4 plants m^{-2}) than wet sowing (58.7 plants m^{-2}),

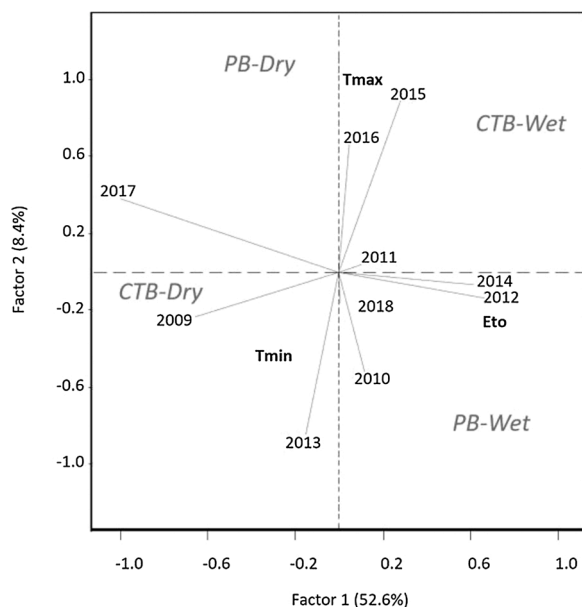


Fig. 3. Biplot of the partial least square regression model for plant stand, numbers indicate harvest years, climate co-variables were included for the first three weeks after sowing: Tmax: daily maximum air temperature, Tmin: daily minimum air temperature, Eto: reference evapotranspiration.

showing again the larger reduction in plant stand under dry sowing in PB vs CTB. In five years (2010, 2012, 2014, 2015 and 2016), average plant stands were below 50 plants m^{-2} in both PB and CTB with dry sowing (Fig. 2).

The biplot of the PLS showed a clear separation of plant stand between agronomic environments (Fig. 3). The contrast was especially large between the two sowing irrigation types within one tillage system, showing a strong negative correlation. The first principal component accounted for 52.6 % of the variance and separated dry (left quadrants) from wet sowing (right quadrants), whereas the second principal component accounted for 8.4 % of the variance and separated tillage environments. The five years with low plant stand for dry sowing in both PB and CTB (Fig. 2) were all found in the right quadrants of the biplot (Fig. 3). The dry sown environments in the left quadrants seemed favored by lower reference evapotranspiration, with CTB-Dry favored more by high minimum temperature and PB-Dry by high maximum temperature. Both wet sown environments seemed to be favored by high reference evapotranspiration years (right quadrants) like 2012 and 2014, although CTB-Wet also seemed to be favored by years with high maximum temperature, like 2016.

NDVII was higher in CTB than PB (NDVI = 0.54 and 0.45, respectively). In the last two cropping cycles (harvest years 2017 and 2018), NDVII was relatively similar for all treatments (Table S2). With wet sowing, NDVII was less variable between years in both tillage systems than with dry sowing (Table S2). In harvest years 2010, 2014, 2015, 2016, NDVII was only half as high in PB-Dry as in PB-Wet, whereas under CTB this was true only 2010 and 2015. This did not occur with wet sowing (Table S2). In 2010, 2014 and 2015, minimum average temperature during the tillering phase was slightly higher in wet sown tillage environments as emergence in wet-sown PB and CTB occurred three to six days earlier.

The coefficient of variation for NDVI 40 days after sowing (CV1) was the highest in PB-Dry and lowest in CTB-Wet, in line with plant stand being lowest in PB-Dry and highest in CTB-Wet (Table 3). CV1 and plant stand were strongly correlated ($R^2 = 0.61$, data not shown). CV1 was highest in 2016 for PB-Dry and lowest in 2009 for CTB-Dry (Table S3).

Plant stand, CV1 and NDVII were not significantly affected by N fertilizer management (Table 4).

3.2. Crop performance

Around 100 days after sowing, NDVI2 was similar across years and treatments (Table 4); all four environments had similar NDVI2 values of 0.70 averaged over ten years (Table 5). The correlation between yield and NDVI2 was $R^2 = 0.65$ and the one between biomass and NDVI2 was $R^2 = 0.66$. The CV2 of around 5 % was similar in PB-Wet, CTB-Wet and CTB-Dry but marginally higher in PB-Dry (8.8 %) pointing towards a slightly patchier plant coverage at the later cropping stage.

Under dry sowing, CTB gave higher yields than PB in 9 out of 10 study years (Fig. 4); the exception was 2017, when plant stand in PB-dry sowing was 113 plants m^{-2} . Under wet sowing, PB obtained higher yields than CTB in six out of ten years. Over ten years, wheat yield was significantly affected by ENV (Table 4) being lowest in PB-Dry (Table 5). In years with very low plant stands (e.g., 2010, 2012 or 2016), wheat plants in fertilized treatments were able to limit yield losses by increased

Table 4

F-probabilities (significance values) for the effects of environment (ENV) and N fertilization (FERT) on crop establishment, performance, quality and fertilizer-based NUE indices averaged over ten years (CV1: coefficient of variation for NDVI 40 days after sowing, CV2: coefficient of variation for NDVI 100 days after sowing; NDVI1: NDVI reading 40 days after sowing, NDVI2: NDVI reading 100 days after sowing, TKW: thousand kernel weight, TW: test weight) and over three years (N_{grain} : Grain N concentration, N_{straw} : straw N concentration, AE: agronomic efficiency, PFP: partial factory productivity, RE: apparent recovery efficiency) without the 0 N control treatment at CENEB in Ciudad Obregón, Mexico.

Parameter	ENV	FERT (ENV)
Plant stand	<0.0001	1
CV1	<0.0001	1
CV2	0.0001	0.9852
NDVI1	<0.0001	0.9995
NDVI2	0.0641	0.4185
Grain yield	<0.0001	0.2055
Biomass	0.0005	0.2946
Straw	0.0054	0.4501
TKW	<0.0001	0.8393
TW	<0.0001	0.9108
N_{grain}	<0.0001	0.0014
N_{straw}	0.0002	0.0035
AE	<0.0001	0.0379
RE	<0.0001	0.0116
PFP	0.0003	<0.0001

tillering to compensate low plant stands, resulting in grain yields similar to other years. In contrast, 2015 was a year with very low plant stand and low yields, with high precipitation during grain filling and highest average temperature during the photothermal phase. Years with the highest plants stands (2011 and 2017) did not result in the highest crop yields. The correlation between plant stand and yield was weak ($R^2 = 0.15$; $P=0.0002$). N fertilizer management did not significantly affect grain yield and other crop performance parameters (Table 4).

As the PLS biplot reflects, grain yield performance varied across years (Fig. 5). Climatic co-variable data for various growth stages were included in the model. Positive interactions between year and dry sowing systems (both CTB and PB in lower left quadrant) were associated with high minimum temperatures at germination and tillering. This effect was especially visible in 2016, 2017 and 2018. The years 2010–2013 favored CTB-Wet. Performance of PB-Wet was highly positively correlated to higher temperatures during the photothermal period. However, there was no year when this treatment performed especially well. The two first principal factors explained 72.7 % of the variability for yield, pointing to the overall importance of climate for crop yield formation.

Biomass correlated highly with grain yield ($R^2 = 0.94$) and was the highest in PB-Wet followed by CTB-Dry (Table 5). Biomass was the highest in 2010 (14.13 t ha⁻¹) with the coldest minimum temperature during the grain filling phase and the lowest in 2015 (7.8 t ha⁻¹). Highest amounts of wheat straw were left in PB-Wet (5.82 t ha⁻¹) compared to the lowest amounts in PB-Dry (5.50 t ha⁻¹, Table 5), following yearly

variations similar to biomass.

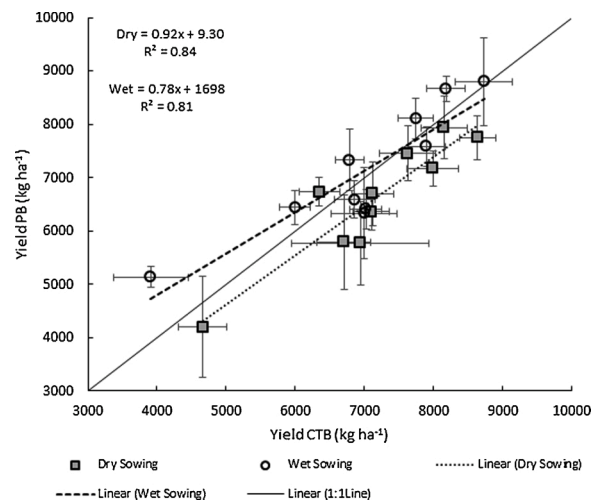


Fig. 4. Wheat yield (kg ha⁻¹) for ten years averaged over five N fertilization treatments without 0 N control treatment for each tillage × irrigation treatment (PB: permanent raised beds, CTB: conventionally tilled beds) at CENEB in Ciudad Obregón, Mexico. Error bars depict standard deviation for CTB (horizontal lines) and PB (vertical lines).

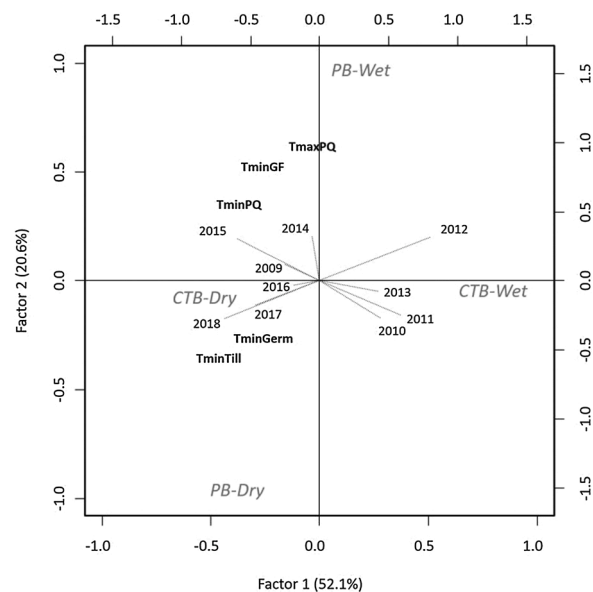


Fig. 5. Biplot of the partial least square regression model for grain yield, numbers indicate harvest years (compare Table 2 for abbreviations of climatic co-variables).

Table 5

Crop performance traits (TKW: thousand kernel weight, TW: test weight) over 10 years without the 0 N control treatment averaged (AV, SD-standard deviation with $n = 180$) for each environment (tillage × irrigation) (PB: permanent raised beds, CTB: conventionally tilled beds, DRY: dry sowing, WET: wet sowing) at CENEB in Ciudad Obregón, Mexico. Means with the same letter are not significantly different by the least square significant difference test at $P < 0.05$.

	PB-Dry			PB-Wet			CTB-Dry			CTB-Wet		
	Mean	SD		Mean	SD		Mean	SD		Mean	SD	
NDVI2	0.70	0.06	AB	0.69	0.07	B	0.71	0.03	A	0.68	0.06	B
CV2 (%)	8.8	8.7	AB	6	3.2	B	5.4	2.6	B	5.3	2.5	B
Grain yield (kg ha ⁻¹)	6588	1229	B	7140	1213	A	7118	1147	A	7005	1324	A
Biomass (kg ha ⁻¹)	11,293	2225	C	12,105	2002	A	12,015	1911	AB	11,676	1995	B
Straw (kg ha ⁻¹)	5495	1224	B	5821	1157	A	5751	1021	A	5512	967	B
TKW (g)	49.6	3.2	B	49.4	3.2	B	50.1	3.4	B	51.4	3.5	A
TW (kg hl ⁻¹)	82.2	1.2	D	82.8	1.1	C	83.0	1.3	B	83.4	1.2	A

Thousand kernel weight and test weight (TW), two important grain quality traits, showed high yearly variability. Both were significantly affected by ENV, being significantly highest in CTB-Wet (Table 5). The overall average for TW was 82.9 kg hl⁻¹ and 50.1 g for TKW (Table 2). Test weight and TKW were not significantly affected by N fertilizer management (Table 4). Test weight was lowest in 2015 (81.0 kg hl⁻¹) and 2017 (81.4 kg hl⁻¹). The year 2015 was exceptional due to precipitation during grain filling and the highest average temperature during the photothermal phase. Strong precipitation events were also recorded during the photothermal phase (20 days before to 10 days after flowering) in 2017. TKW was lowest in 2011 (47.4 g) and 2017 (44.5 g). The year 2011 was cold, with the lowest minimum temperature during the photothermal phase. Climatic co-variables showed that regional weather extremes were related to reduced wheat quality. In both PB environments and for CTB-Dry, the highest TKW and grain N concentration were attained when 240 kg of N ha⁻¹ was applied as a split application.

3.3. Grain N concentration and fertilizer-based NUE indices

Grain and straw N and resultant fertilizer-based NUE indices, were significantly affected by N fertilization (Table 4; three-year averages for the harvest years 2011, 2012 and 2013). Grain N was lowest under PB with wet sowing (Table 6). Because grain yield was lowest in PB-Dry (Fig. 4), the amount of extracted grain N ha⁻¹ in PB-Dry was lower (117 kg N ha⁻¹) compared to 123, 138 and 139 kg N ha⁻¹ under PB-Wet, CTB-Dry and CTB-Wet, respectively. N fertilizer efficiency traits showed similar results, with significant effects of ENV (Table 6). The agronomic efficiency (AE) under PB with wet sowing (16.7 kg kg⁻¹) was higher than with dry sowing (10.7 kg kg⁻¹), but there were no significant differences for CTB. For RE and PFP, CTB had overall higher efficiencies compared to PB, without significant differences between dry and wet sowing (Table 6).

Grain N and yield were positively correlated in the four tillage-sowing irrigation environments (Fig. 6). The slope of the four environments was similar whereas the intercept was lowest in PB-Wet and highest in CTB-Dry. Averaged for all four ENV with N fertilizer applications, lowest grain N concentration of 1.76 % was obtained with the lowest N dose of 120 kg N ha⁻¹ split application (120S). Without N fertilizer, grain N concentration averaged 1.59 % over all four environments (Fig. 6). With fertilization, highest average grain N concentration of 2.07 % was reached in CTB-Dry with 240S and lowest of 1.70 % in PB-wet and 120S (Fig. 6). Translated into grain protein concentration (GPC) for wheat quality assessment and commercialization purposes, GPC ranged from 8.4 % in 0 N PB-Wet to 11.8 % CTB-Dry with 240 kg N ha⁻¹ split application.

Averaged over three years, partial factor productivity (PFP) was higher than 100 % in 120S for all environments (Fig. S2). For the highest N dose (240 kg N ha⁻¹), no differences in PFP were observed between the basal or split fertilizer application treatments. In PB-Dry, the lowest AE (8.6 kg grain kg⁻¹ N) occurred with a basal application of 180 kg N (180B), compared to 11.2 kg grain kg⁻¹ N with a split application (180S)

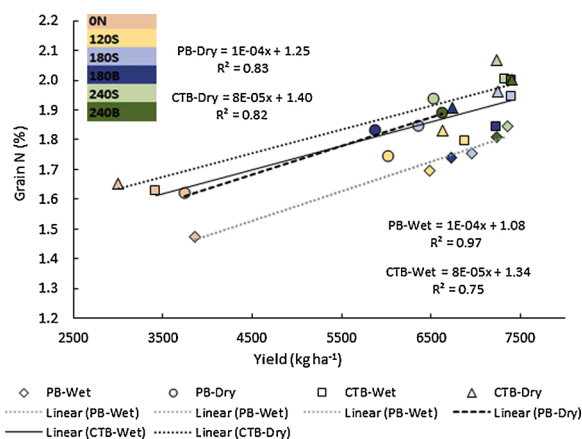


Fig. 6. Nitrogen grain concentration (Grain N in %) versus grain yield (kg ha⁻¹) of durum wheat at four levels of N availability and two different modes of timing and application for each tillage × irrigation environment (PB: permanent raised beds, CTB: conventionally tilled beds, Dry: dry sowing, Wet: wet sowing, S-split, B-broadcast) at CENEB in Ciudad Obregón, Mexico. N fertilization treatment abbreviations are explained in Table 1. Data are means for n = 9 (three replicates over three years).

(Fig. S3). The 120S N treatments with the highest AE had only half of the AE in PB-Dry (14 kg grain kg⁻¹ N) compared to dry sown CTB (30 kg grain kg⁻¹ N). With wet sowing, differences were much smaller with 22 and 29 kg grain kg⁻¹ N in PB and CTB, respectively (Fig. S3).

4. Discussion

4.1. Reduced plant stand with dry sowing

The lower soil temperature under dry sowing compared to wet sowing in the three weeks after sowing (Fig. 1), could be due to the fact that soil particles have a lower heat capacity and greater heat conductivity than water (Rai et al., 2019). Therefore, wet soils, in this case the dry sowing treatments, warm and cool more slowly than dry soils. Lower temperatures during germination and emergence may reduce plant stand at emergence. However, in the two years in which soil temperature was measured, it was reduced to the same extent in dry sown PB and CTB, while plant stand was reduced more in PB (Table 3), indicating that other factors also played a role.

During germination and emergence, soil moisture content was higher under dry sowing, a result confirmed by four measurements in the 0–7 cm soil layer during 2015–16 cropping cycle (Prince et al., 2020). With dry sowing, the soil was water-saturated under both tillage treatments for ten days after sowing and afterwards soil moisture decreased more rapidly under CTB than PB (Prince et al., 2020), raising the risk of hypoxia in PB. The effect of reduced germination in wet and cold conditions, especially in conjunction with direct seeding systems, has been reported before (Cochran et al., 1977; Ellis and Lynch, 1979). Studies have shown that wheat seed germination under excess water can

Table 6

Fertilizer-based NUE indices (N_{grain}: Grain N concentration, N_{straw}: straw N concentration, AE: agronomic efficiency, PFP: partial factory productivity, RE: apparent recovery efficiency) over three years without 0 N control TRT averaged (AV, SD-standard deviation with n = 45) for each tillage × irrigation treatment (PB: permanent raised beds, CTB: conventionally tilled beds, Dry: dry sowing, Wet: wet sowing) at CENEB in Ciudad Obregón, Mexico. Means with the same letter are not significantly different by least square significant difference test at P < 0.05.

	PB-Dry			PB-Wet			CTB-Dry			CTB-Wet		
	Mean	SD		Mean	SD		Mean	SD		Mean	SD	
N _{grain} (%)	1.85	0.12	B	1.77	0.13	C	1.95	0.11	A	1.92	0.11	A
N _{straw} (%)	0.60	0.10	B	0.56	0.11	C	0.66	0.07	A	0.61	0.08	B
AE (kg kg ⁻¹)	10.7	5.1	C	16.7	4.8	B	22.1	6.7	A	21.0	7.4	A
PFP (%)	79.8	19.8	B	84.2	21.8	B	94.0	19.6	A	93.4	19.1	A
RE (%)	29.5	9.2	B	35	9.6	B	47.6	10.3	A	45.3	11.5	A

be improved by applying a mixture of antibiotics and fungicides (Beres et al., 2020; Gaber and Roberts, 1969), thereby reducing the competition for scarce oxygen. In an experiment at CENEB, Mulvaney et al. (2014) showed that seed treatment with a combination of thiamethoxam, difenoconazole and mefenoxam improved plant stand density under dry sowing, in conditions where no infection by pathogens was observed without the treatment. Plant stand in CTB-Dry was favored more by high minimum temperature in the three weeks after sowing and in PB-Dry by high maximum temperature (Fig. 3). This could be related to the drying process needed to shorten the waterlogged period, which in PB would need higher maximum temperatures and related radiation, since straw residues retained on the soil surface increase the reflection of solar radiation and isolate the soil from heating (Shinners et al., 1994).

4.2. N fertilizer management

Soil residual N was not determined in this study. Hence, although an unfertilized maize crop was planted most summers to reduce residual soil N, it cannot be excluded that the fertilizer-based NUE indices reflect to some extent a soil legacy effect that increased over time (Meier et al., 2021; Quan et al., 2021), as the N fertilizer treatments were repeated in the same physical location every year and fertilizer-based NUE indices were calculated for the fourth, fifth and sixth year of the experiment. Although fertilizer-based NUE indices, like AE and RE, account for background (indigenous) soil N in experiments with an unfertilized control plot as implemented in this study, they cannot account separately for residual soil N build up from the previous years of fertilization (Congreves et al., 2021). In a different experiment at the same experimental site with application of 278 kg N ha⁻¹ to wheat in winter and 203 kg N ha⁻¹ to maize in summer, Grahmann et al. (2018a) evaluated N balance nine years after the start of the experiment. Before wheat fertilization and sowing, soil mineral N content (NO₃-N and NH₄-N) at 0–90 cm depth was 187 kg N ha⁻¹ in CTB and 254 kg N ha⁻¹ in PB (Grahmann et al., 2018a). This points to considerable amounts of residual soil N, however, the highest yearly N dose in the current study (240 kg N ha⁻¹) was only half of the yearly application of N in the experiment in Grahmann et al. (2018a).

N fertilizer management has been thoroughly studied in the Yaqui Valley for different tillage treatments and N fertilizer practices (Ahrens et al., 2010; Christensen et al., 2006; Grahmann et al., 2018a, 2014; Millar et al., 2018) but different sowing irrigation practices had not been considered yet. The basal N fertilizer was applied before the sowing irrigation, which in wet sowing happened three weeks before sowing and in dry sowing one or two days after sowing. This likely increased N leaching and nitrification in wet sowing (Grahmann et al., 2018b, 2018a; Millar et al., 2018; Riley et al., 2001) and grain N levels in dry-sown wheat, particularly under PB (Table 6). However, even after N application at first node, wheat plants in PB-Dry were not able to absorb enough N to offset lower, patchy plant stands and lower yields through higher grain quality and did not achieve AE similar to the other tillage × sowing irrigation environments (Fig. S3).

When PFP is higher than 100 %, the extracted N in grain and straw is attributed to mineralized soil N and points to a depletion of the soil N pool (“soil mining”, Congreves et al., 2021). This occurred for three consecutive years under both tillage treatments with a fertilizer dosage of 120 kg N ha⁻¹ in 120S (121 %, 130 % and 105 % in 2011, 2012 and 2013, respectively), indicating that this level of fertilization was insufficient because more N was extracted by grain and straw than was added by mineral fertilizer (Fig. S2). In studies with more available soil N, grain yield and grain N concentration are commonly less negatively correlated (Triboi et al., 2006). In this study, grain N and crop yield were positively correlated for all environments (Fig. 6), pointing at a non-limiting N environment in the fertilized treatments and supporting the lack of N fertilizer treatment effect on yield in those treatments (Table 4). PB-Wet had the lowest intercept of the grain N vs. yield relationship, in line with earlier studies reporting that PB reduced grain

N concentration compared to CTB (Grahmann et al., 2014).

Basal application of N at sowing led to lower fertilizer NUE than split application, which confirms results of previous studies (Limon-Ortega et al., 2000). The lowest AE in PB-Dry occurred with a basal application of 180 kg N ha⁻¹, compared to higher AE with a split application (Fig. S3). This differs from results in a study of bread wheat under wet-sown PB, where basal and split application of 150 kg N ha⁻¹ incorporated into furrows resulted in an AE of 21 and 20 kg grain kg⁻¹ N, respectively (Santillano-Cázares et al., 2018). In the present study, those high levels of AE were reached in CTB but not in PB treatments. This could be due to the different wheat species used, since bread wheat has been found to have greater N accumulation capacity and a more efficient use of N than durum wheat, especially under low-yielding conditions (López-Bellido et al., 2008; Marti and Slafer, 2014).

4.3. Crop performance and practical implications

In PB-Dry, the highest plant stand did not automatically result in the highest average yields, since growing conditions later in the season were also important for yield determination (Verhulst et al., 2011b). Low plant stands did not lead to low yields in the years 2010 and 2016, which was also reported by Bastos et al. (2020) for different yield environments. Similarly, Fischer et al. (2019) found a minimum plant stand of 20 plants m⁻² was enough to reach high yields and acceptable AE, whereas plant stands over 20 plants m⁻² but with 0 N fertilizer were not able to increase tillering for yield compensation. In our study, dry sowing not only reduced plant stand, but also made it patchier (Table S3), especially on PB, which further reduced how efficiently the crop could use resources like N and water and compensate low plant stand by tillering, compared to an evenly spaced plant stand.

In another wet-sown experiment at the same site, CTB had lower soil water content and dried out faster than PB and the difference was most notable before the first auxiliary irrigation when plots were not irrigated for 48 days (Grahmann et al., 2018a). Wet sown PB had higher yields than CTB-Wet in six out of ten years, probably because of reduced water stress. However, higher soil moisture in the profile was also found to increase the risk of N leaching (Grahmann et al., 2018b), making it unavailable to plants, which could partly explain the lower fertilizer NUE in PB-Wet compared to CTB.

Conservation agriculture paired with dry sowing seemed to produce conditions that inhibited germination, resulting in patchy emergence in PB-Dry. We have observed patchy emergence in irrigated wheat fields with dry sowing in farmers' fields in the Yaqui Valley, the Mexicali Valley close to the US border and the Bajío region in Central Mexico, although often to a lesser extent than described in this study. Therefore, the phenomenon described here does not seem to be specific to the experimental station in the Yaqui Valley. Farmers and farm advisors tend to attribute this patchy emergence to machinery failure or low seed quality, or the conservation agriculture system per se, which can lead to disadoption. Therefore, we consider it is important that researchers in other irrigated areas with dry sowing are aware of the potential reduction of plant stand with these practices, so they can be quickly remediated when they occur. Part of the reason that the issue is more obvious in the Yaqui Valley could be because durum wheat is less competitive than bread wheat at early growth stages (Lemerle et al., 1996). Options to improve plant stand include switching to wet sowing (Fig. 2) or treating seed with fungicide (Mulvaney et al., 2014), but the right seed treatment should be identified for each cropping system.

5. Conclusions

This study presents the first long-term results for durum wheat that thoroughly studied the combined effects of tillage and sowing irrigation practices on plant stand, yield and grain quality. Plant stand at emergence was reduced by dry sowing compared to wet sowing in some years, especially on permanent beds and was related to soil temperature

and moisture. However, climatic co-variables during photothermal and grain filling period were the primary factors influencing yield. Tillage and sowing irrigation practice had smaller effects. We recommend that farmers adopting permanent beds with dry sowing closely observe plant stands. If patchy plant stands are observed, wet sowing could be used instead of dry sowing or other options like seed treatments could be evaluated. More research is needed to elucidate the causes of lower plant stands with dry sowing and identify appropriate seed treatments to address this issue. Additionally, permanent beds with wet sowing led to lower grain N concentration and fertilizer-based NUE indices than conventionally tilled beds. Future studies should focus on the development of appropriate N fertilizer management strategies to improve grain quality in conservation agriculture systems.

Data availability statement

The data of this study are freely available on DataVerse: Verhulst, N., Grahmann, K., Honsdorf, N., Govaerts, B., 2021, "Durum wheat performance (10 years of data) and grain quality (three years of data) with two tillage and two sowing irrigation practices under five nitrogen fertilizer treatments in northwestern Mexico", <https://hdl.handle.net/11529/10548582>, CIMMYT Research Data & Software Repository Network, V1.

CRediT authorship contribution statement

Kathrin Grahmann: Methodology, Formal analysis, Writing - original draft, Visualization, Writing - review & editing. **Nora Honsdorf:** Investigation, Writing - review & editing. **Jose Crossa:** Methodology, Formal analysis, Visualization. **Gregorio Alvarado Beltrán:** Methodology, Formal analysis, Visualization. **Bram Govaerts:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Nele Verhulst:** Conceptualization, Methodology, Investigation, Data curation, Writing - review & editing.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.fcr.2021.108310>.

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