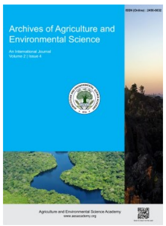
Archives of Agriculture and Environmental Science 5(1): 1-10 (2020)
https://doi.org/10.26832/24566632.2020.050101

e-ISSN: 2456-6632

This content is available online at AESA

Archives of Agriculture and Environmental Science

Journal homepage: www.aesacademy.org



ORIGINAL RESEARCH ARTICLE

Using the DSSAT-CROPGRO model to simulate gross margin and N-leaching of cowpea fertigated with human urine

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ARTICLE HISTORY

Received: 22 January 2020
Revised received: 13 March 2020
Accepted: 18 March 2020

Keywords

Fertigation
Gross margin
N-leaching
Risk aversion
Stochastic dominance

ABSTRACT

This study simulated the biophysical, economic and environmental implications of cowpea fertigated with human urine (equivalent to 60 kg N ha^{-1}) as source of organic N. The DSSAT CROPGRO model was used to simulate harvested cowpea yield, $N_{(leached)}$, $N_{(uptake)}$, monetary returns or gross margins in ($) under two different treatments: without fertigation or human urine (T_0) and with fertigation (T_1). Biophysical analysis using the Cumulative Probability Distribution (CPD) showed a 50% probability of the harvested cowpea yield under T_1 being higher than under T_0 at 1060 and 600 kg ha^{-1} respectively, accounting for a 43.4% difference. The Mean Gini Stochastic Dominance (MGSD) analysis was used to assess the gross margin and helped in deciding on the best strategic and management option. The findings of this study revealed a 50% probability ($CPD_{0.5}$), of higher gross margin under T_1 at $ -215 higher than under T_0 at $285. This was a $70 difference per season under T_1 and so enhancing a faster payback and a larger monetary return on overall investments. Similarly, seasonal analysis with fertigation showed that at $CPD_{0.5}$, the $N_{(leached)}$ was still < 4 kg N ha^{-1} per season and so posed no environmental risks. The simulation results also showed higher a probability of $N_{(uptake)}$ of about 270 kg N ha^{-1} during fertigation compared to about 95 kg N ha^{-1} under T_0. Therefore, the DSSAT CROPGRO model can be used to successfully forecast future cowpea yields, gross margin, $N_{(leached)}$, $N_{(uptake)}$ under different management practices to enable smallholder farmers in South Sudan make informed decisions on sustainable cowpea production.

Citation of this article: Lomeling, D. and Huria, S.J. (2020). Using the DSSAT-CROPGRO model to simulate gross margin and N-leaching of cowpea fertigated with human urine. *Archives of Agriculture and Environmental Science*, 5(1): 1-10, https://dx.doi.org/10.26832/24566632.2020.050101

INTRODUCTION

There are increasing concerns about the accessibility, availability and affordability of industrial N-fertilizers to boosting crop yields especially in developing countries. For most smallholder farmers in Africa, these are compelling reasons enough to start seeking alternative N-sources. Studies have shown that most soils in Sub-Sahara Africa are over 80% N-deficient (Liu *et al.*, 2010), whereas other studies have reported increasing acidification due to poor agronomic practices and long term use of inorganic N-fertilizers like; Diammonium Phosphate (DAP $(NH_4)_2HPO_4$)) or Calcium Ammonium Phosphate (CAN $(Ca(NO_3)_2 \bullet NH_4 \bullet 10H_2O)$) although with lesser acidic effect in soils than DAP. As in most rural and peri-urban settings in S. Sudan, over 95% of all human excreta (*feces and urine*) are disposed of, arbitrarily onto the environment, or through a decentralized sewer system comprising mostly of individual septic tanks at households that are occasionally emptied by commercial exhausters. For Juba City and its peri-urban surroundings with an approximated population of 450,000, it is estimated that the human urine amounts generated daily would be about 225,000 liters. If properly stored and handled, this nutrient rich and readily available organic N-source would augment the already scarce industrial fertilizer market supply in the country and be part of an ecosystem-based adaptation practice. However, current published data on the application of human urine (Sene *et al.*, 2013; Ranasinghe *et al.*, 2016; Andersson, 2016; Araújo *et al.*, 2017) as a viable fertilizer option are derived from short term studies and are insufficient to adequately assess the agronomic, economic and environmental implications of its use. However, one critical risk component in the widespread use of human urine or fertigation (*ferti*-lizer + irri-*gation*) across many developing countries of Sub-Sahara Africa would be the local and regional water scarcity. Water scarcity compounded by the erratic spatial and temporal rainfall distribution variabilities would make its use difficult or outright impossible. Thus, it is imperative, that knowledge on the spatio-temporal water availability and accessibility for most smallholder farmers who practice rainfed agriculture, be integrated into the respective country agricultural policies and implementation programs when evaluating the use of human urine. Moreover, farmers' willingness to adopt the use of human urine will depend not only on the available infrastructure in terms of hygienic storage, transportation and dosing, but also on the anticipated increased yields and profitability.

For the sustainable use of human urine as an economically and ecologically viable option for most households in Sub Sahara Africa, systematic research and long-term field tests need to be carried out and simulations conducted with dynamic crop models such as the CROPGRO of the DSSAT (Jones *et al.*, 2003). The model under different management conditions can be used to quantify crop yields, economic returns as well as assess environmental impacts due to N-leaching.

Cowpea is one the major food crops in Central Equatoria State of South Sudan and an indispensable source of cheap and easily available plant protein. The young and tender leaves are consumed traditionally as *ŋete* while the ripened and mature seeds as *pirinda* (Lomeling *et al.*, 2014a). With fertigation, cowpea can be produced in small farms or household backyards during any time of the year. It is a highly remunerative crop with price increase several times its normal value especially during the annual "*hunger spells*" of mid-July to Mid-August. However, increasing price of potable water and the large influx of Internally Displaced Persons (IDPS) due to current civil war, cowpea production per household has significantly decreased within and around Juba municipality. Similarly, cowpea production, as a cheap source of plant protein, is not only threatened by a reduced availability of irrigation water but also declining soil fertility caused increased and extreme elimination of soil nutrients as well as decrease in soil functional characteristics (Lomeling *et al.*, 2016a). As a drought resistant plant, reduced irrigation is not necessarily a limiting factor, since soil moisture requirements during cowpea phenology show temporal variability between 15-30% (Lomeling *et al.*, 2016b). However, soil moisture contents <15% at any one developmental stage of growth has adverse effects on the germination rate, flowering, canopy height, pod-setting and maturity (Abayomi and Abidoye, 2009; Suliman and Ahmed, 2010; De Souza *et al.*, 2017). Reduction in cowpea yield is not only attributable to insufficient soil moisture during growth, but also to such abiotic stress factors like phosphate (P) deficiency (Jemo *et al.*, 2017; Goufo *et al.*, 2017; Fatokun *et al.*, 2012; Agele *et al.*, 2018). Although *Eutric leptosols* are the major soil type around Juba County and can be perceived to be of moderate to good fertility, sustained cultivation over longer period without any concerted soil amendments may ultimately pose serious soil fertility challenges. Cowpea is known to sustain soil health by fixing atmospheric N to about 200 kg N ha^{-1} (Giller, 2001; Rusinamhodzi *et al.*, 2006; Adjei-Nsiah *et al.*, 2008) social evaluation of productivity, yield and N_2-fixation in different cowpea varieties and their subsequent residual N effects on a succeeding maize crop and can leave a positive soil balance of up to 92 kg N ha^{-1} (Chikowo *et al.*, 2004; Rusinamhodzi *et al.*, 2006). The use of composted tannery sludge was also found to sustain cowpea yield during a six-year period (Araújo *et al.*, 2016); increased cowpea yield after application of biochar in loamy sand soil (Pudasainia *et al.*, 2016); increased cowpea biomass after addition of nitrogen fertilizers (Hasan *et al.*, 2010).

The CROPGRO model as an ex ante analytical tool has been successfully demonstrated across a broad range of soil, management and climatic conditions in tropical environments (Bastos *et al.*, 2002; Banterng *et al.*, 2010; Lomeling *et al.*, 2014; Zinyengere *et al.*, 2015). It can used for assessing the effects of diverse management options on crop phenology as opposed to that of "*business as usual*" or the status quo. It also can be used to assess the type of promising or similar climate smart technologies whose "*low scale*" investments are not only remunerative, but also financially affordable as is the case for most smallholder farmers in South Sudan. Model projections during simulations can be used as basis for long-term actionable trends in terms of assessing food demand and agricultural production based on projected changes in population, income, technology, and climate (Robinson *et al.*, 2015). Examples on the use of CROPGRO models have been reported in several studies on bean (Oliveira *et al.*, 2012); on saaflower (Singh *et al.*, 2017); on faba bean (Boote *et al.*, 2002); on peanut (Halder *et al.*, 2017).

Rainfall forecasts for South Sudan are mostly reported by (FEWSNET, 2018) and are generally limited to short-term one to three months lead time. South Sudan still lacks a good infrastructure, network of weather stations as well as skilled personal to capture and store weather data in real-time. The absence of such important historical weather data therefore makes any long-term predictions on rainfall occurrence, amounts and intensity difficult. The CROPGRO model requires daily, monthly or annual rainfall amounts as an input variable, thus, simulation of crop yield for most parts of South Sudan in the absence of such relevant data may simply be a speculative exercise. In our study, we sought to assess the effects of fertigation on cowpea yield and the economic and ecological implications using CROPGRO-DSSAT model.

MATERIALS AND METHODS

Study region

The experimental study was conducted as from May till September 2015 at the Demonstration and Research Plots of the Department of Agricultural Sciences, University of Juba. The study area is located in Juba County, Central Equatoria State at 4°51´33 N latitude, 31° 34´ E longitude and at elevation of about 500 m above sea level. The climate is sub-tropical with mean annual rainfall of 800–1200 mm and a predominantly unimodal distribution. About 80–90% of the rainfall occurs during the rainy months (April–October) with a short dry spell around July. The soil (*Eutric leptosol*) is sandy loam in texture, mild acidic to alkaline in reaction (pH 6.5 - 7.5), low organic carbon by weight (0.55%), CEC in soil (14 cmol/kg) (Table 1).

Experimental design and treatments

The experiment was a Randomized Complete Block Design (RCBD) with two different treatments with five replications each and was conducted from May to September 2015. Each trial was arranged in four randomized complete blocks. Traditional agricultural practices of tillage, seed bed preparation and pest control against aphids, grasshoppers, leaf sucking bugs using ashes from burnt plant leaves were applied. Occasionally, a broad-spectrum pesticide Malathion with application rate of 0.5 l/ha was applied, where the traditional pest control method proved ineffective. Each plot consisted of 5 rows, 2.5 m long, with a spacing of 30 cm between plants and 50 cm between rows. The size of each plot was 5.4 m² with seeds drilled at a sowing depth of 5 cm and density of 30 plants/m^2. The control treatment (irrigation water + No human urine) was designated as T_0 while (irrigation water + human urine: 2 liters per 20 liters water) as T_1. The calculated N fertilizer from T_1 was about 60 kg/ha. Irrigation under both treatments was done once the soil moisture level reached about 15%v/v and was measured using the Theta Soil Moisture Sensor ML3 (Eijkelkamp Agrisearch).

CROPGRO model runs

All input variables and modules for soil (SAUR900001.SOL) and cultivar (CGRO045.CUL) were kept unchanged as reported by (Lomeling *et al*., 2014b). The required weather data for DSSAT WEATHR module, the WGEN subroutine was run to capture the daily rainfall, minimum and maximum air temperature, solar radiation, relative humidity, and wind speed. For Juba County, these data were obtained from the publicly accessible servers of the National Oceanic and Atmospheric Administration (NOAA) of the US Department of Commerce for the years 1980-2014. For the biophysical analysis, the simulated yield in kg ha^{-1} was that valued at physiological maturity while the observed yield (kg ha^{-1}) derived from 1000-seed weight. For model calibration (Y2014), cowpea yield from 2014 was used.

Estimation of monetary returns

The seasonal analysis for the 2015 season was used to assess the gross margin and economic returns for a five-year period. In our study, the base production or total variable costs, that included: labor costs, material, costs (seed purchase, water for irrigation, insecticide, transport, ancillary cost, levy taxes) were constant during the simulation period. Similarly, the produce sale or accrued total revenue, ignoring price volatility due to inflation and price hiking were also kept constant. The Gross Margin (GM) per unit time or season was estimated as the difference between the Total Revenue (TR) and the Total Variable Costs (TVC) as (Eq. 1).

$$\mathrm{GM} = \sum_{i=1}^{n} [\mathrm{TR} - (\mathrm{TVC} + \mathbb{R})]_{(n+1)} \qquad (1)$$

Where n, is the number of growing seasons, (n+1) each subsequent growing season and R, an intrinsic and inevitable risk factor that is quantifiable and depends on unpredictable weather conditions, arbitrary tariff barriers (illegal taxes by corrupt officials), accidents, poor sale price as well as other unaccounted risks. R, in an especially risk-prone production area like in S. Sudan, makes its assessment imperative, as it determines degree of risk aversion of most smallholder farmers. For our study, the breakdown cost-variables used for the seasonal analysis for the test plots are projected to real field dimensions are given in Table 2.

Strategy Analysis-Mean Gini Stochastic Dominance (MGSD)

The estimation of the GM in (Eq. 1) for both treatments may be used to examine and compare the MGSD. This is a measure of the most economically viable and preferable management option with a stochastic dominance. For two risky options, x and y, then x dominates b by MGSD, should (Eq. 2 and Eq. 3).

$$E(x)>E(b) \qquad (2)$$

or if:

$$E(x) - \Gamma(x) > E(y) - \Gamma(y) \qquad (3)$$

Where E (*) is the means of the GM and Γ(*) the Gini coefficient, 0 £ G(*) £ 1.

RESULTS AND DISCUSSION

Biophysical Analysis: Grain yield and fertigation

The biophysical analysis compares the harvested yield (kg ha^{-1}) under both treatments and expressed as a cumulative function in 0, 25, 50, 75 and 100th percentiles. We used the Cumulative Probability Distribution (CPD) to estimate the probability of the tested variables (yield, $N_{(uptake)}$ or $N_{(leaching)}$) under either treatment. The results of the five-year simulation with CROPGRO cowpea when considering the highest $CPD_{0.75}$, were well simulated and consistent with the one-year empirical findings of the calibrated cowpea yields of 2014. The yield values were about 705 and 983 kg ha^{-1} for T_0 and T_1, respectively, while the calibrated value in 2014 was at 588 kg ha^{-1} (Table 3).

The observed yield difference between T_0 and calibrant Y2014 was 117.0 kg ha^{-1}this was 16.6% higher, whereas the difference of the under T_1 to T_0 was 278 kg ha^{-1} about 28.2%. The mean value between T_1 and calibrant Y2014 was about 394.8 kg ha^{-1} and 40.2%. The simulated cowpea yield at $CPD_{0.25}$ for T_0 and T_1 were 760 and 1050 kg ha^{-1} respectively, accounting for a 27.6% difference. At $CPD_{0.5}$, the simulated yields for T_0 and T_1 were 800 and about 1075 kg ha^{-1} respectively accounting for 26% difference. At $CPD_{0.75}$, the simulated harvested yield for T_0 and T_1 were 750 and about 1115 kg ha^{-1} respectively, accounting for 32,7% difference (Figure 1). The simulation shows that, the probability of having higher yields especially under fertigation was significantly high. The CROPGRO model satisfactorily simulated the positive effect of human urine on cowpea yield. This positive effect is particularly attributable to the role of macro- and micro elements contained in the urine (Lomeling and Huria, 2019).

In other words, even when considering the lowest $CPD_{0.25}$, there was still a 25% probability that the simulated yield under either T_0 or T_1 treatment would still be greater than the average yield of 588.4 kg ha^{-1} (considering the calibrant Y2014). Furthermore, the yield range under both treatments was consistent with that reported by (Saka *et al.*, 2018; Kamai, 2014) for semi-arid zone of Nigeria; but comparatively higher than that reported by (Kimiti *et al.*, 2009) in the semi-arid zone of Eastern Kenya. The results of the five-years simulation study showed that, fertigation using human urine is a viable and stopgap indispensable option to obviate any shortcomings of inorganic fertilizer availability and supply for smallholder farmers in Africa. The simulated mean difference in cowpea yields under both treatments was consistent and invariable even at $CPD_{0.75}$ and $CPD_{1.0}$ respectively, suggesting the viability of T_1 treatment as a better option for most farmers to achieving higher yields than T_0.

Seasonal Analysis: Nitrogen uptake during cowpea phenology

During cowpea phenology, the five-years long-simulation results identified $N_{(uptake)}$ as the predominant pathway in the N-balance (Figure 2). At $CPD_{0.25}$, the $N_{(uptake)}$ for T_0 was about 85 kg ha^{-1}, while this about 250 kg ha^{-1} for T_1 indicating a 66% difference of about 165 kg ha^{-1}. At $CPD_{0.50}$ the $N_{(uptake)}$ was at about 95 kg ha^{-1} for T_0 and 260 kg ha^{-1} for T_1 showing a 65.4% difference of about 165 kg ha^{-1}. At $CPD_{0.75}$, this was about 95 kg ha^{-1} for T_0 and 275 kg ha^{-1} for T_1 indicating a 65.5% of about 180 kg ha^{-1}. The study showed that at any rate, there was a high probability that the average $N_{(uptake)}$ between both treatments would be about 167 kg ha^{-1}. This is attributable to the positive effect of fertigation. Especially Phosphorous (P) contained in the urine must have enhanced further nodulation and N-fixation (Kyei-Boahen *et al.*, 2017) as well as boosted microbial activity within the rhizosphere. The resultant effect is, increased vegetative growth during phenology inevitably leading both to increased water as well as N-uptake. Unlike under treatment T_0, the significance of fertigation under T_1 in enhancing N-fixation and uptake can be understood from the role of "*micronutrients*" contained in the urine. Several micronutrients like Iron (Fe) are essential for legume-rhizobium symbiosis (Brear *et al.*, 2013), copper (Cu) for the synthesis of cupro-proteins during N-fixation (Senovilla *et al.*, 2017), zinc (Zn) whose role in Cu-rich soils can influence N-fixation (Stowhas *et al.*, 2018). However, the sandy loam soil (*Eutric leptosol*) in our study, was found to have very low levels of Cu, Fe, Zn and so therefore, supplementing these micronutrients through fertigation was particularly critical for N-fixation and eventual uptake.

Figure 3 shows the effect of fertigation on cowpea yield in kg ha^{-1} per irrigation schedule. At $CPD_{0.25}$ the simulated yield under T_0 and T_1 were about 12.5 and 15 kg ha^{-1} per irrigation schedule respectively, accounting for about 2-3 kg or 16,7% difference between both treatments. The yield remained unchanged between 2-3 kg/irrigation schedule at both $CPD_{0.5}$ and $CPD_{0.75}$. Apparently, a ten-fold increase in irrigation schedules for both T_0 and T_1 would yield an agronomic response of between 20-30 kg. Therefore, increasing irrigation schedules to about 20 times especially during dry spells would yield a further 40-60 kg. It appears, that further increase in irrigation schedules would positively correlate with yield increase of cowpea under both treatments but could conversely increase production costs through purchase of further water barrels thereby reducing the gross margin.

N-leached during fertigation

The soil $N_{(leached)}$ varied considerably between both treatments, ranging from 0 to 14 kg ha^{-1} (Figure 4). There was no significant difference in $N_{(leached)}$ for both treatments at $CPD_{0.25}$ and $CPD_{0.5}$, indicating that there was a 25 or 50% probability that the $N_{(leached)}$ would not exceed 2 kg ha^{-1}. The results of this study showed that the application of 60 kg N during fertigation did not result in higher $N_{(leached)}$ as when under T_0, suggesting that, this was an optimum N crop requirement for cowpea and reflecting good N-fertilizer use efficiency. Such low $N_{(leached)}$ would indicate higher $N_{(uptake)}$ of especially NO_3^- after both nitrification and ammonification processes in the soil. There was a slight difference at $CPD_{0.75}$ though not significant ($p<0.05$). The largest difference in $N_{(leached)}$ was at CPD greater than 0.75 at 7 and 13 kg ha^{-1} for T_0 and T_1 respectively. The magnitude may be influenced by several soil and agronomic factors, e.g. type of soil, actual amount of soil moisture, preceding crops, type and quantities of manure or plant residues. Similar studies reported higher NO_3^- leaching of about 20 kg ha^{-1} y^{-1} after faba bean cultivation, than after non-leguminous crops in clay soil (Stenberg *et al.*, 2012); while during a 3-year test trial on loamy sand, the NO_3^- leaching was about twice as high following a barley–pea intercrop compared with spring wheat or spring barley (De Notaris *et al.*, 2018). Another study by (Kayser *et al.*, 2010) on a sandy soil in northwestern Germany reported 83 kg N ha^{-1} leached in triticale following field bean. Despite fertigation and the high anticipated N-leaching under T_1, the $N_{(leached)}$ under both treatments was correspondingly low and could be attributable to: a) the rapid rate of ammonification or mineralization of organic N to NH_4^+; b) immobilization of NH_4^+ by soil microorganisms

Table 1. Some of the physical and chemical properties of sandy loam soil (*Eutric leptosol*) at University of Juba Research and Demonstration Farm.

Soil physical and chemical features	Description
Soil mapping unit*	Eutric leptosol
Texture Classification	Sandy loam
Drainage Class (0-0.5)	Moderately well
Sand (average)	48.9%
Silt (average)	43.7%
Clay (average)	7.4%
pH (LaMotte STH Test Method)	7.0
Nitrate-Nitrogen	22.68 kg/ha
Phosphorus	170.1 kg/ha
Sulphate	1000ppm (parts per million)
Iron	1.36 kg/ha
Magnesium	Medium
Calcium	396.9 kg/ha
Bulk density	1.34 (gm/cm^3)
Humus content	2.95%

*Source: Harmonize World Soil Data viewer version 1.2.

Table 2. Cost-price for different input variables for cowpea under two different treatments.

Variables	Cost/unit in $	Quantity(ies)	Mean amount ($)
Irrigation water	1.5[a)] per barrel (200 liters)	20,000 liters (ca. 2 water tankers)	150
Cowpea seed cost	1.2[b)] per kg	20	12
Labor	none	none	none
Fertilizer or organic amendments (N, P, K)	none	none	none
Mean sale price (*simulated* under T_0)	1.6 per kg	800 kg ha^{-1}	640
Mean sale price (*simulated* under T_1)	1.6 per kg	1070 kg ha^{-1}	856
Mean sale price (observed under T_0)	1.6 per kg	705.4 kg ha^{-1}	563.5
Mean sale price (observed under T_1)	1.6 per kg	983.1 kg ha^{-1}	786.5
Mean sale price (under calibrant Y2014	1.6 per kg	588.4 kg ha^{-1}	470.7

a) and b) 1 $ equivalent to 25 South Sudanese Pounds (2014) prior to inflation.

Table 3. The effects of fertigation on some phenology parameters of cowpea.

Treatment	Nr of pods/ plant	Nr of seeds/ pod	Nr of seeds/ plant	1000-seed weight (gm)	Mean observed yield (kg/ha)	Mean simulated yield (kg/ha) at $CPD_{0.5}$
T_0	14	11	154	81.8	705.4	850
T_1	16	13	208	84.4	983.1	1125
Calibration Year 2014	12	11	132	79.6	588.4	

Table 4. Nitrogen Use Efficiency (NUE) in cowpea fertigated with human urine.

Treatment	Soil $N_{(indigenous)}$ (kg ha^{-1})	$N_{(fertigation)}$ (kg ha^{-1})	$N_{(uptake)}$ (kg ha^{-1}) at $CPD_{0.75}$	$N_{(leached)}$ (kg ha^{-1}) At $CPD_{0.75}$	$N_{(residual)}$ (kg ha^{-1})	NUE[3] = $N_{(up)}/[N_{(up)} + N_{(le.)}]$
T_0	22.7	0	93	2	68.3	79%
T_1	22.7	60	272	3	186.3	76%

[3)] NUE=Nitrogen Use Efficiency; $N_{(up)}$ = amount taken up by plant kg ha^{-1}; $N_{(le)}$ = amount of N lost by leaching in kg ha^{-1}; $N_{(res)}$ = residual amount of N in kg ha^{-1}.

Table 5. Mean-Gini Dominance analysis for two different treatments for cowpea.

Treatment	E(x)	E(x)-r(x)	Efficient (Yes/No)
T_0 (simulated)	640	454.4	N
T_1 (simulated)	856	710.5	Y

E(x): mean return $/ha. r(x): Gini coefficient $/ha.

owing to the relatively high C:N ratio, or c) fixation at the cation exchange sites of clay minerals contained in the soil. Since the soil at the test site lay fallow for 6 months with much of the plant residues let to bio-degrade in-situ, it can be assumed that, this enhanced soil microbial activity and accelerated N mineralization (Abiven *et al.*, 2005; Chaves *et al.*, 2007).

Poor understanding of the N-balance between applied N-fertilizer amounts, $N_{(uptake)}$ by plants, $N_{(immobilized)}$ in the soil matrix is one of the main reasons leading to overuse of N-fertilizers and subsequently to $N_{(leached)}$. High concentrations and excessive use of human urine during fertigation may lead to Na-accumulation in soils (Sene *et al.*, 2013; Sheneni *et al.*, 2018) thus, inhibiting plant growth. Furthermore, excessive use of human urine may also increase the risks of NO_3^- leaching and electric conductivity (EC). Studies by (Worcester *et al.*, 2017) on both men and women subjected to prescribed diet, found out that the pH of women urine samples was higher than in men. Other studies also reported biochemical changes in urine samples stored for longer periods (Kuwornu and Obiri-Danso, 2015). These and other considerations are critical, if human urine is to be a viable option as a cheap source of organic fertilizer for most smallholder farmers. Due to the low levels of urine used in our study, there was therefore, no risk for N-leaching. However, long term and increased urine levels may under unfavorable environmental conditions lead to N-leaching.

Nitrogen dynamics and balance

The simulation results underlined the significant effect of fertigation on N-balance under both treatments (Table 4). For both treatments, the $N_{(uptake)}$ and $N_{(residual)}$ at $CPD_{0.75}$ were close to three-fold more under T_1 than T_0 with correspondingly high NUE at 79 and 76% respectively. Like in most soils, much of the organic-N (oN) in the soil is in the form of amino acids (Brackin *et al.*, 2015; Paungfoo-Lonhienne *et al.*, 2012) and is known to increase NUE when compared to inorganic-N (iN) (Arkoun *et al.*, 2012; Franklin *et al.*, 2017). Such high NUE under both treatments indicates the ability of the cowpea in utilizing both oN and iN components that naturally coexist in soils. However, during fertigation, there is a correspondingly larger oN pool compared to iN, thus increasing the predisposition for preferential $N_{(uptake)}$ under T_1 than T_0. Such preferential oN uptake by wheat plants was reported by (Geisseler *et al.*, 2009). The $N_{(uptake)}$ under T_1 was 63% higher than under to T_0 and, would suggest the increased preferential oN uptake leading to increased cowpea biomass and grain yield (Franklin *et al.*, 2017).

The amount of $N_{(residual)}$ under T_1 was three-fold higher than under T_0 at 68.3 and 186.3 kg ha^{-1} respectively. Such a high $N_{(residual)}$ amount invariably represents a large N-reserve initially taken up by the cowpea plants. Upon decay and decomposition, this would release significant amounts of organic-N that would subsequently be incorporated within the soil matrix. Much of the organic-N in the residues of leguminous plants have been reported to have positive effect on the yield of subsequent non-leguminous plants (Adeleke and Haruna, 2012; Njoku *et al.*, 2015). Although not directly part of our investigation, inference on the four-fold $N_{(uptake)}$ by T_1 than under T_0, would suggest the significance of fertigation as well as the role of N in enhancing cowpea nodulation, which in turn must have facilitated increase in $N_{(uptake)}$. Although cowpea plants symbiotically fix atmospheric nitrogen, the additional application of 60 kg ha^{-1} of organic nitrogen fertilizer enhanced a three-fold $N_{(uptake)}$ and so positively affected cowpea phenology and yield significantly (Lomeling and Huria, 2019). The findings of (Xia *et al.*, 2017) showed that low concentrations of nitrogen (<50 mg/L) added to soybean plants tended to increase nodulation while higher concentrations (>50 mg/L) had an inhibitory effect. Similar results by (Singh and Kalidindi, 2011) found out that application of 40 kg ha^{-1} other than 120 kg ha^{-1} of urea to specific cowpea EC-244390 (G4) and EC-240900 genotypes significantly enhanced nodulation and nitrogen fixation.

However, depending on legume type, stage of phenology, applied inorganic N-fertilizers, there appears to be a varied influence on nodulation, N-fixation thus, bio-mas and yield. Studies by (Abayomi *et al.*, 2008) on three legumes; cowpeas, groundnuts and soybean showed that addition of 30 kg ha^{-1} of urea yielded higher nodulation in the different three legumes than at 60 kg ha^{-1}. On the other hand, phosphorous has been reported to have an influence on legume nodulation (Tenebe *et al.*, 1995; Owolade *et al.*, 2006). It can be presumed therefore, that the phosphorous contained in the urine dilution applied during fertigation may equally have enhanced cowpea nodulation.

Strategic Analysis: Gross margin benefits of fertigation

The seasonal analysis program of DSSAT 4.7 was used to compare two management options with and without fertigation. The simulations were carried out for a 5-year period with daily climate data consisting of rainfall derived from NOAA rainfall database for Juba from 1996-2015 historical time series. Figure 5 shows the differences in gross margin under both treatments as represented by the cumulative probability distribution (CPD). Analysis of Stochastic Dominance (SD) (Figure 5) showed that T_0 generally had a low variance in terms of monetary returns, and a correspondingly lower Mini-Gini Dominance (MGD) than T_1 and therefore represented a more riskier investment option.

The economic incentives due to fertigation with human urine at $CPD_{0.25}$ were about $-290 for T_0, while this was about $-250 for T_1 accounting for a 14% difference. At $CPD_{0.5}$, T_0 was about $-285 while T_1 was about $-215 accounting for a 23% or $75 difference. At $CPD_{0.75}$, the T_0 was $-280 while this for T_1 was at $-180 making out a 35.7% or $100 difference. The probability for higher returns increased with further increase in each percentage point especially under T_1, suggesting that all investments under T_1 treatment had the best options. For example, there was a 75% probability that the total revenues accrued under T_0 would not be more than $-260, while this would not be more than $-180 under T_1. In effect, the deficit under T_1 and other financial obligations incurred would easily be recovered during the subsequent growing seasons than under T_0. This study also suggests that for risk averse smallholders, the combined effect

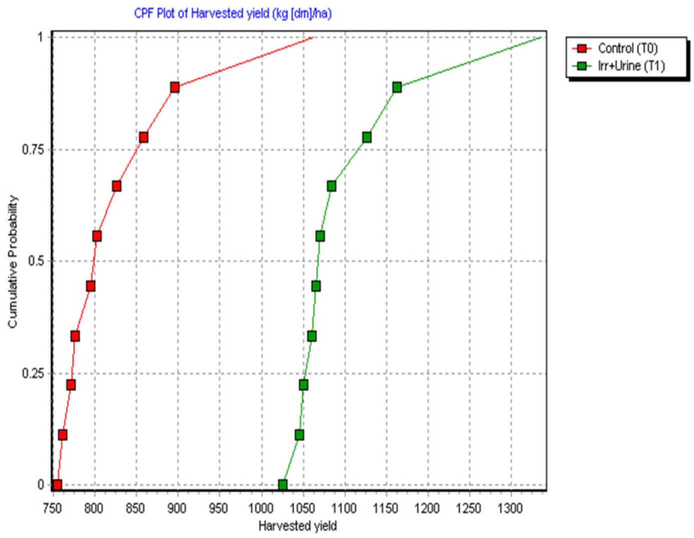

Figure 1. *Cumulative Probability Distribution curves on harvested yield of cowpea under T_0 and T_1 treatments.*

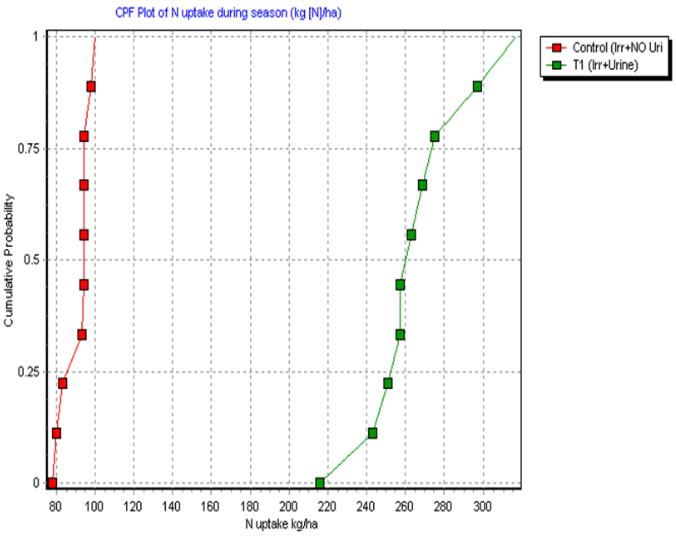

Figure 2. *A CPD on the N-uptake during fertigation under two different treatments.*

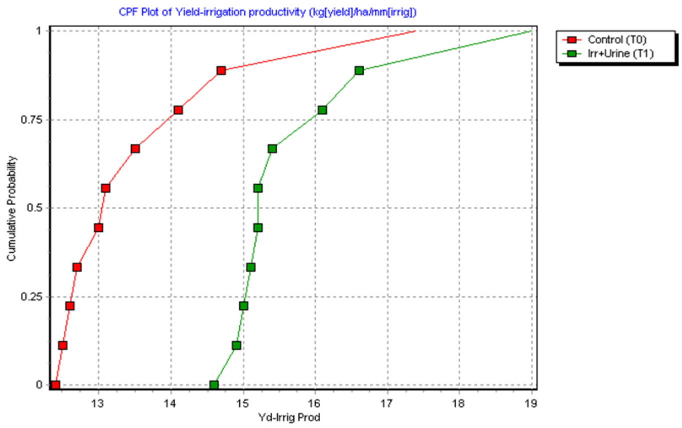

Figure 3. *A CPD on the estimated yield of cowpea per irrigation schedule under two treatments.*

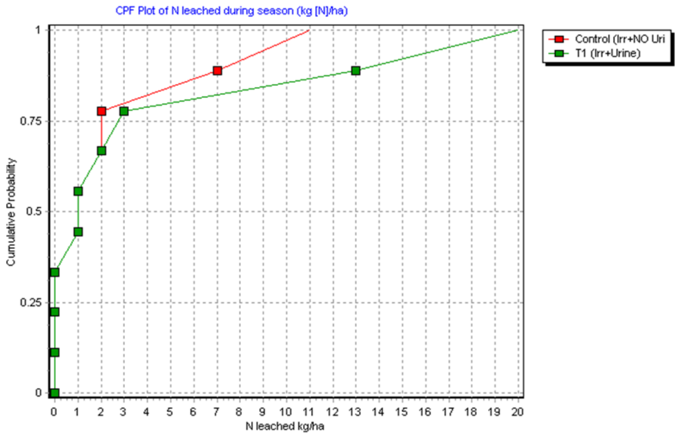

Figure 4. *Simulation of N leached in kg ha^{-1} during growing season of cowpea under different treatments.*

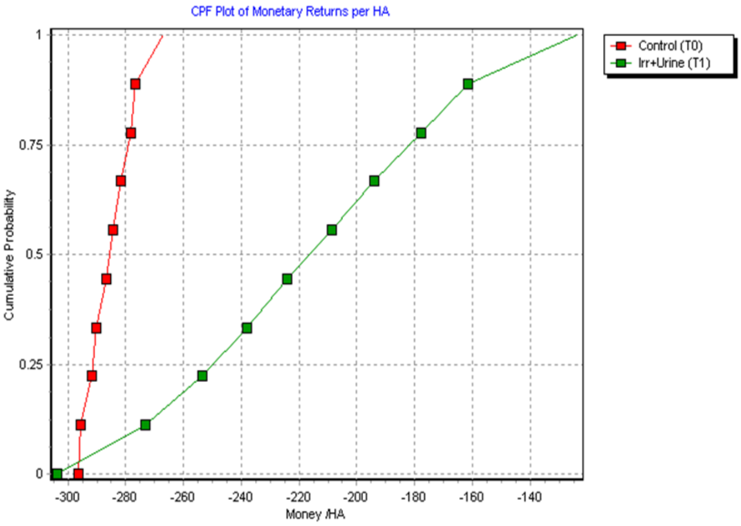

Figure 5. *Cumulative Probability Distribution (CPD) for monetary returns in $ under T_0 (no human urine application + irrigation) and T_1 (human urine application + irrigation) treatments of cowpea yields.*

of fertigation especially during periods of less and erratic annual rainfall is remunerative and would have a faster payback period with comparatively large gross margins. Negative returns ($ ha^{-1}) on the CPD plot highlighted low gross margins, i.e. high TVC with low TR as in (Eq. 1) implying that there was less monetary return anticipated relative to the huge production costs per season.

The simulated gross margin of fertigated cowpea crop with human urine also indicated that investment of about 10-12 kg ha^{-1}, or the equivalent of about $12-15, and 20 barrels of irrigation water (4,000 liters), or the equivalent of about $ 30-40 translated into mean generated revenues of about $680 and $900 for T_0 and T_1 respectively, accounting for a 24% difference. When compared to the potential gross margin under measured values, the results showed that this was $563.5 and $786.5 for T_0 and T_1 respectively, accounting for 28.4% difference. In contrast, the gross margin under observed T_1 compared to the calibrant Y2014 alone was about $493.2 that was about 40.2% difference. Assuming therefore, that all TVCs were constant for both simulated and observed treatments, the net returns would still be correspondingly higher for T_1 than for T_0.

The stochastic dominance analysis (Table 5) showed that for risk averse, cowpea production under T_1 than under T_0 was a better and less risky option, since this had lower variance in monetary returns and was to the left of T_1 in the CPD plot.

Conclusion

Given the low affordability, low availability and inaccessibility of industrial N fertilizers for most rural farmers in S. Sudan, whilst considering the low cowpea yield at less than 600 kg ha^{-1}, the use of human urine as a viable organic-N fertilizer has become an indispensable option. If properly applied, there is a 75% probability that cowpea yield levels, especially for - risk avert producers - this could be increased up to 1100 kg ha^{-1} from the current low levels with positive monetary returns or gross margins. Risk assessment prior to crop production and prediction of gross margins during each season remains a big challenge for risk averse smallholder farmers who opt for fertigation. Further, climate change impact considerations due to urine application showed that, if at the current application levels and rate as predicted by the CROPGRO model, the relatively low $N_{(leached)}$ pose no immediate risks to the environment. However, possible N-leaching would be contingent on the use, type of soil and rainfall intensity or antecedent soil moisture conditions, which would have to be validated and calibrated under varying farming scenarios.

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