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Potential of the APSIM model to simulate impacts of shading on maize productivity

Aynalem Dilla · Philip J. Smethurst · Karen Barry · David Parsons · Mekuria Denboba

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Abstract A number of agroforestry models have been developed to simulate growth outcomes based on the interactions between components of agroforestry systems. A major component of this interaction is the impact of shade from trees on crop growth and yield. Capability in the agricultural production systems simulator (APSIM) model to simulate the impacts of shading on crop performance could be particularly useful, as the model is already widely used to simulate agricultural crop production. To quantify and simulate the impacts of shading on maize performance without trees, a field experiment was conducted at Melkassa Agricultural Research Centre, Ethiopia. The treatments contained three levels of shading intensity that reduced incident radiation by 0 (control), 50 and 75% using shade cloth. Data from a similar field experiment at Machakos Research Station, Kenya, with 0, 25 and 50% shading were also used for simulation. APSIM adequately simulated maize grain yield ($r^2 = 0.97$) and total above-ground biomass ($r^2 = 0.95$) in the control and in the 50% treatments at Melkassa, and likewise in the control ($r^2 = 0.99$), 25% ($r^2 = 0.90$) and 50% ($r^2 = 0.98$) treatments at Machakos. Similarly, APSIM effectively predicted Leaf Area Index attained at the flowering ($r^2 = 0.90$) and maturity ($r^2 = 0.94$) stages. However, APSIM under-estimated maize biomass and yield at 75% shading. In conclusion, the model can be reliably employed to simulate maize productivity in agroforestry systems with up to 50% shading, but caution is required at higher levels of shading.

Keywords Agroforestry · LAI · Light · Modelling

Introduction

Ensuring sustainable agricultural production through improved management and utilization of resources is a global interest that is particularly important in Africa. Declining soil fertility is the main cause of marginal agricultural productivity in smallholder farms in Africa (Greenland and Nabhan 2001), and productivity is vulnerable to climate change impacts.

A. Dilla (✉) · P. J. Smethurst · K. Barry · D. Parsons
School of Land and Food, University of Tasmania, Private Bag, 54, Hobart, TAS 7001, Australia
e-mail: amdilla@utas.edu.au

A. Dilla · K. Barry · D. Parsons
Tasmanian Institute of Agriculture, University of Tasmania, Private Bag 98, Hobart, TAS 7001, Australia

P. J. Smethurst
CSIRO, Private Bag 12, Hobart, TAS 7001, Australia

D. Parsons
Swedish University of Agricultural Sciences, Umeå, Sweden

M. Denboba
Centre for Environmental Science, College of Natural Sciences, Addis Ababa, Ethiopia

Agroforestry, which is deliberate integration of trees with food crop production (Atangana et al. 2014), provides options to improve agricultural productivity, as trees can improve soil fertility, moisture availability, and crop microclimate in some situations (Beedy et al. 2010; Nair 2007).

Maize is one of the major crops grown by smallholder farmers in the semi-arid low rainfall areas of Ethiopia (Abebe et al. 2005). However, maize production in semi-arid areas is constrained by moisture deficit, especially when a dry period coincides with tasseling and silking stages (Tilahun 1995). In these systems, farmers deliberately preserve large numbers of trees or shrubs for a variety of benefits including soil and microclimate amelioration, firewood, fodder, fencing and cash income.

Microclimate amelioration by trees can increase growth and productivity of understory crops (Bayala et al. 2014; van Noordwijk et al. 2014), especially when meristem temperature persistently exceeds the optimum during periods of drought (Lott et al. 2009; Ong et al. 2007). For example, study of the effects of trees on microclimate and soil fertility in the central Rift Valley of Ethiopia concluded that crop failure under some circumstances was due to extreme microclimatic conditions and can be prevented by incorporating trees into farm lands (Tanga et al. 2014). Similarly, a study by (Jonsson et al. 1999) showed that millet seedlings grown under *Parkia biglobosa* (Nere) and *Vitellaria paradoxa* (Karite) tree canopies were less exposed to excessive temperature (>40 °C for only 1–9 h week^{-1}) compared to crops grown in the open fields (27 h week^{-1}). Conversely, excessive shading by tree canopies may have negative impacts on understory crops, especially for crops using the C4 photosynthetic pathway, like maize and sorghum. Kessler (1992) found that shade by scattered *Parkia biglobossa* (Nere) and *Vitellaria paradoxa* (Karite) trees reduced sorghum yield by 70 and 50%, respectively, compared to crop yields in open fields. Jonsson et al. (1999) assert that reduction of incident radiation, for example by 25%, could adversely affect crop production.

Predictive models, when combined with field experiments, provide the capacity to quantitatively synthesise our understanding of the complex interactions among various components of a production system. Various agroforestry models such as WaNuLCAS (Van Noordwijk and Lusiana 1999) and HYPAR (Mobbs et al. 1998) have attempted to simulate the impacts of management practices and gradients in resources such as water, nutrients and light on system performance (García-Barrios and Ong 2004). However, Luedeling et al. (2014) outline that the major challenges of these agroforestry models are the complex interactions that occur in these systems and high data requirements to calibrate the models. Incorporating an agroforestry modelling ability into existing crop models like agricultural production systems simulator (APSIM) (Holzworth et al. 2014) could provide an alternative for simulating complex agroforestry systems. Doing so would allow researchers to avoid duplication of crop modelling efforts, and instead concentrate on bridging the knowledge gaps that hinder our ability to simulate systems that include trees (Luedeling et al. 2014).

The ability of APSIM to simulate crop performance in response to various management decisions such as irrigation and fertilization has been tested in many contexts (Holzworth et al. 2014). Results of those studies show generally good agreement between predictions and observations (Fosu-Mensah et al. 2012; Holzworth et al. 2014; Shamudzarira and Robertson 2002). However, the ability of the APSIM model to simulate competition for light in complex agroforestry systems has not been evaluated. This study aims to investigate the effects of shading on maize growth and development (under maize-only situations using artificial shading without trees) and to determine the extent to which the APSIM model adequately simulates those effects. The hypotheses of the study were; (a) proportional reduction in maize productivity would result from 0 to 75% shading, and (b) APSIM could adequately simulate these impacts on maize performance. Although there is ample evidence that crops and trees interact for water, nutrients and light, the focus of this research was to isolate the light effect by using data from only high water and nutrient availability conditions.

Materials and methods

Field experiment description: Melkassa, Ethiopia

A field experiment was conducted in the Central Rift Valley of Ethiopia at Melkassa Agricultural Research Centre (MARC), located 115 km south-east of Addis

Ababa. The Centre is located at 8°24′N latitude 39°12′E longitude, and is at an elevation of 1550 m above sea level. The location has a bimodal rainfall distribution, with mean annual rainfall of 763 mm. The short rainy season extends from March to May and the long rainy season from June to October. Annual mean minimum and maximum temperatures range between 14 and 28 °C (Shenkut et al. 2013). The soil is a deep and well-drained silty clay loam; classified as Haplic Andosol developed from volcanic parent material. Surface soil (0–30 cm depth) had approximately 0.31% organic carbon, 0.08% available nitrogen, pH 7.4 (1:2.5 soil:water ratio) and bulk density 1.3 g cm^{-3}, 50% silt, 18% sand and 32% clay (Araya et al. 2015; Mesfine et al. 2005).

The experiment was conducted to investigate the effect of shading on maize productivity. It was set up as a randomised complete block design with six replications. The treatments were 0, 50 and 75% shading, i.e. unshaded or reduced incident radiation by 50 or 75% using spectrally neutral shade cloth, respectively. Plots were 3 m by 4 m containing four rows of maize with a spacing of 0.3 m within rows and 0.75 m between rows. The long side and row direction of the plot was in an east–west orientation. Shade cloth 3 m wide was erected at 2 m height over the plot and extended at 45° to 20 cm above ground at both the east and west ends of the plot to provide shade throughout the day. Shade cloth did not extend north or south beyond the 3 m plot boundary. Sidelight was measured using a light meter (AccuPAR LP-80, Decagon Devices) in the centre of one plot of an additional maize-free 100% shade treatment at the perimeter of the experiment using black plastic; the measurements were taken for three consecutive days at 9:00 am, 10:30 pm, 12:00 pm, 1:30 pm, 3:00 pm and 4:00 pm. Gravimetric water content of soil was determined by taking soil samples, using an auger. Soil samples were taken from two randomly selected locations in each plot at depths of 0–15, 15–30, 30–60, 60–90 and 90–120 cm; at sowing, flowering and physiological maturity stages. Samples for each plot and depth were bulked; and oven dried for 24 h at 105 °C.

The maize cultivar Melkassa-2 was planted on June 15, 2015, by placing seeds in a handmade furrow at a depth of 60 mm. Recommended rates of nitrogen and phosphorus fertilisers were applied (by broadcasting) to each plot. Nitrogen fertiliser (Urea, 100 kg N ha^{-1}) was applied at sowing and half the rate of N was applied 10 days after sowing; while phosphorus (diammonium phosphate, 23 kg P ha^{-1} and 9 kg N ha^{-1}) was applied at sowing only. Plots were irrigated (approx. 50 mm) weekly to prevent water stress and weeding was done manually.

Dates for phenological stages were recorded when 50% of the plant population per plot attained emergence, anthesis and physiological maturity stages. Plant biomass and grain yield of the crops in each plot were determined by hand harvesting all plants from the central two rows of maize, each having row length of 4 m. Leaf area of plants was measured by harvesting three plants from each plot using a leaf area meter (LI-3100C, Biosciences) at flowering and physiological maturity stages. Leaf area index (LAI) was then calculated by dividing the total leaf area of the harvested plants by the ground surface area available for their growth (Bavec and Bavec 2002).

Field experiment description: Machakos, Kenya

Data on the response of maize to reduced radiation were taken from the literature for a similar experiment at Machakos Research Station, Kenya. The station is located about 80 km south-east of Nairobi (1°33′S, 37°8′E, 1560 m). The location has a bimodal rainfall distribution with annual mean rainfall of 782 mm; long rainy seasons extend from March to June, and short seasons from October to December. Annual mean daily minimum and maximum temperatures are 13.8 and 23.2 °C respectively. The soil is a well-drained, shallow to moderately deep sandy clay loam classified as a luvisol, based on FAO classification (Lott et al. 2009).

The experiment had three treatments with four replicates, in which incident radiation in the maize-only plots (cv. Katumani composite) was reduced by 0, 25 or 50% using spectrally neutral shade cloth. The size of each plot was 3 m × 4 m, and each plot was enclosed by a shade cloth supported initially 80 cm above the ground and raised as the maize grew taller. Maize was sown in the maize-only plots at a spacing of 1 m between and 0.3 m within rows during the long 1994 and 1995 and short 1994 and 1995 cropping seasons. Sowing was assumed to occur within a sowing window of 1st to 5th March for long, and 1st to 5th November for short seasons each year. Maize biomass and yield were measured by harvesting four randomly selected plants in the central three rows of the plots at the end of each cropping season (Lott et al. 2009).

Model set-up

The APSIM Next Generation model (Holzworth et al. 2014) was used to evaluate the impacts of shading on maize yield. Datasets for daily temperature and rainfall were obtained from the weather stations at Melkassa and Machakos research centers, and solar radiation data for Melkassa were obtained from a NASA database (2016). Soil and management in the model were based on measurements of organic matter, total nitrogen, pH, moisture, and bulk density; and management data included sowing date, plant density, planting depth, irrigation and fertiliser. Plant phenology coefficients were obtained from local cultivar information (Table 1).

The data on soil properties and management were used to parameterise APSIM. Soil properties such as initial available water and initial nitrogen concentrations were tuned for both sites (Table 2) at the 0% shading level to match observed and simulated yield, biomass and LAI. Ability of the model to simulate the response of maize to reduced radiation was then evaluated by reducing 25, 50 or 75% of the total amount of radiation received per day provided in the meteorological data file of the APSIM model.

Tuning of the model was required only for soil water (DUL and LL) and nitrogen parameters (NO_3 and NH_4), which was justified as the values of several parameters were not provided in the literature. An iterative process of parameter adjustment was used for maize in unshaded treatments of each site. Parameters were adjusted within reasonable limits based on previous experience to achieve an approximate match between observed and predicted grain yield. Values provided in Table 2 are those arrived at by calibration (DUL, LL, NO_3 and NH_4) or as provided in the literature (Jama et al. 1995; Madegwa 2015; Nair et al. 1986). The release version of the maize model was used, and therefore not recalibrated for plant parameters.

Statistical analysis and model testing

Field observations were analysed by analysis of variance (ANOVA) using the mixed procedure of SAS 9.4 (SAS Institute, 2013). Soil moisture, which was measured three times and leaf area measured twice, were analysed separately as repeated measurements. Significant differences ($P < 0.05$) between treatment means were determined by LSD. Performance of the APSIM model in predicting grain yield, biomass and LAI was evaluated using the square of the correlation coefficient (R^2) and graphically using 95% confidence intervals of prediction (SigmaPlot©). Relative biomass and yield were calculated as a fraction of the maximum simulated biomass or yield, i.e. under 0% shade. Data used for calibration were not included when calculating evaluation statistics for a combined comparison of both sites.

Table 1 Genetic coefficients used for modelling maize at Melkassa (*Melkassa-2*) and Machakos (Katumani) that are provided in APSIM

Coefficient	Definition	Values	
		Melkassa (*Melkassa-2*)	Machakos (Katumani)
tt_emerg_to_endjuv	Thermal time accumulation from seedling emergence to end of juvenile phase (°C days)	230	150
tt_endjuv_to_init	Thermal time accumulation from end of juvenile to floral initiation (°C days)	0	0
tt_flower_to_maturity	Thermal time accumulation from flowering to maturity (°C days)	710	660
tt_flag_to_flower	Thermal time accumulation from flag stage to flowering (°C days)	10	10
tt_flower_to_start_grain	Thermal time accumulation from flowering to start of grain filling (°C days)	160	120

Table 2 Soil properties used for modelling maize in Mekassa (Ethiopia) and Machakos (Kenya) sites

Soil properties	Soil depth							
	0–20	20–40	40–60	60–80	80–100	100–120	120–160	160–180
Melkassa								
BD (g cm^{-3})	1.11	1.11	1.13	1.17	1.17	1.17	1.17	1.17
SAT (mm mm^{-1})	0.54	0.45	0.45	0.45	0.45	0.45	0.45	0.45
DUL (mm mm^{-1})	0.24	0.29	0.3	0.33	0.33	0.33	0.33	0.33
LL (mm mm^{-1})	0.11	0.15	0.16	0.18	0.21	0.21	0.21	0.21
OC (%)	0.85	0.83	0.81	0.76	0.74	0.74	0.74	0.74
NO_3 (μg g^{-1})	12.47	12.61	7.81	5.05	2.11	2.86	2.05	2.22
NH_4 (μg g^{-1})	12.82	12.71	7.16	2.79	2.43	3.16	2.77	2.43
Machakos								
BD (g cm^{-3})	1.35	1.35	1.4	1.4	1.4	1.4	1.4	1.4
SAT(mm mm^{-1})	0.25	0.37	0.37	0.38	0.38	0.38	0.38	0.38
DUL(mm mm^{-1})	0.19	0.2	0.22	0.24	0.24	0.24	0.24	0.24
LL (mm mm^{-1})	0.05	0.08	0.08	0.15	0.17	0.17	0.17	0.17
OC (%)	1.2	1.1	0.8	0.6	0.2	0.1	0.1	0.1
NO_3 (μg g^{-1})	5	2	0.5	0.5	0.2	0.2	0.1	0.1
NH_4 (μg g^{-1})	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

BD bulk density, *SAT* saturation, *OC* organic carbon, *DUL* drained upper limit, *LL* crop lower limit, *NH_4* ammonium, *NO_3* nitrate

Results

Biomass and grain yield

There were no significant treatment difference in soil moisture at any depth when sampled, i.e. at planting and flowering (Fig. 1, data shown for soil moisture measured at flowering) regardless of shading level. Light measurements under black plastic (100% shading) indicated that the amount of side light experienced under each treatment was a maximum of 19.4% of incident radiation, which occurred at ground level at 3:00 PM in the centre of the plot (Fig. 2). Integrated over a full day, the value was 18.5% at ground level, 6.1% at 1.3 m height and 5.3% at 2 m height (Fig. 3).

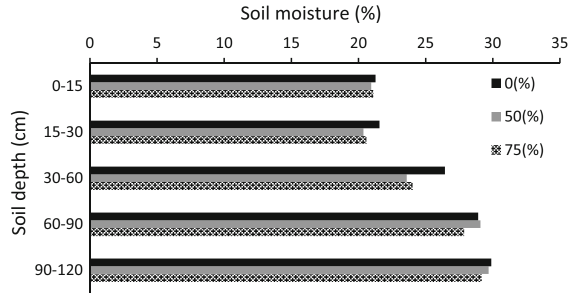

Fig. 1 Soil moisture contents measured at flowering under 0, 50 and 75% shade treatments at five soil depths (treatment differences not significant at any depth)

Shading significantly reduced both maize yield ($P < 0.0001$) and biomass production ($p < 0.0001$) of maize plants. Shading of 50% led to 44% reduction in biomass and 56% in yield compared to no shading, but there was no significant difference between 50 and 75% shading treatments in either maize yield or biomass production (Table 3).

APSIM simulated biomass ($r^2 = 0.95$, Fig. 4) and maize yield ($r^2 = 0.97$, Fig. 4) well in the control and 50% treatments; with a quadratic regression being more significant than a linear trend. However, the model underestimated yield and biomass under 75% shade (Fig. 4), particularly when sidelight, which might have accounted for about 10% of the incident radiation in all the shaded plots (Fig. 2), was not included in the simulations. Simulated relative maize yield was also slightly less than for biomass at high reductions in light (Fig. 5).

At Machakos, there was a strong correlation between simulated and observed values of maize yield in the control (0%), 25 and 50% shading treatments (Fig. 6). Combining the data from both sites, but excluding the poorly predicted 75% shading

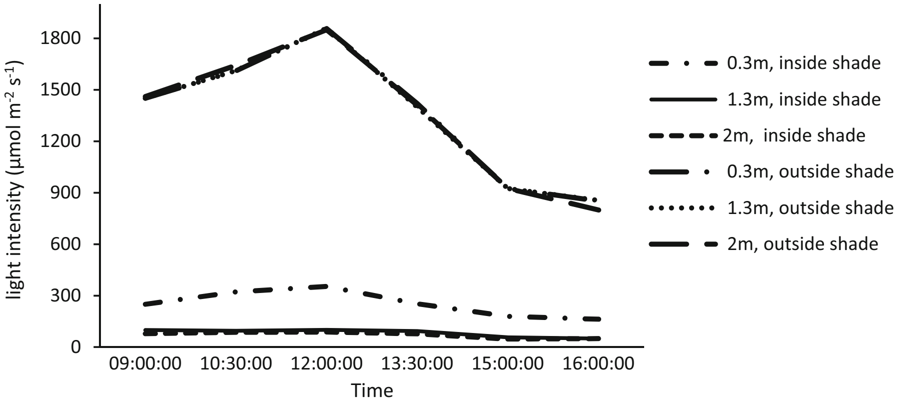

Fig. 2 Light measured under the *centre* of black plastic shade and *outsid*e the shade at different times of a day at 0.3 m, 1.3 m and 2 m height. '*Inside shade*' is for light measured under the black plastic shade and '*outside shade*' is for light measured outside

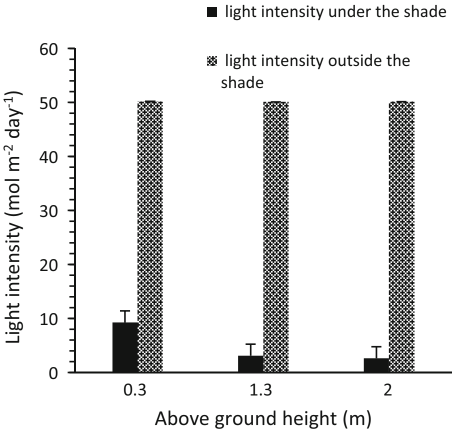

Fig. 3 Daily integrated radiation measured at different heights, under and outside black plastic shade at Melkassa (Ethiopia)

treatment at Melkassa, and the 0% shading treatment at both sites (as they were used for calibration), a strong relationship is shown for predicted vs observed values that is valid for up to 50% shading and up to 3 t ha^{-1} yield (Fig. 6).

Leaf area index

Reduced incident radiation had a significant effect on LAI ($P < 0.01$). The highest value of LAI (4.2) at Melkassa was recorded in the control (0% shading intensity) treatment at the flowering stage. There were strong relationships between predicted and observed values of LAI at both the flowering and physiological maturity stages (Fig. 7). The number of days to attain tasseling and physiological maturity was also well simulated by the model, with three days difference between simulated and observed for both stages (data not presented).

Table 3 Measured and simulated biomass (t ha^{-1}) and grain yield (t ha^{-1}) for maize grown under different shade treatments at Melkassa (Ethiopia)

Shade treatment	Biomass (t ha^{-1})			Yield (t ha^{-1})		
	Observed	Predicted (without side light)	Predicted (with side light)	Observed	Predicted (without side light)	Predicted (with side light)
0%	15.1a	16.0a	16.0a	6.6a	6.7a	6.7a
50%	8.5b	6.1b	9.0b	2.9b	2.7b	2.7b
75%	7.3b	0.3c	1.6c	2.4b	0.0c	0.3c

Values for in the same column with different letters differ significantly at $p < 0.05$

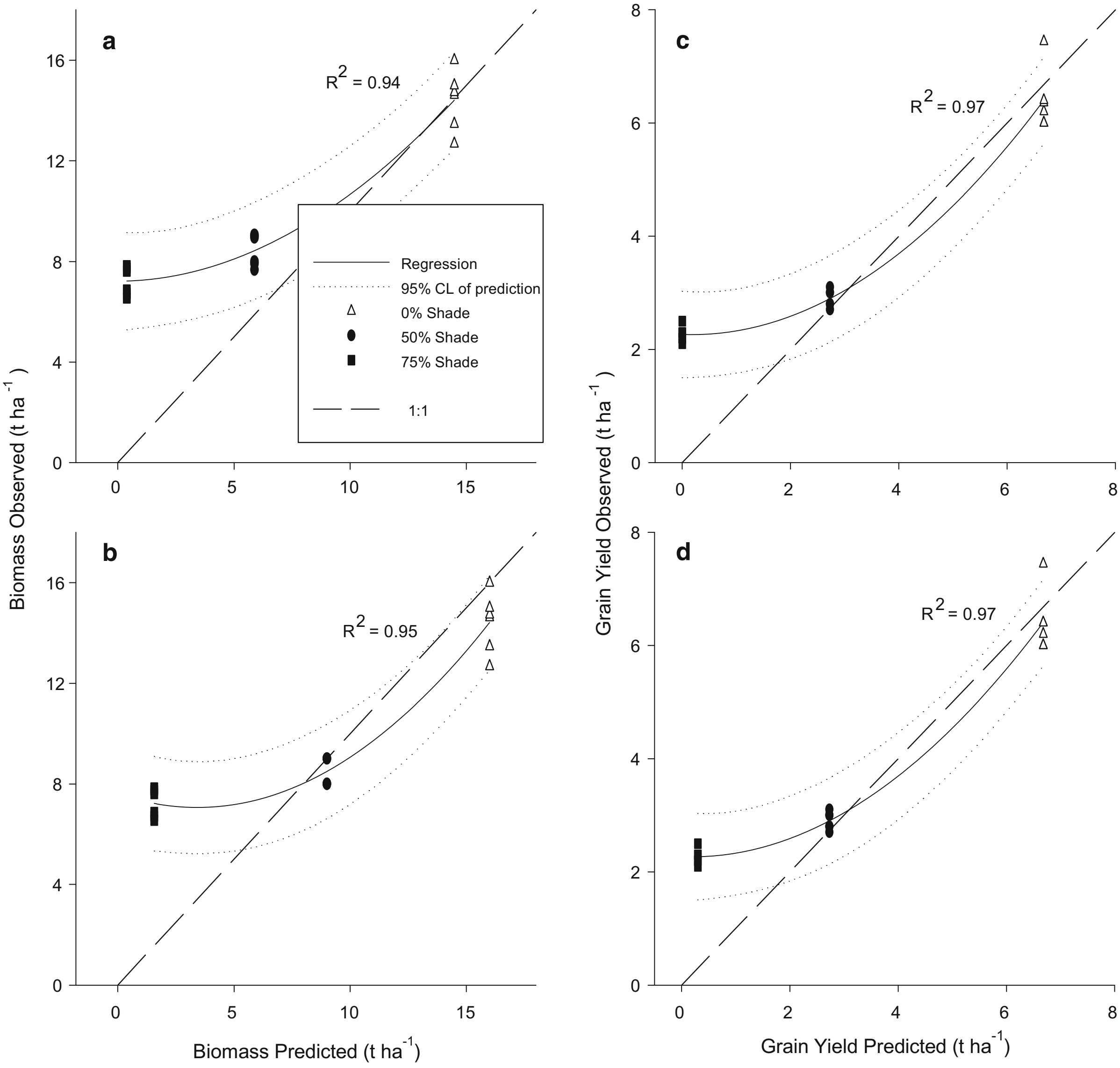

Fig. 4 Comparison of measured and simulated maize biomass, without sidelight (**a**) and with sidelight (10% radiation added for each shade levels) (**b**), and maize yield, without sidelight (**c**) and with sidelight (10% radiation added for each shade level) (**d**), for different levels of shading at Melkassa (Ethiopia)

Discussion

As expected, reduced radiation caused by shading had a significant negative effect on maize production and productivity, as solar radiation is the primary limiting factor when growth is not constrained by the availability of water or nutrients. For 0–50% shading, results at Melkassa were in general agreement with those of Lott et al. (2009) at Machakos. Their work in a *Grevillea robusta* agroforestry system in Kenya showed that 25% reduction in incident radiation led to significant reductions in maize biomass (29%) and yield (42%), while a 50% reduction in radiation resulted in reductions in biomass (29%) and yield (58%). Similarly, Bayala et al. (2002) argued that a 38–50% reduction in incident radiation is enough to result in significant reductions in crop yield. In the current study, about 50% of the plants attained the flowering and maturity stages in a similar number of days in both the control (0% shading) and in the 50%

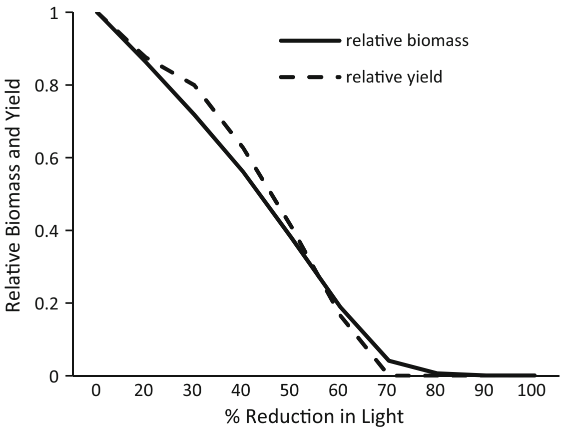

Fig. 5 Simulated relative maize biomass and yield at different shading levels. Relative yield is defined as yield or biomass as a fraction of the maximum simulated, i.e. under 0% shade

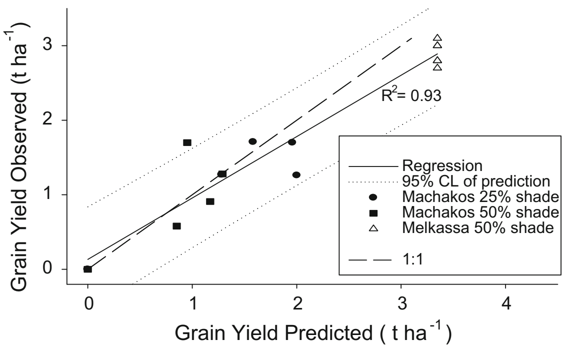

Fig. 6 Comparison of predicted and observed maize yields at Machakos (Kenya) and Melkassa (Ethiopia) with 50% shade and at Machakos with 25% shade

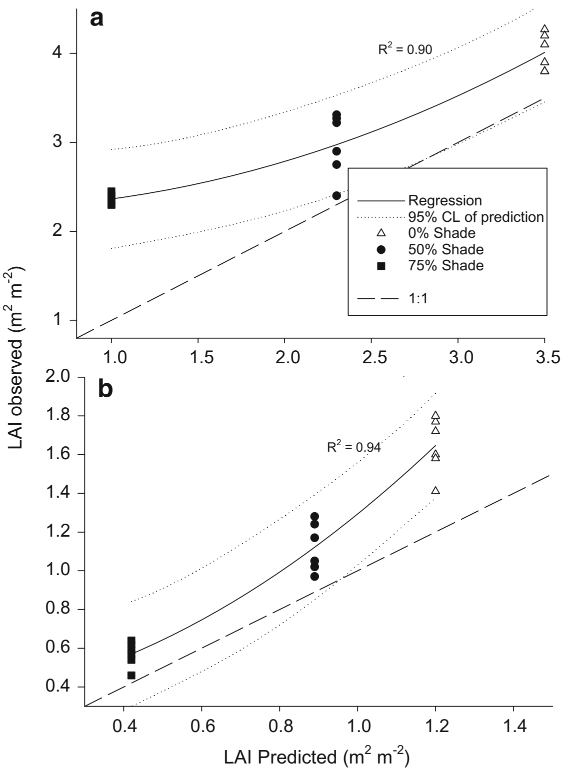

Fig. 7 Simulated and observed LAI for different levels of shading at Melkassa (Ethiopia), at flowering (**a**) and physiological maturity (**b**) stages

shading intensity treatments. Lott et al. (2009) also reported that delayed time to flowering due to artificial shading was insignificant (less than five days). Hence, shading appears not to greatly affect the timing of maize development stages, but up to 50% shading reduces light capture and plant development by approximately a similar percentage.

The present study showed that APSIM adequately simulated the impacts of 0–50% shading on maize performance as there was a strong correlation between simulated and observed yield ($r^2 = 0.97$, Fig. 4) and biomass ($r^2 = 0.95$, Fig. 4) values. However, reductions of yield and biomass under the 75% shade treatments were over-estimated by the model. Simulated relative maize yield was also more underestimated than biomass at more reductions in light (Fig. 5). This could be attributed to sidelight that may have become an important growth factor at very low radiation levels, meaning that the plants in the 75% shade treatment actually experienced 65% reduction. Moreover, the light measurements at the Melkassa field experiment might not have fully detected side light as they were taken only for three consecutive days and in the centre of the plot.

Low maize yield prediction by APSIM in intercropping systems, wheat/maize or fieldpea/maize relay intercropping systems, was also reported by Knörzer et al. (2011), in which case the model assumed the radiation fraction received by the intercropped maize was only 0.2% of the incident radiation. However, in that study it was unclear what the actual gradients in shade and yield were in relation to distance from a neighbouring taller plot. In addition, the version of APSIM used included the CANOPY model for calculating shade, which was shown to be flawed; as the model assumes competing canopies are well mixed in the horizontal dimension, it could not deal with one crop occurring in the relay intercropping (i.e. adjacent to) wheat or maize and was in need of a 2D model to adequately simulate such systems. Our results, however, confirm that further development and validation of the APSIM maize model is needed at shade levels greater than 50%. This result suggests that there is probably a need to improve the mechanistic processes simulated in APSIM governing the responses to >50% shade. Key processes to consider would be radiation-use efficiency (RUE) and biomass allocation. For example, APSIM uses the RUE of maize to calculate daily biomass production; the model uses an RUE value of 1.6 g MJ^{-1} from emergence to the start of grain-filling, and 1.06 g MJ^{-1} from the start of grain filling. Lott et al. (2009) estimated RUE in a shaded and unshaded treatment at Machakos (separate to the experiment reported here) to be 1.04 and 0.88 g MJ^{-1}, respectively. However, the low precision with which RUE can be estimated may cause uncertainty about the accuracy of model simulations (Lindquist et al. 2005).

In contrast, where other species have been shaded, several studies have revealed the reliable performance of APSIM to capture the impacts of competition for light, water and nutrients in row-intercropped systems. For instance, Robertson et al. (2001) reported reasonable performance of the APSIM model in simulating competition for light, nutrients and water between canola and wild radish species in an experiment conducted in New South Wales, Australia. APSIM also performed credibly in predicting yield, biomass and LAI of maize and intercropped Stylosanthes in Maize/Stylosanthes intercropping systems in Northern Australia (Carberry et al. 1996). This implies good performance by the model in predicting the effects of competition for light, nutrients and water on crop growth. Nevertheless, the present study showed that maize yield was underestimated at very low radiation levels.

Competition for solar radiation is one of the key components in agroforestry systems, as shade cast by trees reduces the amount of radiation reaching understory crops. The modular frame work of APSIM could be utilised to simulate such competition interactions in those systems (Luedeling et al. 2016). However, the present study suggests the need to consider the low predictive capability of APSIM to simulate the responses of crops to high reductions in incident radiation. Unlike most agroforestry systems, *Faidherbia albida* parklands are reported to exhibit low competition for light because of the reverse phenology (lack of leaves during the wet cropping season) (Barnes and Fagg 2003; Kho et al. 2001). A study conducted by Suresh and Rao (1998) showed that reductions in incident radiation under *Faidherbia albida* was less than 28% during the cropping season of 1993 (June to September). Light competition could also be minimised by pruning (Osman et al. 1998; Semwal et al. 2002; Siriri et al. 2010). Thus, APSIM could be employed to simulate impacts of light competition on understory crop production, in agroforestry systems where low-medium competition for light occurs, e.g. in much of the *Faidherbia albida* parkland of Ethiopia. However, this study did not explore the effects of competition for water and nutrients and the CANOPY model used in APSIM may require further improvements to accommodate the competition effects (Knörzer et al. 2011) that occur in agroforestry systems.

Conclusion

The present study concludes that APSIM was able to simulate grain yield and biomass of maize adequately when incident radiation was reduced by 50% or less. These results show promise that the model could be used to simulate agroforestry systems such as *Faidherbia albida* parklands where incident radiation is reduced by less than 50%. However, the model may require further improvement for higher levels of shading before it can be used to simulate agroforestry systems with higher light competition due to shading of understory crops by trees. Similar experiments in the future should eliminate side light as a source of measurement error. The ability to model agroforestry crop productivity is likely to enable many climate scenarios to be explored, which can inform management of these agroforestry systems.

Based on this experience, we make the following recommendations for improving experimentation and modelling of heavily shaded conditions, with negligible competition for other resources such as soil nutrients and water:

(1) Use large buffers of shade cloth to avoid sidelight affecting growth in the inner measurement plots;

(2) Conduct diurnal light measurements in a 2D vertical grid to potentially detect sidelight and characterise the light conditions of the plot;
(3) Estimate RUE and biomass allocation in relation to shade level; and
(4) Modify APSIM where necessary.

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