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LEAF AREA INDEX AND GRAIN YIELD OF DURUM WHEAT IN SOUTHERN SONORA, MEXICO, DURING THE SEASON 2020-2021

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ABSTRACT

The objective was to determine the relationship between leaf area index (LAI) and wheat grain yield with durum cultivar CIRNO C2008, in thirty fields in the Yaqui (YV) and Mayo Valleys (MV), Sonora, Mexico, during the season 2020-2021. Field surveys were carried out to monitor crop development and to take LAI readings at different phenological stages using a linear ceptometer. Four samples of 1 m-2 in each field were harvested to calculate yield and count the spikes produced; also, grain protein and incidence of yellow berry were determined. Temperature, relative humidity, and cold units were recorded in an hourly format from 16 stations from the automated weather station network in Sonora, and which were closest to the fields. The LAI increased as the crop progressed, and had its highest expression (7.768) during the half grain-filling stage in YV, and at the end of flowering (8.109) in MV; the regression between grain yield and LAI had an R2 of 0.324. The avg. grain yield in YV was 7.95 t ha-1, while 7.24 in MV, but the latter had one less irrigation. The avg. spike number m-2 was 400 in YV and 370 in MV. The avg. grain protein content in YV was 10.49% and 39.6% for yellow berry, while in MV 11.26% and 13.8%, respectively. The overall avg. temperature during the season, relative humidity and the accumulated cold units for YV and MV were 16.96 and 16.97 °C, 68.31 and 69.13%, and 817 and 867, respectively.

Keywords: Leaf area index, Durum wheat, Triticum durum, Grain yield.

1. INTRODUCTION

Wheat (*Triticum* spp.) is one of the cereals most cultivated worldwide due to its high energetic value and great protein content. The main cereals produced around the world are maize (*Zea mays* L.), wheat, and rice (*Oryza sativa* L.) (FAOSTAT, 2020). About 3.1 million t of wheat were produced in Mexico in the year 2021, 56.66% was durum wheat (*Triticum durum* Desf.) and 43.34% bread wheat (*Triticum aestivum* L.). The state of Sonora stands out in the country contributing with 54.77% of the wheat production, while 36% is produced by the states of Baja California, Guanajuato, Michoacán, and Sinaloa (SIAP, 2021). Productivity and quality of wheat is controlled by genetic characteristics of cultivars, and they can be modified to certain extent by the agronomic management (availability of nutrients in the soil, nitrogenous fertilization, sowing date, control of pests and diseases), and by the climatic conditions that prevail during the crop season (Peña Bautista *et al*., 2008). The selection of the sowing date is of great importance for a successful cultivation of wheat, therefore, several factors must be considered since they affect directly and indirectly the yield potential of the cultivar to be used (Noriega-Carnoma *et al*., 2019). Solís Moya *et al*. (2004) reported that for early sowing (November 16) in Celaya, Guanajuato, Mexico, the crop season was longer because the climatic conditions favored the crop, and consequently led to a greater grain production per unit area and greater grain yield; on the contrary, late sowing (January 15) the season up to physiological maturity was reduced as a consequence of the speed up of plant development. On the other hand, reduction in the foliar area is one of the many problems that affect crops, and generate yield losses of different magnitude, since the interception of the photosynthetically active radiation decreases (Herranz *et al*., 2017). The leaf area index (LAI) is half of the amount of leaf area per unit horizontal ground surface area. Consequently, accurate vegetation extraction in remote sensing imagery is critical for LAI estimation (Wu *et al*., 2022). The determination of LAI is a key parameter that allows to estimate the photosynthetic capacity of plants, and helps to understand the relationship between biomass accumulation and yield under the prevailing climatic conditions in a given region (Intagri, 2016); therefore, it is a variable for quantifying the growth and agronomic yield of crops (Elings, 2000; Hernández-Hernández *et al*., 2011; Liu *et al*., 2016; Pokovai and Fodor, 2019). Hasan *et al*. (2019) reported that LAI is not only an important parameter for monitoring crop growth, but also an important input parameter for crop yield prediction models and hydrological and climatic models. Benbi (1994) indicates that changes in the LAI of wheat are predicted by using information on daily heat units, atmospheric evaporative demand, water supply, and nitrogen. The leaf area index, the leaf orientation value, and the extinction coefficient are important structural parameters of crop populations. By affecting light distribution, they directly affect crop photosynthetic efficiency, and ultimately show an impact on crop biological yield and its distribution in various plant organs (Chang-Wei *et al*., 2020). The critical period of the reduction of the leaf area in wheat occurs 30 days around flowering, covering stem elongation, heading, flowering, and the first stages of grain filling; therefore, a reduction of LAI during that period can cause a reduction of real number of spikes m^{-2}, spikelets/spike, number of grains m^{-2}, and grain weight (Herranz *et al*., 2017). During this critical period the yield components are defined, so adverse factors that affect the foliar area such as biotic and abiotic ones influence in a significant and irreversible manner. However, determination of LAI is carried out by two ways: direct and indirect methods (Bréda, 2003; Weiss *et al*., 2004). The direct or destructive method consists in analyzing leaves from the experimental plants, and analyze them with the help of an integrated electronic area measurer, that is, it requires the elimination of the sample biomass and also it is a highly laborious and costly technique (Blanco and Folegatti, 2005; Casa *et al*., 2019). The indirect or nondestructive method consists in acquiring a series of readings taken directly in the field with specific instruments, based primarily on measuring the photosynthetically active radiation (PAR) on the adaxial and abaxial sides of leaves, and on the use of complex mathematical models (Jonckheere *et al*., 2004; De la Casa *et al*., 2007; Casa *et al*., 2019). One of the indirect techniques widely used is the optical, based on the law principles of Beer Lamberth (Jonckheere, *et al*., 2004), which allows to model the behavior of light that trespasses the top cover. From that principle, commercial equipment has been developed like Tracing Radiation and Architecture of Canopies (TRAC) (Chen *et al*., 1997), AccuPAR (METER Group, 2022), LAI-2000 Plant Canopy Analyzer (LI-COR Biosciences, 2022), SS1 SunScan Canopy Analysis System (Delta-T Devices, 2022), hemispheric photography (Rich, 1990) or images obtained by remote sensors (SPOT5 (Aguirre-Salado *et al*., 2011), Landsat (Anderson *et al*., 2004), LiDAR (Jensen *et al*., 2008). The normalized difference vegetation index (NDVI) is one of the most important vegetation indices in crop remote sensing. It features a simple, fast, and non-destructive method and has been widely used in remote monitoring of crop growing status. Beer-Lambert law is widely used in calculating crop LAI, however, it is time-consuming detection and low in output (Chang-Wei *et al*., 2020). According to Yadav *et al*. (2019), the modified water cloud model shows great potential for LAI estimation of the wheat crop, by incorporating optical data (i.e. Sentinel-2) in terms of the scale invariant vegetation fraction with synthetic aperture radar data (i.e. Sentinel-1A). Determination of the relation between LAI and grain yield, could be a useful tool for development of precise prediction models for harvest. The main objective of this work was to determine the relationship between the leaf area index and wheat grain yield, during the crop season 2020-2021 in southern Sonora, Mexico.

2. MATERIALS AND METHODS

This work was carried out during the crop season fall-winter 2020-2021, in the Yaqui and Mayo Valleys, Sonora, Mexico, in commercial wheat fields sown with the durum wheat cultivar CIRNO C2008 (Figueroa-López *et al*., 2010), under irrigated conditions. Each field was selected during sowing by doing surveys throughout the valleys from November 15 to December 15, period considered as the optimum range of dates for wheat sowing in southern Sonora (Figueroa-López *et al*., 2011). Field selection was done randomly choosing 15 in each valley (Table 1 and Figure 1), but taking into consideration a field area of approximately 15 to 20 ha. Readings for the foliar index area were taken using a linear ceptometer AccuPAR LP-80 at different phenological stages of the plant: at anthesis complete (Zadoks stage 69, Zadoks *et al*., 1974), then when a quarter of the grain was formed, a half, three quarters, and at full grain formed (Zadoks stage 70).

Table 1. Commercial durum wheat fields sown with cultivar CIRNO C2008, selected for leaf area index readings and for evaluation of grain yield in the Yaqui (YV) and Mayo (MV) Valleys, during the crop season fall-winter 2020-2021, in southern Sonora, Mexico.

Valley	Sowing date	Field location	Latitude	Longitude
YV	Dec-2	B-922	27.3544722	-109.820417
YV	Nov-22	B-2324	27.11625	-109.769306
YV	Nov-20	B-2624	27.0430833	-109.768694
MV	Nov-24	Chucarit	27.05075	-109.54275
MV	Nov-16	Sapomora	27.0371944	-109.497861
MV	Nov-25	Ote Etchojoa	26.9049167	-109.610167
MV	Nov-15	Los Girasoles	26.9294167	-109.499222
MV	Nov-26	El álamo	26.8385833	-109.499194
MV	Nov-22	Huatabampo	26.8308056	-109.622333
MV	Nov-26	Huichaca	26.8836667	-109.694444
MV	Nov-28	El Júpare	26.8000556	-109.657944
MV	Dec-10	Etchoropo	26.7669167	-109.686083
MV	Dec-14	Sahuaral Otero	26.8943611	-109.735194
YV	Dec-5	B-402	27.4640833	-109.994056
YV	Nov-18	Casa Belen	27.5194444	-110.131389
YV	Dec-11	B-421	27.4640367	-110.219408
YV	Nov-20	B-529	27.4454722	-110.301722
YV	Nov-22	B-821	27.4002222	-110.219222
YV	Dec-4	B-514	27.43775	-109.872833
YV	Dec-1	B-1512	27.2536111	-109.892139
YV	Dec-13	B-2410	27.0851111	-109.922833
YV	Nov-30	B-1906	27.1713333	-109.95325
YV	Nov-26	B-1604	27.22675	-109.981417
MV	Dec-1	Chihuahuita	27.1026389	-109.483861
MV	Dec-14	Batacas	26.9766944	-109.559611
MV	Dec-9	La Union	26.8026111	-109.613611
MV	Dec-10	Los gallos	26.8172778	-109.566111
MV	Dec-11	Sábila	26.7550556	-109.622944
YV	Dec-13	B-706	27.4089722	-109.96975
YV	Dec-4	B-902	27.3565556	-110.014361

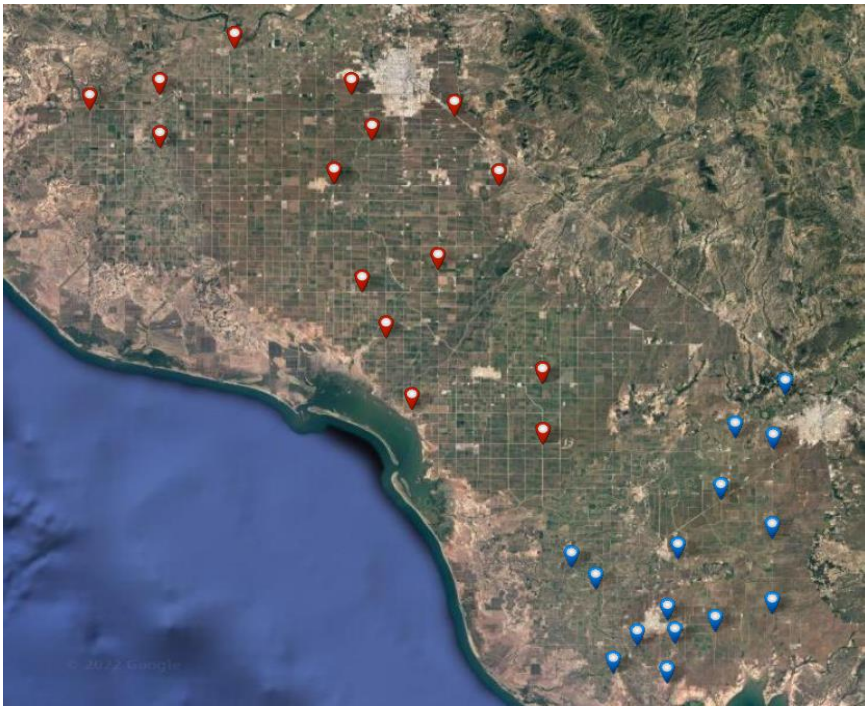

Figure 1. Geographic location of the fields evaluated in the Yaqui (red icons) and Mayo Valleys (blue icons), during the crop season 2020-2021.

The procedure consisted in measuring the light intensity over and under the crop canopy only under clear sky conditions and during 10:00 am to 14:00 pm; the ceptometer bar was placed in perpendicular position in relation to the sowing row. Readings were taken in a bed about the middle of the field and in four spots every 50 m; there were two readings in each field between the first node and the grain filling stage (Figure 2). Four 1 m^{-2} samples were harvested using a sickle, in order to calculate grain yield, but previously, the number of spikes per sample were counted. Later on, the grain protein content was determined with an Inframatic 9500 NIR Grain Analyzer. Temperature data, relative humidity (RH) and cold units (CU) ($\geq$ 10 °C (Félix-Valencia *et al*., 2009) were obtained from the automated weather station network of the state of Sonora (REMAS, 2021) (selecting those closest to the wheat fields), from November 2020 to April 2021, in order to determine their relationship with the LAI and grain yield. Data from the variables evaluated were subjected to an analysis of variance with the statistical package InfoStat (2008). Mean comparison was performed with the Least Significant Differences (LSD) at *p*= 0.05. Simple Pearson correlation was done between the leaf area index and grain yield.

Figure 2. Taking readings of the leaf area index area using a linear ceptometer AccuPAR LP-80.

3. RESULTS AND DISCUSSION

The average monthly temperature was rather similar in both valleys throughout the crop season (Figure 3). In the second fortnight of November the avg. temperature was 20.5 ºC, in December 15, and 14, 16, 16.5, and 22ºC in January, February, March, and April, respectively. The overall avg. was 16.96 °C for the Yaqui Valley and 16.97 for the Mayo Valley. The temperatures recorded by the 16 weather stations showed consistency in a gradual decrease in the first two months and a half, and then, a gradual increase in the rest of the season; this favored the accumulation of CU which were recorded from November 15, the date authorized for wheat sowing in the region, up to April 15 when the wheat sown after December 15 is at the initiation of the dough stage (stage 85, Zadoks *et al*., 1974). The number of CU was high with a peak for both valleys in January; CU were favorable for tillering and for the normal growth of the crop; as the number of CU increases, the physiological processes of the plant slow down and consequently the growth period extends, which in general generates a higher grain yield (Félix-Valencia *et al*., 2009). The Mayo Valley had greater accumulation of CU (867) than the Yaqui Valley (817) during the crop season, a difference of 50 CU, which were more evident during December, January, and March (Figure 4). The monthly average RH did not reach 80% during the crop season, which contributed to a better phytosanitary status during plant growth; the overall avg. RH for the Yaqui and Mayo Valleys were 68.31 and 69.13%, respectively (Figure 3). Leaf rust caused by *Puccinia triticina* Eriks. was detected in only two of the fields, but late during the season, and because of the growth stage of the crop the disease did not pose any risk.

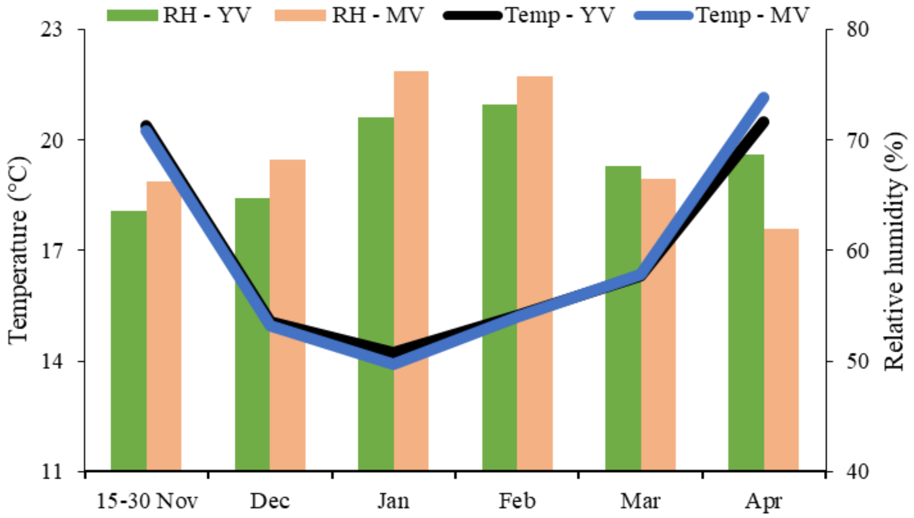

Figure 3. Average monthly temperature and relative humidity of 16 selected weather stations in the Yaqui and Mayo Valleys, Sonora, Mexico, during the crop season fall-winter 2020-2021.

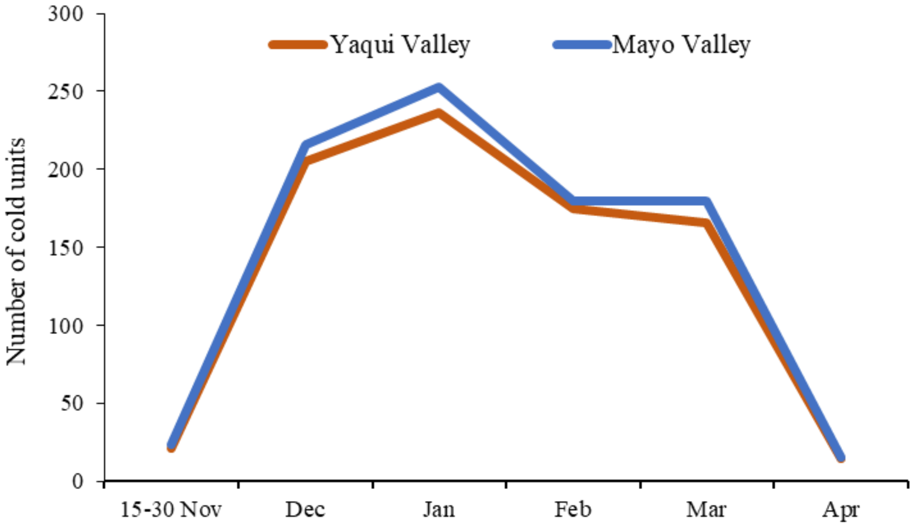

Figure 4. Accumulated average cold units every month in 16 selected weather stations in the Yaqui and Mayo Valleys, Sonora, Mexico, during the crop season fall-winter 2020-2021.

The Yaqui Valley produced the highest avg. grain yield with 7.95 t ha^{-1}, while the Mayo Valley had 7.24 t ha^{-1} (Table2). Based on observations, most of the fields had a uniform development with good plant density, but in some of them, there were weed problems. Another important aspect to consider which has an impact on wheat production is the management of the irrigation water; although the water sheet was not quantified during irrigations, the number of irrigations was considered. Most of the area of the Mayo Valley had two complementary irrigations while the Yaqui Valley had three.

Table 2. Yield components and grain protein of durum wheat cultivar CIRNO C2008 in southern Sonora, Mexico, during the crop season fall-winter 2020-2021

Region	Grain yield (t ha^{-1})	Spikes/m^{-2}	A 1000 grain weight (g)	Protein (%)
Yaqui Valley	7.95 (± 1.04)	399.83 (± 35.16)	51.60 (±3.52)	10.49 (± 1.04)
Mayo Valley	7.24 (± 1.30)	370.17 (± 52.46)	50.01 (± 4.98)	11.26 (± 1.76)
Mean	7.59	385	50.81	10.88

( )= Standard desviation.

The range of grain yield in the Yaqui Valley was 6.54 to 10.44 t ha^{-1}; these extreme yields were obtained in the sowing date of November 20 and December 1. The avg. spike number m^{-2} was 400; sowing dates of November 30 and December 1 had the highest spike number with 473 and 461, respectively (Figure 5). The average protein content was 10.49% (Table 2) which is in the low scale of a normal range 9 to 18% (Gallagher, 2008) and from the data obtained by Félix-Fuentes *et al*. (2010), when the durum wheat cultivar CIRNO C2008 was evaluated as an advanced line, with a range of 12.8 to 16.6 and 14.1% avg. The quality of durum wheat is highly correlated with the quality of its end products. Durum wheat, with its high kernel weight, test weight, protein content, and gluten strength, is known to be associated with the firmness and resiliency of the cooked pasta products and the stability of cooking (Elias and Manthey, 2005). The low grain protein content obtained could have been due to the high percentage of yellow berry in 13 of the 15 fields; the range was 0 to 90.9% and the overall avg. was 39.6% (Figure 6). The highest grain yield obtained in the Mayo Valley was 9.12 t ha^{-1}, in the sowing date of November 22, and the lowest yield was 4.36 t ha^{-1} in the sowing date of December 11. The avg. spike number m^{-2} was 370, but the sowing dates of November 16 and 24 had 426 and 482, respectively (Figure 7). The protein content was 11.26% (Table 2), and in contrast to the Yaqui Valley, the overall percentage of yellow berry was much lower (13.8%), although the range in the 13 fields affected was 2.8 to 37.3% (Figure 6).

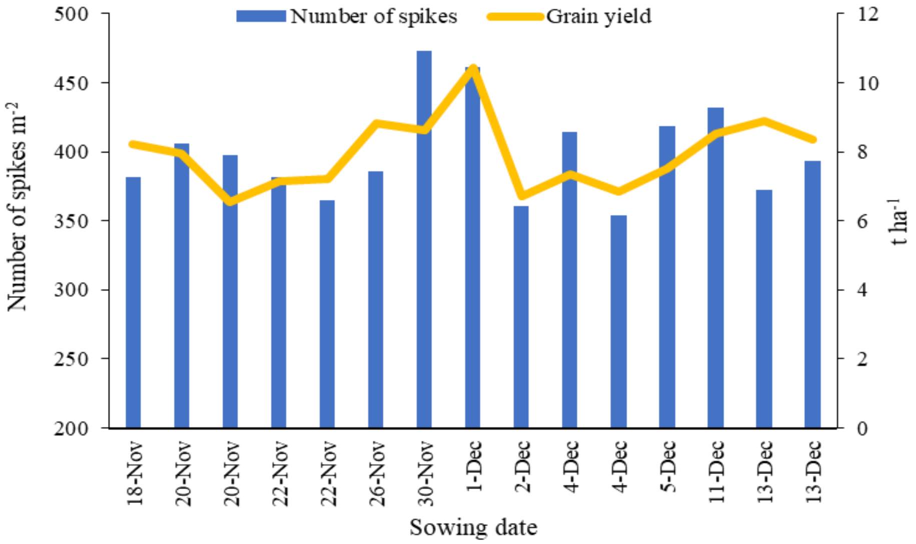

Figure 5. Grain yield and number of spikes m^{-2} in commercial fields in the Yaqui Valley, Sonora, Mexico, during the crop season 2020-2021.

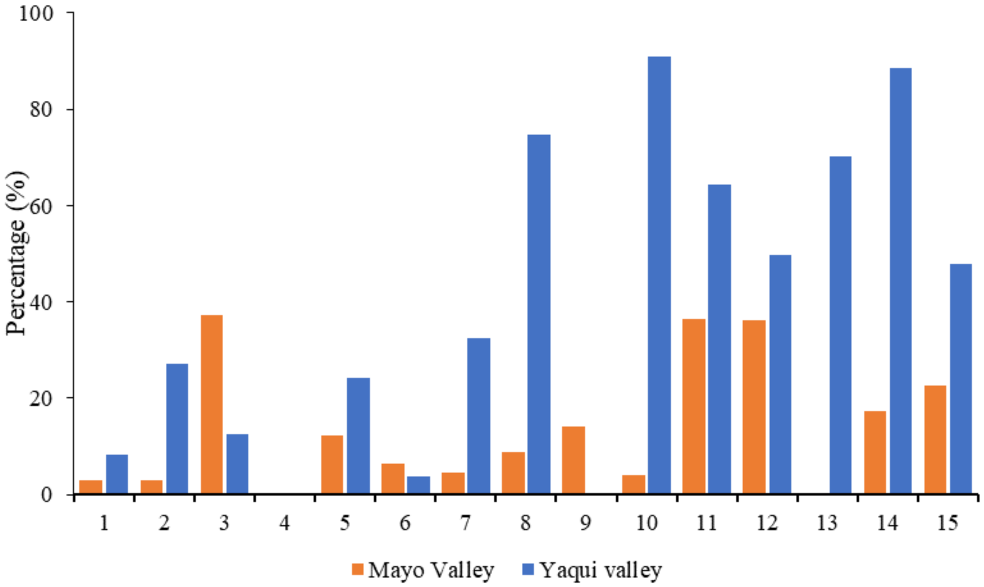

Figure 6. Incidence of yellow berry in 15 wheat fields in the Yaqui Valley and 15 in the Mayo Valley, in southern Sonora, Mexico, sown with durum wheat cultivar CIRNO C2008, during the crop season 2020-2021.

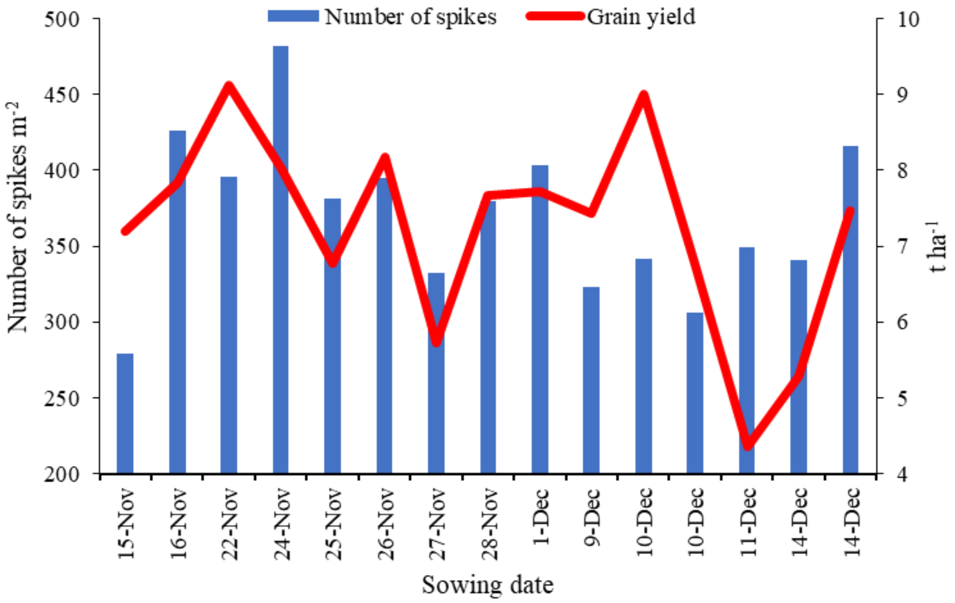

Figure 7. Grain yield and number of spikes m^{-2} in commercial wheat fields in the Mayo Valley, Sonora, Mexico, during the crop season fall-winter 2020-2021.

In the Yaqui Valley, the expression of the LAI increased in function of the growth stage up to half-grain formation, stage at which the highest LAI values were obtained (7.768) and thereafter, values decreased, but were maintained until grain-filling (7.083). The LAI was not constant in the Mayo Valley and did not have a pattern like in the Yaqui Valley; the highest values were expressed (8.109) at the end of the flowering stage, and thereafter lower values were recorded, showing the lowest one (4.447) during full-grain formed (Table 3).

Table 3. Average leaf area index of durum wheat cultivar CIRNO C2008 at different growth stages in southern Sonora, Mexico, during the crop season fall-winter 2020-2021.

Region	Growth stage				
	End of flowering	1/4 grain	1/2 grain	3/4 grain	Full grain
Yaqui Valley	5.978 (± 1.93)	6.666 (± 1.84)	7.768 (± 2.21)	7.124 (± 0.10)	7.083 (± 0.46)
Mayo Valley	8.109 (± 1.30)	6.99 (± 1.23)	7.399 (± 1.46)	6.388 (± 1.83)	4.447 (± 0.89)
Mean	6.83	6.855	7.621	6.878	5.519

( )= Standard deviation.

The LAI varies according to weather conditions that occur in each region during crop development; Valverde and Arias (2020) indicate that climatic factors generate significant variations to LAI, such as the case of cloudiness which increases the underestimation of the LAI; also, wind speed greater than 5 km h^{-1} generate up to 60% variability of the LAI values. The agronomic management by the farmers also has an impact, since LAI increases with greater rates of nitrogenous fertilizers, irrigation frequency, plant density, and generally shows a tendency of first rising, reach a peak at the boot stage or heading, and then decrease as the growth stages progress (Feng *et al*., 2019). As it can be observed in the values obtained in the Yaqui Valley, LAI values increased from flowering up to half grain filling; a similar case was observed by Inzunza-Ibarra *et al*. (2010) where the highest LAI expression occurred at the initiation of flowering, and from that stage on, it decreased so that the lowest LAI values were obtained during physiological maturity. The regression between grain yield and the leaf are index had a coefficient of determination of R^2 = 0.324 (Figure 8) which shows clearly a group of outliers, possibly generated by the agronomic management by wheat farmers or by wind speed, factors with were not considered in this work. However, in the Yaqui Valley the first seven fields with lower grain yield had a range of 6.54 - 7.53 t ha^{-1} with avg. of 7.05, and LAI range of 3.75 – 8.95 with avg. of 6.31, while the other eight fields with higher grain yield had a range of 7.97 – 10.44 t ha^{-1} with avg. of 8.73, and LAI range of 5.22 – 9.14 and avg. of 7.35. In the Mayo Valley the first seven fields with lower grain yields had a range of 4.36 - 7.43 t ha^{-1} with avg. of 6.22, and LAI range of 3.55 – 8.19 with avg. of 5.80, while the other eight fields with higher grain yield had a range of 7.48 – 9.12 t ha^{-1} with avg. of 8.12, and LAI range of 5.52 – 9.03 and avg. of 7.40.

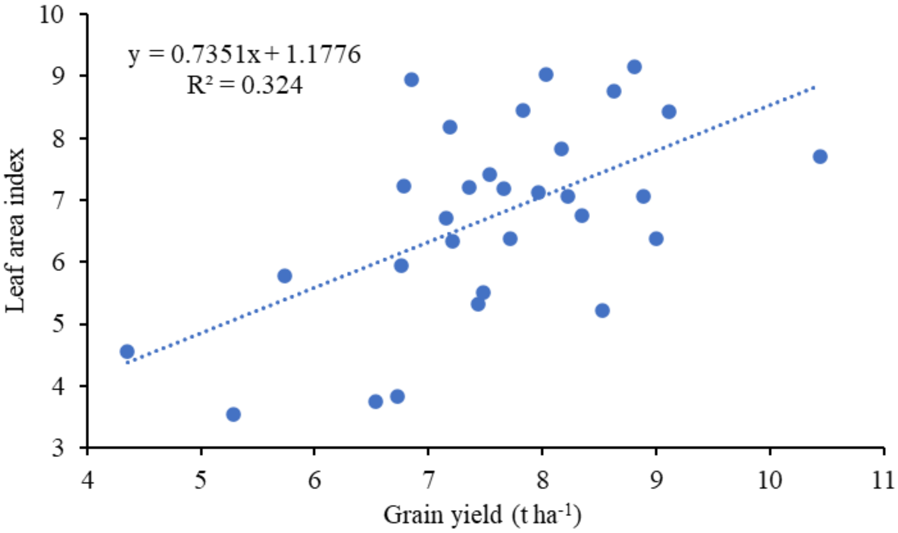

Figure 8. Linear regression between grain yield and the leaf area index in evaluated commercial wheat fields with durum cultivar CIRNO C2008 in the Yaqui and Mayo Valleys, Sonora, Mexico, during the crop season fall-winter 2020-2021.

Wheat grain yield can be estimated based on LAI from flowering to initiation of grain-filling through indirect nondestructive methods. Similar results were reported for bean under rainfed conditions in the state of Zacatecas, Mexico (Acosta Díaz *et al*., 2008), as well as in poblano pepper (*Capsicum annuum* L.) cultivated in greenhouse using a ceptometer, which demonstrated to be an adequate and reliable method (Mendoza-Pérez *et al*., 2017). Maize yield under irrigated conditions in large areas of the state of Sinaloa, Mexico, was forecasted through LAI estimates from spectral data (Báez-González *et al*., 2005). Benbi (1994) reported that the rate and extent of leaf area development and its decline were dependent on the amount and pattern of water supply, and that wheat grain yield is determined by the maximum leaf area index (LAI_{max}) and the cumulative water supply from the LAI_{max} to maturity; LAI_{max} was dependent on the combined effect of NO_3-N in the 180 cm soil profile at sowing plus fertilizer N added. According to Yadav *et al*. (2019), the modified water cloud model shows great potential for LAI estimation of the wheat crop, by incorporating optical data (i.e. Sentinel-2) in terms of the scale invariant vegetation fraction with synthetic aperture radar data (i.e. Sentinel-1A). Hasan *et al*. (2019) estimated LAI of winter wheat at the jointing stage in Xinjiang, China, using parameters derived from unmanned aerial vehicle (UAV) RGB images; their results showed that it is feasible to use UAV RGB images for inverting and mapping the LAI of winter wheat; the UAV RGB images can also provide more reliable and accurate data for precision agriculture management. Wu *et al*. (2022) investigated the potential of high-resolution UAV imagery combined with multi-sensor data fusion in LAI estimation; high-resolution UAV imagery was obtained with a multi-sensor integrated MicaSense Altum camera to extract the wheat canopy's spectral, structural, and thermal features. After removing the soil background, all features were fused, and LAI was estimated using Random Forest and Support Vector Machine Regression. They found that the soil background reduced the accuracy of the LAI prediction of wheat, and soil background could be effectively removed by high-resolution UAV imagery, so the prediction accuracy improved significantly. Chang-Wei *et al*. (2020) tried to improve the accuracy of monitoring LAI through remote sensing by integrating the normalized difference vegetation index (NDVI) and Beer-Lambert law. This law was modified to construct a monitoring model with NDVI as the independent variable, and experimental data of wheat from different years and various plant types (erectophile, planophile, and middle types) were used for validation. This modified model was better than Beer-Lambert law model and NDVI-LAI direct model; it was feasible to quantitatively monitor the LAI of different plant-type wheats by integrating NDVI and Beer-Lambert law, especially for erectophile-type wheat (coefficient of determination $R^2 = 0.905$, root mean square error RMSE = 0.36, relative error RE = 0.10). The monitoring model proposed can accurately reflect the dynamic changes of plant canopy structure parameters, and provides a novel method for determining plant LAI.

4. CONCLUSIONS

The leaf area index (LAI) increased from the end of flowering to a half grain-filling in the Yaqui Valley (YV) (7.768), and decreased as the season progressed (7.083); however, in the Mayo Valley (MV), LAI was the highest at the end of flowering (8.109); the regression between grain yield and LAI had an R^2 of 0.324. LAI can be an adequate and reliable method to estimate grain yield in wheat, but it should also take into consideration the weather conditions and the agronomic management by farmers. The avg. grain yield in YV was 7.95 t ha^{-1}, while 7.24 in

MV, but the latter had one less irrigation. The avg. spike number m^{-2} was 400 in YV and 370 in MV. The avg. grain protein content in YV was 10.49% and 39.6% for yellow berry, while in MV 11.26% and 13.8%, respectively. The overall avg. temperature during the season, relative humidity and the accumulated cold units for YV and MV were 16.96 and 16.97 °C, 68.31 and 69.13%, and 817 and 867, respectively.

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