INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
ISSN Print: 1560–8530; ISSN Online: 1814–9596
23–0369/2024/32–1–16–26
DOI: 10.17957/IJAB/15.2171
http://www.fspublishers.org

*Full Length Article*

# Intense Continuous Shading is Detrimental to the Development and Production of White Oat Grains

**Camila Cigel, Clovis Arruda Souza*†, Gesieli Priscila Buba†, Franciele Fátima Fernandes† and Leonardo Berkenbrock†**
*Department of Agronomy, Santa Catarina State University, Lages, SC 88520-000, Brazil*
*For correspondence: souza_clovis@yahoo.com.br
†Contributed equally to this work and are co-first authors
*Received 14 September 2023; Accepted 15 November 2023; Published 26 May 2024*

## Abstract

Knowledge of the tolerance of annual cultures to less intense solar radiation is essential to achieving sustainable and more productive systems. The objective of this study was to assess grain performance and yield of white oat plants under intensities and orientations of artificial shading ranges during their growth cycle. The experiments were carried out during the 2020 and 2021 growing seasons, using white oat (*Avena sativa* L.) cultivar URS Altiva. The study used a completely randomized design, in a 3x2+1 factorial arrangement, with three shading intensities: low (25%), medium (50%), high (75%), two orientations: north/south, east/west, and additional treatment (control – under full sun). There were losses mainly under high shading intensity, e.g., a reduction in the Soil Plant Analysis Development (SPAD) and Normalized Difference Vegetation Index (NDVI) at 70 days after the onset of solar radiation restriction, leading to delayed leaf senescence by 42 days (2020) and 21 days (2021); reduced plant height by up to 19.1% (2020) and 21.7% (2021); reduced dry weight at pre-harvest (2021) up to 36.1%, in comparison to the control (274.3 g) and reduction of yield components, number and grain weight. The orientation of the north/south ranges differed from that of the east/west ones by their detrimental effect on grain growth and yield components. In conclusion, low shading intensity throughout the cycle on white oat plants did not cause significant damage to plant development and yield, while high intensity affected them negatively, particularly in the north/south orientation.

**Keywords:** Adaptability; While oat; Grain yield; Solar radiation; Orientation

## Introduction

White oat (*Avena sativa* L.) is gaining importance, mainly in the southern region of Brazil due to its nutritional and economic values. Increased cultivation of white oat is reflected by greater grain production and yield (CONAB 2023), release of new cultivars through genetic breeding programs, a wider range of cultivation systems and use of crop as pasture for animals (Danielowski *et al.* 2021). In addition, white oats are characterized as an optional winter species in the region, especially because few crops are grown in the winter after harvest of summer crops (Balbinot Junior *et al.* 2009).

Integrated production systems are alternatives for optimizing production areas (Bi *et al*. 2019). For example, integrated crop-forestry systems, in which trees are planted between bands of annual crops or perennial crops, can provide short- and long-term financial returns (Burner *et al.* 2018). Therefore, some local environmental factors may be affected in these systems, *e.g.*, the incidence of direct solar radiation, which may vary, especially for plants grown in the lower stratum or among tree rows. This variation in solar radiation is due, among other factors, to the sun's position, time of day, direction of the rows, distance between the trees, height and shape of the canopy and wind-induced crown movement (Way and Pearcy 2012; Cordeiro *et al.* 2015).

Solar radiation is crucial for photosynthetic performance, which is vital for plants (Stirbet *et al*. 2020), because it is responsible for producing the carbohydrates required for plant growth and development (Taiz *et al.* 2017). Crop yield, in turn, is directly related to the production of photosynthates by leaves and/or green organs of plants and their subsequent efficiency to synthesize reserves for grain development (Goffman *et al.* 2005). Thus, plants have internal mechanisms for increasing light use efficiency when there is low intensity or mechanisms for reducing and repairing damage induced by more intense light (Nevo *et al.* 2012). One of these mechanisms is a change in leaf chlorophyll content in response to low light intensity. According to Xie *et al.* (2022), plants that are tolerant to low light conditions or have shade prevention mechanisms that present lower a/b chlorophyll ratio and a higher ratio between

**To cite this paper:** Cigel C, CA Souza, GP Buba, FF Fernandes, L Berkenbrock (2024). Intense continuous shading is detrimental to the development and production of white oat grains. *Intl J Agric Biol* 32:16–26

photosystems II and I; in this sense, they differ from plants under optimal light conditions.

Assessing the tolerance of white oat crops cultivated under low solar radiation or shading can provide new possibilities for cultivation in integrated grain production systems. However, black oat plants grown together with tree species under limited solar radiation in integrated systems presents reductions of leaf area index, growth rate, net assimilation and leaf weight (Sgarbossa *et al*. 2020), which causes a reduction in plant dry matter and yield, when they are intercropped with native trees (Nicodemo *et al.* 2016). In addition, a study evaluating the performance of white oat grown close to eucalyptus rows in an agroforestry system, reported an increase in plant yield that was proportional to the largest distance between the white oat plants and the eucalyptus plants (Deiss *et al*. 2016).

With this background, there is a need for studies on the adaptation and tolerance of white oat to shading, considering the constant release and use of modern and more productive cultivars. Thus, the objective of this study was to assess grain yield performance of white oat plants of the cultivar URS Altiva under simulated shading conditions (intensities and directions) throughout the continuous cycle.

## Materials and Methods

### Setup and conduction of the experiments

The study was conducted at the Center of Agricultural Sciences (CAV) at Santa Catarina State University (UDESC), in Lages, Santa Catarina state, under geographic coordinates 27°52’ South latitude, 50°18' West Longitude, and average altitude of 930 m. The municipality has an average annual temperature of 15.7°C and precipitation of 1500 mm, according to information from the Climate Atlas of Southern Brazil (Wrege *et al.* 2012). The soil of the site is characterized as an aluminic humic Cambisol with clayey texture (Embrapa 2013). Weather data on temperature, precipitation, and solar radiation incident throughout conduction of the experiments (Fig. 1), was compiled according to data published by the National Institute of Meteorology (INMET 2019).

The experiments were carried out on the white oat (*Avena sativa* L.) cultivar URS Altiva in the 2020 and 2021 growing seasons. This cultivar was released in 2015 and is characterized by early cycle, great height and moderate lodging resistance (Danielowski *et al.* 2021). The cultivar URS Altiva stands out for its high grain yield potential and hectoliter weight (Carvalho *et al*. 2023; Lucas *et al*. 2023).

Sowing was carried out in August 2020 and July 2021. Fertilization was carried out according to recommendations of the Soil Chemistry and Fertility Commission (CQFS 2016), based on soil analysis, aiming at 6 t $ha^{-1}$ of grain yield potential. Soil chemical characteristics determined by analysis were pH 6.5; SMP index 6.1; phosphorus 18.7 mg $dm^{-3}$; potassium 173.2 mg $dm^{-3}$; H+Al 4.0 cmol $dm^{-3}$; CEC pH 7.0 of 18.4 cmol $dm^{-3}$; organic matter 3.1% and base saturation (V) 48.0%. Fertilization at sowing consisted of 400 kg $ha^{-1}$ of the NPK 5-20-10 formulation; twice N topdressing fertilization were used (30 kg $ha^{-1}$), split between the tillering and stem elongation stages.

Weed control during crop development was performed by hand. Phytosanitary treatment was applied to control insects and diseases according to technical indications for the oat (MAPA 2009). Regarding water availability, complementation was performed through manual irrigation according to the need of the plants.

The shading structures were made of wood, with 1.5 × 1.5 m width and length, similar to those described by Varella *et al.* (2011). These structures differed in terms of distance between boards (shading intensities) and installation orientation (direction of boards – east/west or north/south). The structures were installed at a height of 0.6 and 1.2 m from the soil level, which was increased as the plants grew taller.

Harvest was performed by cutting the plants present in the usable plot when the plants of the control treatment (no shading) were between the hard dough (87) and soft dough (85) stages in the 2020 and 2021 growing seasons, respectively (Zadoks *et al*. 1974). These growth stages were chosen aiming to escape herbivory by birds.

### Experimental design

The experiment used a completely randomized design in a 2 × 3 + 1 factorial arrangement, with two orientations of the shading bands, north/south (N/S) and east/west (E/W) directions; three levels of limited solar radiation, namely low (25%), medium (50%) and high (75%) and additional treatment (control) with plants grown under full sun. Four replicates were used, in a total of 28 experimental plots. The research design was based on research feasibility, related to number of factors, available space, and regular assessments. The local conditions were chosen considering the greatest possible homogeneity of soil and incident solar radiation. The plants were shaded at stage 11 *i.e*., when its presented with the first unfolded blade-shaped leaf, according to the phenological scale of Zadoks (Zadoks *et al.* 1974) and they remained under such conditions until the end of the cycle. Each usable experimental plot was composed of a 1.0 m row, with inter-row spacing of 0.20 m, within a larger area 1.2 m wide and 2.0 m long, containing 10 sowing rows.

### Assessments

The plants were assessed at different times. Assessments were carried out weekly (SPAD, NDVI and height), monthly (leaf area and dry weight) and after the plants had been cut (yield components and grain retention on sieves). After the shading structures were installed over the plants, the following assessments were made on a weekly basis: plant height (distance from the base of the plant at ground level to the end of the last leaf or panicle); indirect chlorophyll assessments, based on the SPAD index, using a SPAD handheld meter (SPAD-502 Plus, Konica Minolta), while NDVI was determined with an NDVI handheld meter (NDVI 310, PlantPen). The assessments were made in three plants per experimental unit, previously demarcated throughout the period, between seven and 70 days after installation of the structures.

Plant dry weight and leaf area were determined monthly, 30 and 60 days after shading had been applied. Plant leaf area was determined by measuring leaf blades with photosynthetically active tissue, obtained from three plants per experimental unit, using a bench-top leaf area meter (LI-3100, Lincoln, Nebraska, USA). After that, the plants (shoot) were dried in a forced air circulation oven at 65 ± 2°C to constant weight for dry weight quantification using a 0.01 g precision balance (model BL3200H, Shimadzu, Japan).

For assessment of yield components, the number of panicles and spikelets was determined by counting the plants collected in each experimental plot. Subsequently, the plants were dried at 65 ± 2°C for 72 h in a forced air circulation oven. The harvest index (HI) was determined by weighing plant dry matter (corresponding to biological yield), threshing, and separating and weighing the grains. The following formula was used (1):

$$\text{HI}\ (\%) = \left(\frac{\text{GY}}{\text{DWt}}\right) \times 100 \qquad (1)$$

Where HI is harvest index, GY is grain yield and DWt is total dry weight (Takeda *et al*. 1980).

Grain weight or yield was determined after manual threshing and thousand grain weight (TGW) was determined by counting and checking the weight of one thousand grains in each plot. Sieve analysis was made with oblong sieves with diameters of 0, 1.75, 2.0, 2.2, 2.5, 3.0 mm × 22 mm, followed by weighing the grains retained on each sieve, with results expressed as a percentage.

### Statistical analysis

The data were submitted to the normality test of the residuals and homogeneity of variances, and then submitted to analysis of variance by the F-test at 5% significance. When significant, the means of the variables shading levels and shading orientation were compared by Tukey's test ($P < 0.05$). Comparison was made between treatment means using Dunnett's test ($P < 0.05$). Results of post-harvest analyses were presented proportionally to the control, which was a standard of 100%. The statistical software R (R Core Team 2018) was used.

## Results

### Chlorophyll indexes

There was variation in the results for the SPAD index (Fig. 2) and NDVI (Fig. 3) of white oat plants assessed over time, regarding shading levels and orientations (Table S1). This finding is in line with the weekly assessment performed after the condition was imposed, for both years (Table S1; Table S4). The SPAD index in plants under full sun (control) was higher in the first weeks of assessment performed after the beginning of shading, while in the final weeks of crop development, there was an inverse effect, with higher SPAD in plants under high shading intensity. In 2021, the initial difference was limited to high shading intensity, particularly in the north/south orientation (N/S) and at the end of assessments in the east/west (E/W) one (Fig. 2). It is noteworthy that at 70 days after the beginning of shading, the plants were already in stages close to maturity, but in 2021 there was delayed plant maturity.

In general, white oat plants grown under low shading intensity presented higher means for SPAD index, in comparison to high intensity, with an increment ranging from 6.6 to 18.0%, depending on the evaluation period. There was a difference between the orientations at 14, 56, 63 and 70 days; the E/W direction had the highest means for SPAD, in comparison to the N/S orientation, whose means ranged from 41.2 to 52.2 and from 38.7 to 49.7, respectively (Table S2).

For NDVI, there was a difference between plants grown under different shading intensities and control (full sun), especially in 2020. There was a higher contrast between treatments and control at 70 days (2020): most of the shaded plants presented a similar behavior was identified by the SPAD index (Fig. 2) but higher NDVI than when under full sun (Fig. 3).

The chlorophyll index, indirectly assessed through NDVI, had an effect in 2020 at 28, 42 and 63 days, with significant interaction between the factors shading levels and orientations. At 28 days, under east/west orientation and high level of shading, NDVI differed from the other days (means 6.8) with a lower value of 6.5. This also occurred under low intensity in the N/S shading orientation at 42 days, with a value of 6.7 and 6.4% less than the means of the other days. On the other hand, at 63 days the NDVI of white oat plants was reduced between orientations at the high level of shading, with a reduction (5.6%) for N/S, and between the levels: it was lower under low shading intensity (6.9), in contrast with the high level (7.2) (Table S3).

### Growth

Height of the plants grown under different shading levels and orientations differed from that of the control treatment at the beginning and end of the cycle. Initially, the shaded plants had greater height, but at final stages of the cycle, height was lower as compared to control (plants under full sun). This trend was confirmed in both the growing seasons (Fig. 4). The height of white oat plants, evaluated throughout the cycle, had a significant interaction between shading intensities and orientations in 2020 and isolated factors in 2021. In the first growing season, there was significance for plant height among treatments at 42 days after the start of shading. Plant height was lower under high shading intensity in the E/W orientation,

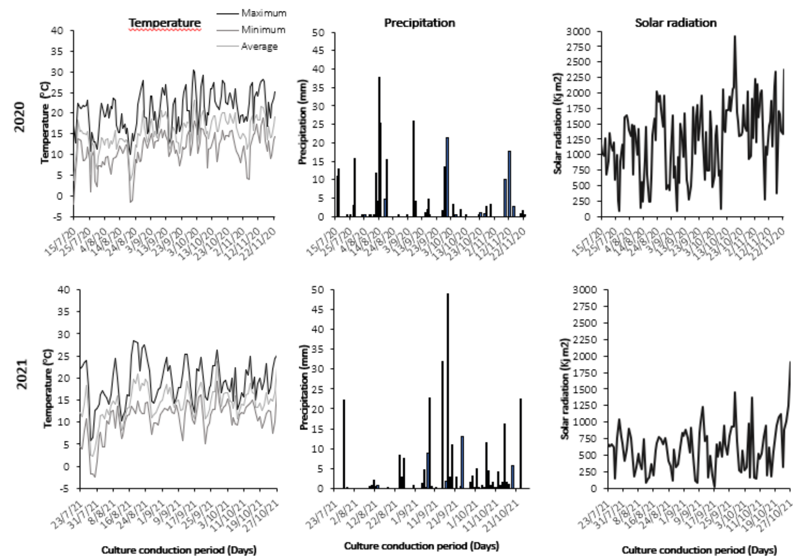


**Fig. 1:** Temperature maximum (T° MAX), minimum (T° MIN) and average (T° MEAN), rainfall and global solar radiation global during experiments with artificial continuous shadding on white oat. Lages-SC, 2020/20 e 2021/21 growing seasons
Source: Adapted from INMET (2019)

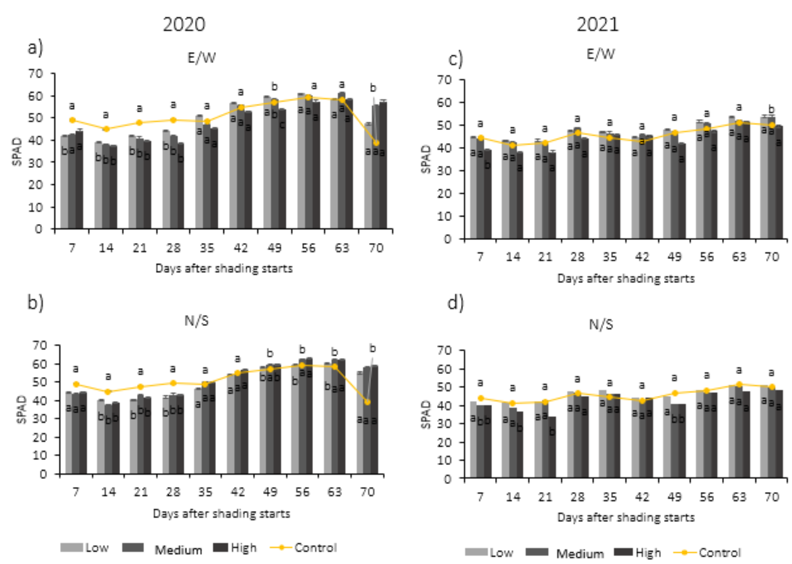


**Fig. 2:** Evolution of the SPAD index of white oats grown under different shading levels and orientations during the cycle, in the 2020 and 2021 growing seasons
*Bars represent standard error of mean for each treatment; *Same letters do not differ between treatments and control by Dunnett's test ($p \leq 0.05$)

with reductions ranging from 11.3 to 19.1%. In 2021, there was a detrimental effect of shading in most assessments, when the plants were under high shading intensity, with a reduction of up to 21.7% at the time. Regarding the orientations, the lowest plant height averages were found for N/S (<6.7%), compared to east/west (Table S4).

There was an effect for leaf area (LA) and dry weight (DW) of white oat plants, at 30 and 60 days after the onset of light restriction, except for LA at 60 days; there was a difference between the E/W and N/S orientations. The reduction of LA and DW under high solar radiation ranged from 3.9 to 45.6 and 46.6 to 92.9%, respectively, under low light intensity, between the years and the evaluation period (Table 1). For LA of plants at 30 days (2020), there was a negative effect of shading at medium and high intensity, with averages between 93.3 and 108.4 $cm^2.plant^{-1}$, compared to plants under full sun (138.0 $cm^2.plant^{-1}$). Similar results were found in 2021, when LA of shaded plants ranged between 87.6 and 130.8 $cm^2$ $plant^{-1}$, compared to the control treatment in the same year (165.3 $cm^2$ $plant^{-1}$). However, there was higher LA at 60 days (2021), with 296.7 and 289.9 $cm^2$ $plant^{-1}$ for E/W and N/S orientations, respectively (Table 1).

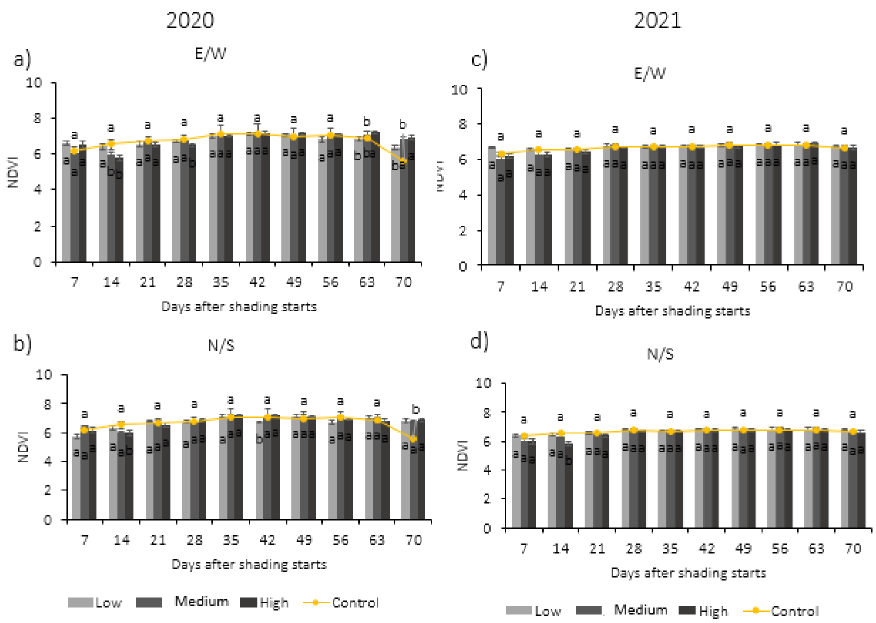


**Fig. 3:** Evolution of the NDVI of white oats grown under different shading levels and orientations during the cycle, in the 2020 and 2021 harvests
*Bars represent standard error of mean for each treatment; *Same letters do not differ between treatments and control by Dunnett's test (p≤0.05)

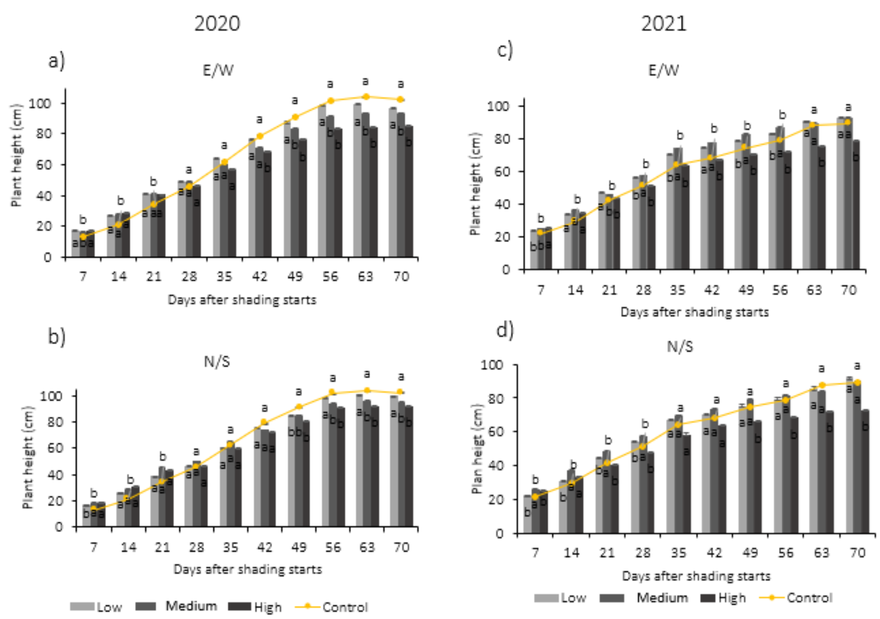


**Fig. 4:** Height of white oat plants grown under different shading levels and orientations during the cycle, in the 2020 and 2021 harvests
*Bars represent standard error of mean for each treatment; *Same letters do not differ between treatments and control by Dunnett's test (p≤0.05)

Plant DW differed from the control as it showed lower results, mainly at medium and high levels of shading, indicating negative effects of shading at 30 and 60 days and at pre-harvest. In 2020, DW of white oat plants under medium and high shading intensities presented the lowest averages at 30 and 60 days after the start of shading. Compared to the control group (0.8 g plant$^{-1}$), there were reductions by up to 46.3 and 43.7% for the shaded plants at medium and high intensity levels, respectively (Table 1). In 2021, at both assessments and at the end of the cycle, the lowest averages for plant DW were found under high shading level (75%), with reductions by up to 55.8% (30 days), 28.7% (60 days) and 36.1% at end of cycle (Table 1). For final DW (2021), there was an effect for the shading orientations: DW was increased by 9.1% under the E/W orientation, in comparison to shading under the N/S orientation (213.7 g) (Table 1).

**Table 1:** Leaf area and dry weight of white oat plants grown under different shading levels and orientations during the cycle, in the 2020 and 2021 harvests

| Orientation | Shading levels | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2020 | | | | | | | | 2021 | | | | | | | |
| | Low | | Medium | | High | | Average | | Low | | Medium | | High | | Average | |
| | | | | | | | | Leaf area 30 days (cm$^2$ plant$^{-1}$) | | | | | | | | |
| East/West | 126.98 | ns | 113.90 | | 98.72 | * | 113.20 | ns | 155.61 | ns | 130.79 | * | 103.44 | * | 129.95 | a |
| North/South | 119.31 | | 108.43 | * | 93.30 | * | 107.01 | | 122.59 | * | 132.61 | | 87.59 | * | 114.26 | b |
| Average | 123.15 | A | 111.17 | AB | 96.01 | B | | | 139.10 | A | 131.70 | A | 95.52 | B | | |
| Control | | | | | 137.96 | | | | | | | | 165.25 | | | |
| | Leaf area 60 Days (cm$^2$ plant$^{-1}$) | | | | | | | | | | | | | | | |
| East/West | 176.02 | ns | 176.22 | | 168.91 | | 173.72 | a | 228.67 | ns | 296.69 | * | 211.25 | | 245.54 | ns |
| North/South | 147.64 | | 169.75 | | 158.76 | | 158.71 | b | 211.04 | | 289.90 | * | 211.99 | | 237.64 | |
| Average | 161.83 | ns | 172.98 | | 163.83 | | | | 219.85 | B | 293.30 | A | 211.62 | B | | |
| Control | | | | | 151.51 | | | | | | | | 174.41 | | | |
| | | | | | | | | Dry weight 30 days (g.plant$^{-1}$) | | | | | | | | |
| East/West | 0.66 | ns | 0.55 | * | 0.40 | * | 0.53 | ns | 0.75 | ns | 0.53 | * | 0.43 | * | 0.57 | ns |
| North/South | 0.63 | * | 0.50 | * | 0.47 | * | 0.53 | | 0.55 | | 0.58 | | 0.31 | * | 0.48 | |
| Average | 0.64 | A | 0.52 | B | 0.43 | B | | | 0.65 | A | 0.55 | A | 0.34 | B | | |
| Control | | | | | 0.80 | | | | | | | | 0.77 | | | |
| | | | | | | | | Dry weight 60 days (g.plant$^{-1}$) | | | | | | | | |
| East/West | 3.17 | ns | 2.70 | * | 2.01 | * | 2.63 | ns | 2.72 | ns | 2.77 | | 1.81 | | 2.43 | ns |
| North/South | 3.05 | | 2.43 | * | 2.18 | * | 2.55 | | 2.35 | | 2.54 | | 1.67 | | 2.19 | |
| Average | 3.11 | A | 2.57 | B | 2.10 | C | | | 2.54 | A | 2.66 | A | 1.74 | B | | |
| Control | | | | | 3.73 | | | | | | | | 2.44 | | | |
| | | | | | | | | Final dry weight (g.plant$^{-1}$) | | | | | | | | |
| East/West | 209.06 | ns* | 193.19 | * | 168.21 | * | 190.15 | ns | 276.05 | ns | 238.93 | | 184.69 | * | 233.19 | a |
| North/South | 182.28 | * | 177.82 | * | 180.99 | * | 180.36 | | 232.91 | * | 242.34 | | 165.98 | * | 213.74 | b |
| Average | 195.67 | ns | 185.50 | | 174.60 | | | | 254.48 | A | 240.59 | A | 175.33 | B | | |
| Control | 255.16 | | | | | | | | 274.27 | | | | | | | |

*Same lowercase letters in the column and uppercase in the row do not differ by Tukey's test ($p \leq 0.05$); *means differ from the control by Dunnett's test ($p \leq 0.05$). ns: non-significant statistical difference

## Yield components

The number of panicles per linear meter in 2021 under low shading intensity was higher, with 98.6% panicles per linear meter, while the remaining medium and high levels reached only 89.3 and 82.6% of the total percentage of panicles for plants under full sun. The number of panicles of plants shaded mainly under high intensity (82.6%) differed from that of the control (100%), with a reduction by 17.4%, regardless of orientation (Table 2).

For number of grains per linear meter (NG), there was significance for the interaction between the factors in 2021: shaded plants were negatively affected, except under low intensity in the E/W orientation. It was found that under low shading in the N/S orientation, the number of grains was lower, compared to E/W and the control, with 72.7% in comparison to the control with 100% (Table 2). In addition, with shading in the E/W and N/S orientations under high intensity, the NG per linear meter was affected, with percentages of 54.5 and 48.7%, while under low shading, the percentages were 101.6 and 72.7%, respectively, considering the NG under full sun as 100%. The NG per linear meter under low solar radiation level in the E/W orientation (101.6%) did not differ from that of the control (100%).

The weight of white oat grains per linear meter (WG) was negatively impacted on the shaded plants in comparison to the control for both seasons tested, especially under medium and high intensities (Table S4). In 2021, there was a difference between intensities; under low shading level, grain weight had a higher proportion than the other levels, with 78.6%, compared to the control *i.e.*, 100% (Table 2).

In both growing seasons, TGW of white oat shaded mainly under medium and high intensity levels, in both orientations, differed from that of the control, indicating a negative effect of these conditions on thousand grain weight (Table 2). TGW presented an interactive effect between shading levels and orientations for the 2020 growing season. TGW for plants under high shading intensity in both orientations, and the mean in N/S, presented a lower percentage in comparison to the other intensities and the control (100%): 69.6% in E/W (high intensity), and 81.1 (medium intensity) and 78.7% (high intensity) in S/N. In the second growing season, TGW was 84.3 and 86.9%, for E/W and N/S, respectively, in comparison to the control (100.0%).

For HI of white oat plants, there was an effect between shading levels for orientations in 2020, and for shading intensities in 2021. The HI (2020) under N/S shading (105.3%) was higher, compared to E/W (97.7%). Furthermore, in 2021, the HI was 73.4 and 76.1%, for S/N and E/W, respectively. The HI under low shading intensity (2021) differed from high intensity, with 84.1 and 67.1% of the total HI of plants grown under full sun radiations (Table 2).

For percentage of grain retention on different sieves, there was a difference for the control (full sun) when compared to the values found for the shaded plants. The

**Table 2:** Percentages of number of panicles and grains, grain weight, thousand grain weight (MMG) and harvest index (HI) of white oats grown under different shading levels and orientations during the cycle, in the 2020 and 2021 harvests

| Orientation | Shading levels | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2020 | | | | | | | | 2021 | | | | | | | |
| | Low | | Medium | | High | | Average | | Low | | Medium | | High | | Average | |
| | Number of Panicles per linear meter (% in relation to the control) | | | | | | | | | | | | | | | |
| East/West | 104.86 | ns | 101.72 | | 96,46 | | 101,01 | ns | 102,65 | ns | 91,31 | | 83,54 | * | 92,50 | ns |
| North/South | 110.38 | | 94.11 | | 87,91 | | 104,87 | | 94,44 | | 87,67 | * | 81,67 | * | 87,83 | |
| Average | 93.25 | B | 104.05 | AB | 111,53 | A | | | 98,55 | A | 89,34 | B | 82,61 | B | | |
| Control | | | | | 100.00 | | | | | | | | 100.00 | | | |
| | Number of grains per linear meter (% in relation to the control) | | | | | | | | | | | | | | | |
| East/West | 86.32 | ns | 95.61 | | 8,72 | | 90,22 | ns | 101,64 | aA | 75,52 | aB* | 54,48 | aC* | 77,21 | a |
| North/South | 83.02 | | 93.04 | | 97,48 | | 91,18 | | 72,71 | bA* | 75,90 | aA* | 48,72 | aB* | 65,78 | b |
| Average | 84.67 | ns | 94.33 | | 93,10 | | | | 87,17 | A | 75,71 | B | 51,60 | C | | |
| Control | | | | | 100.00 | | | | | | | | 100.00 | | | |
| | Mass of grains per linear meter (% in relation to the control) | | | | | | | | | | | | | | | |
| East/West | 75.93 | ns* | 83.15 | | 61,58 | * | 73,55 | ns | 90,63 | ns | 63,14 | * | 45,02 | * | 66,26 | ns |
| North/South | 75.52 | * | 75.90 | * | 75,50 | * | 75,64 | | 66,62 | * | 65,08 | * | 41,08 | * | 57,59 | |
| Average | 75.72 | ns | 79.53 | | 68,54 | | | | 78,62 | A | 64,11 | B | 43,05 | C | | |
| Control | | | | | 100.00 | | | | | | | | 100.00 | | | |
| | Thousand grain weight (% in relation to the control) | | | | | | | | | | | | | | | |
| East/West | 87.87 | aA* | 87.06 | aA* | 69,60 | aB* | 81,51 | ns | 88,87 | ns | 83,39 | * | 80,74 | * | 84,33 | ns |
| North/South | 92.52 | aA | 81.14 | aB* | 78,66 | bB* | 84,10 | | 91,34 | | 85,58 | * | 83,79 | * | 86,90 | |
| Average | 90.20 | A | 84.10 | A | 74,13 | B | | | 90,11 | ns | 84,48 | | 82,27 | | | |
| Control | | | | | 100.00 | | | | | | | | 100.00 | | | |
| | Harvest index (% in relation to the witness) | | | | | | | | | | | | | | | |
| East/West | 91.55 | ns | 109.04 | | 92,36 | | 97,65 | b | 89,73 | ns | 72,09 | * | 66,34 | * | 76,06 | ns |
| North/South | 103.97 | | 106.55 | | 105,49 | | 105,34 | a | 78,54 | | 73,59 | * | 67,90 | * | 73,35 | |
| Average | 97.76 | ns | 107.80 | | 98,93 | | | | 84,14 | A | 72,84 | AB | 67,12 | B | | |
| Control | | | | | 100.00 | | | | | | | | 100.00 | | | |

*Same lowercase letters in the column and uppercase in the row do not differ by Tukey's test (p≤0.05). ns: non-significant statistical difference

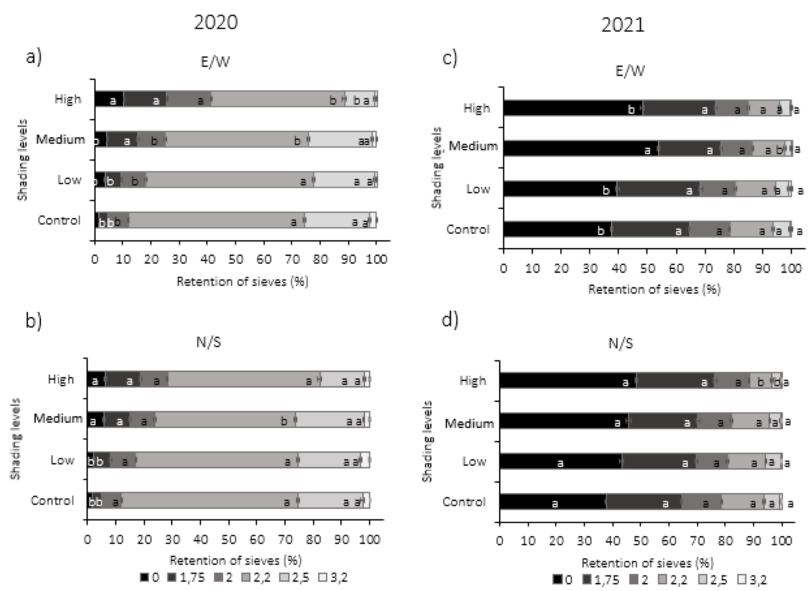


**Fig. 5:** Sieve retention of grains from white oat plants grown under different shading levels and orientations during the cycle, in the 2020 and 2021 harvests
*Bars represent standard error of mean for each treatment; *Same letters do not differ between treatments and control by Dunnett's test (p≤0.05)

percentage of grain retention on 1.75 mm sieves was higher under high and medium shading intensities, with a mean of 13.8 and 10.2% between orientations, compared to the control (1.6%). A similar effect was found for non-retained grains (empty grains), whose percentage under high level was 8.4%, which accounts for an increase by 6.8% in comparison to the control (Fig. 5). This indicated that the shaded plants produced small grains.

Grain size assessment through sieve retention (2020) showed an effect on shading intensities of the sieves of 2.5; 2.2; 1.75 and 0, and interaction for sieve diameter of 2.0 mm (Fig. 5). The grain retention on 2.5 and 2.2 sieves was higher under low intensity (21.4%) and differed from the percentage for high intensity shading (13.3%). In addition, the percentage of grain retention on 1.75 and 0 sieves (non-retained) of shaded plants at medium and high levels was higher than that of the control, with increases of up to 38.0%, indicating that grains produced by shaded plants had lower accumulation of reserves (Fig. 5). This confirmed the results obtained in the first harvest. In 2021, grain retention percentage differed between the levels only on sieves of 2.5 and 2.2 mm. Highest retention means were found for the sieve of 2.5 mm under low intensity (5.2%) and the sieve of 2.2 mm under low (13.5%) and medium (12.3%) intensities (Table S5), confirming that plants under shading produce grains with lower accumulation of reserves (Fig. 5).

## Discussion

The environments in integrated or forest grazing systems present dynamic local environmental conditions, changing the structure of plants, compared to full-sun cultivation. This indicates that the morphological adaptation capacity of the species in shaded environments should be included in the crop management analyses chosen in such a system (Garcez Neto *et al.* 2010). It was found that high shading intensity affected the development and yield of grains, but under low intensity, there were no significant deleterious effects, indicating the possible adaptation of the plants to such condition. This indicated that high shading intensities (75%), together with N/S orientation, in general, caused damage to chlorophyll indexes, plant height and plant dry weight, grain yield and yield components. The white oat plants grown under full sun (control) showed better performance in comparison to the shaded plants, especially when compared to intense shading. For the orientations, the results indicated that shading provided by E/W simulation bands did not impair crop development, compared to N/S, which was disadvantageous to plant development.

Weather conditions that vary throughout the years, such as precipitation and temperature, also interfere with plant responses (Matysiak 2006). The sowing time of white oat crops characterizes the temperature range, length of day and cumulative thermal sum, which influence the speed of development and growth, and the earliest cultivars are the most sensitive to such environmental variations (Sponchiado 2017). It was found that in 2021, there was lower availability of sunlight and lower average temperature. This fact may have caused slower plant development and higher yield losses, compared to 2020 and intensified the condition of reduced sunlight on plants.

Chlorophyll content is related to the photosynthetic efficiency of plants, since they are pigments that act in the photochemical phase of photosynthesis and are specialized in light capture (Taiz *et al*. 2017). The assessments of the SPAD and NDVI showed negative effects of high shading intensity on the chlorophyll content of the plants immediately after the onset of light limitation, indicating possible stress by changing the condition, but with subsequent recovery (Fig. 2–3). Corroborating the present results, Yang *et al.* (2020) found that sensitive wheat cultivars under higher shading and duration intensities presented a reduction in chlorophyll content and damage to the leaf photosynthetic apparatus. Wang *et al.* (2020) found that under a 30 and 50% reduction in sunlight after heading, corn plants showed a yield reduction of up to 70%, in biomass accumulation, leaf chlorophyll, soluble protein content and the activity of enzymes related to nitrogen metabolism, such as nitrate reductase, glutamine synthetase and glutamate synthase. However, these studies have reported an increase in the translocation of assimilates stored in the vegetative organs in the previous period.

At the end of the crop cycle, the highest chlorophyll index in shaded plants may account for delayed leaf senescence and increased plant cycle. It is known that to advance the senescence process, there is a need to reduce the leaf chlorophyll content, because there is a higher rate of degradation of these pigments (Jespersen *et al*. 2016). These findings corroborate those of Yasin *et al.* (2019), who reported that some weed species needed a longer period to start flowering when submitted to reduced daily solar radiation. Moreover, Inurreta-Aguirre *et al*. (2018) found that wheat plants produced in agroforestry systems with a mean reduction of 50% of solar radiation reached maturity later in comparison to full-sun cultivation, ranging from days to week, depending on crop growing seasons. Zhang *et al.* (2019) found that the shading of early flowering mutant plants and premature senescence of rice cultivar caused delayed leaf senescence and increased yield because there was less accumulation of reactive oxygen species in these plants. These results refer to the differences in thermal time, observed in the agroforestry system, air warming during the night and air cooling during the day.

A low solar radiation intensity on plants interferes with their photosynthetic rate (Mu *et al.* 2010; Li *et al.* 2014; Wang *et al.* 2015; Poorter *et al.* 2019; Jumrani and Bhatia 2020) and causes reductions in growth (Yasin *et al.* 2019), dry weight, and grain yield (Jumrani and Bhatia 2020). The results for height and dry weight of white oats were impaired under shaded conditions (especially under high level of intensity). The initial height of the shaded plants indicated the effect of stem etiolation. Later, as the cycle progressed, the shaded plants showed lower height and dry matter accumulation, in comparison to plants grown under full sun, a fact that may be related to limited growth resulting from the use of reserves for grain formation.

A greater height of plants under high shading intensity at the beginning of development may have been due to responses to the shadow avoidance syndrome, in which there is relocation of the photosynthates to promote greater internode elongation, together with a reduction in diameter (Stamm and Kumar 2010; Zhang *et al.* 2020). These results corroborate those reported by Li *et al.* (2010) when testing shading levels of 0, 8, 15 and 23% on a wheat crop from booting growth to maturity, in which the stems were elongated and had lower dry weight per internode unit of the plants.

The effects for dry weight accumulation in plants may be directly related to a reduction in the source-sink ratio (Asseng *et al.* 2017). The beneficial effect of the low shading level may be related to the favorable effect of this condition to plants for the photosynthetic rate and possibly for a decrease in saturation (Kanniah *et al*. 2012). The oat is C3 photosynthetic metabolism plant (Castro *et al*. 2012), showing saturation of $CO_2$ assimilation under conditions with 30 to 40% of the total radiation, corresponding to 600–900 µmol $m^{-2}$ $s^{-1}$ (Ilic and Fallik 2017). Similar results were found in weeds under low light intensity conditions (6 to 20% solar radiation) or under low photosynthetic photon flow density (PPFD), which gives lower biomass production under such conditions (Yasin *et al.* 2019).

Reduction in the number of panicles in plants may be closely linked to the interference of absence of light over the leaf production rate in the main stem and leaves in tillers. This fact was reported by Tilley *et al.* (2019) for wheat plants, which showed a lower number of leaves under continuous shading. This is due to the production of new tillers when plant reserves are higher than necessary for their growth (Charles-Edwards 1984). Thus, the accumulation of photosynthates may have been impaired by the intense restriction of solar radiation, and limited development of new tillers in plants, as reported in oat (Dietz *et al.* 2023) and *Urochloa decumbens* and *U. brizantha* species (Martuscello *et al.* 2009).

Continuous solar radiation restriction on the plants during development affects spikelet pollination (Kobata *et al*. 2013; Deng *et al.* 2021) and consequently, grain formation. Also, there was an increase in the number of empty spikelets and lower spikelet filling (Wang *et al.* 2015). These facts can justify the results for reduced number of grains per linear meter (NG) of shaded white oat plants (Table 2). Nicodemo *et al.* (2016), when growing black oat in integrated crop-forestry systems, found an increase in plant dry matter, thousand grain weight, number of grains per panicle and panicles per square meter, when spaced further apart from rows of native trees, where the photosynthetically active radiation available to oats was higher, indicating harmful effects of high levels of shading when the plants were closer to the trees.

The weight of white oat grains (quantified per linear meter of cultivation – WG) under continuous shading was sensitive to the condition, as well as TGW in both agricultural years, whose values were decreased at the highest shading levels. Considering the importance of the source in the source-sink ratio during plant development and grain formation, the results can be related to the harmful effect of limiting the amount of source tissues by imposing the solar radiation restriction (Asseng *et al.* 2017). These results may be due to reduced photosynthetic rate and damage to the photosynthetic apparatus, together with decreased chlorophyll content and stomatal conductance (Yang *et al.* 2020). Thus, it may have affected the tillering phase, the differentiation of the floral primordium, anthesis and grain filling. These stages are characterized by determination of the number of panicles per plant, spikelets, and number of grains, and grain weight, respectively (Danielowski *et al.* 2021). Yang *et al.* (2019) when growing wheat in agroforestry systems reported that when close to the trees, the plants reduced their chlorophyll content, leaf area index, photosynthetic rate and stomatal conductance, plant biomass, number of grains and thousand grain weight, when compared to full-sun cultivation.

A reduction in the harvest index (HI) of the shaded plants indicates that this condition affected the destination of photosynthates to the grains, as well as the partition of the vegetative parts to the grains, owing to lower rates for growth and accumulation of photosynthates in the plants (Labra *et al*. 2017). Inurreta-Aguirre *et al.* (2018) found reduction in the yield of wheat plants when assessing the effect of full-sun and agroforestry cultivation systems on genotypes, with means of 203.0 and 62.0 g.$m^{-2}$ respectively, in 2016. This can be seen by the reduction of tillering, spikelets, and number of grains. In addition, they found variation in the HI values in both systems and years. Under the agroforestry system, the mean harvest index was 0.29 and 0.21, while plants under full sun presented values of 0.23 and 0.28, for 2015 and 2016, respectively.

Shading, especially at high intensity, has been shown to be harmful to the development and production of grains by white oat plants. The condition of continuous limited solar radiation, that is, during all plant development, may have directly resulted in the reduction of the source-sink ratio (Asseng *et al.* 2017). According to Sandaña and Pinochet (2011), the reduction in biomass accumulation in plants, arising from lower interception of photosynthetically active radiation, has a negative impact on grain yield. This situation was found to occur in the present work. Therefore, the effects of shading on white oat plants, on grain yield and yield components indicated that white oat has mean sensitivity (dependent on the intensity of light restriction) to the shading condition during the cycle – a fact that has been confirmed in two crop growing years.

## Conclusion

The chlorophyll index in the leaves (evaluated by optical sensors) confirms that intense shading results in damage to photosynthesis with negative consequences to the yield of white oat grains of the cultivar URS Altiva. A low level of (continuous) shading during the cycle of white oat plants does not cause significant damage to their development and production (leaf area (LA), dry weight (DW), NG, WG, TGW and HI). Nonetheless, continuous shading of the plants in the N/S orientation was more harmful to the production process of white oats than shading in the E/W orientation.

## Acknowledgement

The authors would like to thank CNPq, CAPES, FAPESC/UDESC/PAP, UDESC/PROBIC and UNIEDU/FUMDES for their financial support to the present research and the scholarships granted to the authors.

## Author Contributions

All authors actively contributed to this paper's formulation, discussion of findings, and composition, collectively assuming responsibility for its content.

## Conflict of Interest

All authors declare no conflict of interest.

## Data Availability

Data presented in this study will be available on a fair request to the corresponding author.

## Ethics Approval

Not applicable to this paper.

## References

Asseng S, BT Kassie, MH Labra, C Amador, DF Calerini (2017). Simulating the impact of source-sink manipulations in wheat. *Field Crops Res* 202:47–56

Balbinot Junior AA, A de Morais, M da Veiga, A Pelissari, J Dieckow (2009). Integração lavoura-pecuária: Intensificação de uso de áreas agrícolas. *Cienc Rural* 39:1925–1933

Bi Y, P Zhou, S Li, Y Wei, X Xiong, Y Shi, N Liu, Y Zhang (2019). Interspecific interactions contribute to higher forage yield and are affected by phosphorus application in a fully-mixed perennial legume and grass intercropping system. *Field Crops Res* 244:107636

Burner DM, AJ Ashworth, KF Laughlin, ME Boyer (2018). Using sketchup to simulate tree row azimuth effects on alley shading. *Agron J* 110:425–430

Carvalho IR, JAG Silva, MT Pacheco, LC Federizzi, KMA Arruda, CR Riede, M Caraffa, NC Lângaro, AOC Oliveira, JL Almeida, M Zilio, CA Souza, RP Mello, MM Celano, EHG. Maschietto, G Ribeiro, VL Barros, LC Pradebon (2023). Análise conjunta do ensaio brasileiro de cultivares de aveia branca, 2022. In: Resultados XLII Reunião da Comissão Brasileira de Pesquisa de Aveia. *Anais Capão do Leão(RS) FAEM – UFPel*. Available at: http//www.even3.com.br/anais/reuniaodaaveia2023 (Accessed 01 July 2023)

Castro GSA, CHM da Costa, JF Neto (2012). Ecofisiologia da aveia branca. *Sci Agrar Parana* 11:1–15

Charles-Edwards DA (1984). On the ordered development of plants 2. Self-thinning in plant communities. *Ann Bot* 53:709–714

CONAB Companhia Nacional de Abastecimento (2023). Acompanhamento da safra brasileira de grãos: levantamento safra 2022/23. Brasília: *CONAB* 10:107

Cordeiro LAM, L Vilela, RL Marchão, J Kluthcouski, GB Maryha Júnior (2015). Integração lavoura-pecuária e integração lavoura-pecuária-floresta: Estratégias para intensificação sustentável do uso do solo. *Cad Ciên Tecnol* 32:15–43

CQFS-RS/SC Comissão De Química E Fertilidade Do Solo – RS/SC (2016). *Manual de adubação e de calagem para os estados do Rio Grande do Sul e Santa Catarina*. Porto Alegre: SBCS – Núcleo Regional Sul/UFRGS, Brasil

Danielowski R, M Caraffa, CS Moraes, NC Lângaro, IQ Carvalho (2021). Informações técnicas para a cultura da aveia: 40° Reunião da comissão brasileira de pesquisa de aveia. *Sociedade Educacional Três de Maio*, Três de Maio (Ed.). SETREM, Brazil

Deiss L, A de Moraes, A Pelissari, VP da Silva, VRM Andreolla (2016). Oat grain yield under nitrogen uses in an eucalyptus intercropping system in Subtropical Brazil. *Rev Ciênc Agron* 47:462–470

Deng F, Y Zeng, Q Li, C He, B Li, Y Zhu, X Zhou, F Yang, X Zhong, H Chen, W Zhou, W Ren (2021). Decreased anther dehiscence contributes to a lower fertilization rate of rice subjected to shading stress. *Field Crops Res* 273:108291

EMBRAPA SOLOS Empresa Brasileira de Pesquisa Agropecuária – Solos (2013). Sistema brasileiro de classificação de solos. *Centro Nacional de Pesquisa de Solos*: Rio de Janeiro, Brasil

Garcez Neto AF, R Garcia, DJ Moot, KF Gobbi (2010). Aclimatação morfológica de forrageiras temperadas a padrões e níveis de sombreamento. *Rev Bras Zootec* 39:42–50

Goffman FD, AP Alonso, J Schwender, Y Schachar-Hill, JB Ohlogge (2005). Light enables a very high efficiency of carbon storage in development embryos of rapeseed. *Plant Physiol* 138:269–2279

Ilic ZS, E Fallick (2017). Light quality manipulation improves vegetable quality at harvest and postharvest: A review. *Environ Exp Bot* 139:9–90

INMET Instituto Nacional De Meteorologia (2019). Estações Automáticas. Available at: http://www.inmet.gov.br/portal/index.php?r=estacoes/estacoesAutomaticas (Accessed 29 December 2021)

Inurreta-Aguirre HD, P Lauri, C Dupraz, M Gosme (2018). Yield components and phenology of durum wheat in a Mediterranean alley-cropping system. *Agrofor Syst* 92:961–974

Jespersen D, J Zhang, B Huang (2016). Chlorophyll loss associated with heat-induced senescence in bentgrass. *Plant Sci* 249:1–12

Jumrani K, VS Bhatia (2020). Influence of different light intensities on specific leaf weight, stomatal density photosynthesis and seed yield in soybean. *Plant Physiol Rep* 25:277–283

Kanniah KD, J Beringer, P North, L Hutley (2012). Control of atmospheric particles on diffuse radiation and terrestrial plant productivity: A review. *Prog Phys Geogr* 36:209–237

Kobata T, H Yoshida, U Masiko, T Honda (2013). Spikelet sterility is associated with a lack of assimilate in high-spikelet-number rice. *Agron J* 105:1821–1831

Labra MH, PC Struik, JB Evers, DF Calderini (2017). Plasticity of seed weight compensates reductions in seed number of oilseed rape in response to shading at flowering. *Eur J Agron* 84:113–124

Li H, D Jiang, B Wollenwebr, T Dai, W Cao (2010). Effects of shading on morphology, physiology and grain yield of winter wheat. *Eur J Agron* 33:267–275

Li T, L Liu, C Jiang, Y Liu, L Shi (2014). Effects of mutual shading on the regulation of photosynthesis in field-grown sorghum. *J Photochem Photobiol B Biol* 137:31–38

Lucas LHF, CA Souza, VCS Borges, C Cigel, PM Almeida, FF Fernandes, RO Silva, DC Benites, VS Simões, LR Moreira, W L. Luz, CCA Nunes (2023). Ensaio brasileiro de cultivares de aveia branca em Lages, 2022. In: Resultados XLII Reunião da Comissão Brasileira de Pesquisa de Aveia. *Anais Capão do Leão(RS) FAEM – UFPel*, 2023. Available at: http//www.even3.com.br/anais/reuniaodaaveia2023 (Accessed 23 June 2023)

Ministério da Agricultura, Pecuária e Abastecimento (MAPA) (2009). Sistema de Agrotóxicos Fitossanitários-AGROFIT, Brasil. Available at: http://extranet.agricultura.gov.br/agrofit_cons/principal_agrofit_cons (Accessed 10 September 2022)

Martuscello JA, L Jank, MM Gontijo Neto, VA Laura, DNFV da Cunha (2009). Produção de gramíneas do gênero Brachiaria sob níveis de sombreamento. *Rev Bras Zootec* 38:1183–1190

Matysiak K (2006). Influence of trinexapac-ethyl on growth and development of winter wheat. *J Plant Prot Res* 46:133–143

Mu H, D Jiang, B Wollenweber, T Dai, Q Jing, W Cao (2010). Long-term low radiation decreases leaf photosynthesis, photochemical efficiency and grain yield in winter wheat. *J Agron Crop Sci* 196:38–47

Nevo R, D Charuvi, O Tsabari, Z Riech (2012). Composition, architecture and dynamics of the photosynthetic apparatus in higher plants. *Plant J* 70:157–176

Nicodemo MLF, PP Castiglioni, JRM Pezzopane, P Tholon, AA Carpanezzi (2016). Reducing competition in agroforestry by pruning native trees. *Rev Árvore* 40:509–518

Poorter H, U Niinemets, N Ntagkas, A Siebenkas, M Maenpaa, S Matsubara, T Pons (2019). A meta-analysis of plant responses to light intensity for 70 traits ranging from molecules to whole plant performance. *New Phytol* 223:1073–1105

R Core Team (2018). *R: A Language and Environment for Statistical Computin*g. R Foundation for Statistical Computing, Vienna, Austria

Sandaña P, D Pinochet (2011). Ecophysiological determinants of biomass and grain yield of wheat under P deficiency. *Field Crops Res* 120:311–319

Sgarbossa J, EF Elli, F Schwerz, C Nardini, E de Cristo, D de Oliveira, BO Caron (2020). Morphology, growth and yield of black oats cultivated in agroforestry systems in southern Brazil. *Agric Syst* 184:102911

Sponchiado JC (2017). *Estratégias de Manejo Para Altas Produtividades na Aveia Branca*. Tese (Doutorado em Produção Vegetal) – Universidade do Estado de Santa Catarina, Lages, Brazil

Stamm P, PP Kumar (2010). The phytohormone signal network regulating elongation growth during shade avoidance. *J Exp Bot* 61:2889–2903

Stirbet A, D Lazár, Y Guo, G Govindjee (2020). Photosynthesis: Basics, history and modelling. *Ann Bot* 126:511–537

Taiz L, E Zeiger, IM Moller, A Murphy (2017). *Fisiologia e Desenvolvimento Vegetal*, 6th (edn.). Artmed, Porto Alegre, Brazil

Takeda K, KJ Frey, TB Bailey (1980). Contribution of growth rate and harvest index to grain yield in F9-derived lines of oats (*Avena sativa* L.). *Can J Plant Sci* 60:379–384

Tilley MS, RW Heiniger, CR Crozier (2019). Measuring tiller development and mortality in winter wheat under field conditions. *Agrosyst Geosci Environ* 2:1–11

Varella AC, DJ Moot, KM Pollock, PL Peri, RJ Lucas (2011). Do light and alfalfa responses to cloth and slatted shade represent those measured under an agroforestry system? *Agrofor Syst* 81:157–173

Wang L, F Deng, WJ Ren (2015). Shading tolerance in rice is related to better light harvesting and use efficiency and grain filling rate during grain filling period. *Field Crops Res* 180:54–62

Wang Y, SJ Burgess, EM de Becker, SP Long (2020). Photosynthesis in the fleeting shadows: An overlooked opportunity for increasing crop productivity? *Plant J* 101:874–884

Way DA, RW Pearcy (2012). Sunflecks in trees and forests: From photosynthetic physiology to global change biology. *Tree Physiol* 32:1066–1081

Wrege MS, S Steinmetz, C Reisser Junior, IR de Almeida (2012). *Atlas climático da Região Sul do Brasil: Estados do Paraná, Santa Catarina e Rio Grande do Sul*, 2nd (edn.). EMBRAPA, Brasil

Xie X, H Cheng, C Hou, M Ren (2022). Integration of light and auxin signaling in shade plants: From mechanisms to opportunities in urban agriculture. *Intl J Mol Sci* 23:3422

Yang H, B Dong, Y Wang, Y Qiao, C Shi, L Jin, M Liu (2020). Photosynthetic base of reduced grain yield by shading stress during the early reproductive stage of two wheat cultivars. *Sci Rep* 10:14353

Yang T, ZP Duan, Y Zhu, YW Gan, BJ Wang, XD Hao, WL Xu, W Zhang, LH Li (2019). Effects of distance from a tree line on photosynthetic characteristics and yield of wheat in a jujube tree/wheat agroforestry system. *Agrofor Syst* 93:1545–1555

Yasin M, E Rosenqvist, SM Jensen, C Andreasen (2019). The importance of reduced light intensity on the growth and development of six weed species. *Weed Res* 59:130–144

Zadoks JC, TT Chang, CF Konzak (1974). A decimal code for the growth stages of cereals. *Weed Res* 14:415–421

Zhang Q, J Zhai, Y Wei, L Lu, C Peng (2019). Effects of shading on the senescence and photosynthetic physiology of the early-flowering rice mutant ftl10 at noon. *J Plant Growth Regul* 39:776–784

Zhang R, F Shan, C Wang, C Yan, S Dong, Y Xu, Z Gong, C Ma (2020). Internode elongation pattern, internode diameter and hormone changes in soybean (*Glycine max*) under different shading conditions. *Crop Past Sci* 71:679–688