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The effect of crop rotation on agricultural sustainability in the North-Western Free State, South Africa

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Abstract

Crop rotation has potential to maintain and improve agricultural sustainability. The effects of crop rotation are known to be site-specific which led to this study's objective of determining the effect of three different maize rotational systems in the North-Western Free State. This semi-arid region with its sandy soils is dominated by maize production. A field trial with maize in rotational systems with soybean and cover crops was established. Three aspects of sustainability were monitored: Soil health, total digestible nutrition and yield. Soil and maize kernel samples underwent soil health and nutritional testing respectively while yield data was collected. All data were analysed using descriptive and inferential statistics. Rotational systems and seasonal variation played a role in all aspects of sustainable agriculture investigated. Seasonal variation was seen in the wetter second season, with soil health and yield negatively affected. Although there was an association between maize soil health and yield, a rotational effect excluding soil health was observed, with the maize in rotation with cover crop and soybean performing better despite unhealthier soils. In addition, soybean production improved up to 40% over time in rotational systems. Overall, rotational systems focusing on maize production in the area were viable and contribute to agricultural sustainability and food security.

Keywords: Agricultural sustainability, crop rotation, maize production, North-Western Free State, soybean production

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1. Introduction

Crop rotation, which is the successive growing of different crop species, has potential to accelerate the achievement of environmental, social and economic sustainability – the three pillars of sustainable agricultural development (Nel 2005; Bobojonov et al., 2012). The influence of a specific crop on the production of a following, different crop is known as the rotational effect, which can either be positive or negative (Marques et al., 2020). The rotational effect is caused by many different factors, processes and mechanisms (Marques et al., 2020). These include the specific crops included in the rotational systems (Marques et al., 2020), the soil properties (Zheng et al., 2023), the climate conditions (Teixeira et al., 2018), and the incidence of weeds, pests and diseases (Marques et al., 2020). The fact that there are a number of influential factors make rotational systems site-specific (Lampridi, Sørenson and Bochtis 2019; Nortjè and Laker 2021). Therefore, it is important to incorporate suitable and profitable crops ideal for a certain environment (Strauss et al., 2021).

The North-Western Free state is a major contributor to South Africa's maize (*Zea Mays*) production, which is mostly produced in monoculture systems. Maize in monoculture has led to the use of mineral fertilizers and pesticides that are able to replenish soil nutrients and control pests and diseases but have undesirable long-term effects on the environment (Prashar and Shah 2016). Although these negative effects together with other events such as erosion, soil compaction and the breakdown of soil aggregates are recognised, the crop options for rotational systems are limited by the semi-arid climate and sandy soils in the area (Nortjè and Laker 2021). Maize-soybean (*Glycine max*) rotations are ideal in that they require simple management, similar equipment, sufficient seed availability, and have relatively high market prices (Feng et al., 2021). Soybean are able to fix nitrogen in symbiosis with Rhizobium (Coskan and Dogan 2011; Acevedo-Siaca and Goldsmith 2020) and act as a protein-rich food companion to maize (Costa et al., 2020).It has been suggested that including a cover crop mixture as a third crop improves the rotational system's productivity by minimising erosion, preventing leaching and increasing organic matter (Magdoff and Van Es, 2021; Smit, Strauss and Swanepoel 2021).

The objective of this study was to determine the effect that crop rotation has on sustainable agriculture in the North-Western Free State by focusing on the three pillars of sustainability. Namely, the environmental pillar in terms of soil health, the social pillar in terms of maize nutrition and the economic pillar in terms of crop production and profitability. The study further determined the association between these pillars.

2. Materials and methods

2.1 Site description

The study was conducted in the North-Western Free State, South Africa. This area forms part of South Africa's maize quadrangle (Figure 1). General climate conditions of the region include hot summers, mild winters and an annual rainfall of approximately 500 mm per year (Nortjè and Laker 2021). A common characteristic of the maize quadrangle is the non-oscillating patterns of low rainfall seasons, followed by high rainfall seasons (Laker 2008).

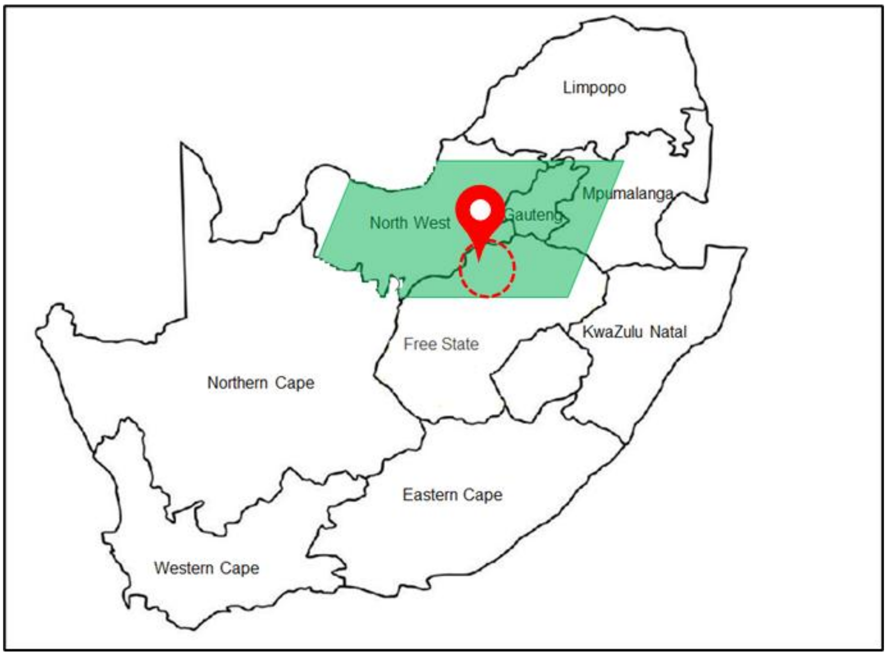

Figure 1: Map of South Africa showing the location of sample collection (authors compilation)

The North-Western Free State is also known for its extremely sandy soils which contains very little organic material, silt and clay (Beukes et al., 2019; Strauss et al., 2021). Only about 1-2% of the soil is made up of silt while the clay content in the A-horizon is normally less than 10%, and less than 15% in the B-horizon (Nortjè and Laker 2021). These sandy soils are vulnerable to wind erosion (especially during August and September when westerly winds are strong), susceptible to soil compaction and are normally infertile (Nortjè and Laker 2021; Strauss et al., 2021). In addition, the soil has a relatively high rate of water filtration however, the layer of clay at a depth of 1,5 - 2m prevents water drainage, often forming a temporary water table (Beukes et al., 2019). The ability of the North-Western Free State soils to effectively capture and store rainwater through the temporary water table, is a major contributing factor to the high maize production in the area (Beukes et al., 2019).

2.2 Trial layout and management

A trial comparing different crop rotational systems (maize-cover crop-soybean (MCS), maize-soybean-maize (MS) and maize-maize-soybean (MMS)) with monoculture maize (MM) as a control were established on the farm Christinasrus near the agricultural town of Bothaville. The MMS system was further identified as MMS1 and MMS2 to distinguish between the first (MMS1) and second (MMS2) season of maize. The cover crop mixture was made up of 60% grasses (sorghum and pearl millet) and 40% legumes (dolichos and cowpeas).

A randomised complete block design with three replicates was used for the trial layout. There were 27 plots in total, of which each were 80 x 24.4m in size. Rotational systems were assigned to plots and each crop within each system, representing a different stage, was assigned to a plot in each season to be able to distinguish between seasonal and rotational effects. The trial was monitored for three consecutive seasons: 2020/2021, 2021/2022 and 2022/2023.

At the start of each season (September) the trial was cultivated with a tandem ripper at depth of 750mm. Preplant fertilization including 100-140kg urea $ha^{-1}$was applied at a depth of 300mm. Trials were planted in the November/ December of each season respectively. Maize plots received additional fertilization at planting and were top dressed with an overall seasonal rate of 116-135 kg ha^{-1}nitrogen (N), 12-16 kg ha^{-1}phosphorous (P) and 5-19 kg ha^{-1}potassium (K). Soybean and cover crop received no additional fertilizer. Maize and soybean plots were sprayed with round-up (glyphosate) for the control of weeds. All field actions were done with commercial equipment. No biomass was removed nor utilised by any farm animals.

2.3 Seasonal rainfall

A favourable rainfall season was experienced during the 2020/2021 season. A total of 686 mm was measured from September 2020 to May 2021, with most rainfall falling between December and February (477mm). The 2021/2022 season had a very wet start compared to the previous season. A total of 922 mm was measured between September 2021 and May 2022, with 309 mm of rain being measured in December 2021 alone. The third season saw a more wide-spread rainfall season. A total of 700 mm of rain was measured between September 2022 and January 2023 (24% less than in 2021/2022).

2.4 Data collection

An array of samples was collected from the field trials to determine the sustainability of different rotational systems. Soil samples were collected approximately 100 days after planting from all maize plots in each season. Samples were taken randomly within each plot 200 mm from the plant row and combined to form a composite sample. The overall soil health of the samples was determined using the Haney Soil Health Test (HSHT) (Haney et al., 2018). Maize kernels were collected after maturity (in May of each season) for nutritional analysis from all maize plots during each season. Two samples were randomly taken per maize plot. Samples from the same rotational system were combined to give a composite sample per rotational system. Samples underwent nutritional analysis using South African National Accreditation System (SANAS) accredited methods. Finally, production and profitability of crops were measured using commercial farm equipment and enterprise data.

2.5 Data analysis

Data were cleaned and prepared for SPSS version 29 where it was further analysed using descriptive and inferential statistics. Descriptive analysis included measures of central tendency. Inferential statistics included analysis of variance (ANOVA), which were run to determine if there was a statistically significant interaction effect of rotational system and season on soil health, total digestible nutrition (TDN) and yield. (The rotational system variable was transformed into a dichotomous cropping system variable to compare the TDN values in maize after maize and in maize after soybean).Assumption testing included testing for outliers, normal distribution, and homogeneity of variances. Post hoc Least Significant Difference (LSD) tests were run for statistically significant ANOVA results. In addition, linear regressions were run to determine associations between soil health, TDN and maize yield. Assumption testing included testing for outliers, normal distribution, and homoscedasticity. A prediction equation was determined based on the regression results. Statistical significance was accepted at $p \leq 0.05$.

3. Results

3.1 Soil Health

The overall soil health scores obtained from the HSHT are shown in Figure 2. All soil health scores were below the ideal value of 7.00, varying from 2.70 (MCS in 2021/2022) to 5.07 (MMS1 in 2020/2021) (Haney et al., 2018). The two-way ANOVA showed that soil health was affected by season ($F(2) = 48.13$, $p< 0,001$) but not the rotational system ($F(4) = 0.17$, $p = 0.95$), with no interaction between these variables, $F(8) = 1.27$, $p = 0.30$. In addition, LSD results showed the mean difference in soil health to be statistically significant between all seasons, with season one (2020/2021) having the highest average soil health score (4,72 ± 0.65) and season two (2021/2022) the lowest (2.98 ± 0.34). The average soil health dropped 37% in the second season (2021/2022) and improved again by 17% in the third season (2022/23).

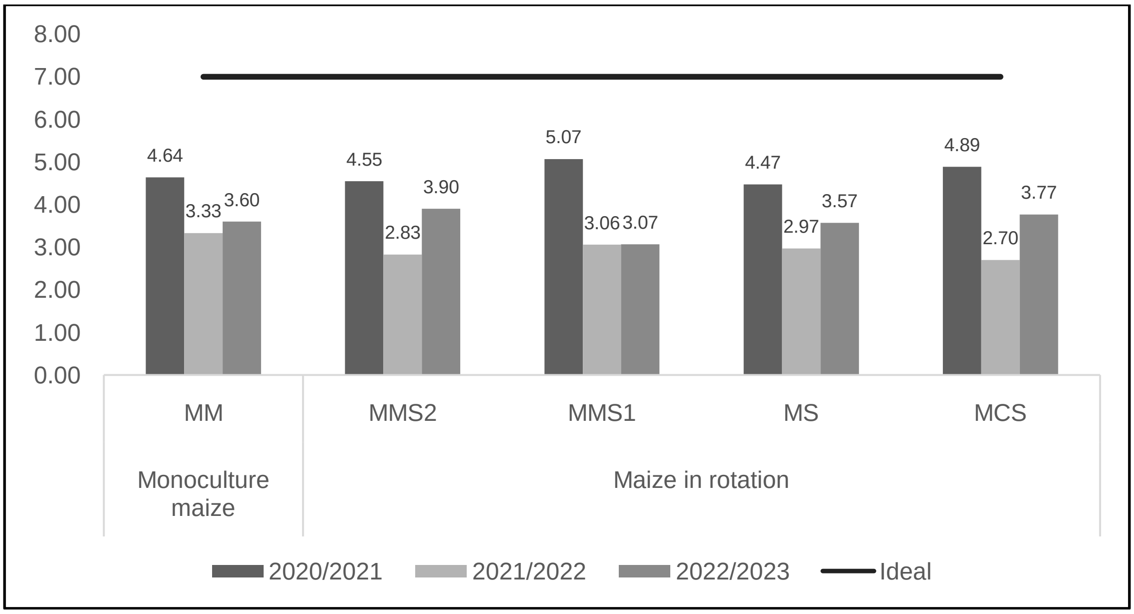

Figure 2: Mean soil health score of maize plots in different rotational systems for three seasons (2020/2021, 202/2022 and 2022/23)

3.2 TDN value

The TDN values are shown in Figure 3 and varied from 89 to 91%. The two-way ANOVA results show that TDN was not affected by season ($F(2) = 0.70$ $p = 0.51$) nor cropping system ($F(1) = 3.81$, $p = 0.06$), but there was an interaction affect between these variables, $F(2) = 6.67$ $p = 0.003$. Maize after soybean had a 1-2% higher TDN than maize after maize in season one (2020/2021) and two (2021/2022) respectively, while the opposite was seen in the third season (2022/2023), where maize after maize had a 1% higher TDN than maize after soybean.

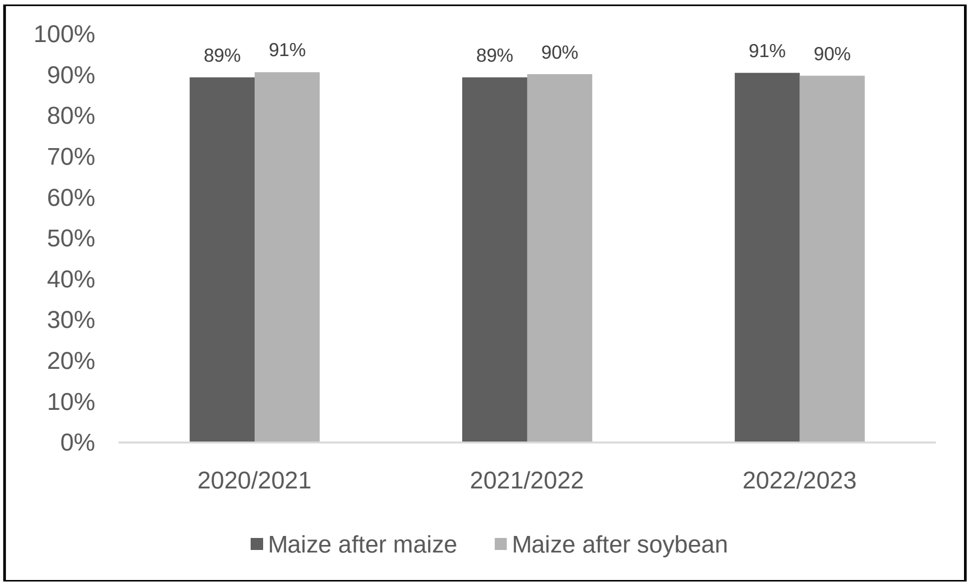

Figure 3: Mean TDN value in cropping systems for all three seasons (2020/2021, 202/2022 and 2022/23)

3.3 Production and profitability

Maize yield is shown in Figure 4 and varies from 1.69 to 8.49 ton ha^{-1}. The two-way ANOVA results show that the maize yield was affected by rotational system ($F(4) = 4.17$, $p = 0.01$) and season ($F(2) = 61.78$, $p < 0.001$). There was also a statistically significant interaction between these variables, $F(8) = 2{,}61$ $p = 0{,}03$. Maize in the MCS rotational system had the highest mean yield (5.91 ton ha-1), 14% higher than the mean yield for monoculture maize. Additional analysis showed that maize yields after soybean were 18% higher than maize yields after maize ($F(1) = 6.08$, $p = 0{,}02$). LSD results showed that the mean maize yield was statistically significantly different from the second season (2021/2022), with maize yield from this season being 58-60% lower than season one (2020/2021) and season three (2022/2023).

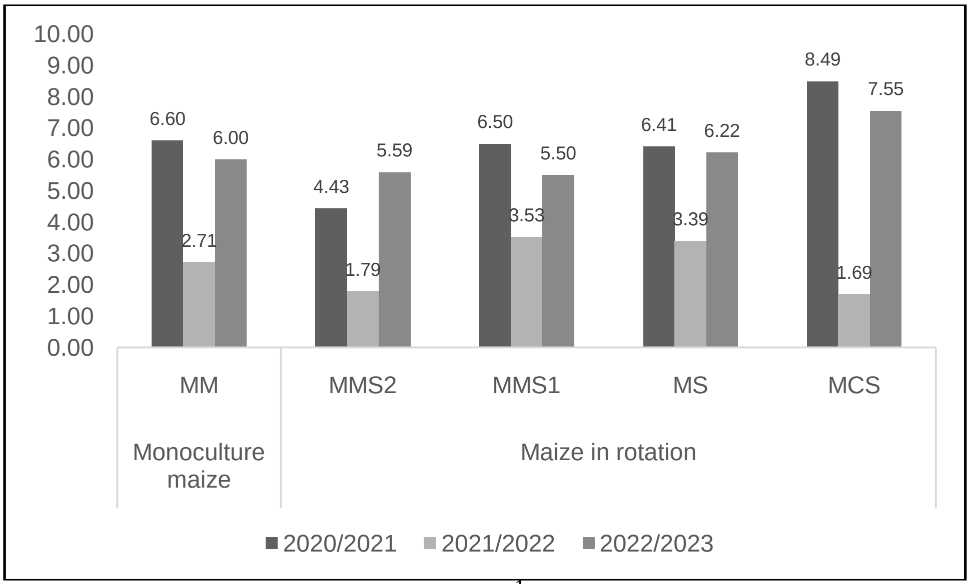

Figure 4: Mean maize yield (ton ha^{-1}) in different rotational systems for three seasons (2020/2021, 202/2022 and 2022/23)

The soybean yield ranged from 0.76 to 3.97 ton ha^{-1} and showed an overall improvement from the first season (2020/2021) to the third season (2022/2023) (Figure 5). The MCS rotational system had the greatest improvement of 40%. The two-way ANOVA show that soybean yield was not affected by rotational system but was affected by season ($F(2) = 140.60$, $p = 0.03$). LSD results show that all season's soybean yield differed significantly (p values < 0.05). There was also a statistically significant interaction affect between rotational system and season, $F(4) = 3.32$ $p = 0.03$. The MMS rotational system was the rotational system with the highest soybean yield in the first season (2020/2021), 9% more than MS and 33% more than MCS. In the wetter second (2021/2022) and following third season (2022/2023) soybean in the MS rotational system performed up to 42% better than the MMS rotational system.

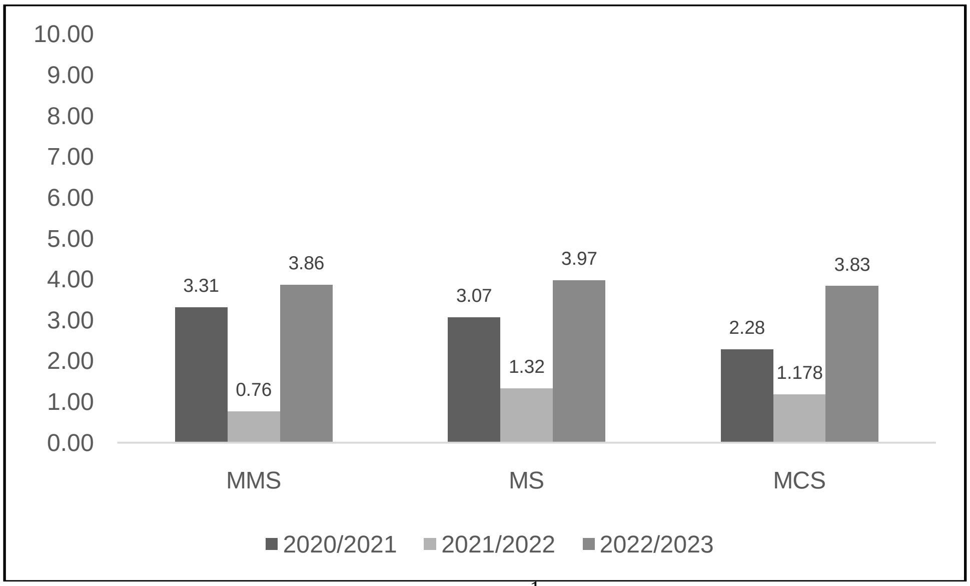

Figure 5: Mean soybean yield (ton ha^{-1}) in different rotational systems for three seasons (2020/2021, 202/2022 and 2022/23)

The mean cover crop biomass ranged from 2.64 to 11.37 ton ha^{-1}. ANOVA and LSD results show that the cover crop biomass was statistically significantly different between seasons ($p \leq 0.05$). The highest cover crop biomass was in season one (2020/2021), 35% higher than season two (2021/2022) and 78% higher than season three (2022/2023). The third season's cover crop biomass was well below the expectation of at least 7 ton ha^{-1}, and was therefore regarded as a failure.

The gross margin of both maize and soybean varied from season to season. The highest gross margin for maize production was seen in the MCS rotational system in 2020/2021 (R16 604,50 ha^{-1}) and 2022/2023 (R15 949,96 ha^{-1}), 32-33% more than the gross margin for maize production of monoculture maize in the respective seasons. In the unfavourable second season (2021/2022), the MMS1 rotational system had the highest gross margin (R2 960,65 ha^{-1}), 95% more than the gross margin for maize production of monoculture maize (R136,66 ha^{-1}). Soybean production in the MMS rotational system had the highest gross margin in the first season (2020/2021), while soybean production in the MS rotational system did better in the second and third season (2021/2022 and 2022/2023), resulting in an overall 14% higher gross margin for soybean production in the MS rotational system compared to the MCS and

MMS rotational systems. Estimating the gross margin of the cover crop, the mean gross margin of the rotational systems were: MS > MCS > MMS > MM.

3.4 Association between soil health, TDN and maize production

Table 1 summarises the mean soil health, TDN and maize yield for each rotational system over the duration of the study. No relationship was found between TDN and soil health, nor between TDN and maize yield. However, there was a statistically significant association between soil health and maize yield, with 40% of the variation in maize yield explained by the regression model, $F(1.43) = 30.46$, $p< 0.001$. Soil health added statistically significantly to the prediction of maize yield ($p< 0.001$) with a one unit increase in soil health resulting in a 1.62 ton ha^{-1} maize yield. Therefore, a positive association was determined between soil health and maize yield, with a regression equation of: Maize yield = -1.02 + (1.62 x (soil health)).

Table 1: Mean soil health, TDN and maize yield for each rotational system for 2020/2021, 2021/2022 and 2022/2023

Rotational system	**Soil health**	**TDN**	**Yield**
MM	3.86	89%	5.10
MMS2	3.76	90%	3.94
MMS1	3.74	90%	5.18
MS	3.67	90%	5.34
MCS	3.78	90%	5.91

4. Discussion

Maize rotational systems as well as seasonal variation played a role in all three aspects of sustainable agriculture (soil health, TDN and crop production) investigated in this study. Seasonal variation was mainly seen in the wetter second season, with soil health and yield being affected negatively. This could be as a result of anaerobic conditions caused by waterlogging which inhibited beneficial soil organisms and promoted pathogenic bacteria (Horneck et al., 2011). Sitthaphanit et al. (2009) further explains that when rainfall intensity is high decomposition occurs too quickly, causing organic matter and nutrients to be lost through leaching, rather than being released slowly into the soil, resulting in a lower water extractable organic nitrogen (WEON) and water extractable organic carbon (WEOC) which are key determinants of the overall soil health score.

As was expected, an increase in soil health resulted in an increase in maize production, this is often the case, as described by Awoonor, Dogbey and Quansah (2023) and Batool (2023). These results link the environmental and economic pillars of sustainability, which according to the sustainability model make the conditions viable, where environmental practices are able to maintain economic stability (Mulligan 2014; Purvis, Mao and Robinson 2019). Despite soil health not directly influencing TDN, the influence of soil health on maize yield enhanced nutritional value in terms of quantity albeit it not in quality (Farre et al., 2010). If this indirect association were to be included, together with the fact that TDN remained high in all systems, the social pillar of sustainability could be incorporated into the model resulting in overall sustainability.

Although a higher soil health was associated with higher maize yield, the highest yield in this study did not come from the healthiest soil. All maize after soybean rotational systems (MMS1, MS and MCS) had higher yields than monoculture maize albeit lower soil health scores. The MCS system had a 14% higher maize production than monoculture maize despite a 2% lower soil health. This suggests a rotational effect not captured in the soil health score. The proposed rotational effect is that the soil of maize after soybean and/ or cover crop is replenished more naturally compared to monoculture maize which received more inorganic fertiliser, allowing for a slower release of nutrients over a longer period of time, resulting in a higher maize yield (Hernandez et al., 2021). Studies by Mtambanengwe and Mapfumo (2006), and Mamuye et al. (2021) showed that a combination of organic and inorganic nutrients result in better yields. In addition, soybean can significantly reduce the prevalence of Striga (*Striga hermonthica*), a parasitic weed, by inducing suicidal germination which decreases Striga presence and reduces weed pressure in subsequent maize rotations (Acevedo-Siaca & Goldsmith, 2020). Furthermore, rotational systems disrupt pathogen cycles resulting in a breakdown of diseases and boost in productivity (Shah, Prasad & Kumar, 2021).

The soybean production was not influenced by rotational systems, however it did show an overall improvement from season one (2020/2021) to season three (2022/2023) with the MCS rotational system showing the greatest improvement. This is in conjunction with Acevedo-Siaca and Goldsmith (2020) who mentioned that the incorporation of soybean in maize-rotation not only has a benefit for the maize crop but also improves soybean yield. Similar to maize, improved soybean yield indirectly affects nutrition in that it acts as a protein-rich companion to maize, providing a more balanced diet (Engelbrecht et al., 2020). It appears that soybean tolerated waterlogged conditions better than maize due to the production of aerenchyma (Takahashi et al., 2014). Aerenchyma is a type of tissue that enhances aeration and is regulated by ethylene, which is a plant hormone that accumulates under anaerobic conditions (Boru et al., 2003; Qi et al., 2023). Soybean produces secondary aerenchyma which is more adaptable and flexible than primary aerenchyma produced by maize (Boru et al., 2003; Takahashi et al., 2014). Furthermore, soybean is able to prevent oxygen leakage by forming a barrier, which maize is unable to do (Langan et al., 2022).

With the predictions of more frequent extreme weather conditions in the future (Chemura et al., 2022) it is important to note that the MMS1 system outperformed the favoured MCS system in wetter conditions. Excessive water possibly suppressed organisms such as *Trichoderma viride* and *Aspergillus sp*, which are responsible for the loss of sorgoleone (Bansal 2020). Sorgoleone is produced by the sorghum in the cover crop mixture and has allelopathic properties which suppress the growth and yield of proceeding crops in certain seasons, especially on sandy soil (Bansal 2020; Sarr et al., 2020).

5. Conclusion

In conclusion, rotational systems focusing on maize production in the North-Western Free State are viable and contribute to agricultural sustainability in the area. According to Lampridi, et al. (2019), the sustainability assessment of such practices can be difficult due to case-specific variables that need to be taken into consideration. It was determined that in the extremely sandy soils of the North-Western Free State the incorporation of soybean and cover crops in rotation with maize have a positive effect on its sustainability as well as food security.

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Data availability: The datasets used and/ or analysed during the study are available from the corresponding author on reasonable request.

Authors contribution: Melanie de Bruyn: Conceptualization, Methodology, Formal analysis, Investigation, Writing – Original Draft, Visualization, Funding acquisition. **Andre Nel:** Conceptualization, Methodology, Validation, Investigation, Writing – Review & Editing, Supervision, Project administration. **Johan van Niekerk:** Validation, Project administration

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