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Sorghum radiation use efficiency and biomass partitioning in intercrop systems

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ABSTRACT

The objective of intercropping is to improve resource efficiencies for land, water and radiation. Few studies have focused on the interactive effects of water stress on radiation use efficiency (RUE) in an intercrop system. The study determines the effect of intercropping sorghum with either cowpea or bottle gourd on RUE and biomass accumulation in response to water stress. This was assessed using a split-plot design with crop sequences sole sorghum, sole cowpea, and sole bottle gourd and intercrop systems sorghum–cowpea and sorghum–bottle gourd assigned as sub-plots arranged in randomised complete blocks within main plots, water regimes: full irrigation, deficit irrigation and rainfed. We quantified specific leaf area, leaf area index as well as biomass accumulation and partitioning. Extinction coefficient, intercepted photosynthetic active radiation (IPAR) and RUE for biomass (RUE_b) and grain (RUE_g) were also determined. Under rainfed conditions, intercropping with either cowpea (26%) or bottle gourd (62%) improved sorghum leaf area. A reduction in specific leaf area was observed for sorghum when it was intercropped with either cowpea (−20%) or bottle gourd (−19%). Under full irrigation, sorghum stems constituted a larger proportion (62%) of final biomass in comparison to sorghum under deficit irrigation (52%) and rainfed conditions (50%). Intercropping sorghum with either cowpea or bottle gourd improved IPAR (38%), RUE_b (93%) and RUE_g (11%) under rainfed conditions. This study showed that under water-limited conditions intercropping reduced sorghum stem mass and increased canopy size, radiation interception, and grain yield and improved RUE. In agreement with our proposition, water availability was closely associated with radiation use efficiency. Intercropping can be recommended for semi-arid environments since it improves RUE and sorghum biomass and grain yield.

1. Introduction

Agriculture in the semi-arid and arid regions of sub-Saharan Africa (SSA) faces challenges related to water scarcity (Cairns et al., 2013), land degradation and climate change. Among the strategies suggested to improve productivity of these cropping systems are use of improved/appropriate varieties and increasing resource use efficiencies for land, water and solar radiation. In this regard, intercropping drought tolerant cereals such as sorghum with legumes, and other crops, has emerged as a strategy for maximising land and water use efficiencies. Few studies, however, have focussed on assessing radiation use efficiency (RUE) and determining whether there are any trade-offs between increasing land, water and radiation use efficiencies. Such information would be useful to determining most synergistic crop combinations for intercropping.

Under non-limiting conditions, biomass accumulation is primarily influenced by the amount of intercepted photosynthetically active radiation (IPAR) (wavelength in the range of 0.4–0.9 μm) by the green leaf canopy and the photosynthetic efficiency of its conversion (Curt et al., 1998). Crop responses to environmental stresses often lead to canopy and physiological adjustments that inadvertently result in a reduction in total IPAR (Collino et al., 2001; Wijewardana et al., 2016), hence RUE will vary considerably in response to environmental stresses (Sekhon et al., 2010; Bat-Oyun et al., 2012). As a strategy to improving productivity in rainfed cropping systems, there is a need to promote strategies that improve land and water use efficiency without compromising the efficient use of readily available resources such as solar radiation.

Intercropping is fast becoming an approach of choice to improve resource use efficiencies across diverse agro-ecologies (Ju et al., 2010; Yang et al., 2011; Chimonyo et al., 2015; Silberg et al., 2017). Intercropping improves productivity through enhanced spatial and temporal resource use relative to sole cropping. This is achieved through

Abbreviations: B, Sole bottle gourd; C, Sole cowpea; DI, Deficit irrigation; FI, Full irrigation; IPAR, Intercepted photosynthetic active radiation; *k*, Extinction coefficient; LA, Leaf area; LAI, Leaf area index; RF, Rainfed; RUE, Radiation use efficiency; SB, Sorghum–bottle gourd intercrop; SC, Sorghum–cowpea intercrop; SLA, Specific leaf area; SS, Sole sorghum.

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crop morpho- and eco-physiological modifications (Chimonyo et al., 2016) for the crop components and the system as a whole. The additional crop introduced into a sole crop stand hastens time to full canopy cover hence reducing amount of water lost through soil evaporation and improving water availability for transpiration for all crops. Conversely, increased canopy cover increases surface area for transpiration increasing water loss from the soil. In addition, increased root density leads to enhanced soil water capture and mitigates drainage losses. Enhanced soil water capture allows for maintenance of high stomatal conductivity and internal tissue water status thus allowing for high net assimilation rates and biomass production (Blum, 2009). Then again, the increased canopy size and root function may indirectly result in an increase in competition for water by dominant crop component — in this case the cereal, over the less dominant component. This may result in the reduction in biomass yield and may offset the perceived benefits of intercropping on individual crop components and the whole system, hence reducing resource use efficiency. Thus, under water-limited conditions, intercropping could affect the derivatives of RUE; however, the mechanisms that allow for trade-offs within the system are not fully understood.

The interlinkages between water, radiation interception and plant growth rate have been studied thoroughly in monocropping systems. Information on improved water and radiation use by intercrop systems is widely available; however, these aspects are often investigated separately. Assessing the relationship between water and RUE creates an opportunity to improve productivity synergistically for crop components within an intercrop system. Furthermore, it improves our understanding of hierarchical and synergistic resource use (land–water–radiation) within the intercrop system, which bodes well for sustainability. The aim of the study was to determine RUE for sorghum intercropped with either cowpea (*Vigna unguiculata* L. Walp) or bottle gourd (*Lagenaria siceraria*) under varying water regimes. A previous study already described land and WUE (Chimonyo et al., 2016). Therefore, the current study investigated the interactive effects of water and solar radiation on sorghum RUE. As such, much of the data presented will focus on sorghum, as it was the main crop of interest while some yields of the intercropped species was desired.

2. Materials and methods

2.1. Data collection

2.1.1. Experiment overview

Field experiments were conducted at the University of KwaZulu–Natal's Ukulinga Research Farm (29°37′S; 30°16′E; 775 m a.s.l.) in Pietermaritzburg, South Africa, over two summer seasons (2012/13 and 2013/14). Ukulinga Research Farm is classified as semi-arid with about 80% of the mean annual rainfall of 750 mm received mostly between the months of October and April. The soils are predominantly clay to clay–loam soils and are moderately shallow, ranging from 0.4 m to 0.8 m with medium to low fertility status.

The field experiment was set up as a split-plot design with sub-plots laid out in randomised complete blocks within the main plots, and replicated three times. The main plot was water regime with three levels [full irrigation (FI), deficit irrigation (DI) and rainfed (RF)]. Sub-plots comprised intercrop combinations, sole sorghum (SS), sole cowpea (C), sole bottle gourd (B), sorghum–cowpea (SC) and sorghum–bottle gourd (SB). The intercropping system was designed as an additive intercrop. Cowpea and bottle gourd were "added" to the sorghum by planting additional rows between rows of sorghum whose population was equal to the sole crop. Sorghum was planted at a plant population of 2.6 plants$\cdot$m^{-2} in both the sole and intercrop plots. A similar plant population was also used for sole cowpea; however, under intercropping the population was decreased to 1.3 plants$\cdot$m^{-2}. For sole and intercropped bottle gourd, 0.7 and 0.35 plants$\cdot$m^{-2}, respectively were used. Details of plant materials, experimental designs, treatments and layouts are provided in Chimonyo et al. (2016).

For the water regime treatments, full irrigation was achieved by irrigating crops up to 100% of crop water requirement (ETc) for the duration of the trials. For deficit irrigation, supplementary irrigation was scheduled to meet crop water requirement during sensitive growth stages. Grain sorghum is most sensitive to water stress from initial establishment through to floral initiation and from flag leaf stage through to yield formation (Farahani and Chaichi, 2012). Therefore, irrigation was withdrawn between floral initiation and reinstated upon appearance of the flag leaf. All water regimes were established to meet full water requirements at crop establishment and two weeks after emergence to allow for even crop stand; a total of 123.50 and 68.00 mm of supplementary irrigation were applied across all water regimes for 2013/14 and 2014/15 growing season, respectively. Following crop establishment, no supplementary irrigation was applied to the rainfed trials. Irrigation scheduling was based on daily ETc calculated from the product of sorghum crop factors (*Kc*) (Allen et al., 1998) and Priestley–Taylor (PT) reference evapotranspiration (ETo) values obtained from an automatic weather station (AWS) located within a 1 km radius from the experimental field. In the event of rainfall, irrigation scheduling was adjusted accordingly.

Overall, more rainfall (26.31%) was received in 2014/15 than in 2013/14 (Table 1). Cumulative ETo was marginally higher (2.93%) in 2013/14 (502.61 mm) than in 2014/15. A deficit of 184.14 and 91.49 mm for 2013/14 and 2014/15, respectively, was recorded (Table 1). During 2013/14 supplementary irrigation applied in the FI and DI treatment was 286.50 and 208.05 mm, respectively. During 2014/15 supplementary irrigation applied in the FI and DI treatment was 208.05 and 136.00 mm, respectively.

All cultural practices such as weeding, fertilizer application rates and pest management were done according to recommended best management practices for the crops and site. Specific details of crop management are provided in (Chimonyo et al., 2016).

2.1.2. Crop growth parameters

Specific leaf area (SLA) (m$^2\cdot$ kg^{-1}) was defined as the quotient of the one-sided area of a fresh leaf and its oven dried mass. Specific leaf area was determined weekly for each component crop by destructively sampling one randomly selected plant per plot. Immediately after sampling, leaves were separated from the stem and total leaf area was measured using an LI-3100C leaf area meter (LI-COR, USA). Thereafter, leaves were oven dried at a constant temperature of 85 °C until a constant mass was attained. Specific leaf area was calculated as:

$$SLA = \frac{LA}{LM}\left(m^2 \cdot kg^{-1}\right) \quad (1)$$

where: SLA = specific leaf area (m$^2\cdot$ kg^{-1}), LA (m^2) is the one-sided area of a fresh leaf, and LM is the oven dried mass of leaves.

The remaining plant parts were separated into stalk/stems and reproductive organs and were also dried. Mass of leaves, stems and reproductive organs was used to determine biomass accumulation (total mass) and partitioning.

Leaf area index (LAI) was determined weekly at midday (1200–1400 h) on days with clear skies using the AccuPAR-LP80

Table 1
A comparison of water applied across the water regimes (full irrigation, deficit irrigation and rainfed conditions) and observed reference evapotranspiration (ET_O). Values in superscript represent total water added (irrigated + rainfall) into the system.

	Full irrigation	Deficit irrigation	Rainfed condition	Reference evapotranspiration
2013/14	286.50 $^{608.97}$	208.05 $^{530.52}$	322.47	502.61
2014/15	208.05 $^{610.31}$	136.00 $^{538.26}$	402.26	493.75