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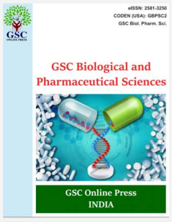

(Research Article)

Relationship between the leaf area index and wheat grain yield in commercial fields in the Yaqui valley, Sonora, Mexico

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Abstract

The leaf area index (LAI) is a key plant parameter for modeling the mass exchange and energy between the biosphere and the atmosphere, which allows the study of development, growth, and agronomic yield of crops. The critical period for diminishing the wheat leaf area occurs 30 days around flowering and may cause a reduction in the real number of spikes/m^2, spikelets/spike, number of grains/m^2, and grain weight. The objective was to determine the relationship between the LAI and grain yield during the phenological development, in different sowing dates in thirteen commercial wheat fields, sown with durum cultivar CIRNO C2008, in the Yaqui Valley, Sonora, Mexico, during the fall-winter 2021-2022 crop season. Field surveys were carried out to monitor crop development, and to take readings of the LAI using a linear ceptometer; also, four 1 m^2 samples were harvested from each field in order to count the number of spikes and to calculate grain yield. The LAI was not constant in ten of the selected fields according to the development of wheat; however, there were three fields (B-703, B-725, and B-1512) where there was a positive correlation between the LAI and grain yield which reached more than 8.2 t ha^{-1}. The highest expression of the LAI occurred during ½ grain formation. The average grain yield of the monitored fields was 7.22 t ha^{-1}, being December 14, 2021, the sowing date with the highest yield (8.43 t ha^{-1}), while the highest number of spikes/m^2 occurred on the December 11 sowing date with 428. Measurement of the LAI indirectly, could be considered an appropriate method, but environmental conditions and agronomic management by producers must be taken into account in order to make yield estimates.

Keywords: Leaf area index; Durum wheat; *Triticum durum*; Grain yield

1. Introduction

The main cereals produced around the world are maize (*Zea mays* L.), wheat (*Triticum* spp.), and rice (*Oryza sativa* L.) [1]. Wheat is the cereal food crop with the highest area and the second most cultivated in the world after maize [2]. Starch from wheat and other cereal grains is the predominant source of human dietary carbohydrate [3], and contributes with about 20% of all calories and protein for humans [4]. Wheat cultivation in Mexico has fluctuated due to the international grain price, disease incidence, and to the capacity for water storage in dams [2]. Wheat sowing in Mexico takes place during the fall-winter crop season in the north and northeastern part of the country, and during the spring-summer crop season in the central region; the fall-winter season is the most important because of the area (87.80%) and production (96.35%) [5]. Northwestern Mexico is the most important wheat-producing region, where the state of Sonora has the highest production, contributing with 58.05 % of the national production, followed by the states of Guanajuato, Baja California, and Sinaloa [5]. Most of the wheat production within the state of Sonora, takes place mainly in the Yaqui Valley and to a lesser extent in the Mayo Valley [6]. Productivity and wheat quality are controlled by the genetic characteristics of cultivars, which can be modified by agronomic management (nutrient availability in the soil, nitrogenous fertilization, sowing date, control of pests and diseases), and by the climatic conditions that prevail during the crop season [7]. The growth and development of the crop results from the use of

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sunlight in the manufacture of the constituent and functional components of the different organs of the plant. The consequences of modifying the moment of crop implantation on its growth result from the impact of temperature, radiation and photoperiod on its phenology, the development of leaf area, and the accumulation of dry matter [8]. The leaf area index (LAI), which describes the amount of leaf area per unit of horizontal soil surface, is a key vegetation parameter for modeling the exchange of mass (water and carbon) and energy (radiation and heat) between the biosphere and atmosphere [9,10,11,12]. There are two main methods for estimating LAI: direct and indirect methods. The decision on which method to use depends on many factors such as: the precision required, the measurement period, the scale of the investigation, the available budget [13]. Direct methods are the most accurate and consist of destructive sampling and involve direct measurement of tree foliage or collection of leaf litter over a period of time; they have the disadvantage of being expensive and time-consuming, and consequently, the large-scale implementation is not feasible [13,14,15]. Indirect methods are generally faster, amenable to automation, and therefore, allow obtaining a larger spatial sample; they consist of a series of readings taken directly in the field with specific instruments, based mainly on the measurement of photosynthetically active radiation (PAR) above and below the foliage, and on the use of complex mathematical models [13,16]. The indirect methods for estimating the LAI may be divided into two categories: measurements by indirect contact (terrestrial measurements that are usually integrated into a single support), and indirect non-contact measurements (aerial and space methods are applied) [13]. One of the most widely applied indirect non-contact techniques has been optics, which has been based on the principles of Beer Lamberth's Law [13], and allows modeling the behavior of the light that passes through the canopy coverage. A range of instruments have been developed to indirectly assess real-time LAI of plant canopies, and are divided into two categories: the first group is based on gap fraction analysis, while the second group is based on the gap size distribution. Some incorporate image analysis techniques of the vegetation cover (hemispheric photographs [17] or images obtained from remote sensors (Landsat [18], LiDAR [19]), while others calculate the LAI by comparing differential light measurements above and below the canopy (AccuPAR [20], LAI-2000 Plant Canopy Analyzer [21], and SS SunScan Canopy Analysis System [22]). However, the light measurements needed to calculate the LAI require clear skies, and in general, there is a need to incorporate a light extinction coefficient that is both site- and species-specific due to leaf angle, shape of the leaves, and grouping of the leaves [23]. The decrease in leaf area is one of the many problems that affect crops, since the interception of photosynthetically active radiation decreases, generating losses of different magnitudes in yield, depending on the moment in which it occurs and its intensity [24]. There is a close relationship between the LAI and the interception of solar radiation, associated with photosynthesis and transpiration processes, aspects strongly linked to biomass accumulation and productivity [10]. Therefore, it is a fundamental variable for the study of development, growth, and agronomic performance of crops [25,26]. In relation to wheat, the critical period of leaf area decrease occurs 30 days around flowering, covering the end of the stem elongation stage, heading, flowering, and the beginning of grain filling. Therefore, the reduction in the LAI can cause a decrease in the real number of spikes/m^2, spikelets/spike, number of grains/m^2, and grain weight [24]. Determining the relationship between the LAI and grain yield could be a useful tool for the development of accurate harvest prediction models. The objective of this work was to determine the relationship between the leaf area index and wheat yield, during its phenological development on different sowing dates in the Yaqui Valley, Sonora, Mexico.

2. Materials and methods

The work was carried out in the Yaqui Valley, Sonora, Mexico, during the fall-winter 2021-2022 crop season, with the durum wheat (*Triticum durum* Desf.) cultivar CIRNO C2008 [27] under irrigated conditions. CIRNO C2008 is the most widely used cultivar by farmers in southern Sonora, despite losing its resistance to the race BBG/BP_CIRNO of leaf rust caused by the fungus *Puccinia triticina* Eriks. [28]; however, during the fall-winter crop seasons 2019-2020 to 2021-2022, it covered 92% of the area sown with wheat in southern Sonora [29,30,31]. Thirteen commercial fields were selected by doing surveys throughout the valley from November 15 to December 15 (Table 1, Figure 1), which is the period considered as the optimum range of dates for wheat sowing in that region [32]. For the selection of the commercial wheat fields, it was also taking into consideration their closeness to a weather station, so that inferences about the effect of some climatic factors upon the growth and grain yield could be made.

During crop development three readings of the leaf area index (LAI) were taken in each field using an AccuPAR LP-80 linear ceptometer [20]; the light intensity was measured above and below the crop canopy only under clear sky conditions and during 10:00 am to 14:00 pm; the ceptometer bar was placed perpendicular to the beds (Figure 2) in four locations of each commercial field. This activity which was programmed from the first survey carried out in each of the fields, and comprised the following phenological stages in a given time in each field: production of the second node (Zadoks stage 32) [33], production of the third node (stage 33), production of the fourth node (stage 34), boot (stage 45), heading (stage 59), flowering (stage 62), then, when a quarter of the grain was formed, a half, three quarters, and at full grain formed (stage 70), and milky grain stage (stage 75); the average of data of each phenological stages from all the fields was then analyzed. In each field, four spike samples were harvested using curved knives from 1 m^2 to calculate the yield; also, the number of spikes in each sample was counted, and the weight of 1000 grains was recorded. Additionally, data on temperature, relative humidity and cold units were obtained in an hourly format from 13 weather stations which were close to each monitored field, from the automated weather station network of Sonora [34], covering the months of November 2021 to April 2022. Later on, simple Pearson correlations and analysis of variance were carried out between the LAI and grain yield.

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 Valley, Sonora, Mexico, during the crop season fall-winter 2021-2022

Fields	Location	Sowing date	Latitude	Longitude
1	Casa Belem	16-Nov	27.51944444	-110.1313889
2	B-703	19-Nov	27.40902778	-110.0375
3	B-1419	20-Nov	27.28088889	-110.2191111
4	B-2324	22-Nov	27.11625	-109.7693056
5	Hornos	27-Nov	27.62569444	-109.8993056
6	B-1512	27-Nov	27.25361111	-109.8921389
7	B-1012	30-Nov	27.35402778	-109.8969444
8	B-1311	06-Dec	27.28152778	-110.1199722
9	B-2816	06-Dec	27.021	-109.8710833
10	B-1730	08-Dec	27.20813889	-109.7278611
11	B-2410	11-Dec	27.08511111	-109.9228333
12	B-514	14-Dec	27.43775	-109.8728333
13	B-725	15-Dec	27.40436111	-110.2606111

Figure 1 Geographic location of the wheat commercial fields in the Yaqui Valley, Sonora, Mexico (yellow dots), and their nearest weather stations (blue dots)

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

3. Results and discussion

3.1. Climatic conditions during the crop season 2021-2022

The beginning of the 2021-2022 fall-winter agricultural crop season was warm during the month of November, with an average temperature of 20.62 °C; from December to February temperatures decreased, with an average of 17.33 °C in December, 15.74 °C in January and 14.53 °C in February (Figure 3). March was considered a cold month, since the average temperature was 16.34 °C, with a range of 2.05 to 12.19 °C in the average daily minimum temperature, and the average daily maximum temperature was 26.81 °C. The average temperature for the month of April was 20.85 °C with a range of 8.97 to 34.31 °C, similar to the beginning of the agricultural crop season. The average relative humidity in the second half of November was 70.22%, 71.04 in December, 75.21 in January which was the highest average of the agricultural crop season, 71.91 in February, 66 in March, and 68.29% in April. Similar to crop season 2020-2021 [35], the average relative humidity did not reach 80% which contributed to a better phytosanitary status during plant growth.

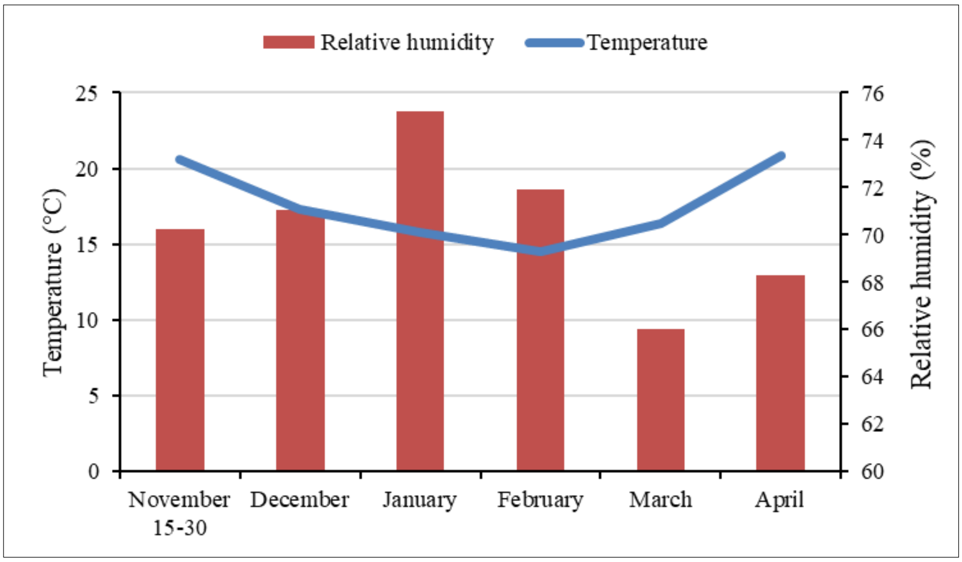

Figure 3 Monthly average temperature and relative humidity from 13 weather stations in the Yaqui Valley, Sonora, Mexico, during the crop season 2021-2022.

The cold units (CU) were recorded from November 15, the date from which wheat sowing is authorized [36], to April 30, a period in which the wheat crop will be in the initial stage of dough grain (stage 85 of Zadoks scale), if sowing is carried out after December 15. The average of the total number of CU of the 13 selected weather stations during the crop season was 656, and the monthly average of each weather station is shown in Figure 4.

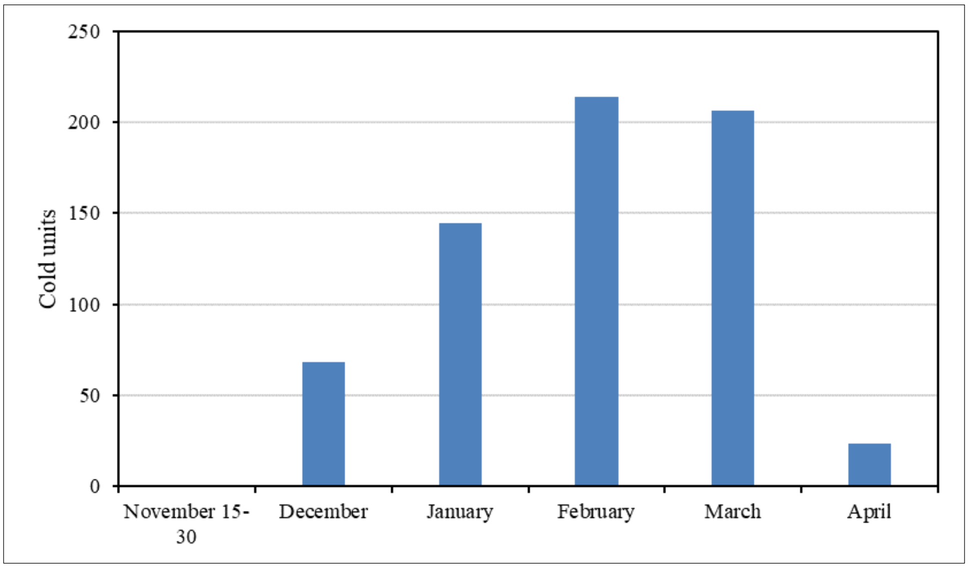

Figure 4 Monthly average of accumulated cold units from 13 weather stations in the Yaqui Valley, Sonora, Mexico, during the crop season 2021-2022.

The number of CU gradually increased from December to February whose peak was 213, unlike crop season 2020-2021 where the highest average number of CU were recorded in January [35]; 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 [37]. Eight weather stations were above average and five were below average (Figure 5). The B-1730 weather station had the highest number of accumulated CU with 938, followed by B-2918 with 792. The weather stations with the lowest number of accumulated CU were B-1423 and B-720 with 314 and 418 CU, respectively. The average temperature of B-720 was 18.83 °C the highest of all the weather stations, but it did not record the lowest number of CU (418), while B-1423 did not record the highest temperature, but the lowest number of CU (314); on the contrary, B-1730 recorded the highest number of CU (938), but it did not record the lowest average temperature 16.75°C, while B-2918 recorded the lowest average temperature (15.97 °C) and the second highest number of CU (792).

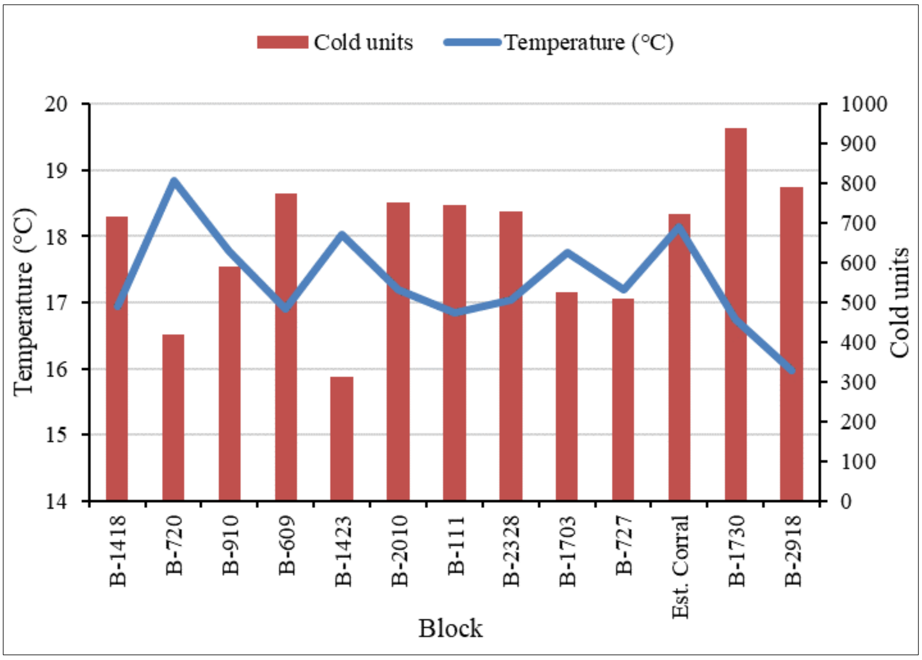

Figure 5 Accumulated cold units and average temperature of 13 weather stations closer to the selected commercial wheat fields sown with durum wheat cultivar CIRNO C2008, in the Yaqui Valley, Sonora, Mexico, during the crop season 2021-2022

3.2. Leaf area index (LAI)

As the different phenological stages of wheat developed, the expression of LAI was not constant. This index varies according to climatic conditions that occur in a particular region during crop development; Valverde and Arias [38] reported that weather factors cause significant variations to LAI, such as cloudiness which increases the underestimation of the LAI; wind speed greater than 5 km h^{-1} causes up to 60% variability of the LAI values. The agronomic management also has an impact, since LAI increases with higher doses 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 [39]. From the stage of booting to flowering, the LAI was maintained between 5.4 and 6.0; the highest expression of the LAI was shown in ½ grain formation with a value of 6.86, then it decreased (5.34), increased during full grain (5.83), and decreased again during the milky grain stage (4.80) (Figure 6); unlike the results obtained by Inzunza-Ibarra *et al.* [40], who used a leaf area integrator (LI 3100, LI-COR) and found that the highest expression of the LAI in wheat occurred at the beginning of the flowering stage, and subsequently, lower LAIs were obtained until physiological maturity was reached. They indicated that in general, treatments with the highest LAI values were those subjected to nonrestrictive soil moisture conditions, while the lowest values were obtained with treatments under severe water deficit; however, in the present work, there was not a follow up in the number of irrigations applied to each individual wheat field. In the case of beans, Acosta Díaz *et al.* [41] who used a linear ceptometer (DECAGON, model 80 with a 48 K datalogger), reported that the LAI increase depended on the phenological stage, obtaining the highest values at the beginning of grain filling.

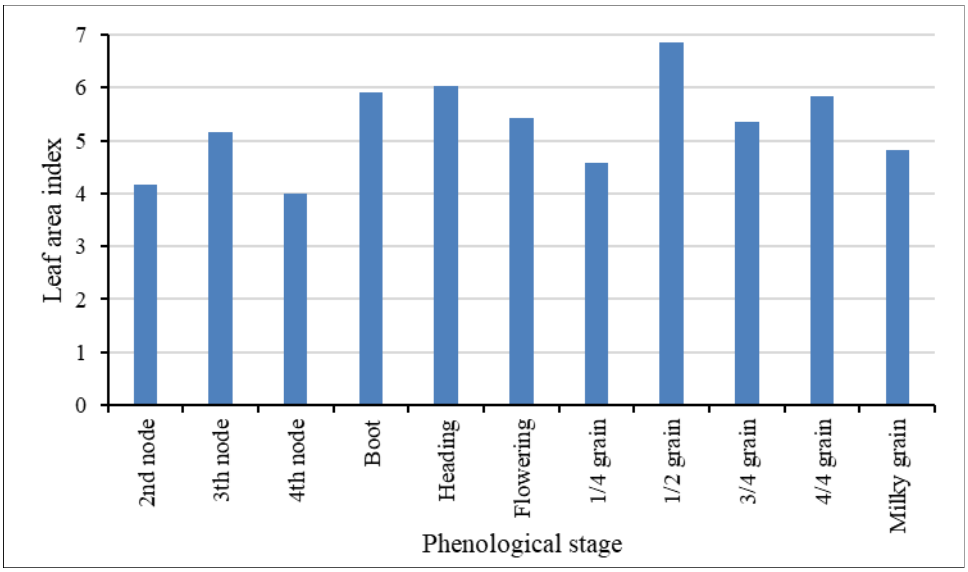

Figure 6 Average leaf area index of wheat during different phenological stages of 13 commercial fields sown with durum wheat cultivar CIRNO C2008, in the Yaqui Valley, Sonora, Mexico, during the crop season 2021-2022.

3.3. Grain yield

According to the reported statistics, the average grain yield of the Yaqui Valley was 7.57 t ha^{-1} [5], while the average yield of the 13 monitored fields was 7.22 t ha^{-1}. Based on the routes that were carried out, in most of the fields differences were observed in terms of weed problems, in some the crop development was advanced and in others there was presence of leaf rust (*P. triticina*) and foliage or cereal green aphid (*Schizaphis graminum* Rondani). On the sowing dates of November 19 (B-703), 27 (B-1512), and December 11 to 15 (B-2410, B-514, B-725), yields above 8 t ha^{-1} were obtained, however, on the date of December 6 (B-2816), the yield was lower than 6 t ha^{-1} (Table 2). The average number of spikes/m^2 was 366 with a range of 309 to 428; the date of December 11 (B-2410) obtained the highest number of spikes with 428, followed by B-703 with 407, and B-2324 with 402; however, on the date of November 30 (B-1012), 309 spikes/m^2 were obtained, being the lowest number of all the monitored fields. In the case of B-2410, B-703, and B-725, the high number of spikes/m^2 contributed for a grain yield above 8 t ha^{-1}, as it was also reported by Iolele *et al.* [42], who found a marked trend and positive correlation; however, B-514 showed the highest grain yield with 8.43 t ha^{-1}, but with only 344 spikes/m^2, below the average of all the fields, although it was third with the highest a thousand grain weight (58.47 g).

The average weight of 1000 grains of the sampled fields was 54.30 g, the B-1419 field had the highest weight with 60.10 g, while the Casa Belem field obtained the lowest weight of 46.96 g (Table 2).

Table 2 Grain yield, spikes/m^2, and a thousand grain weight of 13 commercial fields sown with durum wheat cultivar CIRNO C2008, in the Yaqui Valley, Sonora, Mexico, during the crop season 2021-2022.

Block	**Sowing date**	**Grain yield (t ha^{-1})**	**Spikes/m^2**	**A thousand grain weight (g)**
Casa Belem	16-Nov	6.22	330	46.96
B-703	19-Nov	8.32	407	54.92
B-1419	20-Nov	7.72	373	60.10
B-2324	22-Nov	6.32	402	57.36
Hornos	27-Nov	7.60	332	52.95
B-1512	27-Nov	8.20	361	56.62
B-1012	30-Nov	6.42	309	58.72
B-1311	06-Dec	6.93	367	49.73
B-2816	06-Dec	5.98	361	52.03
B-1730	08-Dec	6.92	345	51.07
B-2410	11-Dec	8.32	428	50.60
B-514	14-Dec	8.43	344	58.47
B-725	15-Dec	8.30	399	56.32

3.4. Relationship between the leaf area index and grain yield

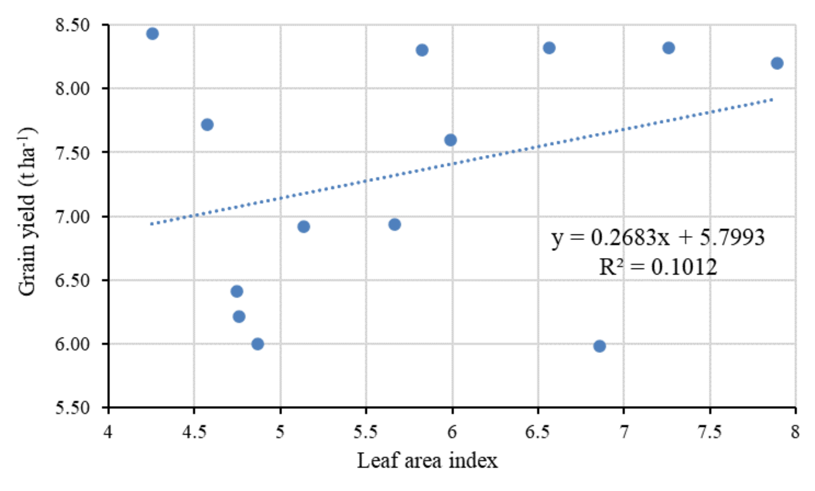

Figure 7 Relationship between the leaf area index and grain yield in 13 commercial fields sown with durum wheat cultivar CIRNO C2008, in the Yaqui Valley, Sonora, Mexico, during the crop season 2021-2022.

The regression analysis carried out with the leaf area indices of the 13 monitored fields and the grain yield, resulted in the linear model shown in Figure 7, where the regression equation was: y=0.268(LAI) + 5.799, which means that for each unit increase in the leaf area index, an increase of 268 kg of wheat per hectare was obtained, within the explored range. Likewise, it can be noted that the analysis of variance carried out for the regression, recorded a multiple correlation coefficient of 0.32 and a determination coefficient of 0.101, which means that there is a weak relationship and that the LAI is capable of explaining up to 10% of the observed variability in grain yield. Therefore, these results indicate that in ten of the monitored fields in this particular work, the model was not conducive to estimate or predict yield in commercial fields under development, contrary to what Báez González *et al.* [43], Acosta Díaz *et al.* [41] and Tinoco Alfaro *et al.* [44] reported, where the LAI was positively related to yield in both beans (*Phaseolus vulgaris* L.) and maize. However, in the case of B-703 (8.32 t ha^{-1}), B-725 (8.30 t ha^{-1}), and B-1512 (8.20 t ha^{-1}), the LAI increased from the 2nd (the first two fields) and 3th (the third field) nodes to boot, flowering, and heading, respectively, to full grain (the first field) and ½ grain formed (the other two fields). It must be considered that the variability in crop production in irrigated and rainfed production systems is caused by environmental conditions, the cultivars used, and the agronomic management of the crop [7,8,38,45].

Fernandez *et al*. [46] reported that wheat cultivars respond differentially to production environments and agronomic management; therefore, favorable production environments present high values in quality parameters. Noriega-Carmona *et al*. [47] reported that the sowing date of November 15 is considered favorable for the production of quality seed for wheat cultivation in the Bajío region, Mexico. In northwest Mexico, the optimum sowing date ranges from November 15 to December 15, which is where the highest yields are obtained and phytopathogenic and pest problems are reduced [4]. Borbón *et al*. [48] reported that in northwest Mexico, the best sowing date for the fall-winter wheat season is December 15, but it may vary depending on the environmental conditions.

4. Conclusions

The leaf area index (LAI) was not constant in ten of the selected fields according to the development of wheat; however, there were three fields (B-703, B-725, and B-1512) where there was a positive correlation between the LAI and grain yield which reached more than 8.2 t ha^{-1}. The highest expression of the LAI occurred during ½ grain formation.

The average grain yield of the monitored fields was 7.22 t ha^{-1}, being December 14, 2021, the sowing date with the highest yield (8.43 t ha^{-1}), while the highest number of spikes/m^2 occurred on the December 11 sowing date with 428.

Measurement of the LAI indirectly, could be considered an appropriate method, but environmental conditions and agronomic management by producers must be taken into account in order to make yield estimates.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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