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Yield Responses of Grain Sorghum and Cowpea in Binary and Sole Cultures under No-Tillage Conditions in Limpopo Province

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Abstract: Climate change is severely disrupting ecosystem services and crop productivity, resulting in lower crop growth and yields. Studies have emphasized the importance of assessing conservation practices through crop modelling to improve cropland productivity. There is a lack of accurate information in the performance of conservation practices as well as data for improved crop modelling. No-tillage sorghum–cowpea intercrop experiments were established to assess the productivity of four sorghum cultivars and cowpea at two densities of 37,037 and 74,074 per plants and generate data for improved crop modelling. The leaf area index (LAI) varied in sorghum cultivars and cowpea densities during the two growing seasons. Cultivars Enforcer and NS5511 produced the highest grain yields of 4338 kg per ha and 2120 kg per ha, respectively, at Syferkuil. Ofcolaco's Enforcer and Avenger were the highest yielding cultivars at Ofcolaco, with mean yields of 2625 kg per ha and 1191 kg per ha, respectively. At Syferkuil, cowpea yield was 93% and 77% more in sole compared to binary cultures during the growing seasons at Syferkuil. At Ofcolaco, sole yielded approximately 96% more grain than binary. The findings confirm that for the sorghum–cowpea intercrop to improve overall system productivity, cowpea density should be increased.

Keywords: climate-smart agriculture; grain yield; yield components; intercropping system; land equivalent ratio

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1. Introduction

Grain sorghum and cowpea are two of the most important grain crops grown in South Africa, particularly in Limpopo Province, where they are staple foods for many subsistence farmers [1]. When conditions are favourable, smallholder farmers can produce up to 20,000 tons per ha of grain sorghum [2]. Cowpeas are also grown in the province for domestic consumption, with the excess sold at the local market to generate revenue. Temperature extremes and precipitation fluctuations have long hampered grain sorghum production in Southern Africa [3,4]. Furthermore, anthropogenic activities such as conventional agriculture, overuse of chemical fertilizers, and continuous cultivation of the same crop on the same plot of land have contributed approximately 12% of the greenhouse gases emitted into the atmosphere globally [5,6]. These practices' negative impact has also contributed to severe land degradation [7,8].

Agriculture must become more productive and diverse to cope with climate change and increased natural resource constraints [9]. Producing more food with fewer resources while preserving and improving farmers' livelihoods is a global challenge. Adopting climate-smart agricultural practices such as intercropping, and conservation tillage can boost crop productivity and alleviate food insecurity in many Limpopo province areas [10]. Intercropping is defined as the simultaneous cultivation of two crops on the same plot of land [11], whereas a no-tillage system is the practice of preparing the soil with minimal soil disturbance [12]. The two systems are widely used around the world due to their efficient use of resources such as land and water, as well as their ability to improve soil fertility and crop intensification. Intercropping system combined with no-tillage system have proved to improve the crop productivity through soil moisture conservation [13].

The most common system used in South Africa is maize-legume intercropping. However, with average maize production threatened by climate change, sorghum has been projected to be one of the most viable substitute crops due to its ability to withstand the harsh conditions in South Africa. As a result, sustainable grain sorghum management and crop use as a maize substitute can secure food for the general populace while mitigating climate change scenarios [14]. Intercropping grain sorghum with cowpea improves soil fertility due to nitrogen fixation by the legume crop. Crop models can be used to assess the productivity of traditional agronomic practices such as intercropping systems in a changing climate. However, in South Africa, the availability of data required to run crop model simulations remains a challenge [15]. The main goal was to evaluate the productivity of four sorghum cultivars (Avenger, Enforcer, Titan, and NS5511) intercropped with cowpea (betch witch) under two cowpea densities and to generate data that can aid in climate-smart practices and crop model analysis.

2. Materials and Methods

2.1. Experimental Sites

A field experiment was carried out in two distinct agro-ecological regions of Limpopo province during the 2018–19 and 2020–21 cropping seasons. The first location was the University of Limpopo Experimental Farm in Syferkuil, which was located at 23°50′02.7″ S and 29°41′25.5″ E. The area receives 350 to 500 mm of rainfall per year, with average maximum and minimum temperatures of 15 °C and 30 °C, respectively. The second location was Itemeleng Ba-Makhutjwa Primary Cooperative at Farmers Field at Ofcolaco, which was located at 24°06′38.3″ S and 30°23′11.8″ E near Tzaneen. Ofcolaco receives approximately 650 to 700 mm of rainfall per year, with an average maximum and minimum temperatures of 18 °C and 35 °C, respectively. The two locations also have different soil types: sandy-clay at Syferkuil and clay-loam at Ofcolaco [16]. The experimental sites were both previously used to plant soybeans, followed by two years of fallow under no-till dryland conditions.

2.2. Weather Conditions

Two automatic weather stations near or at the experimental sites were used to provide daily weather data. At the University of Limpopo experimental farm (Syferkuil), the weather station was located at the farm whereas, at Ofcolaco, a rain gauge placed at the site and an automatic weather station situated 27.9 km from the experimental site were used to access daily weather data during the period of experimentation.

2.3. Soil Samples

Soil samples were collected before planting at the depth of 0–30 cm and 30–60 cm using a random sampling method at the two experimental sites. A total of four composite samples per sampling depth from each location, representing the experimental blocks was collected and analysed in the laboratory for chemical and physical properties (Table 1). The samples were sieved to pass through a 2 mm sieve and analysed for chemical properties. Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), manganese (Mn) and copper (Cu) were following the procedure of Mehlich-III multi-nutrient extraction method. Soil pH was determined in potassium chloride (KCl) [17], soil bulk density using a metal ring at each soil depth following the procedure of [18]. Available mineral nitrogen (N) was determined using the colorimetric method for ammonium and nitrate. The bray method was used to determine available phosphorus (P), cation exchange capacity (CEC) following the procedure of [19]. Walkley and Black method were used to determine organic carbon (org. C). Soil particle size was determined using the hydrometre method [20]. Before planting, Syferkuil soil had higher K, Ca and Mg macronutrients and low Phosphorus P compared to the soil from Ofcolaco. However, Ofcolaco soil had higher micronutrients Zn, Mn and Cu compared to Syferkuil soil. The results further indicated that soil from Ofcolaco has high organic carbon of 1.38% compared to Syferkuil which had about 0.6% organic carbon.

Table 1. Pre-planting soil chemical and physical properties from Syferkuil and Ofcolaco in the two seasons.

Soil Properties	Syferkuil		Ofcolaco	
	2018/19	**2020/21**	**2018/19**	**2020/21**
P (mg/kg)	22.00	26.89	53.75	29.3
K (mg/kg)	433.00	276.36	234.00	158.99
Ca (mg/kg)	1119.75	1059.61	917.25	742.73
Mg (mg/kg)	558.50	592.455	152.25	156.54
Exch. Acidity (cmol/kg)	0.03	0.02	0.04	0.03
Total cations (cmol/kg)	11.32	14.35	6.47	6.65
Acid sat. (%)	0.00	0.00	0.75	0.66
pH (KCL)	6.35	-	6.06	-
Zn (mg/kg)	1.48	2.77	5.48	7.75
Mn (mg/kg)	17.50	13.64	48.25	37.98
Cu (mg/kg)	4.08	2.89	5.13	4.48
org. C (%)	0.60	0.63	1.38	1.37
N (%)	0.05	0.07	0.05	0.06
Clay (%)	30.00	-	23.25	-
Fine silt (%)	7.50	-	8.25	-
Coarse silt and sand (%)	65.50	-	72.25	-
Texture class	Sandy clay loam	-	Clay loam	-

2.4. Experimental Design and Management

Prior to planting, the land at both locations was prepared by first reducing the size of weeds using a motorised slasher, followed by the application of Roundup, a non-selective, systematic, broad-spectrum glyphosate-based post-emergence herbicide one month after slashing. A 250 mL volume of Roundup was used in 10 L of water. The trial was planted 10 days after herbicide application as randomised complete block design (RCBD) in a factorial arrangement with four blocks (replications) under a no-tillage condition. The experimental treatments comprised four grain sorghum cultivars namely Avenger, Enforcer, Titan and NS5511 and two cowpea (var. Betch Witch) densities. Sorghum and cowpea were planted in both sole and binary cultures. Grain sorghum density was maintained at 37,037 plants per ha for each cultivar. Each experimental unit was 3.0 m $\times$ 3.6 m consisting of four rows of sorghum and four rows of cowpea in the intercropped treatment. The net plot size was 604.8 square metres at each experimental site. For grain sorghum, seeds were planted at inter- and intra-row spacings of 0.9 m and 0.3 m, respectively. Cowpea was planted at an inter-row spacing of 0.9 m and intra-row spacings of 0.3 and 0.15 m to obtain treatment densities of 37,037 and 74,074 plants per ha, respectively. The spacing between sorghum and cowpea in the intercropped treatment was thus 0.45 m. The trials were planted on the 17 January 2019 and 20 November 2020 at Syferkuil, whereas at Ofcolaco, the planting dates were 23 March 2019 and 21 November 2020. Each experimental unit received phosphorus in a form of superphosphate (10.5% P) at 20 kg P per ha, based on preplant soil fertility analysis. Nitrogen was applied as Limestone Ammonium Nitrate (LAN) (28% N) at a rate of 100 kg N per ha in a split application of 50 kg N per ha each at planting and knee height of grain sorghum. All fertilisers were banded along the row. Standard crop management practices including thinning, weeding, and pest control for both crops were monitored and addressed when necessary throughout the cropping season. Aphids and stalk borer infestation in cowpea and grain sorghum were controlled using Cypermethrin 200 cm. Hundred and twenty (120) mL of Cypermethrin was diluted with 64 L of water. The damage due to bird attack on sorghum grains from flowering to physiological maturity was prevented by covering sorghum heads using a protective translucent nylon mesh net at the onset of the milk stage.

2.5. Data Collection

Leaf Area Index (LAI) data was collected from two weeks after emergence per experimental unit and continued every two weeks until physiological maturity. The data were collected using AccuPAR LAI Ceptometre LP-80 (Decagon Devices, Inc., Pullman, WA, USA) on middle rows of binary and sole cultures of grain sorghum and cowpea between 10:00 a.m. and 1:00 p.m. LAI on individual fully expanded flag leaves of three plants within an experimental unit was measured at 3 min interval. In the 2020/21 cropping season, cowpea at Ofcolaco failed to produce grain. Hence, only the grain yield of the 2018/19 cropping season from Ofcolaco is presented in this paper. At harvesting, 10 plants with their heads were sampled from two middle rows within an area of 2.7 square metres to determine biomass and grain yield. All cowpea plants from a 2.7-square-metre area were harvested with pods to determine grain yield and biomass. Cowpea leaves that dropped to the ground were retrieved on a continuous basis after flowing to add to the final biomass at harvest. Biomass was oven-dried in the laboratory at 65 °C for 72 h and weighed using a weighing balance to get the weight of dry matter. Grains collected from a 2.7-square-metres area were taken to the laboratory to determine grain yield and yield components. Grain yield was determined by weight of grains per plot and converted to kg per ha. Three grain sorghum from the harvested heads were sampled from 10 heads harvested to determine head weight and head length. The 3 plants were threshed separately to determine seed weight per head as well as shelled head weight. We determined 1000 seed weight by counting and weighing 1000 grain sorghum seeds. Cowpea pod weight was obtained by weight pods collected per plot in 2.7 per square metres and 100 seed weight was determined by counting as well as weighing 100 cowpea seeds. Harvest index (HI) and land equivalent ratio (LER) for each crop were calculated using the following formulas:

$$\text{HI (\%)} = (\text{Grain yield})/(\text{stover yield}+\text{grain yield}) * 100 \quad (1)$$

$$\text{LER} = \text{YSbinary}/\text{YSsole} + \text{YCbinary}/\text{YCsole} \quad (2)$$

where YSbinary is yield of sorghum in intercropping, YSsole is yield of sorghum in sole culture, YCbinary is yield of cowpea in intercropping, and YCsole is yield of cowpea in sole culture.

2.6. Data Analysis

After checking the relevant model assumptions including normality, independence, and constant variance, we used a multivariate analysis of variance (ANOVA) model to fit each response variable using the Statistical Analysis System (21 SAS version 9.4). In grain sorghum, the four cultivars were regarded as factor 1 and the cropping system as factor 2. In the case of cowpea, the cropping system was factor 1 while density was factor 2. For LAI, days after planting (time), cultivars and cropping system were tested for interaction for grain sorghum. The LAI interaction for cowpea was tested among days after planting, cropping system, and density. The interaction of yield and yield components, as well as the harvest index of grain sorghum, was tested between cultivars and cropping system. In cowpea, the interaction was tested between cropping systems and density. Mean separation was performed where the means were different using the least significant difference (LSD) at probability levels of $p \leq 0.05$. Land equivalent ratio (LER) was used to assess the productivity and effectiveness of the intercropping system.

3. Results

3.1. Weather Conditions during Growing Seasons

Syferkuil had daily average minimum and maximum temperatures of 12 °C and 27 °C, respectively, with a total rainfall of 349 mm in 2018/19 and 292 mm in the 2020/21 growing period (Figure 1). Rains of about 156.49 mm and 10 mm were received throughout the planting period at Syferkuil in the 2018/19 and 2020/21 cropping seasons.

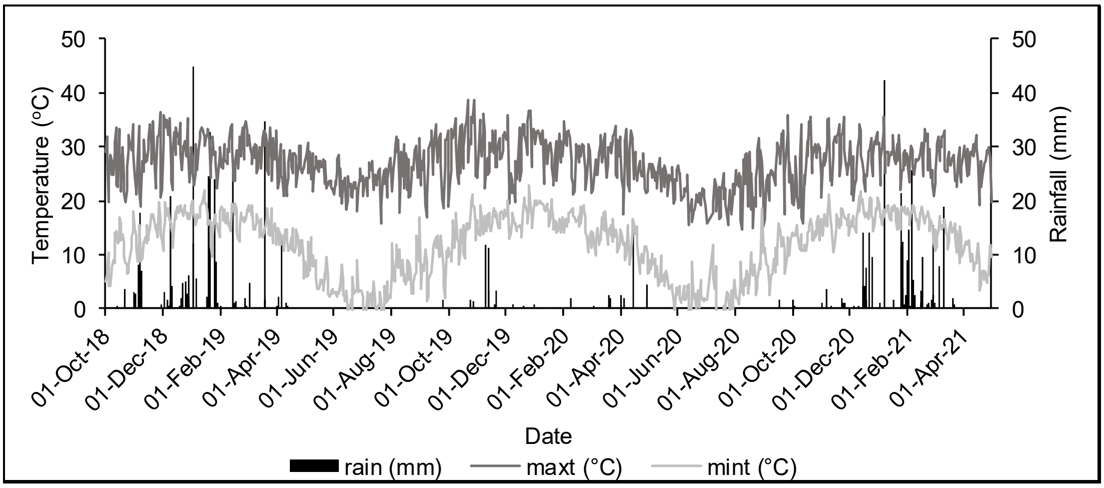

Figure 1. Syferkuil daily rainfall, maximum and minimum temperature during 2018/19 and 2020/21 cropping seasons.

At Ofcolaco, the maximum and minimum temperatures across the two seasons were 31 °C and 18 °C, respectively, with a total rainfall of 261 mm in 2018/19 and 608 mm in 2020/21. During planting months Ofcolaco received rainfall of 5 mm in 2018/19 and 38 mm in 2020/21. The highest rainfall (about 130 mm) in 2018/19 was received in December, when minimum and maximum temperatures were 22 °C and 35 °C, respectively. These were higher compared to the other months. However, in 2020/21, the highest rainfall was received in December, when temperatures were lower compared to other months (Figure 2).

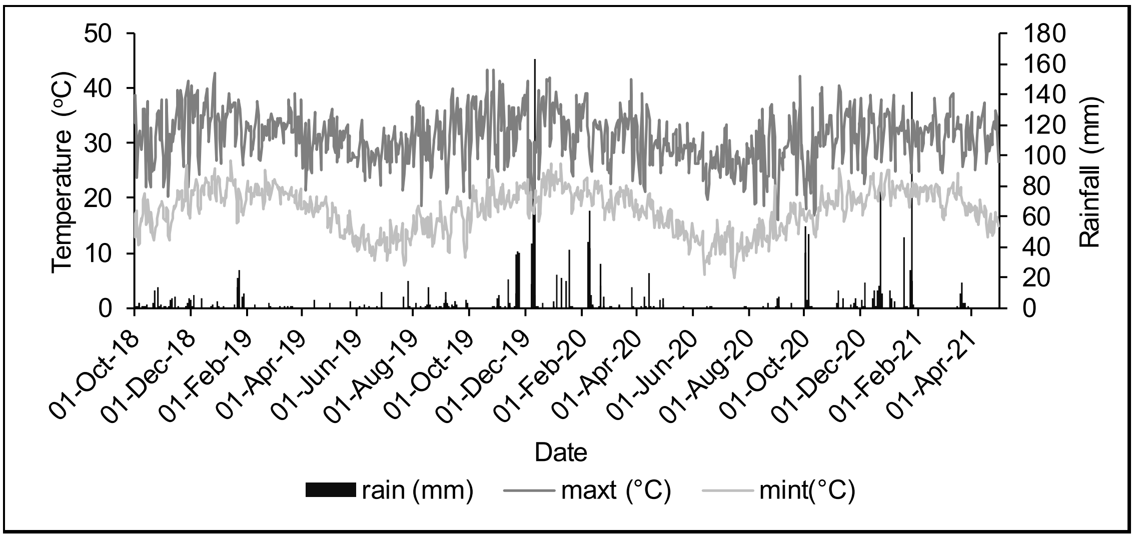

Figure 2. Ofcolaco daily rainfall, maximum and minimum temperature during 2018/19 and 2020/21 cropping seasons.

3.2. Grain Yield and Yield Components of Sorghum and Cowpea

The cropping system and density of the companion cowpea crop had no effect on grain yield of sorghum cultivars at the test sites over two seasons. Grain sorghum cultivars, on the other hand, showed a significant variation ($p \leq 0.05$) in grain yield over the two cropping seasons at Syferkuil and Ofcolaco (Figures 3 and 4). The results from Syferkuil revealed that cultivars Enforcer and NS5511 outperformed Avenger and Titan, with an average grain yield of 4153 kg per ha during the 2018/19 cropping season, while Avenger and Titan produced an average yield of 2607 kg per ha. According to the results, 85.86 kg per ha more grain yield was harvested in 2018/19 at this location than in 2020/21. The cultivar NS5511 with yield of 2120 kg per ha outperformed the cultivars Enforcer, Avenger, and Titan, which had mean yields of 1942 kg per ha, 1652 kg per ha, and 1561 kg per ha, respectively (Figure 3).

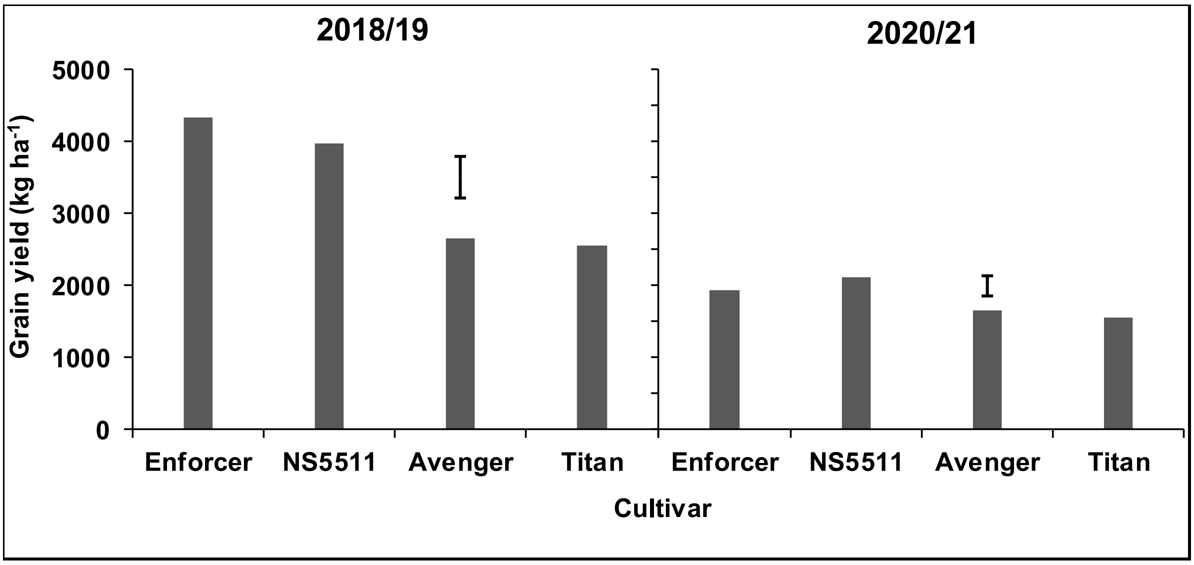

Figure 3. Grain yield of four sorghum cultivars evaluated at Syferkuil during 2018/19 and 2020/21 cropping seasons. Vertical bars represent LSD value ($p \leq 0.05$) for mean separation.

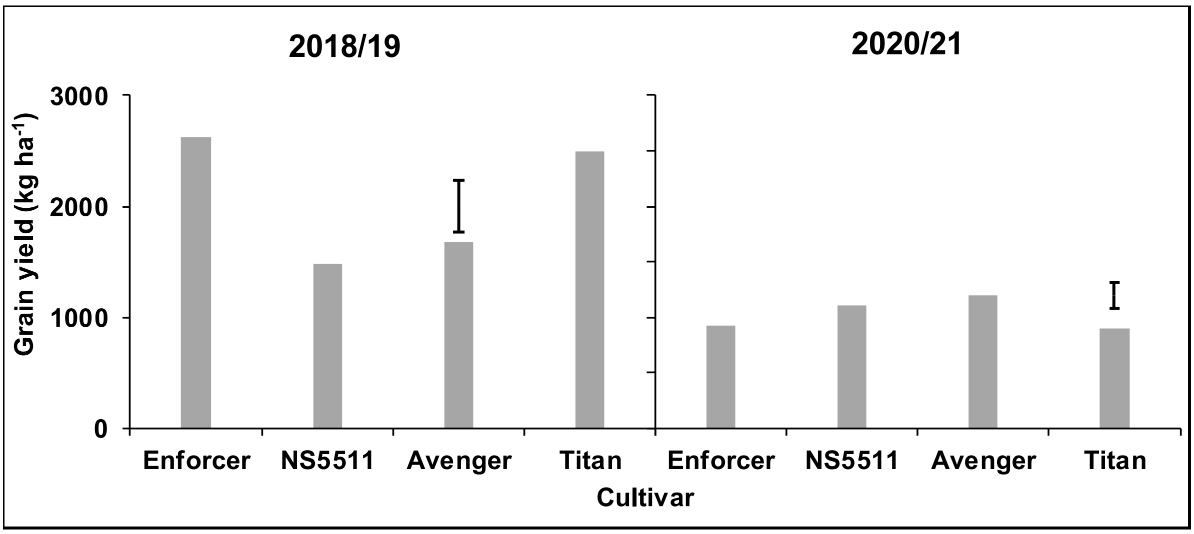

Figure 4. Grain yield (GY) of four grain sorghum cultivars evaluated at Ofcolaco during 2018/19 and 2020/21 cropping seasons. Vertical bars represent LSD value ($p \leq 0.05$) for mean separation.

The grain yield of the sorghum cultivars at Ofcolaco was inconsistent across seasons (Figure 4). Enforcer and Titan, for example, produced higher grain yields than NS5511 and

Avenger in the 2018/19 cropping seasons, averaging 2562 kg per ha and 1584 kg per ha, respectively. However, in 2020/21, NS5511, Avenger, and Enforcer outperformed Titan, which produced a yield of 910 kg per ha.

Harvest index (HI) based on grain production differed significantly ($p \leq 0.05$) between grain sorghum cultivars at the two locations and cropping seasons. Across the two cropping seasons and two locations, Enforcer consistently had the highest harvest index compared to the other cultivars (Figure 5). NS5511 had the second highest harvest index at Syferkuil compared to Avenger and Titan during the 2018/19 cropping season, but the HI were similar in the other seasons and locations.

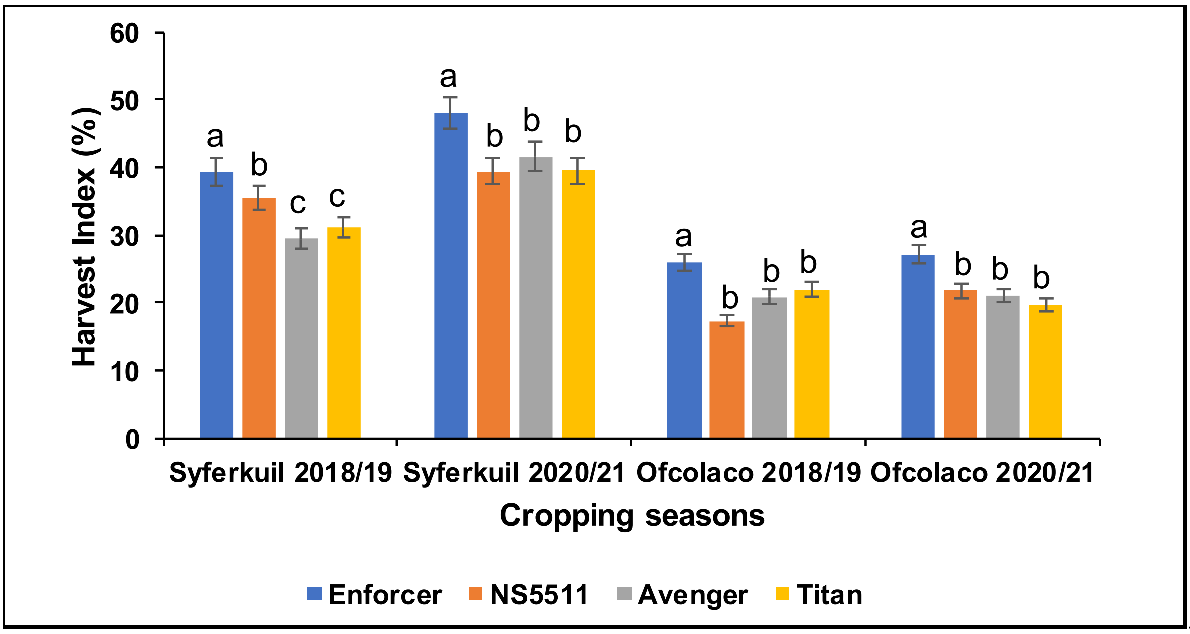

Figure 5. Harvest index of four grain sorghum cultivars in the two agro-ecological regions across different cropping seasons. Different letters indicate that the means were different at $p \leq 0.05$.

Regarding grain sorghum yield components, a significant variation ($p \leq 0.05$) was observed among the grain sorghum cultivars at Syferkuil during the two cropping seasons except for 1000 seed weight and seed weight per head, which did not differ during the 2020/21 cropping season (Table 2). The cultivar Enforcer was generally superior in most of the yield components compared to the other cultivars during the 2018/19 cropping season at this location, except for shelled head weight. The cultivar NS5511 had a relatively higher 1000-seed weight and seed weight per head compared to Avenger and Titan. The cultivar Avenger had a lower seed weight per head and harvest index compared to the cultivar Titan, regardless of having a longer head length, shelled head weight, and head weight compared to the other cultivars in the 2018/19 cropping season. In the 2020/21 cropping season, all the cultivars had a high head length and harvest index compared to cultivar NS5511 (Table 2). The results further revealed that cultivar Avenger produced fewer seeds per head compared to all other cultivars but had a relatively higher head length and shelled head weight. The mean head length and shelled head weight were 29.09 cm and 18.82 g, respectively.

At Ofcolaco, the results indicated that all yield components significantly differed among the grain sorghum cultivars during the two cropping seasons, except head length, which did not vary in 2020/21 (Table 3). The cultivar Avenger was superior in many of the yield components measured compared to all other cultivars except 1000 seed weight and harvest index during the 2018/19 cropping season. Furthermore, the seed weight per head of Avenger and NS5511 (48.15 g per head and 40.10 g per head) was higher than the grand mean of 30.47 g per head. However, the two cultivars (Avenger and NS5511) had lower HI compared to the grand mean. The results further indicated that Enforcer and Titan obtained a higher average HI of 23.94% compared to Avenger and NS5511, with an average of 19.13%. However, the two cultivars (Avenger and NS5511) obtained about 63.79% more seed weight head per head compared to Enforcer and Titan. In the 2020/21 cropping season, the results showed that although there was no statistical variation among the cultivars, the cultivar Avenger had the tendency to produce a higher head length. Although there was no statistically significant difference between cultivars Avenger and NS5511, Avenger had higher head weight and seed weight per head. The cultivar (Avenger) also had a high shelled head weight of 14.26 g per head and a higher 1000 seed weight of 6.29 g compared to all the other cultivars.

Table 2. Yield components of four grain sorghum cultivars evaluated at Syferkuil during 2018/19 and 2020/21 cropping seasons.

			Syferkuil 2018/19		
Cultivars	**Head Length (cm)**	**Head Weight (g Head^{-1})**	**Shelled Head Weight (g Head^{-1})**	**1000-Seed Weight (g)**	**Seed Weight Head (g Head^{-1})**
Enforcer	27.54 ^{a}	109.13 ^{a}	47.01 ^{ab}	28.17 ^{a}	61.21 ^{a}
NS5511	25.07 ^{b}	92.39 ^{b}	43.06 ^{ab}	23.88 ^{b}	49.03 ^{b}
Avenger	26.08 ^{ab}	77.19 ^{bc}	49.65 ^{a}	21.76 ^{c}	27.49 ^{c}
Tittan	25.34 ^{b}	71.76 ^{c}	39.93 ^{b}	27.82 ^{a}	31.80 ^{c}
$p \leq 0.05$	*	*	*	*	*
Grand mean	26	87.62	44.91	25.41	42.38
LSD value	1.79	16.09	8.93	1.51	156.3
			Syferkuil 2020/21		
Enforcer	28.59 ^{a}	108.97 ^{ab}	14.47 ^{b}	39.41	90.13
NS5511	26.54 ^{b}	112.15 ^{a}	16.55 ^{ab}	43.02	90.83
Avenger	29.09 ^{a}	98.35 ^{b}	18.82 ^{a}	38.61	82.39
Tittan	28.67 ^{a}	99.31 ^{b}	17.45 ^{a}	41.03	81.95
$p \leq 0.05$	*	*	*	ns	ns
Grand mean	28.22	104.7	16.82	40.52	86.33
LSD value	1.22	11.6	2.93	6.39	12.92

Means followed by the same letter are not significantly different based on LSD ($p \leq 0.05$). * = Significantly different at $p \leq 0.05$; ns = not significantly different at $p \leq 0.05$.

Table 3. Yield components of four grain sorghum cultivars evaluated at Ofcolaco during 2018/19 and 2020/21 cropping season.

			Ofcolaco 2018/19		
Cultivars	**Head Length (cm)**	**Head Weight (g Head^{-1})**	**Shelled Head Weight (g Head^{-1})**	**1000-Seed Weight (g)**	**Seed Weight Head (g Head^{-1})**
Enforcer	25.61 ^{ab}	28.33 ^{c}	7.43 ^{b}	35.69 ^{c}	17.71 ^{b}
NS5511	21.91 ^{b}	50.04 ^{b}	6.68 ^{b}	45.76 ^{a}	40.10 ^{a}
Avenger	30.95 ^{a}	70.03 ^{a}	12.91 ^{a}	43.59 ^{ab}	48.15 ^{a}
Tittan	29.59 ^{a}	24.69 ^{c}	8.08 ^{b}	39.98 ^{bc}	15.91 ^{b}
$p \leq 0.05$	*	*	*	*	*
Grand mean	27.02	43.27	8.78	41.26	30.47
LSD value	8.81	11.99	2.23	5.68	9.82
			Ofcolaco 2020/21		
Enforcer	30.1	28.37 ^{b}	7.40 ^{b}	4.09 ^{b}	24.29 ^{b}
NS5511	30.34	40.36 ^{a}	9.87 ^{b}	4.55 ^{b}	35.80 ^{a}
Avenger	30.98	44.53 ^{a}	14.26 ^{a}	6.29 ^{a}	38.24 ^{a}
Tittan	30.91	32.37 ^{b}	9.88 ^{b}	4.47 ^{b}	27.91 ^{b}
$p \leq 0.05$	ns	*	*	*	*
Grand mean	30.58	36.41	10.35	4.85	30.81
LSD value	2.02	7.63	1.31	30.2	6.62

Means followed by the same letter are not significantly different based on LSD ($p \leq 0.05$). * = Significantly different at $p \leq 0.05$; ns = not significantly different at $p \leq 0.05$.

During the 2018/19 cropping season, cowpea grain yield was 63 percent higher under high density versus low density at Syferkuil (Figure 6). However, grain yield was 32% higher under high density compared to low density in the 2020/21 cropping season.

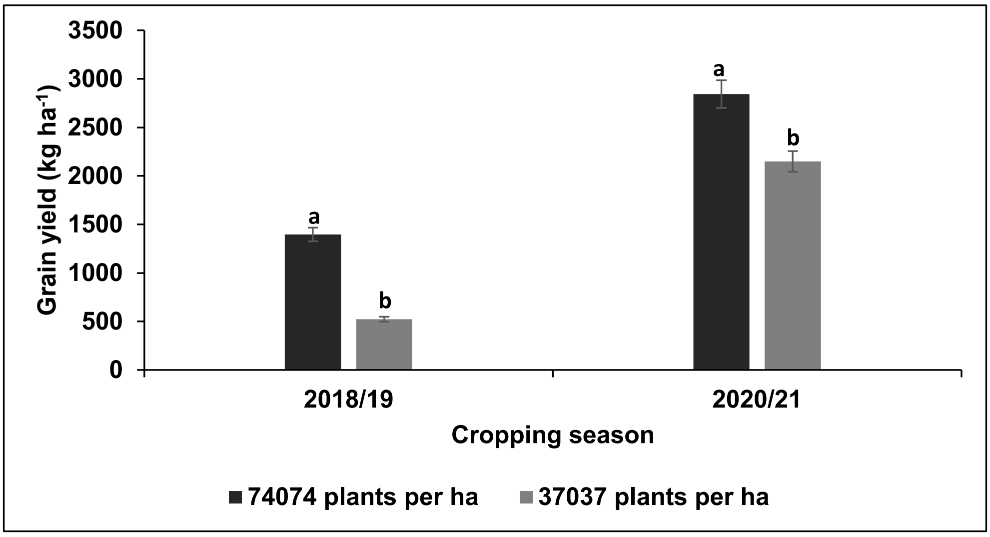

Figure 6. Grain yield of cowpea under two densities of cowpea grown at Syferkuil during contrasting seasons. Different letters indicate that the means were different at $p \leq 0.05$.

In sole compared to binary culture, cowpea produced a higher grain yield in sole with a mean of 1534 kg per ha and 992 kg per ha in high and low density, respectively, during the 2018/19 cropping season (Figure 7). Although in binary cultures there was no statistical difference between treatments, the grain yield of cowpea was higher when intercropped with Titan, followed by NS5511, with a grain yield of 852 kg per ha and 718 kg per ha, respectively. In the 2020/21 cropping season, grain yield was significantly affected by the cropping system. Similar to the 2018/19 cropping season, the results indicated that cowpea attained a higher grain yield when grown in sole compared to binary culture, with a mean of 5045 kg per ha in high density sole and 3411 kg per ha in low density sole (Figure 7).

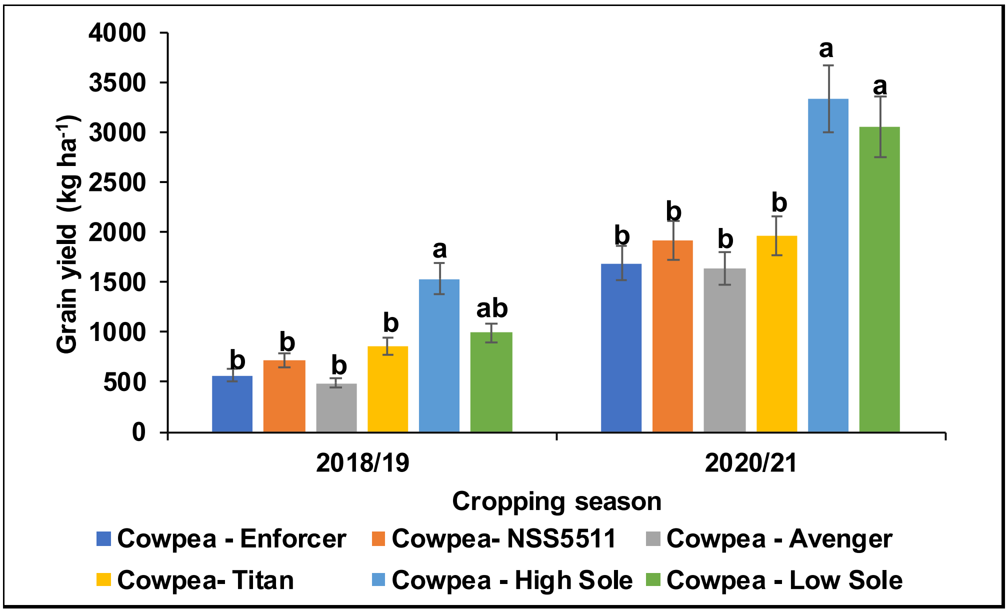

Figure 7. Grain yield of cowpea under in binary and sole cultures grown at Syferkuil during two contrasting seasons. Different letters indicate that the means were different at $p \leq 0.05$.

Grain yield among cowpea treatments was higher under high cowpea density compared to lower density, with means of 3175 kg per ha and 1233 kg per ha, respectively, at Ofcolaco during the 2018/19 cropping season (Figure 8).

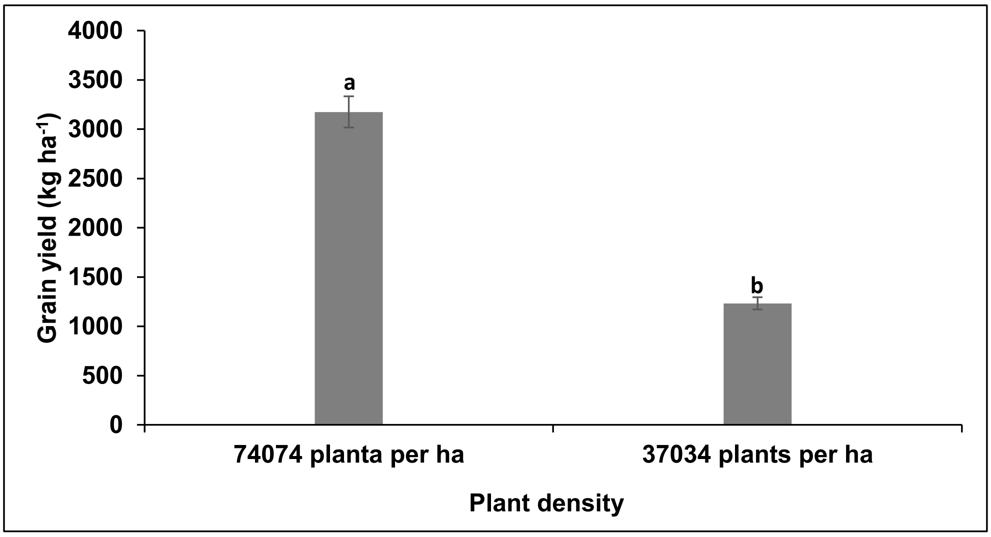

Figure 8. Grain yield of cowpea under two densities of cowpea grown at Ofcolaco during the 2018/19 cropping season. Different letters indicate that the means were different at $p \leq 0.05$.

The results from Ofcolaco revealed that, in binary cultures, cowpea attained the highest yield of 1701 kg per ha when intercropped with Avenger followed by when intercropped with Titan, which produced 1508 kg per ha (Figure 9). Although intercropping with Enforcer attained the lowest grain yield compared to all treatments in binary and sole cultures, a higher harvest index was obtained by this treatment compared to binary cultures.

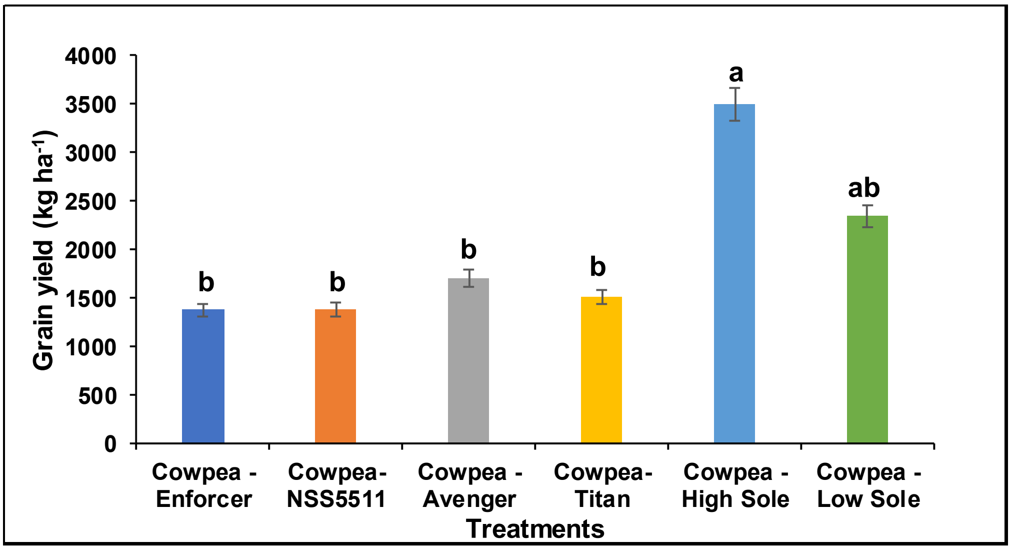

Figure 9. Grain yield of cowpea under in binary and sole cultures grown at Ofcolaco during 2018/19 cropping season. Different letters indicate that the means were different at $p \leq 0.05$.

There was no significant variation ($p \leq 0.05$) in the cowpea harvest index according to the cropping system at Syferkuil and Ofcolaco during the two cropping seasons. Sole cowpea under high density had a higher harvest index compared to the other cowpea treatments during the 2018/19 and 2020/21 cropping seasons at the two locations (Figure 10). The cowpea intercrop with Avenger had the lowest harvest index during the 2018/19 cropping season at Syferkuil. Furthermore, cowpea intercrop with Enforcer and Titan had a higher harvest index compared to sole cowpea in low density culture during the same season. At Ofcolaco and Syferkuil during the 2018/19 and 2020/21 cropping seasons, respectively, binary cultures were not statistically different (Figure 10).

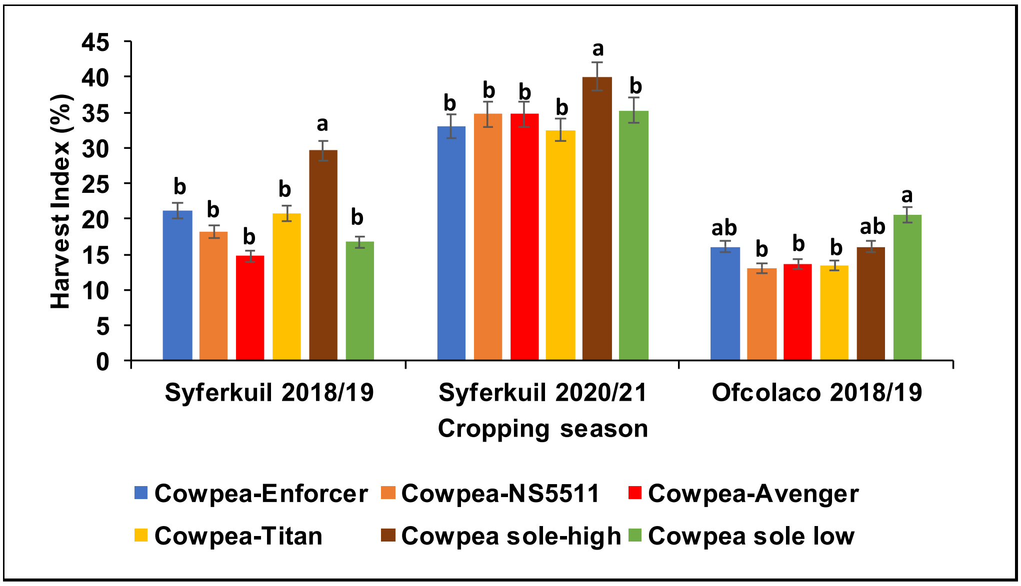

Figure 10. Harvest index of cowpea in binary and sole cultures at Syferkuil and Ofcolaco during 2018/19 and 2020/21 cropping seasons. Different letters indicate that the means were different at $p \leq 0.05$.

Assessing the yield components, the weight of 100 seeds was not significantly different between binary and sole cultures of cowpea at Syferkuil during the 2018/19 cropping season. However, significant variation ($p \leq 0.05$) was found for this yield component in the 2020/21 cropping season. Pod weight per plot was influenced by the cropping system in both seasons at this location (Table 4). The weight of 100 seeds was not significantly affected by the cropping system at Ofcolaco among cowpea treatments in binary and sole cultures during the 2018/19 cropping season. However, pod weight per plot was significantly ($p \leq 0.05$) affected by the intercropping system for cowpea treatments. The cowpea sole under high density resulted in a high pod weight per plot compared to all other treatments (Table 4).

Table 4. Yield components of cowpea in binary and sole cultures evaluated at Syferkuil and Ofcolaco during the 2018/19 and 2020/21 cropping season.

	Syferkuil 2018/19		Syferkuil 2020/21		Ofcolaco 2018/19	
Treatments	100-seed weight	pod weight per plot	100-seed weight	pod weight per plot	100-seed weight	pod weight per plot
Cowpea–Enforcer	16.17	139.73 ^{c}	15.54 ^{b}	336.56 ^{b}	14.71	364.10 ^{b}
Cowpea–NSS5511	16.24	167.23 ^{c}	14.51 ^{c}	384.06 ^{b}	14.68	355.97 ^{b}
Cowpea–Avenger	16.17	114.72 ^{c}	14.65 ^{c}	321.87 ^{b}	14.29	440.97 ^{b}
Cowpea–Titan	16.78	199.10 ^{bc}	15.53 ^{b}	383.44 ^{b}	14.88	307.22 ^{b}
Cowpea–High Sole	16.22	325.51 ^{a}	15.54 ^{b}	681.02 ^{a}	14.96	778.94 ^{a}
Cowpea–Low Sole	16.39	285.19 ^{ab}	16.61 ^{a}	398.36 ^{b}	14.74	715.51 ^{a}
$p \leq 0.05$	ns	*	*	*	ns	*
Grand mean	16.33	205.25	15.39	417.55	14.71	493.79
LSD value	0.86	79.31	0.69	99.31	1.05	170.16

Means followed by the same letter are not significantly different based on LSD ($p \leq 0.05$). * = Significantly different at $p \leq 0.05$; ns = not significantly different at $p \leq 0.05$.

3.3. Partial and Total Land Equivalent Ratio (LER) of Sorghum and Cowpea

The partial land equivalent ratio of cowpea ranged from 0.4 to 0.7 at Syferkuil during the 2018/19 and 2020/21 cropping seasons, respectively. The partial of grain sorghum at Syferkuil was between 0.7 and 1.3 in the 2018/19 and 2020/21 cropping seasons. At Ofcolaco, the partial land equivalent ratio was between 0.4 and 0.6 for cowpea and 0.8–1.4 for grain sorghum in the 2018/19 and 2020/21 cropping seasons. The total LER was above

1.0 in all grain sorghum and cowpea intercrop treatments (Table 5). At Syferkuil, Enforcer had a higher LER when intercropped with low cowpea density compared to high cowpea density, with means of 1.8 and 1.3, respectively, during the 2018/19 season. Avenger had a total LER of 1.6 and 1.7 under low and high density, respectively. However, Titan obtained 1.5 and 1.6 total LER under low and high density, respectively. The results also indicated that Avenger and NS5511 intercropped with cowpea high density had a total LER of 1.7, whereas NS5511 and Titan intercropped with low density had a total LER of 1.6 in the 2018/19 cropping season. In the 2020/21 cropping season, Titan intercropped with cowpea under low and high density had a total LER of 1.8 and 1.9, respectively. Enforcer intercropped with cowpea low density had the lowest total LER of 1.3 compared to all treatments. At Ofcolaco, total LER ranged from 1.4 to 1.9, with the highest observed in NS5511 intercropped with cowpea high density (Table 5).

Table 5. Total land equivalent ratio of grain sorghum and cowpea at Syferkuil and Ofcolaco during 2018/19 and 2020/21 cropping seasons.

Treatments	Syferkuil 2018/19	Syferkuil 2020/21	Ofcolaco 2018/19
Enforcer + Cowpea-low	1.7	1.3	1.7
Enforcer + Cowpea-high	1.3	1.4	1.2
NSS5511 + Cowpea-low	1.5	1.6	1.9
NSS5511 + Cowpea-high	1.7	1.6	1.3
Avenger + Cowpea-low	1.6	1.5	1.6
Avenger + Cowpea-high	1.7	1.7	1.5
Titan + Cowpea-low	1.6	1.8	1.5
Titan + Cowpea-high	1.5	1.8	1.6

Low = 37,037 plants per ha, high = 74,074 plants per ha.

3.4. Leaf Area Index of Sorghum and Cowpea in Binary and Sole Cultures

At Syferkuil, leaf area index (LAI) was significantly different ($p \leq 0.05$) among grain sorghum cultivars at Syferkuil during the 2018/19 and 2020/21 cropping seasons (Figure 11). NS5511 had a higher LAI compared to the other sorghum cultivars, followed by Enforcer during the 2018/19 cropping season. However, Enforcer was superior compared to the other cultivars in the 2020/21 growing season.

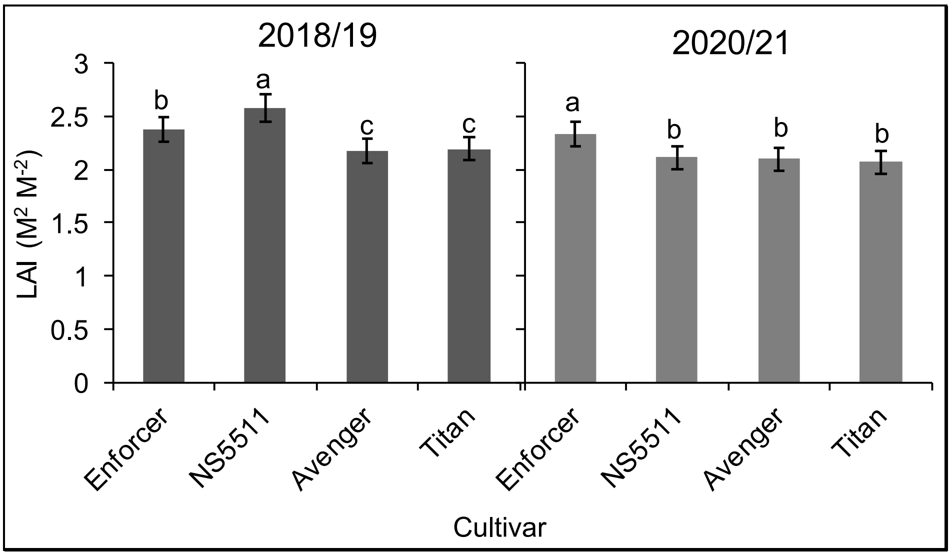

Figure 11. Leaf area index of four grain sorghum cultivars evaluated at Syferkuil during 2018/19 and 2020/21 cropping seasons. Different letters indicate that the means were different at $p \leq 0.05$.

There was no variation among grain sorghum cultivars for LAI at Ofcolaco during the 2018/19 cropping season. However, in 2020/21 there was a significant variation in LAI among the cultivars (Figure 12). The results revealed that NS5511 and Avenger were higher than Enforcer and Titan during the 2020/21 cropping season.

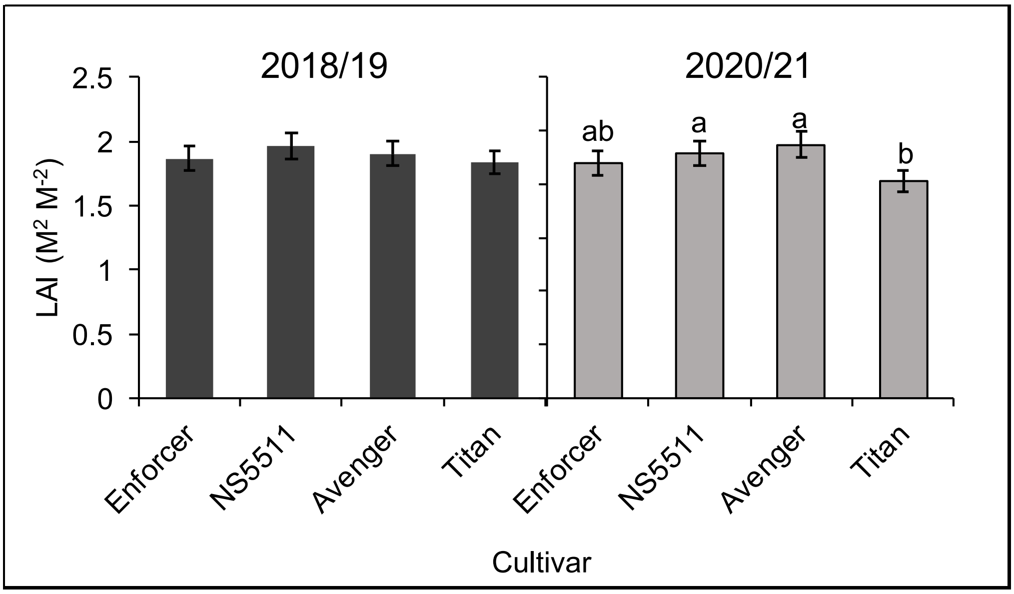

Figure 12. Leaf area index of four grain sorghum cultivars at Ofcolaco during 2018/19 and 2020/21 cropping seasons. Different letters indicate that the means were different at $p \leq 0.05$.

There was a significant interaction effect between the cropping system and days after planting of cowpea at Syferkuil during the 2018/19 and 2020/21 cropping seasons. The results indicated that, in the 2018/19 cropping season, cowpea treatments had higher LAI at 63DAP, excluding cowpea sole under high density. Cowpea sole high density started at a higher rate and remained steady until 83DAP (Figure 13). During the 2020-21 cropping season, cowpea treatments started at a low rate and increased until 67DAP, then decreased until 104DAP (Figure 13).

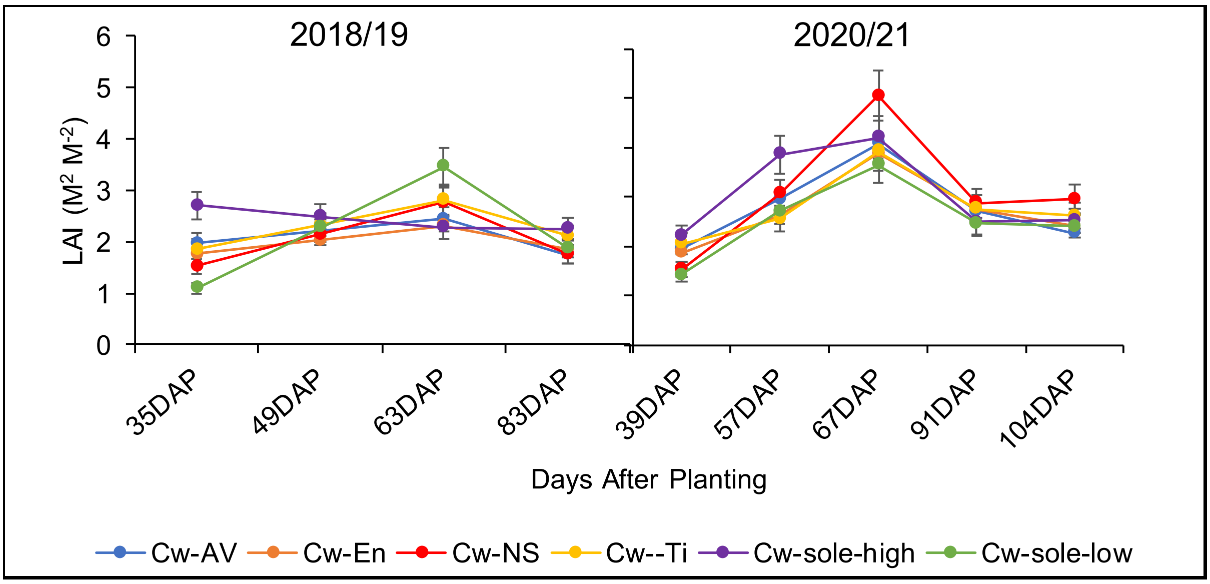

Figure 13. Leaf area index of cowpea treatments in binary and sole cultures at Syferkuil during 2018/19 and 2020/21 cropping seasons.

The results from Ofcolaco were similar to those at Syferkuil, with significant interaction occurring between the cropping system and days after planting during the two cropping seasons. Cowpea treatments had a similar trend during the 2018/19 growing season, with the highest LAI being between 49DAP and 83DAP (Figure 14). However, in the 2020–21 cropping season, cowpea treatments had fluctuating LAI across the days after planting.

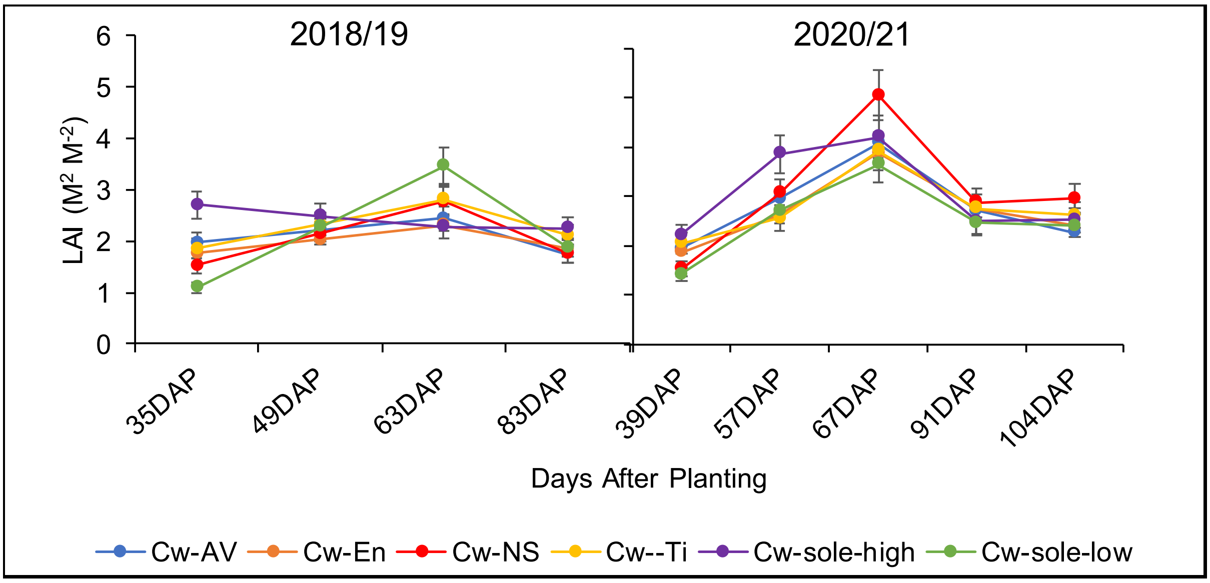

Figure 14. Leaf area index of cowpea treatments in binary and sole cultures at Ofcolaco during.

4. Discussion

The variation in temperatures and rainfall received during the cropping seasons as a result of climate change influenced the agronomic performance of grain sorghum cultivars at the two locations. Ofcolaco was generally warmer than Syferkuil during the 2018/19 and 2020/21 cropping seasons, which may have resulted in variation in crop performance and grain yield. Other studies have reported that the differences in grain yield of sorghum were due to distinct agro-ecological regions which varied across seasons [21,22]. From our study, grain sorghum generally performed better in 2018/19 compared to the 2020/21 cropping seasons, and vice versa for cowpea. The cropping system and the density of the companion crop cowpea did not influence the grain yield of sorghum cultivars at the two test locations across different seasons. The results were contrary to what was observed in another study [23]. The authors reported that sorghum was significantly influenced by the treatment combination in the sorghum-legume intercrop. Grain sorghum cultivars showed a significant variation in terms of grain yield due to the adaptive mechanism of the crop, which varied with cultivar, location, and season. Similar results have been reported elsewhere [24–26].

The density of cowpea and the cropping system significantly influenced grain yield and yield components of cowpea in the two agro-ecological regions and across the cropping seasons. The findings were in line with other studies in which the authors reported that the yield of cowpea was highly influenced by crop density [27]. However, cowpea density did not improve in the pearl millet–cowpea intercrop [28]. In this study, cowpea produced a higher grain yield when grown under high density (74,074 plants per ha), either in binary or sole compared to low density (37,037 plants per ha). Increased density probably allowed more cowpea plants to compete for light and water in binary cultures through improved root density and, ultimately, high yield accumulation. Similar results have been reported by other studies [29–31]. In the sole, cowpea produced more grain yield in the sole compared to the binary culture at Syferkuil and Ofcolaco during the 2018/19 and 2020/21 cropping seasons. This is mainly due to increased canopy size (LAI), which is important for monitoring crop growth and accumulation of grain yield [32].

The results also revealed that cowpea performed better at Syferkuil when intercropped with Titan compared to when intercropped with other grain sorghum cultivars. However, at Ofcolaco, cowpea had a higher yield when intercropped with Avenger, although the results were based on one season of data. High interspecific competition between crops is required for the efficient use of growth resources [33]. However, the efficient use of those resources must be greater than the interspecific competition [34]. In this study, there was high competition for resources such as water, light, etc., between grain sorghum cultivars and cowpea intercrop at Syferkuil, which hindered cowpea yield accumulation under low density when intercropped with Enforcer and Ns5511. However, at Ofcolaco, there was complementarity between cowpea and the two grain sorghum cultivars (Avenger and Titan) in the binary system.

Yield components are important variables used to determine the yield potential of crops in response to different agro-ecological regions [35]. In this study, yield components varied from one location to another and across seasons. For instance, at Syferkuil, Enforcer and NS5511 obtained the highest seed weight per head compared to Avenger and Titan, ultimately resulting in a higher grain yield during the two cropping seasons. Therefore, under the growing conditions of Syferkuil, the seed weight per head can be used to recommend cultivars Enforcer and NS5511 for high-grain-yield production. At Ofcolaco, Enforcer and Titan were superior cultivars in 2018/19, whereas in the 2020/21 cropping season, NS5511 and Avenger obtained higher grain yields. These indicate that the adaptation of grain sorghum cultivars at Ofcolaco is highly dependent on the growing conditions of a particular season. During the two cropping seasons, NS5511 and Avenger had higher seed weight per head compared to Enforcer and Titan. Hence, head weight and seed weight per head can be used by breeders as selection criteria for the recommendation of cultivars to local growers [36]. The higher grain yield of cowpea was explained by the pod weight per plot, which was consistent throughout the cropping seasons at the two test locations.

The leaf area index of a crop canopy is an important parameter that can be used to predict growth and yield [37]. At Syferkuil, the leaf area index of grain sorghum was significantly affected by the cropping system as well as the cultivar. During the two cropping seasons, Enforcer and NS5511, which ultimately accumulated more grain yield, had a higher leaf area index compared to the other cultivars. At Ofcolaco, the leaf area index was significantly influenced by the growing period during 2018/19, whereas in 2020/21, the binary had a higher leaf area index compared to the sole cultures. This further explains the variation in grain yield among grain sorghum cultivars at Ofcolaco. The leaf area index of cowpea was influenced by the cropping system, DAP, as well as cropping seasons. The LAI was higher at 40 and 63 DAP, depending on the cowpea treatment. The capturing of light by canopies at late flowering to mid pod formation stages is important for optimum grain accumulation [32,37].

LER was used in this study to measure the grain sorghum and cowpea intercrop efficiency relative to sole cropping. According to the results, the total LERs were found to vary with the growing seasons and treatments for grain sorghum and cowpea. However, the total LER values calculated were all greater than 1.0 in the test locations and across different seasons, indicating a high yield advantage in the binary cultures and more efficient productivity compared to the sole cultures. Several studies have reported LER values greater than 1.0 in sorghum–cowpea [8,38], sorghum–soybean [39] and maize–cowpea [40]. The results further indicated that the LER was influenced by the density of cowpea as well as the grain sorghum cultivar in intercrop at each experimental site. LER variation due to mixture in various planting patterns has also been reported elsewhere [28,41,42]. The high LER observed in this study was due to the efficient use of resources such as light, water, and nitrogen between grain sorghum cultivars and cowpea [43]. The goal of growers, as well as breeders, is high grain yield, which depends on other yield variables. Hence, the relationship between yield and yield components is important, whether it be positive or negative. According to the results, the strength of the correlation between grain yield and yield components varied with cultivar, intercropping system, and cropping season as well as the agro-ecological region. In conclusion, grain sorghum cultivars were not affected by either cropping system or the density of a companion crop cowpea. Enforcer and NS5511 produced higher grain yield at the two test locations compared to Avenger and Titan. The productivity of cowpea was influenced by the cropping system as well as the crop density. Cowpea performed better in terms of grain yield in sole compared to binary cultures. However, the yield of cowpea improved in binary cultures when the density was 74,074 plants per ha. Head weight of sorghum and pod weight of cowpea can be used as selection criteria for recommendation of cultivars to grow at Syferkuil and Ofcolaco. Based on the results of this study, grain sorghum–cowpea intercrop can be adopted as a climate-smart practice to improve yield compared to mono-cropping. However, the density of cowpea and grain sorghum cultivars should be taken into consideration, as they affect the productivity of the two crops. The research also discovered that in binary cultures, more organic carbon was left in the soil (Table 1), implying that the system could improve soil fertility and benefit subsequent crops. The data generated from this study could be useful in simulating the productivity of intercropping practice as a climate-smart method using crop modelling techniques. It is further suggested that a similar study be carried out to investigate the biological nitrogen fixation of the legume crop cowpea in response to intercropping with different cultivars of grain sorghum. In addition, for better recommendations, the impact of intercropping systems on soil carbon dynamics should be investigated.

Author Contributions: T.E.M. came up with the way to promote intercropping system as an approach to produce sorghum and cowpea sustainably under different agro-ecological conditions. K.K.A., L.M. and Y.G.K. verified the methods and analytical procedure used in conducting the field experiment. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Not applicable.

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