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Winter Cover Crops: Relationship between Photosynthetically Active Radiation Interception and Weed Number and Productivity

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Abstract

The aim of this work was to determine the photosynthetically active radiation interception (iPAR) during the cover crop (CC) growth cycle, the number and aerial dry matter (ADM) of weeds, and productivity in the following soybean and maize rotation crop. To do this, experiments with CC were performed in 2015-2016 using *Hordeum vulgare* L., *Lolium multiflorum* L., *Avena sativa* L., *Bromus unioloides* L., *Vicia villosa* L., *Brassica campestris* L., *Raphanus sativus* L., and *Avena sativa*/*Vicia villosa*. The iPAR at the vegetative and reproductive stage of CC and the number and ADM of weeds were determined. In *Bromus unioloides* L., iPAR in tillering was lower than in the other CC grasses (45% and 65%, respectively). In *Vicia villosa* and *Avena sativa*/*Vicia villosa*, iPAR was close to 100%. In cruciferous CC, iPAR percentages during 2015 were 77% in *Raphanus sativus* and 61% in *Brassica campestris*, whereas they reached 35% in 2016. No significant differences were recorded in soybean grain productivity, but in maize, productivity was maximum in *Avena sativa*/*Vicia villlosa* and *Vicia villosa*. All CC decreased weed number and ADM regardless of iPAR, thus showing that CC use leads to no productivity losses in the following soybean and corn crops and decreased the use of herbicides.

Keywords

Weed management; crop productivity; sustainability

1. Introduction

The excessive use of herbicides has increased selection pressure on weed biotypes, generating resistance to different mechanisms of action [1], which -in turn- accelerates the expansion of resistance. From 1996 until now, twenty-nine resistant weed biotypes have been detected in Argentina, the trend being towards an exponential increase [2]. To minimize selection pressure, it is necessary to implement process agriculture based on plant protection and develop alternative cultures for long-term weed management strategies. In this respect, cover crop (CC) use is key in rationalizing weed management in extensive agricultural systems [3-5].

The use of CC is a technological weed-suppressing alternative that contributes to increasing agroecosystem biodiversity by adjusting a cropping system so that weed populations are kept at relatively low levels, and the negative impact of weeds on crop production is minimized [6-8]. CC interferes with weed growth by preventing weed seeds' emergence, growth, development, and production through competition for aerial and/or underground resources [9, 10].

Crop-weed competition for photosynthetically active radiation (PAR) is one process affecting crop and weed productivity [11, 12]. Weed plant density and canopy structure (growth habit, foliar area, insertion angle, leaf thickness, differences in height) affect solar radiation distribution in the canopy and PAR absorption by the crop [13]. Furthermore, reductions in PAR level and modifications in PAR quality affect growth, aerial dry matter (ADM), and seed production of weeds [14], thus highlighting the importance of the ability of crops to shade weeds. So, Bilalis et al. [15], in experiments with vetch, reported that decreases in the PAR available for weeds caused a decrease in the number and ADM of weeds. Similar results were reported by Brust et al. [16] in experiments with *Sinapis alba* and mixtures of seven species of CC and by Naher and Hossain [17] with *Vigna radiate*, *Vigna mungo* and *Glicine max* in maize intercropped. However, under conditions of aerial competition, weeds can modify their leaf and stem morphology [18] and can therefore reduce branching and increase leaf area, petiole and internode length [14, 19] as well as flowering at earlier stages of development [20]. Studies aiming at elucidating -on the one hand- how different CC species with different canopy structure modify the dynamics of PAR, and determining -on the other- if this affects the number and ADM of weeds are therefore mandatory. Results from such studies will help to choose those CC species that affect weed growth. The choice of cover crop species is crucial for the achieving the highest level of weed suppression [21].

Thus, the hypothesis is that as the iPAR is greater, the number and areal dry matter of weeds will be less. Because of the above, this work aimed to determine the percentage of photosynthetically active radiation interception during CC growth cycle as well as the number and ADM of weeds in each CC and to ascertain if the inclusion of CC may lead to yield losses in the following soybean and corn rotation crop.

2. Materials and Methods

2.1 Site Description and Experimental Design

The experiments were conducted in Estación Experimental Agropecuaria INTA Pergamino (Pergamino, Buenos Aires province, Argentina, 33°51′ S, 60°34′ W) during 2015 and 2016. The soil type corresponds to a typical Argiudol, Pergamino series with 22% clay, 64% silt, 12% sand and 2.91% organic matter. Autumn-winter CC was sown in a corn/soybean rotation and under no-tillage. The experimental design was set up in completely randomized blocks with three replicates. The plots were 10 m wide by 30 m long. The species used as CC were barley (*Hordeum vulgare* L.), ryegrass (*Lolium multiflorum* L.), oat (*Avena sativa* L.), bromegrass (*Bromus unioloides* L.), vetch (*Vicia villosa* L.), rapeseed (*Brassica campestris* L.) and forage radish (*Raphanus sativus* L.). Sowing rates were as follows: 70, 20, 80, 25, 70, 5, and 20 kg ha^{-1}, respectively. Also, planted the consociation of vetch/oat and was sown with densities of 40 and 20 kg ha^{-1}, respectively. At this moment, it was fertilized with 70 kg ha^{-1} of super simple calcium phosphate. A sector was left without CC and with chemical fallow to be used as a negative control. In 2015, CC was sown on April 24 and was killed on August 21, while in 2016, CC was sown on May 3 and was killed on October 18. Thus, the CC growth period was 119 and 168 days for the first (2015) and second year (2016), respectively. In 2015, after planting the CC, on April 28, 2 l ha^{-1} of glyphosate (50.6%) was applied in all treatments, and on July 23, 2 l ha^{-1} of glyphosate (50.6%) in the treatment of CF. In 2016, after planting the CC, 2.2 l ha^{-1} of glyphosate was applied in chemical fallow (CF).

2.2 Variables Evaluated and Methodology Used

The canopy structure of the different CC was characterized using the relative coverage method proposed by Lutman [22]. Thus, photographs of CC at the grass-tillering stage (Z 2.5, [23]) were analyzed. The pictures were taken with a digital camera (Sony, c7 mini) 1 m from the ground. Grids with one hundred and fifty 2 × 1 cm cells were superimposed on the photographs, where it was recorded whether there was crop, soil, or weed in the center of each cell. The percentage of coverage by each CC was estimated i) based on a scale according to which >85% is equivalent to high coverage, 50-85% is equivalent to intermediate coverage, and <50% is equivalent to low coverage, and ii) taking into account if canopy structure was either closed (less than 20% soil) or open (more than 20% soil) as proposed by Satorre and Ghersa [24]. To quantify radiation resource use by different CC, intercepted PAR was determined at the vegetative and reproductive stage with a linear quantum radiometer (1 m) (AccuPar, PAR-80, Decagon Devices Inc., Pullman, USA). For this, the PAR above and below the canopy of CC at 12:00 h pm on a completely sunny day was recorded.

Furthermore, to predict possible relationships between weeds and radiation resource use, the number of weed species and their ADM was determined. To this end, the weeds in 0.25 m^{-2} frames were collected, recorded and placed in an oven at 65°C until constant weight. They were subsequently weighed and ADM was calculated. A correlation analysis between iPAR percentage, number, species and ADM of weeds in the different treatments was performed per year.

The CC growth cycle was interrupted by applying 2.5 l ha^{-1} of glyphosate and 0.50 l ha^{-1} of 2,4-D. This was done at the Z 5.5 (half of the spike visible) and Z 7.3 (early milk stage of grain) stages of the CC [23] for the first and second year, respectively. At these stages, the plant material contained in 0.25 m^{-2} frames was cut at ground level in order to determine the ADM produced by different CC. After this, corn and soybean were sown under no-tillage in 2015 and 2016, respectively. At the time of sowing the corn, it was fertilized with 140 kg ha^{-1} of super simple calcium phosphate and 2 l ha^{-1} of glyphosate + 0.1 l ha^{-1} of topramezone + 3 l ha^{-1} of atrazine were applied in all the treatments. Then, on November 26, the corn was fertilized again with 70 kg ha^{-1} of urea. In 2016, after soybean planting, 2 l ha^{-1} of paraquat and 1 l ha^{-1} of metolachlor were applied in all treatments. At the end of the summer crop cycle (corn/soybean), samples of the reproductive structures were taken from a 2 m^{-2} surface area of each experimental unit to further estimate grain production (g m^{-2}).

2.3 Statistical Analysis

The data analyzed correspond to the CC growth period (i.e., initiation, tillering, and corn sowing during 2015 and initiation, tillering, and end of the cycle during 2016). They were analyzed using an analysis of variance (ANOVA) with general and mixed linear models in the Infostat statistical program, according to experimental design. Treatment means were compared using a DGC test (Di Rienzo, Guzmán, and Casanoves); significant differences were considered with $p < 0.05$. In addition, a correlation analysis between the ADM of CC and the ADM of weeds was performed using Pearson's correlation coefficient [25] in the Infostat statistical program.

3. Results

Rainfall and mean temperature showed no significant differences during the years of the study ($p > 0.05$).

3.1 Canopy Structure and Photosynthetically Active Radiation Interception

From the characterization of the different canopy structures, it was observed that i) CC of vetch, oat/vetch and ryegrass had high and closed covers (99, 100, and 89% of coverage, respectively), ii) CC of oat had intermediate and closed covers (74% of coverage), iii) CC of barley and bromegrass had intermediate and open covers (66 and 69% of coverage, respectively), and iv) cruciferous CC had low and open covers (47 and 44% of coverage to rapseed and forage radish, respectively) (Table 1).

Table 1 Relative coverage (%) of crops, soil and weeds in different cover crops (CC). Pergamino, Buenos Aires province, Argentina, 2015-2016.

CC	% Crop	% Soil	% Weeds
Vetch	99	1	0
Oat//Vetch	100	0	0
Ryegrass	89	11	0
Oat	74	18	8
Barley	66	26	8
Bromegrass	69	24	7
Rapeseed	47	31	22
Forage radish	44	33	23
Chemical fallow	0	95	5

iPAR was highest at the tillering stage of CC grasses. In bromegrass, iPAR at the tillering stage was lower ($p < 0.05$) than in the other CC grasses (45% and 65%, respectively). At the initiation of the bromegrass cycle, interception was very low.

In CC of oat/vetch and vetch, iPAR was close to 100% during the growth cycle (Figure 1e and 1f). In cruciferous CC (forage radish and rapeseed), iPAR was found to be lower in the second year (2016) than in the first year (2015). In the first year, interceptions were 77% and 61% for forage radish and rapeseed, respectively, whereas in the second year, iPAR reached 35% (Figure 1g and 1h).

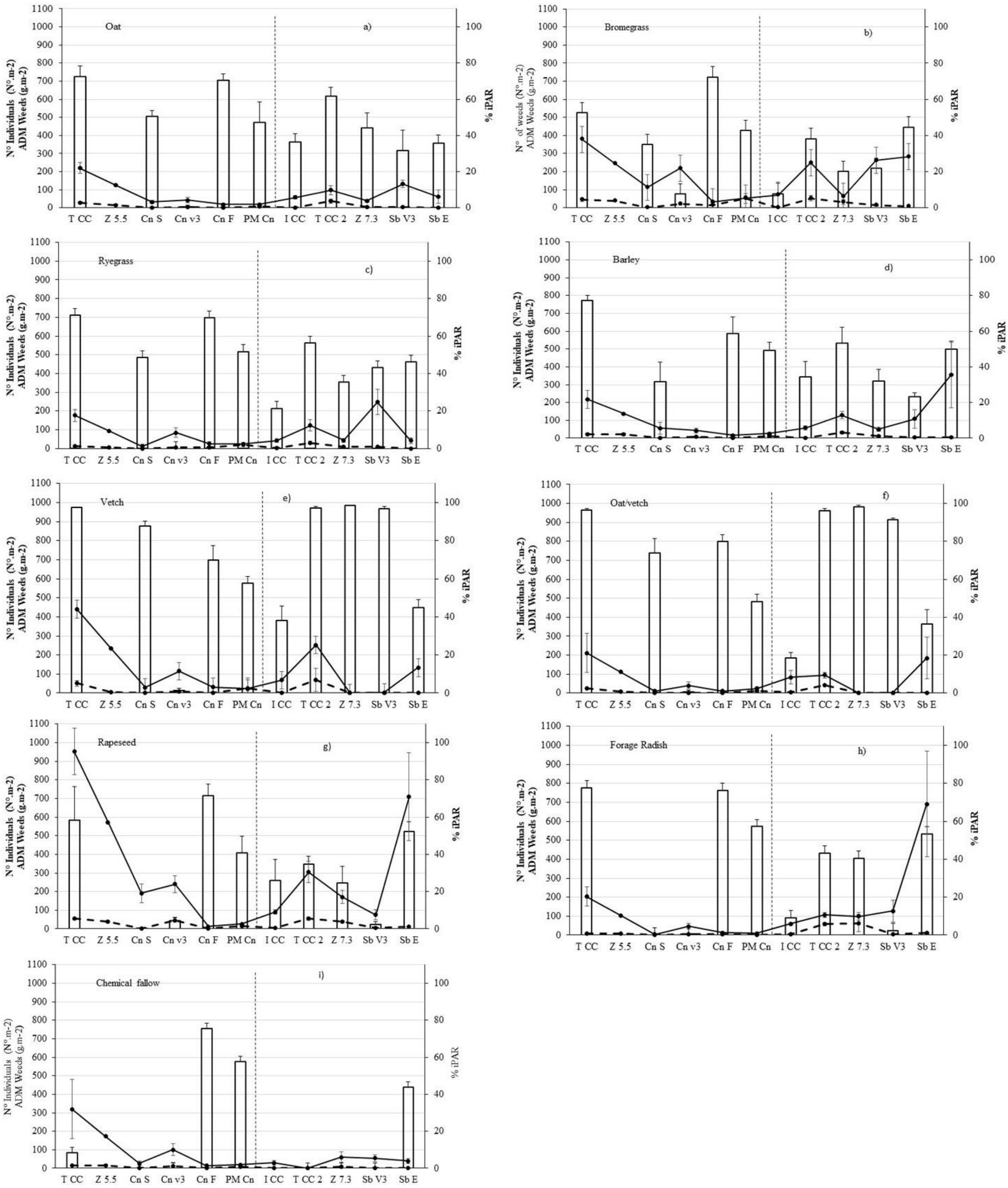

Figure 1 Photosynthetically active radiation interception (iPAR%) (in bars), aerial dry matter (ADM; g m^{-2}) (dotted line) and quantity (N° m^{-2}) of weeds (solid line) in different cover crops (CC) over time. T CC: Tillering of CC, Z 5.5: Z 5.5 of CC, Cn S: corn sowing, Cn V3: corn in stage V3, Cn F: corn in flowering, PM Cn: physiological maturity of corn, I CC: initiation of CC, T CC 2: tillering of CC in the second year, Z 7.3: Z 7.3 of CC; Sb V3: soybean in stage V3, Sb E: end of soybean cycle. The dotted line indicates the separation between years: on the right, 2016, and on the left, 2015. Pergamino, Buenos Aires province, Argentina, 2015-2017.

The iPAR recorded with chemical fallow corresponded to the radiation interception by the weeds present in each experimental unit (Figure 1i).

3.2 Number, Species and Aerial Dry Matter of Weeds

In all CC, it was observed that the number and ADM of weeds were both higher at the tillering stage but lower at the Z 5.5 and Z 7.3 of the CC. With chemical fallow, both the number and ADM of weeds were the same at all times except at the tillering stage when the number of weeds was null. In spite of the differences observed in the canopy structure and iPAR percentages during the first year of the present study, the ADM of weeds was lower when CC of ryegrass and forage radish and chemical fallow were used. The species of weeds registered in greater proportion were *Lamium amplexicaule, Stellaria media, Conyza spp., Bowlesia incana* and in CF low species were registered (Figure 1).

3.3 Relationship between Photosynthetically Active Radiation Interception and the Weeds

In the first year, a) a positive and significant relationship between iPAR and ADM of weeds was observed in ryegrass, forage radish, rapeseed, vetch, barley, and chemical fallow, and b) a positive and significant relationship was observed between iPAR and number of weeds in forage radish, rapeseed, and barley.

In the second year, two negative (i.e., when one variable increased, the other decreased) and significant relationships were found. One of these relationships was between iPAR and ADM of weeds, and the other was between iPAR and the number of weeds. The former was recorded in vetch ($p = 0.0032$), oat ($p = 0.0252$), and oat/vetch ($p < 0.0001$), whereas the latter was observed in ryegrass ($p = 0.0115$), vetch ($p = 0.0003$), and oat/vetch ($p = 0.0002$).

3.4 Aerial Dry Matter of Cover Crops and Weeds

During 2015-2016, it was observed that. In contrast, ADM was highest in the consociation of oat and vetch (436 and 690,67 g/m^2 to 2015 and 2016, respectively) and vetch (416 and 718,67 g/m^2 to 2015 and 2016, respectively), it was lowest in bromegrass (230,67 and 188 g/m^2 to 2015 and 2016, respectively), forage radish (205,33 and 242,67 g/m^2 to 2015 and 2016, respectively), and rapeseed (228 and 282,67 g/m^2 to 2015 and 2016, respectively) (Figure 2). Also, the ADM of CC was higher in 2016.

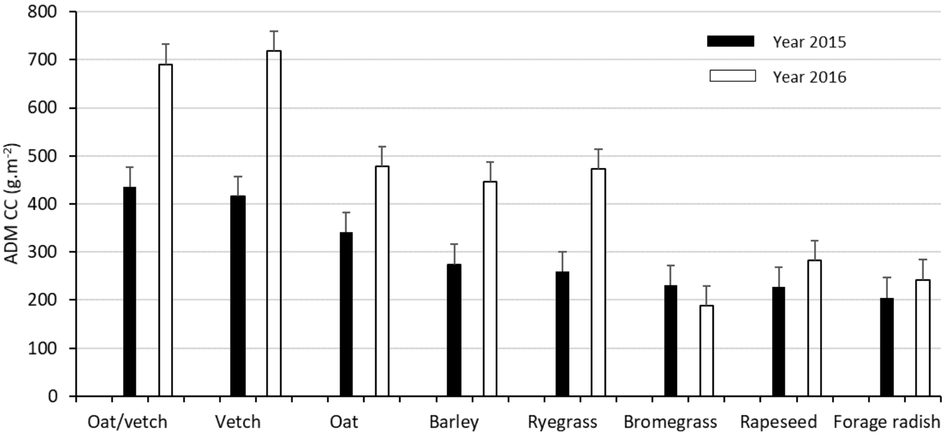

Figure 2 Aerial dry matter of cover crops (ADM CC, g m^{-2}) at Z 5.5 (2015) and Z 7.3 (2016). Filled bars indicate the year 2015, and empty bars indicate 2016. Pergamino, Buenos Aires province, Argentina, 2015-2016.

The relationship between the ADM of CC at Z 5.5 in 2015 and at Z 7.3 in 2016 and the ADM of weeds was both significant and negative ($p < 0.05$) (Table 2). In the first year, the ADM of weeds in barley, oat, forage radish, ryegrass, vetch, and oat/vetch showed no significant differences with chemical fallow. In the second year, the ADM of weeds in barley, oat, bromegrass, rapeseed, forage radish, and ryegrass showed no significant differences with chemical fallow. In contrast, the lowest ADM of weeds was recorded in the CC of vetch and oat/vetch.

Table 2 Relationships between aerial dry matter (ADM) of cover crops (variable 1) at Z 5.5 and Z 7.3 and ADM of weeds (variable 2) at Z 5.5 at Z 7.3. P value < 0.05 indicates significant differences. * Significant at 5% probability. Pergamino, Buenos Aires province, Argentina, 2015-2016.

Variable 1	Variable 2	Pearson coefficient	P Value
ADM of CC Z 5.5	ADM of weeds	-0.32	0.0285*
ADM of CC Z 7.3	ADM of weeds	-0.44	0.0018*

3.5 Grain Crop Productivity

No significant differences were recorded in soybean productivity among the different CC or with chemical fallow. Corn productivity was highest in the CC of oat/vetch and vetch (873 g m^{-2}) but lowest in ryegrass (443 g m^{-2}) (Figure 3).

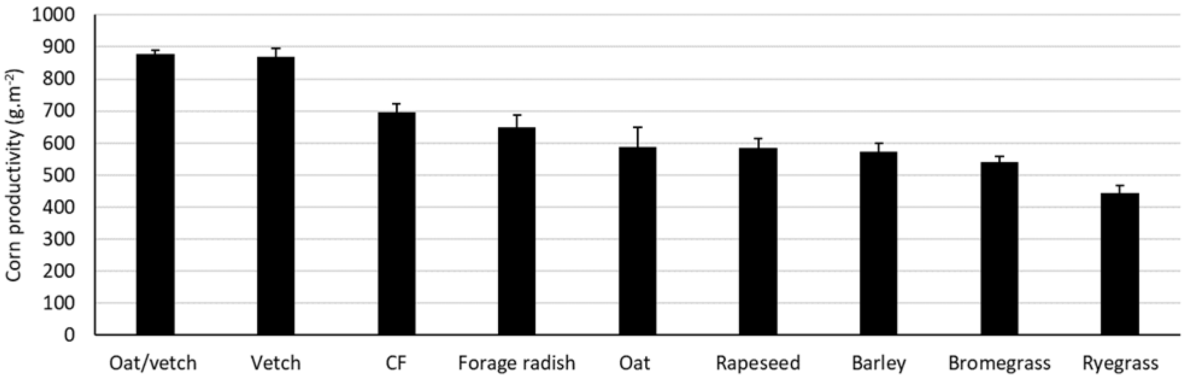

Figure 3 Grain corn productivity (g m^{-2}) of different cover crops. Pergamino, Buenos Aires province, Argentina, 2017.

4. Discussion

4.1 Canopy Structure and Photosynthetically Active Radiation Interception

In the two years of the present study, it was observed that CC of vetch and oat/vetch showed the highest iPAR. This could be due to the closed and high structure of these CC and to the prostrate growth of the vetch. Ryegrass also recorded this type of structure but did not record the highest iPAR. This could be related to the thin and fine leaves of ryegrass, as well as a lower ADM. This agrees –on the one hand– with Hassannejad and Mobli [26], who also determined high coverage in *Vicia villosa* and with Caamal-Maldonado et al. [27] –on the other,– who found that in *Mucuna pruriens* closed canopy (95% and 100% coverage of soil) the iPAR not only decreased in the soil but also inhibited weed growth. In contrast, forage radish and rapeseed presented the lowest interceptions during the second year of the present study, whereas in the first year, interceptions were intermediate. This could be due to the low and open cover of these CC. Hassannejad and Mobli [26] also determined similar coverage percentages for rapeseed CC (47.33%). As for the different CC of grass species, whereas they did show diverse canopy structures, the iPAR showed no significant differences among CC of barley, ryegrass, and oat. This could be due to the distribution of the leaf area in the canopy. Seavers and Wright [28] characterized two cultivars of *Triticum aestivum*, of which the one with an open structure allowed greater iPAR penetration and greater weed biomass than the one with a closed structure. They also observed that the cultivar with a closed structure had a larger foliar area and a higher number of stems per square meter than the cultivar with an open structure.

4.2 Number and Aerial Dry Matter of Weeds

Despite the above-listed differences found in canopy structure and iPAR percentages, it was observed that: i) the ADM of weeds was lowest in CC of ryegrass, forage radish, and chemical fallow in the first year of the study. This could be due to the allelopathic effect of the CC to weeds. Thus, previous research conducted by Ferguson et al. [29], Kunz et al. [30], Gfeller et al. [31] demonstrated allelopathic effects in forage radish and Didon et al. [32], Shekoofa et al. [33]; Vitalini et al. [34] in ryegrass. Also, this agrees with Vasilikiotis et al. [21], who observed that in the CC of rye, despite intercepting low PAR (38.3%), it did not register weeds. This was attributed to the allelopathic effects: ii) the number of weeds was highest in CC of rapeseed. This could be due to this low and open structure, and iii) the remaining CC showed no significant differences. In contrast, in the second year of the present study, no significant differences were recorded in the number and ADM of weeds among all CC. This could be due to the higher ADM of CC this year. This agrees with findings collected by Hassannejad and Mobli [26], who observed a decrease in weed cover in CC of *Vicia villosa*, *triticosecale*, and Brassica napus. Also, previous research conducted by Faget et al. [35] using *Lolium multiflorum* as CC showed decreased the number and ADM of weeds. This agrees with the results from the present study, which also show a decrease in the number and ADM of weeds in all CC during the growth cycle.

4.3 Relationship between Photosynthetically Active Radiation Interception and the Weeds

The results found in the relationships between iPAR and the number and ADM of weeds could indicate that iPAR of CC is not an appropriate indicator of the number and ADM of weeds. Other factors such as the use of underground resources and the allelopathy of CC should be considered.

4.4 Aerial Dry Matter of Cover Crops and Weeds

The differences in CC's ADM could be due to differences in iPAR. Thus, the CC that intercepts higher PAR produces more ADM [17]. Also, in 2016, the accumulation of ADM of CC was higher. This could be due to a longer growth cycle that year. In the two years of the present study, it was observed that the ADM of CC increased, whereas the ADM of weeds decreased. This agrees with Rueda et al. [4], who in a study in which *Lolium perenne*, *Pisum sativum*, and *Secale cereale* were used as CC showed that the ADM of weeds decreased significantly. Furthermore, in a study on *Secale cereale* and *Triticum aestivum* used as CC, Norsworthy et al. [36] attributed the decrease in the ADM of weeds to a low PAR at the soil surface as a result of the high amount of ADM produced by CC (817 and 769.5 g m^{-2} for *Secale cereale* and *Triticum aestivum*, respectively). Also, Yasin et al. [14] demonstrated that reductions in PAR affected both the growth and ADM of weeds. Steinmaus et al. [37] demonstrated that weed suppression was related to iPAR by CC coverage in the majority of weed species. In addition, Hassannejad and Mobbli [26] demonstrated that CC reduces the PAR that reaches weeds, especially decumbent weeds, thus being restrictive for germination and growth. According to the results obtained in the present study, in those cases in which CC were used, the iPAR via weeds was observed to be lower than that recorded with chemical fallow due to the interference generated by CC, even when the ADM of weeds did not show any differences with respect to chemical fallow.

4.5 Grain Crop Productivity

The differences in grain productivity in maize may be due to the contribution of nitrogen generated by the CC of vetch and used by this. Thus, Enrico et al. [38], quantified 159 kg ha^{-1} of nitrogen generated by vetch in the Pampean region argentine. In the two years of the present study, grain productivity was not affected by the implementation of CC. This agrees with results obtained by Barberi [6], Finney and Kaye [8], and Storkey et al. [7], all of whom conclude that the use of CC increases agroecosystem biodiversity, maintaining its productivity and suppressing weed competition. Based on the results obtained, it can be concluded that CC of oat and vetch are adequate corn crop ancestors, while in the case of soybean crop, the same grain productivity is achieved regardless of the CC species ancestor. In this way, despite the differences observed in the weeding of different CC species, their implementation does not seem to yield soybean and corn yield losses compared to chemical fallow use.

5. Conclusions

The results collected in this work show that all the CC species studied decreased the number and ADM of weeds during their growth cycle, regardless of the iPAR percentage. Using CC in productive systems helps reduce the number and ADM of autumn-winter weeds since it does not lead to productivity losses in the next soybean and corn rotation crop. Therefore, it can be concluded that the findings from this study confirm that the inclusion of CC in productive systems is feasible and, therefore, contributes to rational weed management and reducing selection pressure on resistant weed biotypes.

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Author Contributions

Buratovich, M. V.: Software, methodology, writing – original draft, formal analysis, writing – review and editing. Acciaresi, H. A.: Conceptualization, methodology, writing – review and editing.

Competing Interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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