Long-term experimental data and crop modelling to inform the ecological intensification of irrigated wheat production in South Africa

S Magwaza[1], M van der Laan[1,2], D Marais[1]

[1]*Department of Plant and Soil Sciences, University of Pretoria, Private Bag X20 Hatfield, Pretoria 0028, RSA*

[2]*Agricultural Research Council-Natural Resources and Engineering, Private Bag X79 Pretoria, 0001, South Africa*

Corresponding author email: magwazasiboniso91@gmail.com

ABSTRACT

Wheat (*Triticum aestivum* L.) production is threatened by climate change and the decline in agricultural land available due to urbanisation, farmers switching to other crops, and environmental degradation. The aim of this study was to investigate the ecological intensification (EI) of irrigated wheat production in South Africa. Data from the University of Pretoria's long-term wheat trial and an intensive growth analysis conducted in 2019 were used to calibrate and evaluate the APSIM model. Following adequate model performance, improved management scenarios, including crop rotation, manure application, optimised inorganic nitrogen (N) fertiliser application rate, objectively scheduled irrigation, and combining all these improved management practices together were tested. The adoption of all management practices simultaneously was the best practice and achieved an increase of 18% in yield and reduced deep drainage and N leaching by 31%. Whereas measured data indicated a decrease in soil organic matter (SOM) from 1.20% in 1950 to 0.58% in 2019, adopting EI measures could reduce the loss of SOM to only 0.68%. Farmers are

encouraged to adopt one or more of these EI management practices as their site-specific situations allow.

Keywords: APSIM model, deep drainage, fertiliser, grain yield, N leaching, soil organic matter,

1. INTRODUCTION

Due to the projected increase in the world's population to up to 9.6 billion people by 2050 (Searchinger et al. 2014), agricultural production will need to be increased. This may be achieved by increasing yields through optimising management practices, such as improved irrigation scheduling and the use of improved varieties. Intensifying crop production has been highly successful in raising food output over the years, but Pingali et al. (1997) Peng et al. (2010), such as, observed that it has also come with substantial growing environmental changes and financial costs. For example, continuous excessive use of inorganic fertilisers and other agrochemicals resulted in detrimental soil impacts, such as soil acidification, as well as offsite environmental pollution. These impacts can be mitigated by the practice of ecological intensification (EI). The system of EI is described by Adhikari et al. (2018) as a strategy to increase and optimise agricultural production per unit of inputs through better utilisation of resources [for example labour, land, time, seeds nutrients or fertiliser, carbon dioxide (CO_2) and solar radiation]. Ecological intensification is different from climate smart agriculture (CSA) which is distinguished by the focus on climate change, explicitly addressing adaptation and mitigation challenges while working towards food security for all.

The soil is a very dynamic system and soil health is fundamental for sustainable agriculture. One of the major worldwide issues in agricultural soils is nutrient depletion due to nutrient mining, soil degradation and poor nutrient cycling practices (Lal 2009). A soil of low quality cannot be productive, therefore, improving and maintaining the ideal chemical, physical and biological properties for crop production is imperative (Diacono and Montemurro 2011).

Fertilisers are the largest input introduced in modern agriculture for improved crop production. Nutrients applied as inorganic fertilisers are the primary macronutrients (N), phosphorus (P), and potassium (K). Nitrogen is the nutrient required in the largest quantities to increase vegetative growth for high yields. However, the right amount of N should be applied at the right time to optimise efficiency and reduce losses that could lead to environmental pollution and this remains a challenge (Jan et al. 2007, Ragheb et al. 1993). In addition to increasing the yield, using fertilisers may also increase SOM accumulation and biological activity in agriculture systems; in turn, this improves SOC content (Rasmussen and Collins 1991).

Organic matter provides nutrients [nitrogen (N) to produce proteins and carbon (C) containing organic compounds as a source of energy] to the microorganisms. Retaining plant residues to soils maintain soil organic matter (SOM) levels, which improves the water holding capacity of the soil (Maynard 2000, Pan et al. 2009). Soils with higher SOM have increased cation exchange capacity (CEC) thus more essential plant nutrients are held by the soil particles and protected from leaching (McCauley Ann 2017).

Wheat (*Triticum aestivum* L.) is the most important crop after maize (*Zea mays* L.) from a food security perspective in sub-Saharan African (SSA) (Tadesse et al. 2019).

It was historically not a leading staple crop in this region, but due to population growth, changes in diet, and urbanisation, the demand has increased rapidly (Tadesse et al. 2019). Despite the increasing demand for wheat in the SSA region, a decrease in production has been observed in South Africa due to competing land uses from other agricultural commodities (Dube et al. 2020). An estimated 740 000 tonnes reduction in annual production was recorded between 2002 and 2012 in South Africa, which necessitated an average of 1 million tonnes per year being imported from other countries (Dube et al. 2020). An increase in production can be achieved by expanding the area under cultivation or increasing yield on the same amount of land. Since there is always competition with other crops in terms of profitability, increasing yield through EI is an important option. Crop rotation, conservation tillage and retaining plant residues for soil cover as the pillars of conservation agriculture have been of specific interest to farmers to explore improving yields. But factors such as market price fluctuation, profitability and the need to use more intensive tillage to address, soil compaction and prepare fields for the next crop, limited availability of water crop rotation needs, and other factors can be barriers to the adoption of improved management.

Long-term trials can play an important role in helping us understand the effects of different crop management practices and help inform profitable food production while minimising impacts on the environment. Most of these trials are found in North America and Europe, with a few in Africa and South America (Steiner 1995). These experiments were generally initiated to provide information on the types, forms and amount of fertilisers that achieve the highest yields (Johnston and Poulton 2018). Over the years, however, new research objectives have often been developed for these experiments to justify their continuation without compromising the initial aims.

New objectives may include a better understanding of SOM dynamics and the effects of weeds, pests and diseases. The data obtained from these trials can also be very useful to researchers to develop models of long-term processes (Hmielowski 2017), and help provide information on how to manage and avoid the consequences of climate change and natural hazards, while also reducing offsite impacts such as eutrophication (Jolánkai et al. 2010).

Crop models have been successfully used to predict and explain the observations from long-term fertilization practices in cropping systems (Keating et al. 2003). The use of these models can especially help facilitate the development of new crop management approaches and promote sustainable agricultural practices. Process-based example the Agricultural Production Systems sIMulator (APSIM), can simulate crop growth, yield and yield gaps, soil water relations and soil nutrient cycling (Keating et al. 2003, Zhang et al. 2018). APSIM is a mechanistic model that has demonstrated good performance for different cropping systems (Gaydon et al. 2017), and is well documented and widely used in Australia and some parts of Africa.

In South Africa, there is lack of information on how to achieve EI in improved wheat production. The aim of this study was to (i) conduct a detailed wheat growth analysis to parameterise the APSIM model for the site, (ii) to calibrate and test the simulated yield and SOM dynamics using historical observed yield and weather data and (iii) explore the EI of wheat production through testing different improved management practices. The results from this work can benefit farmers and policy makers with understanding the impacts of adopting specific practices.

2. MATERIALS AND METHODS

2.1 Trial location and climate

This study was carried out at the long-term field trial section at the University of Pretoria's Hillcrest Campus Experimental Farm, (25.45° S, 28.16° E 1372 m above sea level). The soil is classified as a sandy loam of the Hutton form which belongs to the Suurberkom Family (Soil Classification and Working Group, 1991). The following climate summary is taken from Carmichael et al. (2017); annual rainfall for Pretoria is approximately 700 mm (standard deviation +/-180 mm) with about 80% of the rain falling during the summer months between October and March. The average annual pan evaporation is approximately 2000 mm, and the site has an aridity index of 0.30 - 0.35. The Koppen Geiger Classification for this region is Cbw (warm temperature, winter dry and warmer summer).

2.2 Experimental design and treatments

The experiment is laid out in a randomized complete block design. Marais (1948) reported that between 1921 and 1938, before the initiation of the experiment, the field was under irrigated winter wheat and summer soybean (*Glycine max* L.) production with zero fertiliser application. The official trial was started in 1939 to help in advising producers on the use of nitrogen (N), phosphorus (P) and potassium (K) fertilisers, manure and irrigation in a wheat-soybean rotation. All the wheat treatments received irrigation as it is a winter crop. The treatments were made in combinations of N/ P/ K, and manure (M), which resulted in a total of 32 treatments with four replications leading to 128 plots (Marais 1948). The rotation with soybean was discontinued in 1999, with a fallow period replacing the soybean crop.

Fertiliser was broadcast before planting, and additional N was applied to the full NPK treatment as top dressing from 1985–2004. Nitrogen was initially applied as ammonium sulphate ($(NH_4)_2SO_4$) (1939-1965), and later in the form of ammonium nitrate (NH_4NO_3) (1966-1983) (Belay et al. 2002), but in recent years to date, it is applied in the form of limestone ammonium nitrate (LAN). Phosphorus is applied in the form of superphosphate ($Ca(H_2PO_4)_2$) and potassium (K) as potassium chloride (KCl). The historical fertiliser application in the different treatments has been changing over time in response to soil analysis results, which have shown the accumulation of some nutrients to high levels (Table 1).

Table 1: Nitrogen (N), phosphorus (P) and potassium (K) applied in the different treatment combinations between 1939 and 2019.

Treatment	Explanation
Control	No fertiliser added since 1939
NP	Received N and P since 1939, but P was discontinued in 1989 due to build-up of P levels >60 mg P kg^{-1} (Bray II). Received 100 kg N ha^{-1} from 1939-1991 and 116 kg N ha^{-1} from 1992-2019.
PK	Received P and K since 1939, but P was discontinued in 1989. Received 100 kg K ha^{-1} from 1939-2019.
NK	Received N and K since 1939. Received 100 kg N ha^{-1} N from 1939-1991, 116 kg N ha^{-1} from 1992-2019, and 100 kg K ha^{-1} from 1939-2019.
NPK	Received N, P, and K since 1939, but P was discontinued in 1989. Received 100 kg N ha^{-1} from 1939-1991, and 116 kg N ha^{-1} from 1992-2019 and 100 kg K ha^{-1} from 1939-2019.

2.3 APSIM model overview

The Agricultural Production Systems sIMulator (APSIM) is a process-based model containing different modules that enables the simulation of a wide range of animal, plant, climate, soil, and management scenarios. The model initialised for this study contains five modules namely: the crop (WHEAT) module that simulates the period from emergence to maturity, the soil water (SOILWAT) module, predicting water movement using a multi-layer, cascading approach (Asseng et al. 1998), the SURFACEOM module that describes the soil surface crop residue cover dynamics and tillage based on PERFECT approaches (Probert et al. 1998), and The SOILIN module that defines the dynamics of C and N in soil.

2.3.1 Model input data

Weather data

Weather data (maximum and minimum temperature, solar radiation, wind speed and rainfall) from 1950-1983 was obtained from the South African Atlas of Climatology and Agro Hydrology developed by the School of Bio-resources Engineering and Environmental Hydrology at the University of KwaZulu-Natal, and from 1984-2000, data was obtained from the South African Weather Service (Maseko et al. 2022). Weather data from 2001-2019 were obtained from an automatic weather station adjacent to the field (Maseko et al. 2022). To test for homogeneity, average annual data from 1950 to 2019 was tested using XLSTAT (XLSTAT 2007). For the maximum temperature a shift was observed in 2009 from an average of 24.62 ^{0}C to 26.86 ^{0}C), and a much smaller shift for minimum temperature in 1995 from 10.89 ^{0}C to 11.47 ^{0}C. Table 2 shows the homogeneity test statistics with computed p-values

(0.0006 maximum temperature and 0.0002 minimum temperature) lower than the significant alpha=0.05. These statistics reveals that, there is a date at which there is a change in the data. These shifts, however, did not coincide with the years at which separate weather datasets were linked. Since the shift was for data from an automatic weather station that was not moved and for which the metadata is available, it was decided this was still the best weather data to use. Average annual rainfall showed no changes in data from the XLSTAT homogeneity test, which means that, the data were homogeneous. Solar radiation data was generated using the method of Bristow and Campbell (1984). The equation estimates solar radiation as a function of the difference between the minimum and maximum temperatures, and estimations of the sun's position relative to the point of interest on the earth's surface calculated by the Julian day. According to a study by Dhanya et al. (2013) on the four models (Bristow-Campbell, Hargreaves, Richardson, and Goodin) that estimate global solar radiation in relation to air temperature, the Bristow-Campbell model was the most precise in estimating global solar radiation because it had a high D-index value of 0.90 and the lowest RMSE of 2.40 MJ m^{-2} day^{-1} when compared to the other three models. To monitor irrigation volumes (determined by the Experimental Farm manager), rain gauges were installed on selected plots.

Table 2: Homogeneity test statistics for maximum temperature (MaxT), minimum (MinT) temperature and average rainfall.

Pettitt's test	MaxT	MinT	Average rainfall
K	645	744	216
t	2008	1989	1965
p-value (Two-tailed)	0.0006	0.0002	0.5642
alpha	0.05	0.05	0.05

Soil data

On May 15, 2019, five soil samples were collected from each of the plots used in this simulation study (control and NPK treatments) and mixed to be representative of the whole plot for nutrient analysis in the laboratory. Other samples from an adjacent, undisturbed site were taken for analysis to represent the initial soil conditions of the trial (Maseko et al. 2022). The samples were taken at 0-0.05 m, 0.05-0.1 m, 0.1-0.3 m and 0.3-0.6 m depths. Soil chemical analysis was done to determine soil pH (H_2O) (Schofield and Taylor 1955) and organic C (Walkley-Black method) (Walkley 1935) (Table 3).

Table 3: Soil parameters used in APSIM for the University of Pretoria Hillcrest Campus Experimental Farm long-term trial.

Soil Layer (m)	OC (%)	BD (Mg m^{-3})	SAT (m^3 m^{-3})	DUL (m^3 m^{-3})	LL15 (m^3 m^{-3})	pH (H_2O)	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	K_s (mm day^{-1})
0.00–0.15	1.6	1.48	0.43	0.24	0.16	6	60	80	500
0.15–0.30	0.7	1.48	0.43	0.29	0.2	6	60	80	1000
0.30–0.60	0.5	1.46	0.43	0.33	0.23	6	60	80	1000
0.60–0.90	0.4	1.45	0.43	0.33	0.23	6	60	80	500
0.90–1.20	0.4	1.46	0.43	0.33	0.23	6	60	80	500

OC= organic carbon; BD= bulk density; SAT= saturated volumetric water content; DUL= drained upper limit; LL15= lower limit. and K_s= saturated hydraulic conductivity.

Growth analysis

For the detailed growth analysis, dry matter production (determined after oven-drying the plant material at a temperature of 70℃ for 72 hours), and leaf area index (LAI) were recorded over the season. Fourteen plants were harvested per plot every two weeks. Leaf area index (LAI) was determined by using a Decagon sunfleck ceptometer (Pullman, Washington,USA), and was measured around midday when there were clear skies. With this method, two reference readings were taken above the wheat canopy and five readings at ground level. Soil volumetric water content (VWC) was monitored weekly using a neutron probe (IntroTek International, New York, USA). Three access tubes were installed in each treatment plot (control and full NPK) and measurements were made at 0.2 m depth increments up to a depth of 1.0 m.

2.3.2 Model set-up

The APSIM model was set-up to have tillage taking place on 1 April, using a disc plough. The seedbed was prepared to a depth of 0.3 m, with 90% of surface residues incorporated into the soil during ploughing. The plant spacing used for the calibration was 0.3 m between rows and 90 seeds per m^2, which gives a planting density of 900 000 plants ha $^{-1}$. The planted cultivar, PAN 3497, was not in the APSIM cultivar database so was adapted by altering thermal parameters of the 'Shatabdi' default cultivar as shown in Table 4. An average of 10 mm irrigation was applied twice a week on Mondays and Thursdays using sprinkler irrigation with an assumed irrigation uniformity of 90%. The full fertiliser NPK plots were simulated to be fertilized with LAN at a rate of 100 kg N ha^{-1} from 1939-1991 and 116 kg N ha^{-1} from 1992-2019. No N fertiliser was applied to the control treatment, and P and K were not considered in the simulation.

Table 4: APSIM calibration parameters for wheat PAN 3497 cultivar.

APSIM label	Definition	Value	Unit
Grains_per gram_stem	Kernel weight per stem at the beginning of grain filling	34	g
Potential_grain filling_rate	Potential daily grain filling rate	0.006	g $grain^{-1}$ day^{-1}
Potential_grain growth_rate	Grain growth rate from flowering to grain filling	0.0022	g $grain^{-1}$ day^{-1}
Max_grain_size	Maximum grain size	0.035	g
tt_start_grain_fill	Thermal time from start grain filling to maturity	500	°C days
tt_floral_initiation	Thermal time from floral initiation to flowering	450	°C days
tt_flowering	Thermal time needed in anthesis phase	110	°C days
tt_end_of_juvenile	Thermal time needed from sowing to end of juvenile	340	°C days
Vern_sens	Sensitivity to vernalisation	2.2	-
Photop_sens	Sensitivity to photoperiod	0	-
Flowering_day	Flowering day after sowing	81	day
Maturity_day	Maturity day after sowing	136	day
Grain_filling	Number of days	55	day
RUE	Radiation use efficiency	1.84	g MJ^{-1}

The soil profile was created using one of the templates from a 'Hutton soil' in the APSoil database. The soil properties parameterised were lower limit water content at 15 bars matric pressure (LL15), drained upper limit (DUL), saturation (SAT), bulk density (BD), organic carbon (OC), and soil pH (H_2O) determined from a soil chemical analysis in 2017 (Maseko et al. 2022). Initial nitrate-nitrogen (NO_3-N) and ammonium nitrogen (NH_4-N) were based on Maseko et al. (2022). Soil water conductivity (SWCON) (drainage coefficient) was set to 0.7 and assumed to be equal for all the depths. The first and second (CONA) stage soil evaporation was kept at 3.5. Soil hydraulic conductivity was measured using a dual-head infiltrometer

(Decagon Devices, Inc. 2365 NE Hopkins Court Pullman WA 99163) and used to parameterise saturated hydraulic conductivity (K_s).

2.4 Testing model performance

Soil VWC, LAI, total above-ground dry matter (TDM), grain yield and N content measurements were used to calibrate (full NPK treatment data) and test (control treatment data) the model for the 2019 growing season. Statistical analyses were performed to objectively compare the measured and simulated values. De Jager (1994) recommended using the square of the correlation coefficient (r^2), which measures the relationship between the simulated and measured data, mean absolute error (MAE), which determines average error, Wilmers index of agreement (D), which shows the size of the difference, and root mean square error (RMSE), summarizing the overall error. Achieving r^2 and D values above 0.8 and MAE less than 20%, indicates that the model is performing well. A low RMSE value for each set of data shows accurate model performance. Yield from 1990 - 2019 was used to test the model's performance. Historical SOM data was not available for the wheat trial from 1939 as it was not measured from the beginning. Initial SOM content for 1950 was therefore estimated using soil samples from an undisturbed site adjacent to the trial. The samples were collected and analysed at the end of the 2016/2017 cropping season.

Table 5: Statistical evaluation of measured and simulated volumetric water content in the control treatment.

Depth (m)	r^2	D	MAE (%)	RMSE (m3 m^{-3})
0.20	0.71	0.91	0.80	0.003
0.40	0.78	0.93	1.75	0.005
0.60	0.63	0.83	2.81	0.009
0.80	0.38	0.78	3.43	0.008
1.00	0.44	0.79	2.78	0.005

Table 6: Statistical evaluation of measured and simulated volumetric water content in the full NPK fertiliser treatment.

Depth (m)	r^2	D	MAE (%)	RMSE (m^3 m^{-3})
0.20	0.80	0.87	1.27	0.005
0.40	0.61	0.81	2.09	0.003
0.60	0.46	0.78	1.15	0.002
0.80	0.64	0.19	2.04	0.004
1.00	0.44	0.79	2.78	0.005

2.5 Long-term EI management scenarios

Different EI management scenario simulations were simulated from 1950 to 2019, with full NPK fertiliser application under monoculture treatment receiving 116 kg ha^{-1} as a benchmark, and then compared to the improved crop production practices. The application rates for manure and increasing fertiliser application were decided after the model was run several times to identify the optimal rates at which growth was not N-limited. A wheat-soybean rotation was selected based on the history of the wheat trial showing that soybean is a feasible rotation crop. Measured data for long-term soybean production was, however, not available to compare with the simulated yield from the model. Soil water deficit (SWD) irrigation was used and triggered when a deficit of 10 mm was reached. The management practices simulated are shown in Table 7.

Table 7: Treatments simulated for the wheat trial at the University of Pretoria's Hillcrest Campus Experimental Farm.

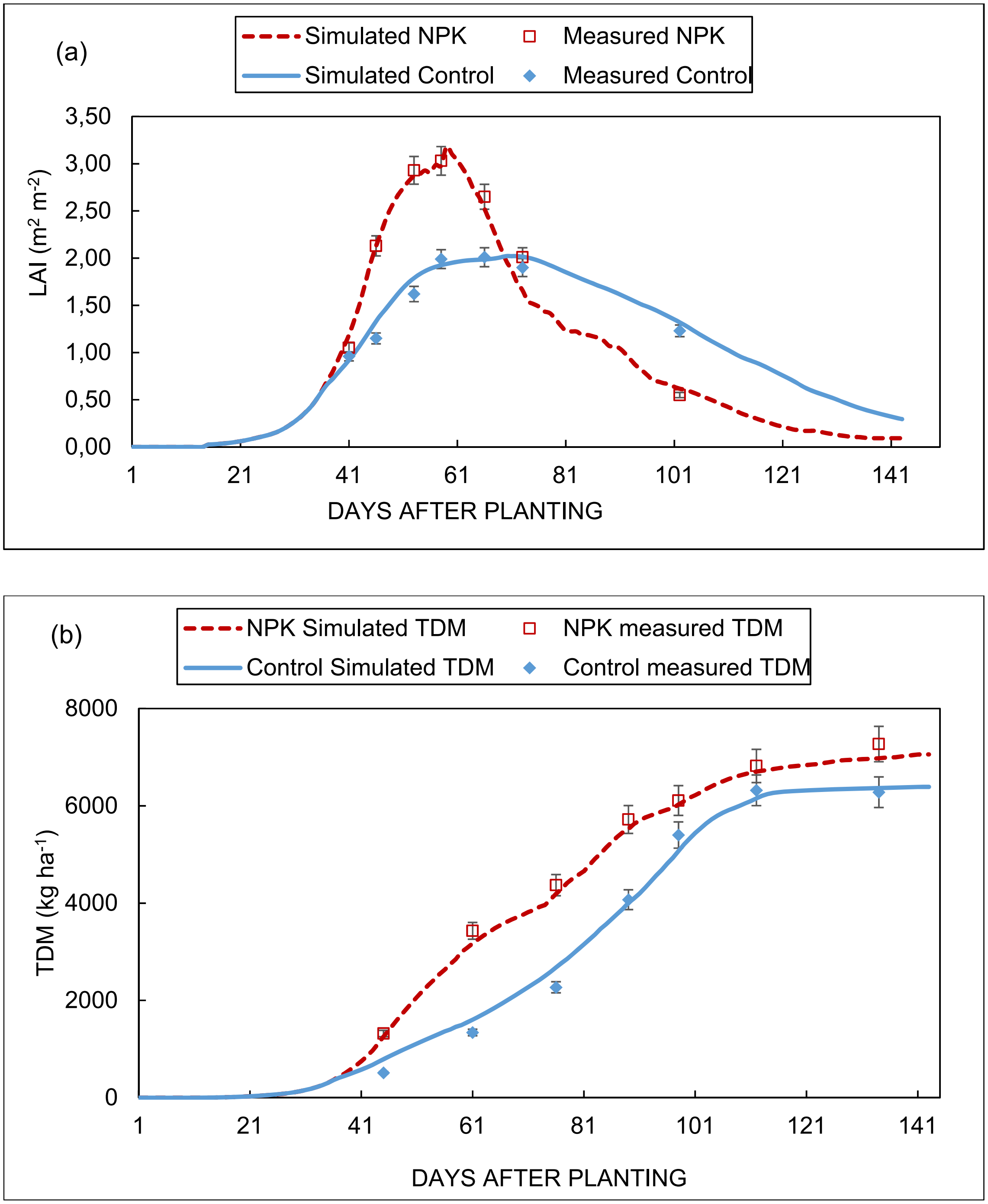
Code	Treatments
S	Standard treatment - wheat monoculture fertilised with 116 kg N ha^{-1}
F+M	Wheat monoculture fertilised with 116 kg N ha^{-1} and 8 t ha^{-1} manure
WSOR	Wheat-soybean rotation. wheat fertilised with 116 kg N ha^{-1}
F150+D	Wheat monoculture fertilised with 150 kg N ha^{-1} and irrigated at soil water deficit (SWD) of 10 mm
MRSO150	Combination of wheat-soybean rotation. 8 t ha^{-1} manure. 150 kg N ha^{-1} and irrigation at SWD of 10 mm

3. RESULTS

3.1 Model parameterisation and validation

The model simulated LAI (Figure 1a), total above-ground dry matter (TDM) production (Figure 1b) and grain yield (Figure 1c) well in the 2019 season for both the full fertiliser NPK and control treatments. Leaf area index for both treatments had the same trend until 36 days after planting (DAP), whereafter the full fertiliser NPK treatment showed a sharp increase in LAI and reached a peak of 3.1 m^2 m^{-2} at 59 DAP, while the control treatment steadily increased but only reached a peak of 2.0 m^2 m^{-2} at 73 DAP. Model performance was very good for both the full fertiliser NPK and the control treatments, as r^2 and D values were all above 0.80. The NPK treatment LAI estimates had 4.6% MAE and 0.14 $m^2 m^{-2}$ RMSE, while the control treatment had 6.2% and 0.13 $m^2 m^{-2}$ MAE and RMSE, respectively. At harvest (143 DAP) in the NPK treatment, simulated TDM was 7 057 kg ha^{-1} and the measured value was 6 850 kg ha^{-1}. For the control treatment, the model simulated 6 390 kg ha^{-1}, while 6 465 kg ha^{-1} was measured. All the statistical model performance criteria were met for TDM for both treatments (r^2 values of 0.99 and 0.98, D values of 1 and 0.98, MAE values of 4% and 8%, and RMSE of 258 kg ha^{-1} and 398 kg ha^{-1}, respectively). For the 2019 growing season, measured grain yield for the full fertiliser NPK treatment was increased by 9% when compared to the simulated treatment. The control measured yield was 1 232 kg ha^{-1} and the estimated was 2012 kg ha^{-1} (38% less than the simulated yield).

For VWC, the control treatment generally had higher soil water content levels than the full NPK fertiliser treatment at all soil depths. For the full fertiliser NPK treatment, only the top 0.20 m met the statistical criteria (r^2 = 0.80, D = 0.87), while the deeper layers all had r^2 and D below the acceptable threshold of 0.80 (Table 6). The r^2 values for VWC in the control treatment ranged from 0.44 to 0.71, while D values in the 0.20 m, 0.40 m and 0.60 m were, 0.91, 0.93 ,0.83, respectively (Table 5). Overall, the model was able to simulate VWC trends well, as the MAE values for all the layers were below 20%. Root mean square error values were also low for both treatments with a higher precision being achieved in the full fertiliser NPK treatment. These values show good calibration and performance of the model.


(a)
Simulated NPK
Measured NPK
Simulated Control
Measured Control
LAI (m² m⁻²)
3,50
3,00
2,50
2,00
1,50
1,00
0,50
0,00
1
21
41
61
81
101
121
141
DAYS AFTER PLANTING
(b)
NPK Simulated TDM
NPK measured TDM
Control Simulated TDM
Control measured TDM
TDM (kg ha⁻¹)
8000
6000
4000
2000
0
1
21
41
61
81
101
121
141
DAYS AFTER PLANTING

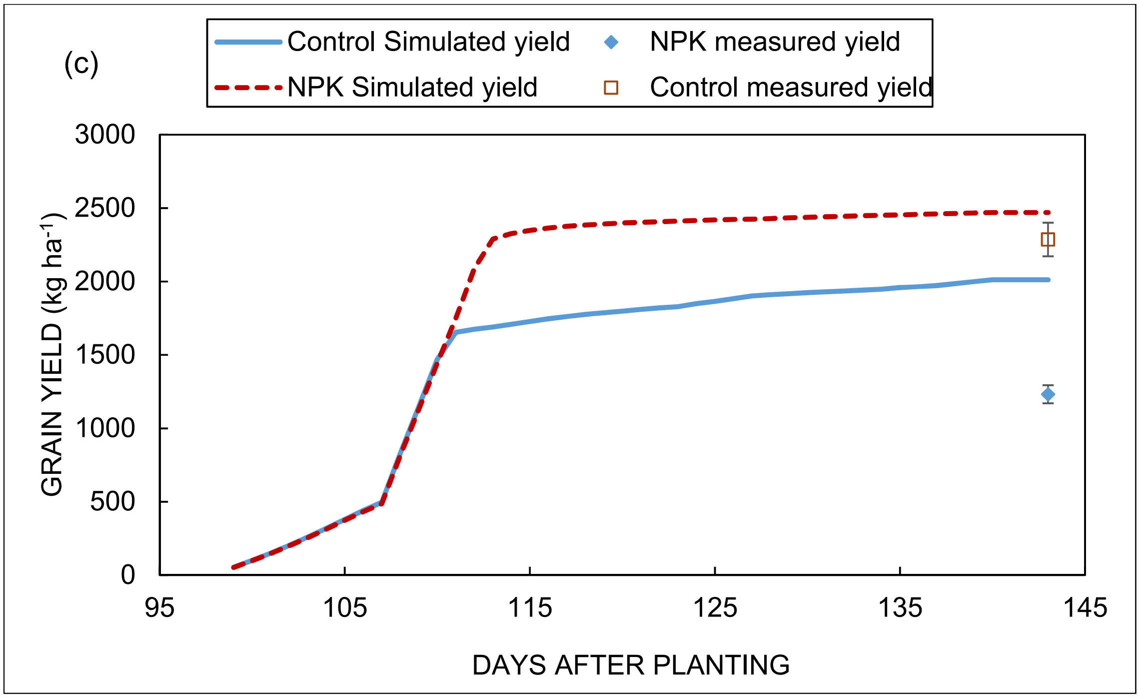


Figure 1: Measured and simulated leaf area index (LAI) (a), total above-ground dry matter (TDM) (b) and grain yield (c) in the control treatments and full fertiliser NPK treatments.

3.2 Long-term fertilisation effects

Wheat grain yields

The zero fertiliser treatment data set from 1990-2019 was used to test the model's performance in simulating long-term scenarios. The full fertiliser NPK fertiliser treatment had constantly higher yields than the zero fertiliser treatment for both the simulated and measured data, as expected (Figure 2). For some seasons, the model over-estimated yields in the NPK treatment, especially from 2008 until 2012. For the zero fertiliser treatment, an under-estimation was observed more often than an over-estimation. Despite that, the model's performance was judged to be good overall. This was indicated by r^2 values of 0.86 and 0.63, D values of 0.93 and 0.85, MAE values of 4% and 6%, and RMSE values of 182 kg ha^{-1} and 549 kg ha^{-1}, for the zero

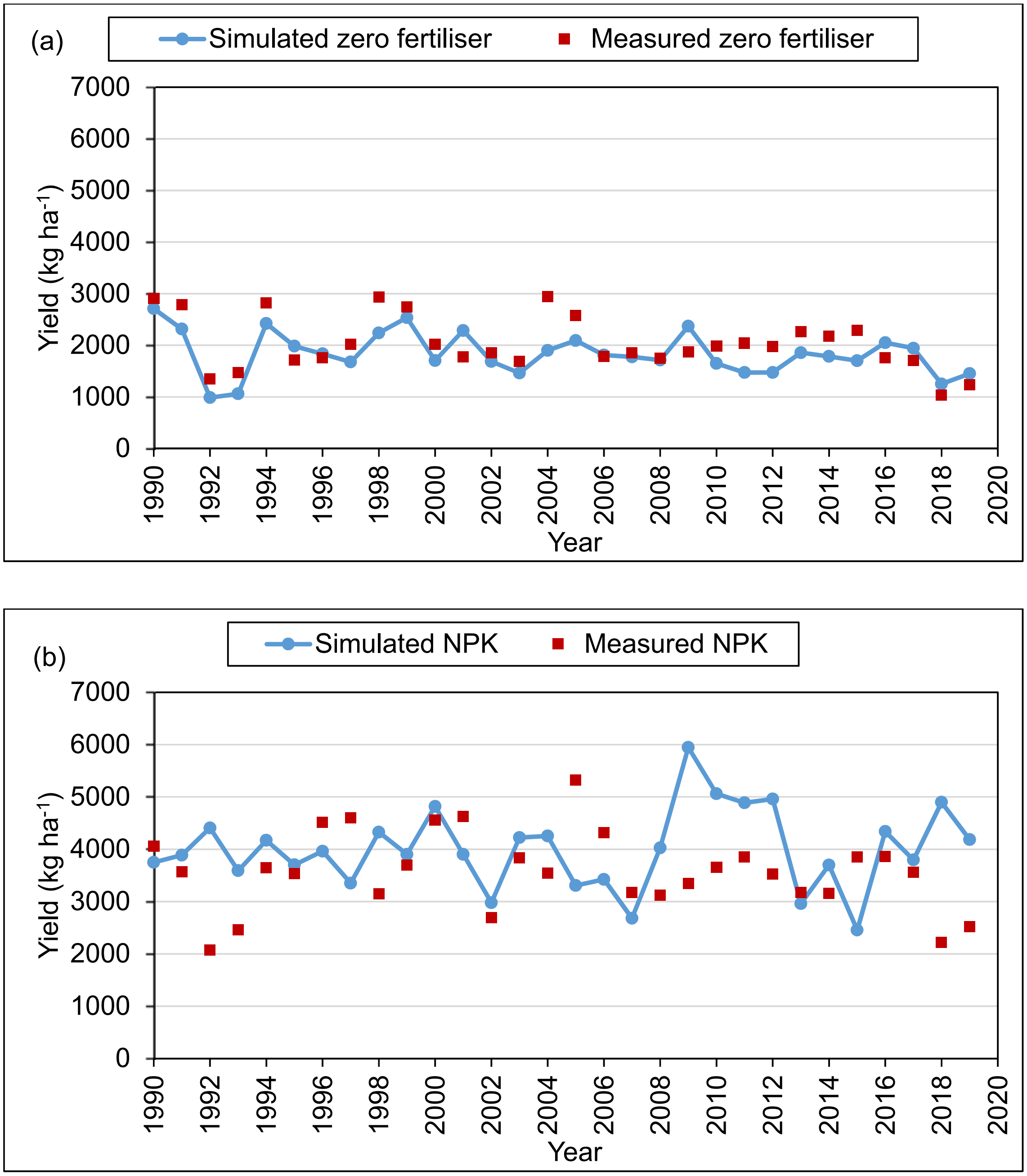


Figure 2: Measured and simulated wheat grain yields for the zero fertiliser (a) and full fertiliser NPK (b) treatments from 1990 to 2019.

and full NPK fertiliser treatments, respectively. The last two years of the measured treatments recorded a decline in yield for both treatments. This was caused by low rainfall received resulting to low soil moisture content simulated by the model in the year 2018 and 2019. From 2007-2013 the measured NPK treatment values were 30% lower than the simulated NPK treatment, while the zero fertilisation treatment measured values were 18% higher than the simulated from 2010-2015. The differences might have caused by soil fertility changes and changing of tillage which the model did not capture.

Soil organic matter content

The model simulated SOM decline well for both treatments, with the zero fertiliser treatment showing greater SOM loss than the full fertiliser NPK treatment for both simulated and measured instances (Figure 3). Soil organic matter for the simulated and measured treatment was reduced from 1.20% in 1950 to 0.52% and 0.48% in 2019, respectively. For the full fertiliser NPK treatment, measured and simulated SOM was also reduced from 1.20% in 1950 to 0.58% and 0.57% in 2019, respectively. Fertiliser application therefore increased organic matter levels by 13% for the fertiliser treatment. It must be noted that only two measured points could be used for comparison, however, at the initiation of the trial, and at the end of the 2019 production season.

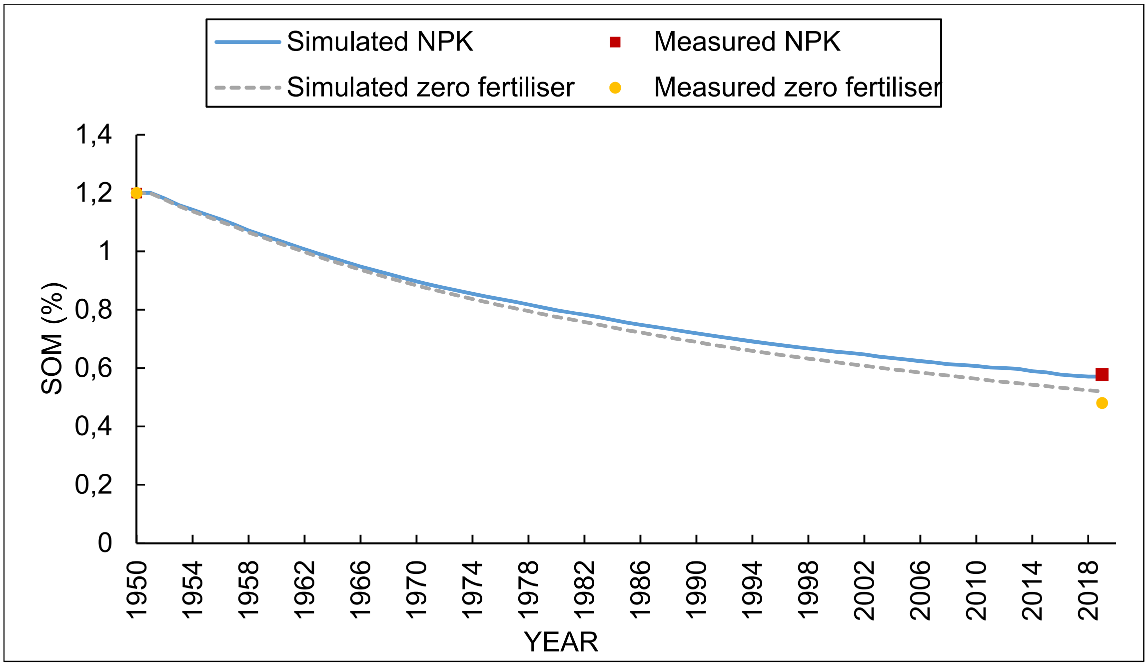


Figure 3: Measured and simulated soil organic matter (SOM) content to a 0.6 m soil depth for the zero fertiliser and full fertiliser NPK treatments.

Deep drainage and nitrogen leaching

The model simulated average deep drainage of 231 mm year^{-1} in the zero fertiliser treatment compared to 211 mm year^{-1} for the full fertiliser NPK treatment. This was a result of more root water uptake by the better growing fertilised crop reducing drainage water losses. Despite higher drainage in the control treatment, the amount of N leached was low when compared to the full fertiliser NPK treatment. The full fertiliser NPK treatment was estimated to have lost 2 952 kg N ha^{-1} since 1950, an average of 42 kg ha^{-1} year^{-1} (Figure 4). This estimation was more than double the zero fertiliser treatment, which was simulated to have an average loss of 19 kg N ha^{-1} year^{-1}.

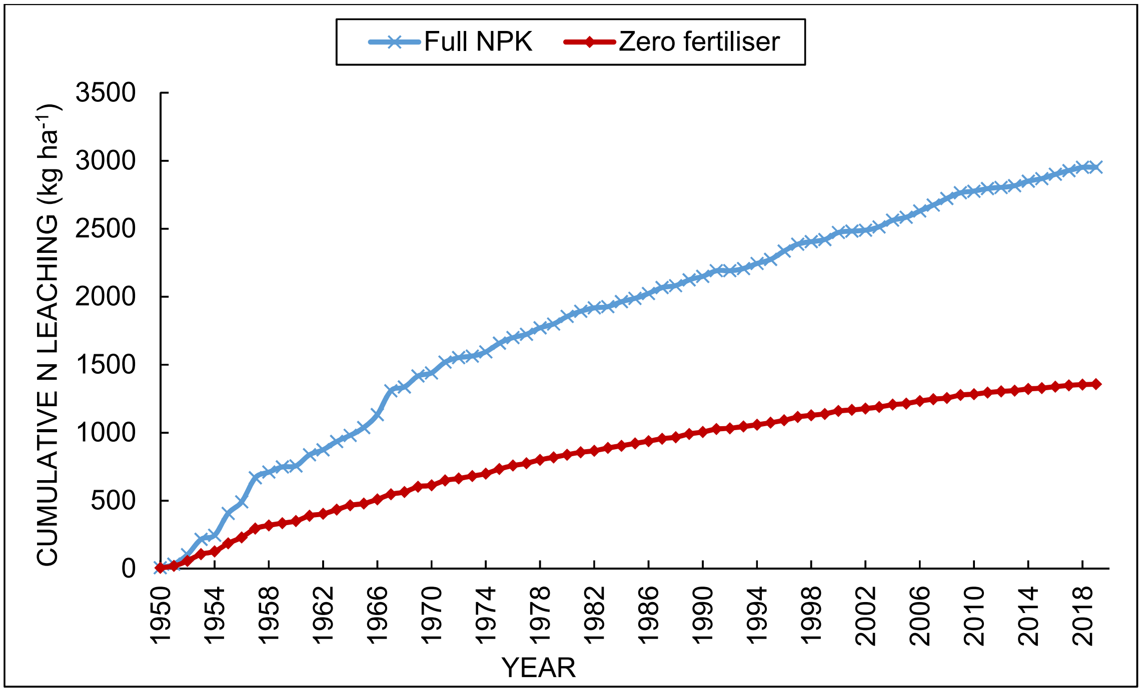
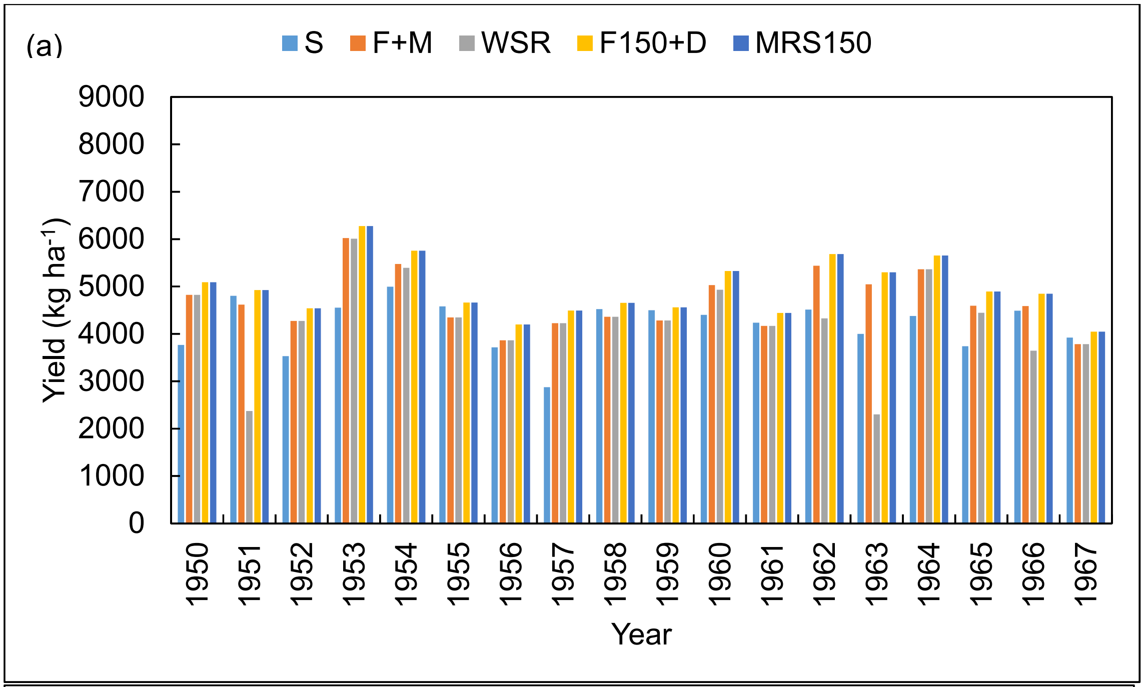
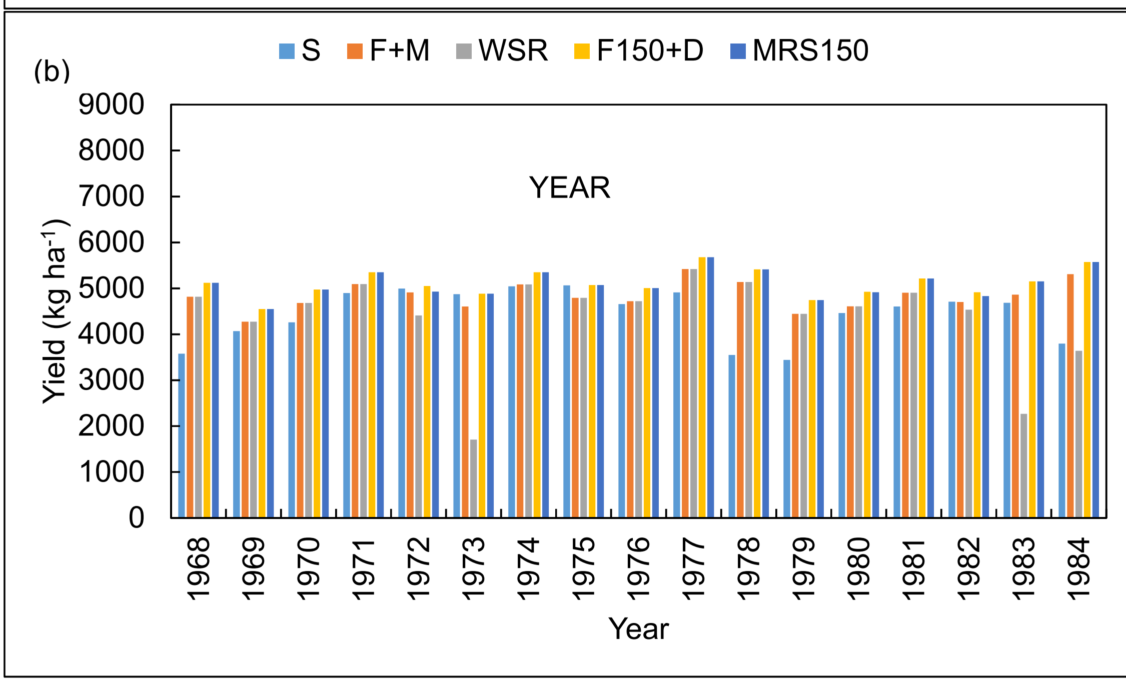


Figure 4: Cumulative nitrogen (N) leaching for the 1950 to 2019 simulation period in the zero fertiliser and full fertiliser NPK treatments.


(a)
S
F+M
WSR
F150+D
MRS150
Yield (kg ha-1)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
Year


(b)
S
F+M
WSR
F150+D
MRS150
YEAR
Yield (kg ha-1)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
Year

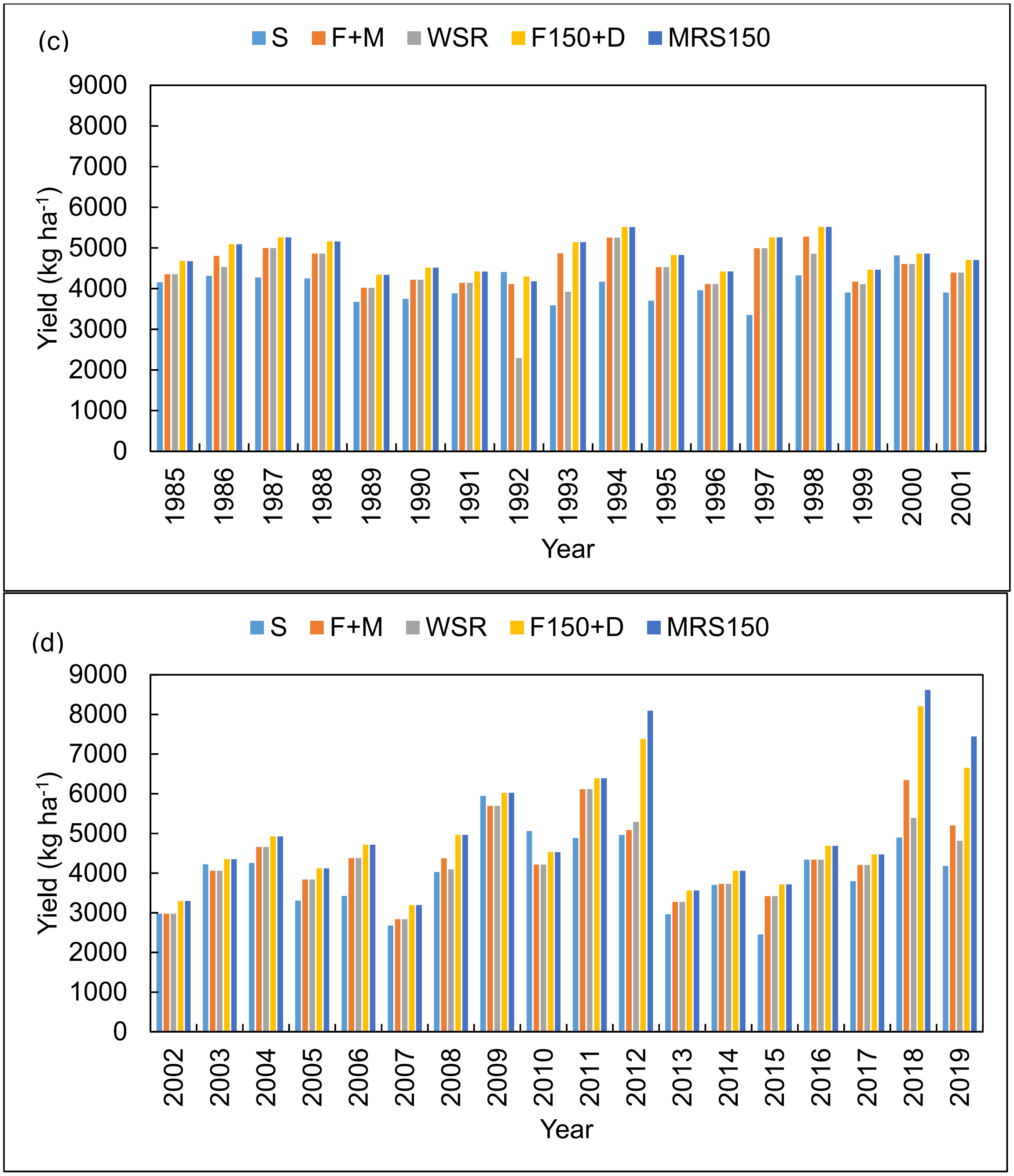


Figure 5: Simulated soybean yield for the full fertiliser NPK treatment from 1950 to 2019.

3.3 Long-term EI management scenarios

Grain yield

The additional application of manure (F+M) increased wheat yields from 4 156 kg ha^{-1} to 4 583 kg ha^{-1} (10%). Under wheat-soybean rotation, the average wheat yield slightly increased by 163 kg ha^{-1} (3%). In some years including 1951, 1963, 1983 and 1992 low yields under crop rotation were observed. This was as result of high soybean yields (above 3 t ha^{-1}) simulated the season before (Figure 5), leading to very high amounts of residue with high C:N ratios immobilising the N fertiliser and leading to reduced N availability for the wheat crop. An increase in N application to 150 kg ha^{-1} and water applied at SWD (F150+D treatment) and the combination of all improved management practices (MRS150 treatment) showed the most positive benefits, to increasing wheat yields by 18% (Figure 6).

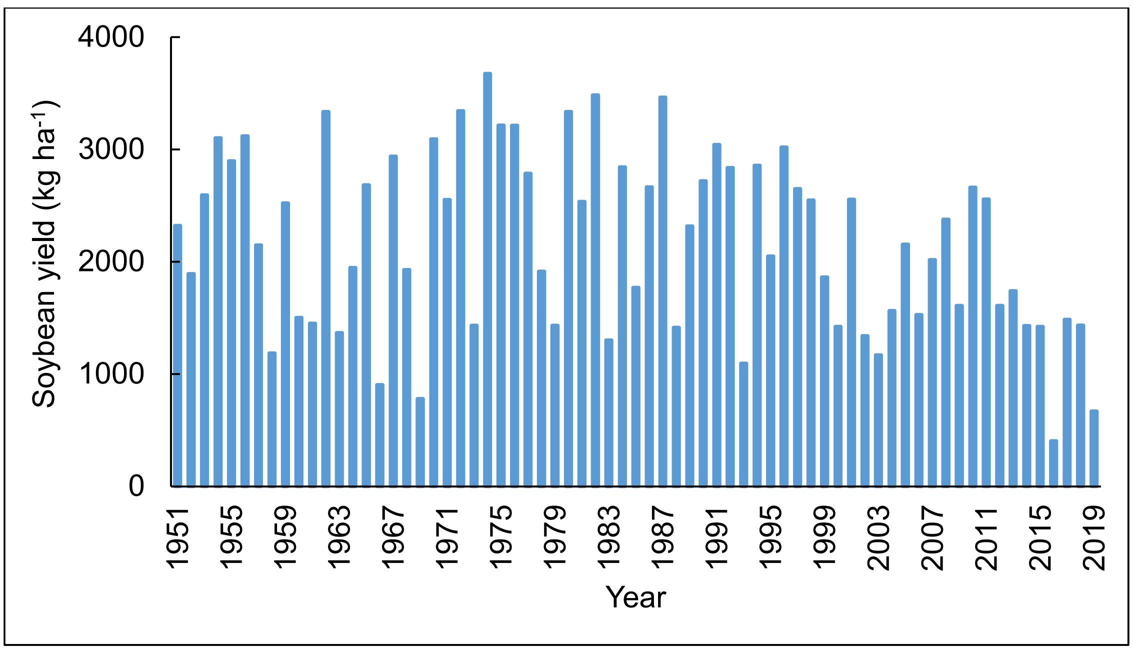


Figure 6: Wheat monoculture fertilised with 116 kg N ha^{-1} (S), wheat monoculture fertilised with 116 kg N ha^{-1} and 8 t ha^{-1} manure (F+M), wheat-soybean rotation (WSOR), fertiliser applied at 150 kg N ha^{-1} and irrigation at SWD (F150+D), and a combination of all the

management practices (MRSO150) average yield from 1950-1967 (a), 1968-1984 (b), 1985-2001 (c), 2002-2019 (d).

Soil organic matter

The application of manure (F+M), the inclusion of crop rotation (WSOR) and the combination of all the treatments (MRSO150) were simulated to be only slightly beneficial in maintaining SOM levels compared to the S and F150+D treatments (Figure 7a). The S and F150+D treatments had the highest amount of SOM loss, from 1.2% in 1950 to 0.58% in 2019 (52% loss over the simulation period). The MRSO150 treatment had the least amount of SOM loss, from 1.2% in 1950 to 0.68% in 2019 (44% loss). Total C was also therefore simulated to decline in all the treatments with the MRS150 and WSR treatments having the least C loss (Figure 7b). This shows that even with manure application, crop rotation and careful irrigation scheduling, these systems will still inevitably lose large quantities of SOM under the scenarios tested.

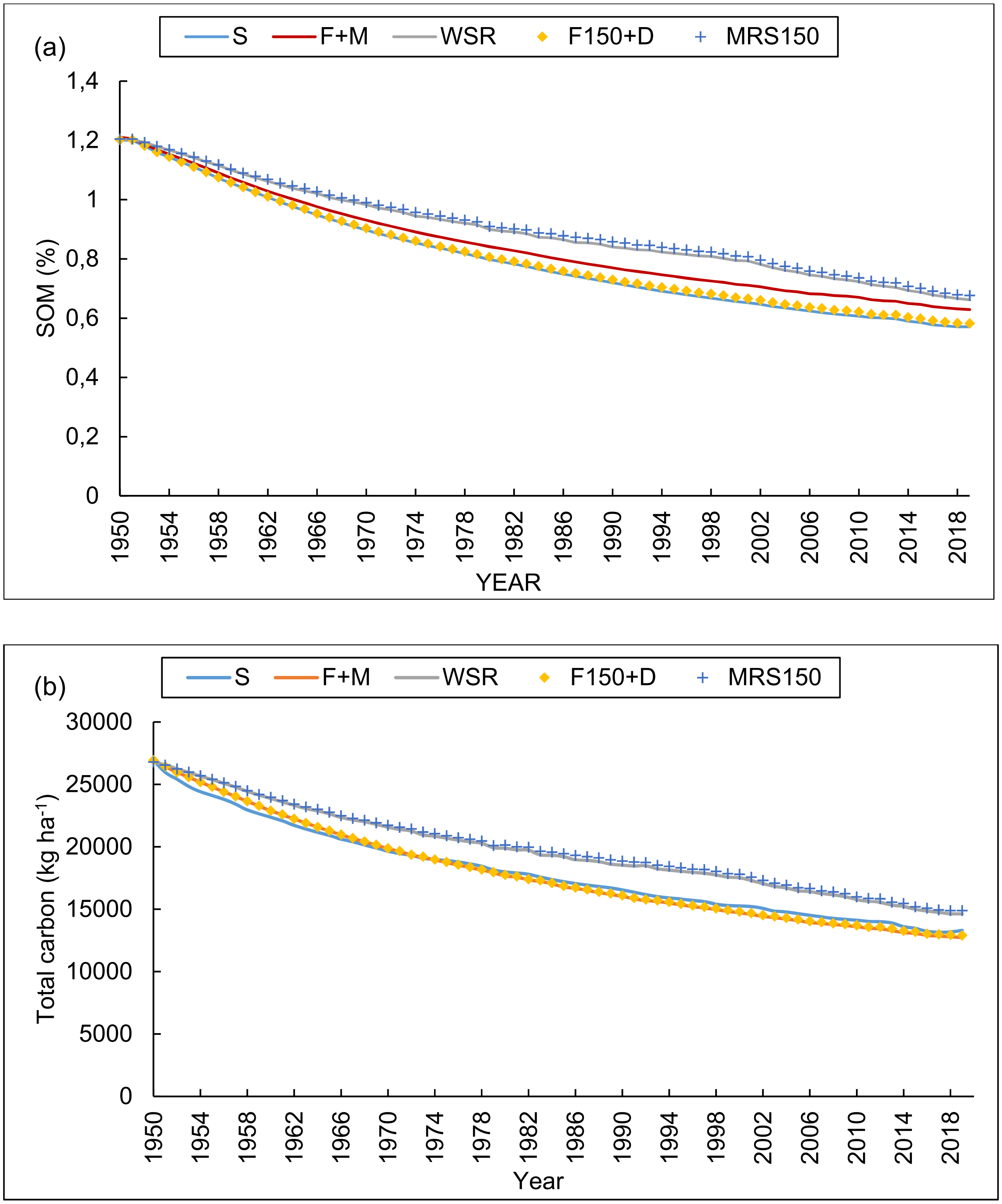


Figure 7: Soil organic matter (SOM) content and total carbon for a wheat monoculture fertilised with 116 kg N ha^{-1} (S), wheat monoculture fertilised with 116 kg N ha^{-1} and 8 t ha^{-1} manure (F+M), a wheat-soybean rotation (WSOR), fertiliser applied at 150 kg N ha^{-1} and irrigation at SWD (F150+D), and a combination of all the improved management practices (MRSO150) from 1950 to 2019 to a 0.6 m soil depth.

Deep drainage and N leaching

The F+M treatment recorded the highest amount of deep drainage of 217 mm year^{-1} the improved management practices, while the MRSO150 treatment was the most effective practice to reduce drainage to an average of 159 mm year^{-1} (25% reduction). The WSOR and F150+D treatments also reduced drainage to 173 mm year^{-1} and 177 mm year^{-1}, respectively (Table 8). Water use efficiency (WUE) was simulated to have increased from 21 kg grain ha^{-1} mm^{-1} year^{-1} in the S treatment, to 30, 36 and 42 kg grain ha^{-1} mm^{-1} year^{-1} in the F150+D, WSOR and MRSO150 treatments, respectively (Table 8).

Table 8: Deep drainage and nitrogen (N) leaching for the wheat trial at the University of Pretoria's Hillcrest Campus Experimental Farm.

Treatment	Deep drainage (mm year^{-1})	N leaching (kg N ha^{-1} year^{-1})	WUE (kg grain ha^{-1} mm^{-1} year^{-1})	NUE (kg grain kg^{-1} N year^{-1})
S	211	42	21	12
F+M	217	63	22	18
WSOR	173	13	36	13
F150+D	177	41	30	22
MRSO150	159	13	42	20

Standard treatment (S) - wheat monoculture fertilised with 116 kg N ha^{-1}. F+M - Wheat monoculture fertilised with 116 kg N ha^{-1} and 8 t ha^{-1} manure. WSOR- wheat-soybean rotation. F150+D - Wheat monoculture fertilised with 150 kg N ha^{-1} and irrigated at soil water deficit (SWD). MRSO150 - Combination of 8 t ha^{-1} manure. wheat-soybean rotation. 150 kg N ha^{-1} and irrigation at SWD. Water use efficiency- WUE. nitrogen use efficiency-NUE.

The highest amount of N leached (63 kg ha^{-1} year^{-1}) was simulated for the F+M treatment and the lowest amount for the MRSO150 and WSOR treatments (both 13 kg N ha^{-1} year^{-1}) (Table 8). With increased N application rate and irrigation at SWD (F150+D treatment), leaching was only reduced by 1 kg N ha^{-1} year^{-1} (Table 8). This shows that increasing the rate of fertiliser application had minimal influence on N leaching as long as irrigation was not over-applied. Nitrogen use efficiency (NUE) was predicted to increase by 6 kg grain kg^{-1} N year^{-1} with the application of manure and NPK fertiliser, 1 kg grain kg^{-1} N year^{-1} under wheat-soybean rotation, and 20 kg grain kg^{-1} N year^{-1} for the combination (MRS150) treatment. The F150+D treatment was the most beneficial in improving grain yields and that was also shown by the highest NUE of 22 kg grain kg^{-1} N year^{-1} (Table 5).

4. DISCUSSION

Model evaluation

Aboveground dry matter, grain yield and LAI of wheat cultivar PAN 3497 were well simulated by APSIM in the 2019 winter growing season for both the full NPK fertiliser and control treatments. The statistical analysis shows that the model was well calibrated, however, there is an uncertainty that the model can simulate well other management practices like EI crop production. Despite the model performing well for the 2019 season, over the long-term wheat yields were not always accurately simulated. Disagreements between the measured and simulated yields to some extent may have been caused by different sowing dates used by the model and the actual planting dates, and different cultivars planted over the history of the trial, while the PAN3497 cultivar was used for the entire simulation period. The management of the long-term trial and yield measurements having been done by different people over the years, can possibly also be a source of yield variation that the model did not capture. The model was also able to simulate VWC trends well for all the treatments, however, the control treatment had higher soil water content levels in the NPK treatment in all the soil depths. This could be due that fertilised plots have higher soil water extraction than unfertilized plots. With more water taken up from the soil through evapotranspiration it benefits crop growth and development.

Grain yield

Addition of manure was simulated to benefit wheat yield and SOM content, but only moderately. There may be additional benefits that result from the application of manure that were not simulated by APSIM. Securing and transporting large amounts of manure may not, however, be economically feasible for large scale wheat producers in South Africa. By alternating different crops (including a legume) on the same field in winter and summer, better nutrient cycling may be achieved. Despite the WSOR treatment being simulated to have higher yields compared to the S treatment, a significant drop in average yields after every 10 or so years was predicted, possibly due to poor rainfall distribution in summer, resulting in a very dry soil profile for the succeeding winter wheat crop in those years. This will require more water for irrigation, which may be a challenge for farmers with limited water resources. Pest and disease build-up would likely have been reduced on such a rotation system which is another factor not represented in the model.

Increased fertiliser application rates improved water and nitrogen use efficiency. This can be especially effective in increasing water productivity in dry areas with a high evaporative demand, because of quick, uniform and healthy crop establishment (Lal and Shukla 2004). Optimising fertiliser application rate has been the most practiced method farmers adopt to improve yields, it is therefore not a challenge to implement, as long as it is financially feasible. The APSIM model was useful in identifying the optimal application rate to maximum yield. Objective irrigation scheduling, on the other hand, may not always be easy to implement due to irrigation system and water availability constraints.

The results from the APSIM simulations suggest that improved management practices can increase yield, however, the benefits were far less than expected. The combination of all the management practices was no more effective than the F150+D treatment in increasing average wheat yields over the long-term. Most of the benefit is therefore attributed to the increased fertiliser application rate and SWD guided irrigation. It may, therefore, not be economically feasible for farmers to adopt one or more of these practices. Commercial wheat production agronomic practices may largely already have been optimised for yield grains in South Africa (Van der Laan et al. 2017), so breeding new cultivars, for example, with medium vernalisation and low photoperiod sensitivity, and short length of floral initiation phase (Bai and Tao 2017), may have the largest impacts on increasing yields per unit area. Policies that reward farmers who achieve higher water and N use efficiency should also be considered.

Soil organic matter

Since the initiation of the trial, a decline in SOM content was observed and simulated in both the full fertiliser NPK and zero fertiliser treatments. Despite the full fertiliser NPK treatment having increased biomass production, the amount was not sufficient to maintain SOM levels. Manure application, crop rotation and the combination of all treatments slowed down SOM decline, but only marginally. The decline in SOM content was mostly caused by tillage in all the treatments. This was also discovered by Swanepoel et al. (2016), who observed that, tillage practices and other soil disturbances result in increased oxidation of residues as well as previously occluded

SOM resulting in the release of CO_2 and decline in SOM levels. Even after 69 years of simulated continuous wheat production, the amount of SOM had not reached an equilibrium and continued to decline. This is in contrast with Swanepoel et al. (2016), who reported that the equilibrium of SOC is reached after 30-40 years, and further SOM analysis and model testing is recommended.

Deep drainage and N leaching

The increased rate of N leaching under the F+M treatment was due to increased loading of manure N. It is, therefore, advisable to take into consideration the amount of N contained in the manure when applied with inorganic fertiliser to match crop demand and reduce groundwater contamination. Under crop rotation, reduced drainage was due to summer rainfall being utilised by soybean, also leading to less N leaching. Effective irrigation improves root development and soil growing conditions and, this helps the rooting system to spread more laterally and reach lower soil depths in search of water and nutrients, potentially reducing deep drainage and N leaching. This was the reason for reduced deep drainage and N leaching in the F150+D treatment, even after an increased fertiliser application rate.

5. CONCLUSION

The APSIM model performed well in simulating N-limited growth for fertilised and unfertilised irrigated wheat grown on the South African highveld during the 2019 season. Further application of the model in this regard is therefore encouraged. The model also did well in simulating long-term yields (1990-2019) and SOM dynamics (1950-2019). Application of the model to inform the EI of wheat production, including through optimised inorganic fertiliser N application, manure application, crop rotation, and objective irrigation scheduling, indicated only modest benefits in improving long-term yields and maintaining SOM. However, WUE and NUE could be greatly improved through the adoption of one or more of these management practices, and it is important that improved management is also promoted and rewarded from an environmental perspective. It is acknowledged that in some cases implementation of these improved management practices is not feasible due to various localised constraints, such as lack of irrigation water and reduced profitability. Based on this and the relatively low yield benefits predicted, other approaches such as improved crop breeding will have a large role to play in the EI of irrigated wheat that can also achieve the objectives of CSA.

Geolocation information

Hatfield, Gauteng Province: latitude 25°45′ S and longitude 28°16′ E

Disclosure statement — The authors have no conflict of interest.

REFERENCES

Adhikari P, Araya H, Aruna G, Balamatti A, Banerjee S, Baskaran P, Barah B, Behera D, Berhe T, Boruah P. 2018. System of crop intensification for more productive, resource-conserving, climate-resilient, and sustainable agriculture: Experience with diverse crops in varying agroecologies. *International Journal of Agricultural sustainability*, 16: 1-28.

Asseng S, Keating B, Fillery I, Gregory P, Bowden J, Turner N, Palta J, Abrecht D. 1998. Performance of the apsim-wheat model in western australia. *Field Crops Research*, 57: 163-179.

Bai H, Tao F. 2017. Sustainable intensification options to improve yield potential and eco-efficiency for rice-wheat rotation system in china. *Field Crops Research*, 211: 89-105.

Belay A, Claassens A, Wehner F. 2002. Soil nutrient contents, microbial properties and maize yield under long-term legume-based crop rotation and fertilization: A comparison of residual effect of manure and npk fertilizers. *South African Journal of Plant and Soil*, 19: 104-110.

Bristow KL, Campbell GS. 1984. On the relationship between incoming solar radiation and daily maximum and minimum temperature. *Agricultural and Forest Meteorology*, 31: 159-166.

Carmichael PC, Siyoum N, Chidamba L, Korsten L. 2017. Characterization of fungal communities of developmental stages in table grape grown in the northern region of south africa. *Journal of Applied Microbiology*, 123: 1251-1262.

De Jager J. 1994. Accuracy of vegetation evaporation ratio formulae for estimating final wheat yield. *Water SA*, 20: 307-314.

Dhanya A, Bodapati B, Parameswaran P, Rao V. 2013. Delineation of air temperature based models for estimation of global solar radiation. *National Seminar on Climate Change and Indian Agriculture - Slicing Down*, 15: 152-155.

Diacono M, Montemurro F. 2011. Long-term effects of organic amendments on soil fertility. *Sustainable Agriculture Volume 2*: Springer. p. 761-786.

Dube E, Tsilo TJ, Sosibo NZ, Fanadzo M. 2020. Irrigation wheat production constraints and opportunities in south africa. *South African Journal of Science*, 116: 1-6.

Gaydon D, Wang E, Poulton P, Ahmad B, Ahmed F, Akhter S, Ali I, Amarasingha R, Chaki A, Chen C. 2017. Evaluation of the apsim model in cropping systems of asia. *Field Crops Research*, 204: 52-75.

Hmielowski T. 2017. The value of long-term data in agricultural systems. *CSA News*, 62: 4-7.

Jan T, Jan MT, Arif M, Akbar H, Ali S. 2007. Response of wheat to source, type and time of nitrogen application. *Sarhad Journal of Agriculture*, 23: 871.

Johnston A, Poulton P. 2018. The importance of long-term experiments in agriculture: Their management to ensure continued crop production and soil fertility; the rothamsted experience. *European Journal of Soil Science*, 69: 113-125.

Jolánkai M, Nyárai F, Kassai K. 2010. Impact of long-term trials on crop production research and education. *Acta Agronomica Hungarica*, 58: 1-5.

Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargreaves JN, Meinke H, Hochman Z. 2003. An overview of apsim, a model designed for farming systems simulation. *European Journal of Agronomy*, 18: 267-288.

Lal R. 2009. Soils and food sufficiency: A review. *Sustainable Agriculture*: Springer. p. 25-49.

Lal R, Shukla MK. 2004. *Principles of Soil Physics*. CRC Press.

Maseko SK, Van der Laan M, D M, Swanepoel C. 2022. Modelling long-term management impacts on yield and soil organic matter dynamics in maize (zea mays l.) cropping system in south africa *Nutrient Cycling in Agroecosystems*.

Maynard AA. 2000. Compost: The process and research. *Bulletin-Connecticut Agricultural Experiment Station*.

McCauley Ann CJ, Kathrin Olson-Rutz 2017. Soil ph and organic matter. In: Unversity MS editor. 135 Culbertson Hall, Montana State University. p. 3.

Pan G, Smith P, Pan W. 2009. The role of soil organic matter in maintaining the productivity and yield stability of cereals in china. *Agriculture, Ecosystems and Environment*, 129: 344-348.

Peng S, Buresh RJ, Huang J, Zhong X, Zou Y, Yang J, Wang G, Liu Y, Hu R, Tang Q. 2010. Improving nitrogen fertilization in rice by sitespecific n management. A review. *Agronomy for Sustainable Development*, 30: 649-656.

Pingali PL, Hossain M, Gerpacio RV. 1997. *Asian rice bowls: The returning crisis?* : International Rice Research Institution.

Probert M, Dimes J, Keating B, Dalal R, Strong W. 1998. Apsim's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agricultural Systems*, 56: 1-28.

Ragheb H, Dawood R, Kheiralla K. 1993. Nitrogen uptake and utilization by wheat cultivars grown under saline stresses. *Assiut Journal of Agricultural Sciences*.

Rasmussen PE, Collins HP. 1991. Long-term impacts of tillage, fertilizer, and crop residue on soil organic matter in temperate semiarid regions. *Advances in Agronomy*: Elsevier. p. 93-134.

Schofield R, Taylor AW. 1955. The measurement of soil ph. *Soil Science Society of America Journal*, 19: 164-167.

Searchinger T, Hanson C, Ranganathan J, Lipinski B, Waite R, Winterbottom R, Dinshaw A, Heimlich R, Boval M, Chemineau P. 2014. Creating a sustainable food future. A menu of solutions to sustainably feed more than 9 billion people by 2050. World resources report 2013-14: Interim findings.

Steiner R. 1995. Long-term experiments and their choice for the research study. *Agricultural sustainability: Economic, environmental, and statistical considerations. John Wiley and Sons, Chichester, UK*: 15-21.

Swanepoel C, Van der Laan M, Weepener H, Du Preez C, Annandale JG. 2016. Review and meta-analysis of organic matter in cultivated soils in southern africa. *Nutrient Cycling in Agroecosystems*, 104: 107-123.

Tadesse W, Bishaw Z, Assefa S. 2019. Wheat production and breeding in sub-saharan africa. *International Journal of Climate Change Strategies and Management*.

Van der Laan M, Bristow K, Stirzaker RJ, Annandale J. 2017. Towards ecologically sustainable crop production: A south african perspective. *Agriculture, Ecosystems and Environment*, 236: 108-119.

Walkley A. 1935. An examination of methods for determining organic carbon and nitrogen in soils 1. *The Journal of Agricultural Science*, 25: 598-609.

XLSTAT. 2007. Statistical software for excel. [accessed 12/09/2022 2022].

Zhang J, Balkovič J, Azevedo LB, Skalský R, Bouwman AF, Xu G, Wang J, Xu M, Yu C. 2018. Analyzing and modelling the effect of long-term fertilizer management on crop yield and soil organic carbon in china. *Science of The Total Environment*, 627: 361-372.