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Nitrate leaching in irrigated inorganic agriculture: A case study of Mashare commercial farm in Namibia, Okavango River Basin

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Irrigation schemes in old flood plains of the Okavango River were identified as major non-point sources of sediment nutrients and leachates despite lack of supporting evidence from studies that measured nutrient levels in the river's mainstream using grab samples. Hence this study sought to check for evidence of loss and transport of nitrates from an irrigated field into the uncultivated riparian zones of the Okavango River. Soil nitrates were tested for using an Eutech ion 6+ pH/mV meter and a nitrate ion selective electrode, in soil samples taken from an irrigated field, a control site and a depression receiving storm water drained from the irrigated field at the Mashare commercial farm. Based on analysis of farm records' fertilizer application rates and soil nitrates results, it was inferred that maize crops grown in the rainy summer seasons contributed more nitrogen fertilizer losses compared to wheat crops planted in dry winter seasons. The top soil derived from Kalahari sandy soils retained more nitrates compared to the subsoil which had high contents of light-coloured calcrete, which contained low nitrate levels especially when dry. High nitrate levels in horizons 150 cm below the root zone, at a 240 cm depth, and more than twice nitrate levels in the vlei compared to the irrigated field and an uncultivated field proved that there was leaching of nitrates from the irrigated into the uncultivated riparian zones of the Okavango River.

Key words: Calcrete, irrigated field, leachate, maize, nitrates loss, Okavango River, wheat.

INTRODUCTION

Agricultural activities and deforested lands are the major non-point sources of sediment, pesticides, nutrients, and pathogens, which are difficult to measure and control (FAO, 2005 a). Loss and transport of nutrients from agricultural fields into rivers occurs through soil erosion and leaching which can be major factors that limit the nitrogen utilisation efficient of crops.

Loss of nitrate-nitrogen because of leaching (washing) from the bottom of the crop root zone is a loss of money to farmers as it result in reduced yields or a need to apply

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more nitrogen, and the fertilizer contaminates water resources (FAO, 1985). The lost nutrients are pollution threats to receiving water bodies and may increase water treatment costs.

Periodic measurements of nutrient concentration in river water can be appropriate for assessing impact of non-industrialised settlements and agricultural activities (Williamson et al., 1999; Mathuthu et al., 1997; Zaranyika, 1997). Okacom (2010) and Trewby (2003) suggested that Okavango River basin's commercial farms irrigating crops on highly permeable sandy soils could be polluting the river with nutrients more than any other land use. Vushe et al. (2014) found out that Okavango River water flows from Angola were of excellent quality (according to Namibian Standards), and the nutrient load was attenuated in the Namibia reach despite over hundred percent increase in irrigated area in Namibia in a period of ten years. There were no statistically significant differences in total phosphorus and total nitrogen between 1993 and 2012, and nutrient measurements in 2011 and 2012 showed that the water was passed on to the Okavango delta (in Botswana), with a lower nutrient load. The assays of nutrient levels in the mainstream water failed to prove that nutrients lost from the irrigated fields were entering the Okavango River's mainstream.

Generally, transports of nutrients from farms into mainstreams through groundwater contamination develop gradually for several years (20 to 30 years) before it becomes apparent (Covert, 2014). Annually, the irrigated farms of the Okavango River basin produce two crops (maize and wheat), with a nitrogen application rate of over 400 kg ha^{-1} per year (Trewby, 2003; Vushe et al., 2014). The general target for nitrogen fertilizer application rates for maize is about 250 kg ha^{-1}, which is about 1.5 times more than the average amounts recommended in South Africa (du Plessis, 2003) and USA's Corn Belt (Sawyer, 2007; Alley et al., 2009). Between 1993 and 2012 human activities along the river increased and intensified, especially irrigated agriculture increased from 300 Ha to 2600 Ha (Vushe et al, 2014).

Therefore, for the nutrient load to be apparent in the Okavango's mainstream, the attenuation capacity of the river's ecosystem must be overwhelmed by the nutrient load from the anthropogenic activities. Vushe et al. (2014) found out that the land use changes in the Kavango Region had low impact on the nutrient water quality of the Okavango River, although Okacom (2010) and Trewby (2003), had suggested that irrigation schemes could be the worst polluters.

Therefore, this study sought to check for evidence of loss and transport of nutrients from an accessible irrigated field into the uncultivated riparian zones of the Okavango River. Nitrates were selected as the indicator nutrient for an assay of loss of nutrients from the irrigated fields because the highly soluble nitrate anion is normally repelled by the soil particles leaving it free to be transported by the water in the soil. This form of N is of special environmental concern and it is generally the form found in groundwater (Hermanson et al., 2000).

METHODOLOGY

In two field trips, soil samples were taken from the irrigated field, a vlei receiving storm water drained from the irrigated field, and a control site located between the irrigated field and the annually flooded riparian zone of the river. The soil samples were tested for nitrates. The control site was on an area elevated 2m above the vlei and cleared of vegetation. A soil auger was used to make a hole and for taking soil samples at 30 cm depth intervals down to hard formations, and sampling points were as shown on a map in Figure 1.

Soil sampling in the vlei was limited to a 210 cm depth. In the field, sampling was limited to 110 cm depth because of hard rocky layers. Hence a pit was dug in the field to a depth of 240 cm for testing for nitrates leached far below the root zone. During the first field trips the highest soil nitrate concentrations were obtained in the low lying northern edge of the field, therefore the position of the pit was selected on the low lying area of the field close to the vlei. The soil samples from each 30 cm horizon were mixed and 50 g of soil was weighed and 100 mL of deionised water was added to form a soil slurry. The soil slurry was allowed to settle and the supernatant water was filtered. Nitrate concentration and pH of the soil were measured using a Eutech ion 6+ pH/mV meter, pH electrode and a nitrate ion selective electrode. Soil nitrate measurements were done during the two separate field trips. The first set of field measurements was done a week after the harvest of a winter wheat crop. The second field trip was taken 35 days after a maize crop had been planted and after the onset of the summer rainy season.

Study area

The study area, the Mashare commercial farm on latitude S 19°53' and longitude E 020°11' is located on the southern old flood plains of the Okavango River 40 km east of Rundu Town in the Kavango East Region of Namibia. The region is a broad sandy plateau dominated by sandy soils, with an average slope of less than 0.07%. The area experiences semi-arid climatic conditions with an average rainfall of 577 mm and potential evaporation is more than 2600 mm per year (Vushe et al, 2013). Namibia contributes almost no surface water to the Okavango, although the length of the Okavango is over 400 kilometres, because Namibian tributaries drain predominantly semi-arid and arid areas (El Obeid and Mendelsohn, 2001; Okacom, 2010). The Okavango River basin's headwaters are located in the Angolan highlands, where the stream flow is generated. Namibia's intensive commercial crop production, even in the rainy summer season relies on irrigation water pumped from the perennial Okavango River.

The commercial farm under study uses a combination of two centre pivots each covering 30 hectares, linear systems and drag horse irrigation systems for irrigating mainly maize and wheat crops. Inorganic fertilizers are applied as a compound (NPK) at sowing and nitrogen is also applied in splits every week through fertigation. The total area under irrigation is 150 Ha and the field is located on the old flood plains of the Okavango River. Between the river's levee and the fields is about 100 m swath of savannah woodland. One thirty hectare centre pivot was selected as the field for this study as shown on the map in Figure 1.

The centre pivot under study has a gentle slope of 0.16% in the south to north direction, and hence surface water draining from the field at the northern edge flow via a steeper area with a 2.19%

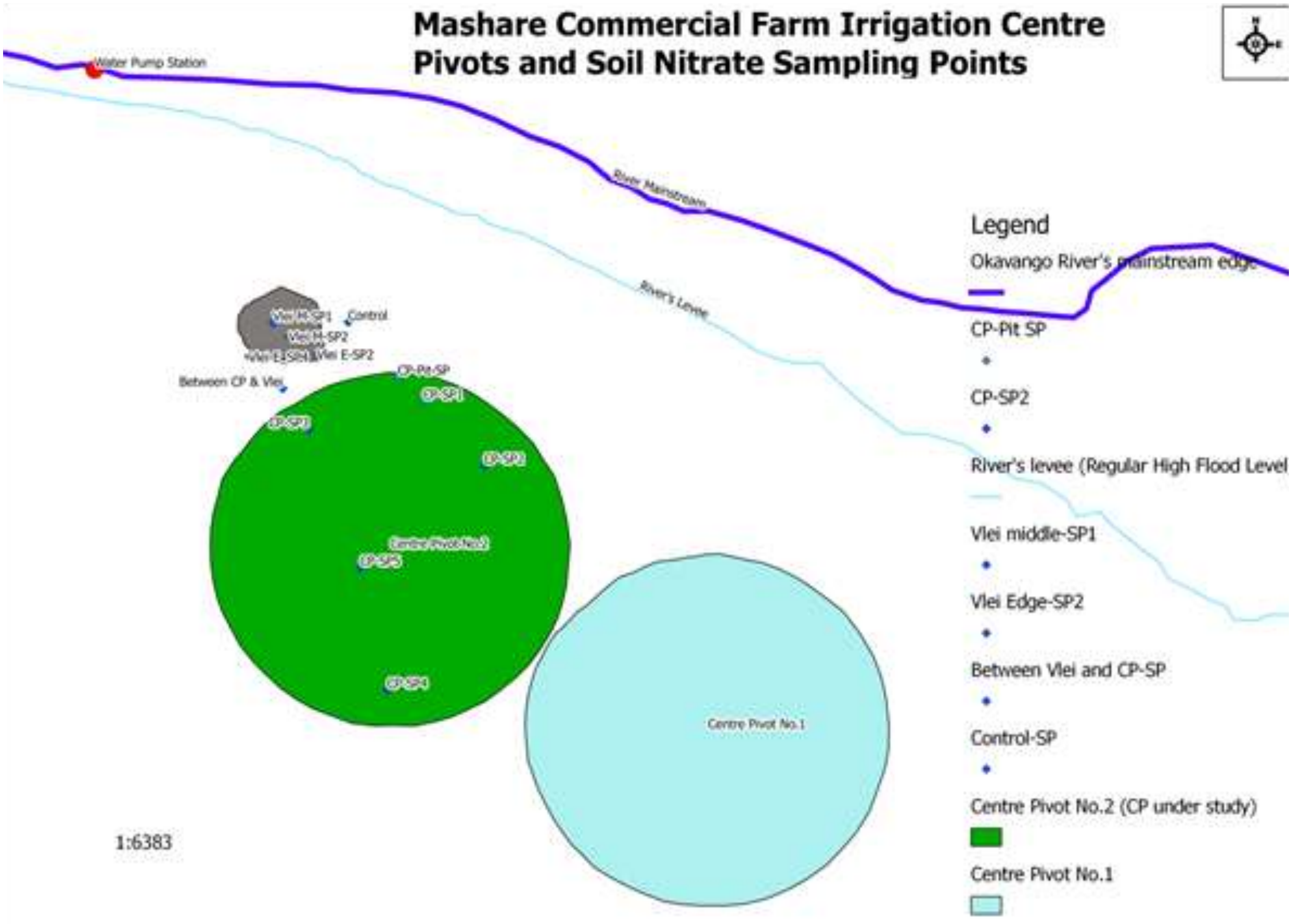

Figure 1. Map of Mashare Irrigation centre pivots and the soil sampling positions.

slope, into a depression or vlei. The vlei is a low lying area of approximately 135 m in diameter, which is located in the old flood plains, between the Okavango River levee and the field under study. Storm water does not flow directly into the Okavango mainstream but ponds in the vlei, and most likely it percolate through ground water flow channels into the river's mainstream. Also, when the Okavango is under extreme flood conditions the vlei is sometimes inundated by the mainstream's flood water. The field's northern edge and the vlei are separated by a 60 m stretch of uncultivated land, which was cleared of vegetation (trees, thorn bushes and grasses) in 2015. The northern edge of the vlei is about 140 m away from the Okavango River perennial high flood edge; the levees. The vlei's edge has sparse perennial grasses and the middle has sparse seasonal grasses. Also, scattered thorny bushes and trees thrive in the black clayey soils of the vlei that have high swell and shrink capacity.

Soils of the study area

The landscape at the study area is composed of three relatively flat land features. Directly south of the river's mainstream is a stretch of frequently flooded plain with dark coloured loamy soils that crack when dry, but the southern boundary of this plain is characterised by sandy levees, and humus rich depressions exist south of the levees. Further to the south a nearly plain area elevated a few meters above the highest river water level follows, which was formed in earlier phases of higher flood levels. These old floodplains are the preferred areas for irrigated crop production due to their soil fertility and safety from frequent flooding, and the Mashare Commercial farm is completely located in this landscape unit. About 150 m from the river's levees the area's gradient generally rises in the southwards direction. Here the land is composed of windblown sandy soils, called Kalahari sands, which have been levelled in part and nowadays forms a slightly undulating landscape covered with Baikiaea-Woodlands or used for cropping activities.

The distribution of soil properties is related to the landscape unit. Soils on the far expanding sandveld of the Kalahari sands are called Arenosols (Driessen and Dudal, 1991; FAO, 2006), which have high infiltration rates, due to coarse granular textures and lack of surface crust development (Ministry of Environment and Tourism, 2000; Andersson, 2006). Medium sands are the dominant size fraction of the Kalahari sands where the total medium sand content is generally about 60% and fine sand about 30%. Clay and silt are less than 10% and often around 6%. The soils are highly permeable and storage of available water is low within normal rooting depths. This is supported by high porosity values of about 42% with a predominance of large and free-draining pores. The sandy textures, cause poor moisture retention and hence rain fed crops can experience prolonged periods of moisture stress. Surface horizons hold slightly higher moisture contents of about 8% compared to subsurface horizons which hold 3 to 6% (Ministry of Environment and Tourism, 2000).

Within the old floodplains where the Mashare Irrigation Farm is located, soils textures were variable whereby soils in the fields are loamier than the Arenosols of the Kalahari sandveld. The mean topsoil texture was 10% clay, 6% silt, 38% fine sand and 45% medium sand. Due to clay illuviation, clay and silt content increases with depth up to 24% on average, therefore most soils in this part of the landscape were classified as Luvisols (Driessen and Dudal, 1991 in FAO, 2006). In the one to two metre depths of the old flood plain, the occurrence of calcrete was responsible for the high pH values and base saturation of the soils. Termites of the Macrotermes genus constructed their mounds, through material transports and construction of holes which improved soil conditions into finer textured soils hence the soils vary from loamy sands to sandy loams around the termite mounds which averaged ten mounds per hectare in some places (Turner et al., 2015). The finer texture improved the water holding capacity significantly compared to the pure sandy Arenosols, hence plant-available water may be about 100 mm per metre depth (Saxton and Rawls, 2006). Although the infiltration capacity of the soils is high because of the loamy texture, the presence of calcrete in subsoil and the compact soil structure may lead to perched water in the subsoil (Grigsby, 1992; National Research Council, 1995), probably causing root aeration problems. Irrigation thus has to be applied carefully not to over-saturate the soil with water and to damage plant growth.

Generally, the Kalahari sandy soils' surface clay contents are lower than subsurface horizons with an average of 6%, increasing irregularly to 14% in lower horizons (Ministry of Environment and Tourism, 2000), which may indicate higher water holding capacities and possibly nutrient retention capacities, in lower horizons (McClellan et al., 2014; University of Hawai'i at Manoa, 2015). Low clay contents combined with low and irregular levels of organic matter are also linked to relatively low nutrient concentrations. These soils are not infertile and they are also not highly productive (Ministry of environment and Tourism, 2000).

Maize is produced under supplementary irrigation in the rainy summer seasons, while wheat is produced in the dry winter seasons under full scale irrigation. For a target of 10 t ha^{-1} maize grain yield, farmers in the Okavango River basin apply about 250 kg per hectare of inorganic nitrogen fertilizers, but in the 2012/13 summer season some farmers applied above 400 kg N ha^{-1} for the maize crop (Vushe et al., 2014), in order to replaced fertilizer lost during numerous long wet spells caused by some torrential rainfall events. On average nitrogen fertilizer application rates are over 40% higher than the recommended rates in South Africa and USA's corn belt (Vushe et al., 2014). There was a high possibility of nitrate leaching in the highly permeable soils of the inorganic commercial farms in the Okavango River basin; hence the main objective of this study was to assess the occurrence of nitrate transport from the irrigated fields. The transport of leached nutrients into the rivers mainstream is expected to occur intermittently but peaks during the river's low flood periods, especially because groundwater flow direction is chiefly from the hinterland towards the river.

There is hardly any recharge of river water into the hinterland's Kalahari aquifer, evidenced by groundwater in the Kalahari aquifer along the banks of the river, which often shows poor quality due to its iron and manganese content, which exceeds the limits for drinking water and high fluoride concentrations in some places (Ministry of Agriculture, Water and Forestry and Ministry of Mines, 2001). Water in the Okavango's mainstream was classified as excellent for drinking (Group A) according to Drinking Water Standards of Namibia (Vushe et al, 2014), but the hinterland's groundwater was classified under poor quality, which indicated that there was low groundwater movement and dilution effects of water from the mainstream into the hinterland aquifer. The Kalahari aquifer recharge by the Okavango River only occured on rare occasions when the Okavango River floods the old flood plains, and this inflow of river water could locally dilute and improve the Kalahari aquifer's groundwater quality (Ministry of Agriculture, Water and Forestry, and Ministry of Mines, 2001). Therefore during the low flow seasons there could be a net flow of leachates from the irrigated farms into the river's ecosystem, hence this study sought for some evidence on presence of transported nitrate nutrients in the river's riparian zone.

RESULTS

Soil profiles

In the irrigated fields and the control site, top soils were mainly Kalahari sand types, but low lying areas and flattened termite mounds in the field had loam soils. A subsoil layer, which was a mixture of calcrete and the Kalahari sands, was observed in the 30 cm to 60 cm depths. In the field, soil sampling with an auger was limited to a depth range of 60 to 110 cm due to the presence of a light-coloured hard calcrete layer.

On the control site and between the field and the vlei, a combination of calcium silicate and hard calcrete rocks also limited soil sampling to a depth range of 60 to 110 cm. The manually dug pit in the irrigated filed had sandy loams in the top 30 cm, a mixture of sandy loam soil and hard light-coloured calcrete rocks in the 30 to 60 cm horizon, and in the 60 to 180 cm horizon there was a hard layer of the light-coloured calcrete rocks, which overlaid a softer reddish-brown calcrete layer. The softer reddish-brown calcrete layer was harder to dig as depth increased and hence the manual digging was limited to a 240 cm depth.

The vlei had a different soil profile to the irrigated field, since it is located at the lowest point, and it is the receiving or illuviation zone of the local soil catena that include the centre pivot irrigated field under study. The vlei has a soil depth of more than 200 cm, which is predominantly a black clay soil (vertisol) which cracks extensively when dry. The top horizons in the 120 cm depth were predominantly black clay soils while the lower horizons had mixtures of clay and light-coloured calcrete, and the amount of calcrete increased with increase in depth. At a depth of 210 cm there was a hard horizon consisting of a mixture of hard calcrete and calcium silicate stones.

Soil pH

Generally, the pH increased with increase in depth in the irrigated field, control site, the vlei and between the vlei and the irrigated field. In the irrigated field, the pH of top soil ranged from 5.81 to 6.77, while the 30 to 60 cm horizon had a pH ranging from 6.68 to 7.73. The control site's pH was 7.01 in the top soil and 7.46 in the 30 to 60cm horizon, but the vlei had the highest pH which ranged from 7.98 to 9.55.

Fertilizer application rates at Mashare commercial farm

For the 2015 wheat crop, Mashare commercial farm applied 194.6 kg N ha^{-1} of inorganic nitrogen fertilizers, harvested 5.5 t ha^{-1} and the protein content of the wheat was above 12%. The N fertilizer was applied as a compound fertilizer (2:3:2 NPK with Zn) at a rate of 21 kg N ha^{-1} at planting, followed by fertigation with 30.6 kgNha^{-1} as urea and 10 kgNha^{-1} as calcium nitrate in the first week. Fertigation with urea was also done in the third and sixth weeks, and at the flag leaf stage at rates of 30.6 kg N ha^{-1}. Fertigation with ammonium sulphate was done in the second and fourth weeks at rates of 10.5 kg N ha^{-1}. In the fifth week fertigation with a compound fertilizer (3:0:1 NPK) was done at a rate of 20.2 kgNha^{-1}.

For maize which is grown in the rainy summer season, the target application rate is 250 kg N ha^{-1}, but 12% more N fertilizer was applied in weekly fertigation splits due to long wet spells in the 2014/15 summer season, and the average yield was 10.5 t ha^{-1}. The nitrogen fertilizer application schedule was 30 kg N ha^{-1} at planting as a basal compound fertilizer (2:3:2 NPK & S + Zn) followed by fertigation with 25.76 kg N ha^{-1} of urea one week after planting and 20.2 kg ha^{-1} of urea in the second week. The weekly urea fertigation schedules of 25.76 kg N ha^{-1} and a 20.2 kg N ha^{-1} application in the following week were repeated five times until the 12th week. Generally, 80% of crop residues are incorporated into the soil for nutrients recycling and soil conditioning.

Soil Nitrates in the control site, irrigated field, between the field and Vlei, the Vlei's Edge and in the Middle of the Vlei

Soil nitrate tests were done on every 30 cm depth down to hard layers which limited the auger's penetration and soil sampling. The depths of the holes were limited between 60 cm and 120 cm except for two holes in the middle of the vlei that had a hard layer at a 210 cm depth. The results of soil nitrate measured per each 30 cm depth at each sampling point in the centre pivot (identified as CP-SP1 to 4), in the middle of the vlei (Vlei M-SP1 to 2), control, manually dug pit (CP-Pit-SP, between the vlei and the centre pivot (between CP and Vlei) and at the vlei's edge (vlei E-SP1 to 4) are shown in Table 1.

Soil Nitrates in centre pivot irrigated field after wheat harvest, before the rains

Five sampling holes were made with an auger and the depths of the holes were limited between 60 cm and 120 cm because of the light-coloured hard calcrete layer. The results of soil nitrate measured per each depth of soil on all five holes were similar to graphs obtained at the two positions shown in Figure 2 and Figure 3.

Soil nitrates tested after some rain events in the centre pivot irrigated field with a maize crop

Eleven days after the onset of the rainy season a pit was dug manually just at the northern edge of the field which had a maize crop, soil nitrates were measured on soil samples obtained on each 30 cm horizon, and results are shown in Figure 4. The top soil (30cm depth) had more nitrates (0.141 g per g soil) compared to the top soil nitrate levels of 0.007 g per g soil which were obtained after the wheat harvest as shown in Figure 3.

Soil nitrates in the Vlei

Soil nitrates measured after harvesting wheat, before the onset of the rainy season showed that the nitrate level in the vlei's top soil was less than 0.002 g per g soil maximum at the 100 cm depth of 0.168 g per g soil and there was a reduction with increase in depth after the 90 to 120 cm horizon as shown in Figure 5. The black clay soil was dry and cracked in the top soil, but soil moisture increased with depth after the 30 cm depth.

Figure 6 shows that after the first summer rains with a total of 82.5 mm in 6 rainfall events in 27 days, soil nitrates levels in the vlei had increased in all horizons to a maximum of 0.311 g per g soil in the 60 to 90 cm horizon compared to nitrate levels measured just after the wheat harvest, before the rains' onset. The top soil had 0.0 g per g soil and the maximum nitrate level was 0.168 g per g soil in the 60 to 90 cm horizon.

DISCUSSION

The nitrogen fertilizer application rates of 194.6 kg ha^{-1} for wheat were similar to rates recommended in Australia, where 176 kg N ha^{-1} could be applied if the target yield is 5 t ha^{-1} of wheat grain with 10% protein, and 210 kg ha^{-1} of N fertilizer was recommended for a target yield of 5 t ha^{-1} of wheat grain with 12% protein (Department of Agriculture and Fisheries, 2012).

In South Africa, the recommended fertilizer application rates for maize was 175 kg N ha-^{1} for a target yield of 8 t

Table 1. Soil nitrate levels test results in first and second field campaigns.

Sampling sites	Depth (cm)	pH	Soil nitrate (g/g soil)
Soil nitrate tests: First campaign			
CP-SP1	30	6.77	0.055
	60	6.97	0.001
	90	6.98	0.001
	120	6.98	0.001
CP-SP2	30	6.77	0.104
	60	7.73	0.020
CP-SP3	30	5.81	0.007
	60	7.17	0.001
	90	7.43	0.001
	120	7.68	0.001
CP-SP4	30	6.48	0.024
	60	6.68	0.002
CP-SP5	30	6.354	0.002
	60	7.065	0.002
Vlei M-SP1	30	8.33	0.004
	60	8.43	0.144
	90	8.47	0.168
	120	8.67	0.164
	150	8.42	0.114
	200	7.98	0.028
Control	30	7.01	0.007
	60	7.46	0.002
Soil nitrate tests: Second campaign			
CP-Pit-SP	30	6.71	0.141
	60	6.95	0.090
	90	8.21	0.118
	120	7.36	0.002
	150	8.09	0.002
	180	6.71	0.013
	210	8.29	0.045
	240	6.94	0.099
Between CP and vlei	30	6.85	0.128
	60	6.69	0.052
	90	8.41	0.002
	110	6.86	0.002
Vlei edge-1	30	6.1	0.030
	60	6.8	0.014
	90	6	0.000
	120	5.85	0.066

Table 1. Contd.

	135	6.73	0.066
Vlei E-SP2	30	5.96	0.003
	60	5.91	0.002
	90	6.73	0.004
	120	7.05	0.002
Vlei E-SP3	30	6.57	0.054
	60	6.68	0.001
	90	6.55	0.001
	110	5.75	0.003
Vlei E-SP4	30	5.9	0.223
	60	7.27	0.070
	90	6.95	0.063
	120	6.52	0.020
	150	6.59	0.057
	170	6.77	0.020
Vlei M-SP2	30	8.58	0.098
	60	9.11	0.150
	90	9.55	0.311
	120	9.5	0.221
	150	8.33	0.084
	180	8.59	0.233
	210	8.52	0.163

ha^{-1} (FAO, 2005b; van der Linde and Pitse, 2006), which were similar to rates recommended in USA's Corn Belt (Sawyer, 2007; Alley et al., 2009). A maize yield of more than 10.2 t ha^{-1} can be harvested if 250 kg N ha^{-1} is applied on a field with a maize plant population of 60000 plants ha^{-1} (FAO, 2006).

For the 2014/15 summer maize crop, the Mashare farmer applied 280 kg ha^{-1} of N fertilizer and obtained a yield of 10.5 t ha^{-1} which indicated more N losses. The increase in N fertilizer application rates from 175 to 286 kg ha^{-1} led to an increase in yield from 8 to 10.5 t ha^{-1}, which indicated a reduction in fertilizer use efficiency from 45.7 to 36.7 kg maize per kg N, and hence there were higher losses of the N fertilizer at the application rate of 280 kg ha^{-1}. This was similar to findings by Zotarelli et al. (2008) that an increase in N fertilizer application rates from 163 to 246 kg/ha, did not increase yield of a zucchini squash crop but decreased nitrogen use efficiency and increased the amount of leached nitrates by 73%.

The Mashare farmer applied more N fertilizer (through a weekly fertigation schedule) in order to compensate for N losses to leaching and gaseous emissions during long wet spells caused by the erratic summer rainfall. Leaching could be the main cause of higher N fertilizer application rates, since the farmer applied more inorganic

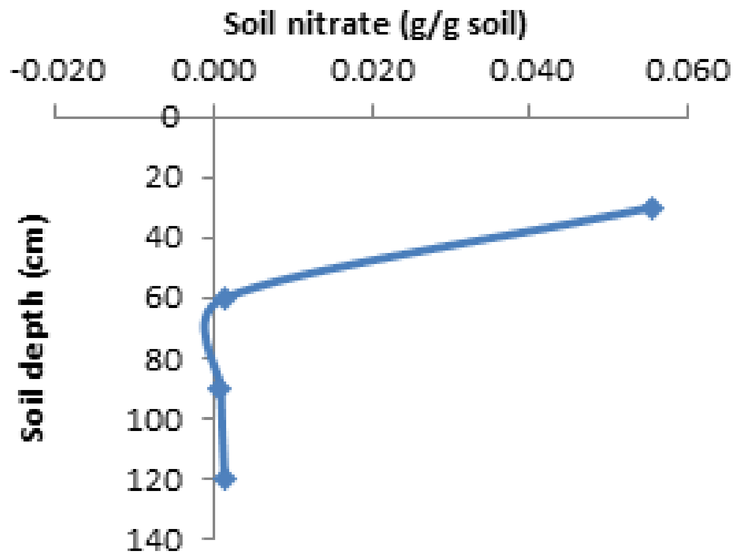

Figure 2. Soil nitrates measured in the centre pivot irrigated field after wheat harvest, sampled using an auger down to 120cm, on position CP-SP1.

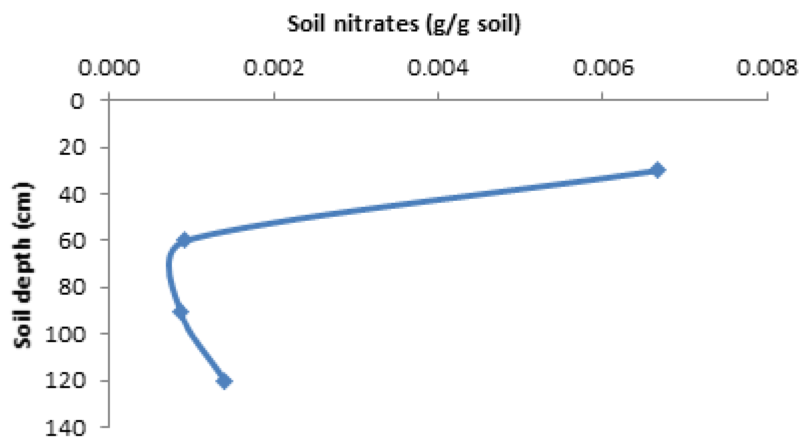

Figure 3. Soil nitrates measured in the centre pivot irrigated field after wheat harvest, sampled using an auger down to 120cm, on position CP-SP3.

fertilizers on a soil which had high hydraulic conductivity and a low water retention capacity. Application of fertilizers (especially organic fertilizers) that improve water and nitrate retention of top soil, and release the nitrates slowly just to meet crop nitrate demand even under saturated moisture conditions might reduce leaching of nitrates during the long wet spells. The farm manager rubbed soil samples between the finger and thumb for soil moisture measurement and irrigation scheduling. The method could be useful but it was less accurate compared to other irrigation scheduling methods that could be used to minimize the excessive fertigation.

An analysis of root zone soil nitrate concentration and matching fertigation schedules with a maize crop nitrate demand curve might help in reducing the N fertilizer over application and nitrates leaching during the long wet spells. Further studies may be required, in order to evaluate if more accurate supplementary irrigation scheduling methods complimented with agronomic practices that increase nitrate retention capacity of the root zone can reduce fertilizer application, and hence reduce leaching, without causing maize yield reductions.

According to Bowman et al. (1998), environmental conditions and management practices may affect N nutrition and nitrate leaching. Wheat is grown in the cool and dry winter months while maize is grown in the rainy

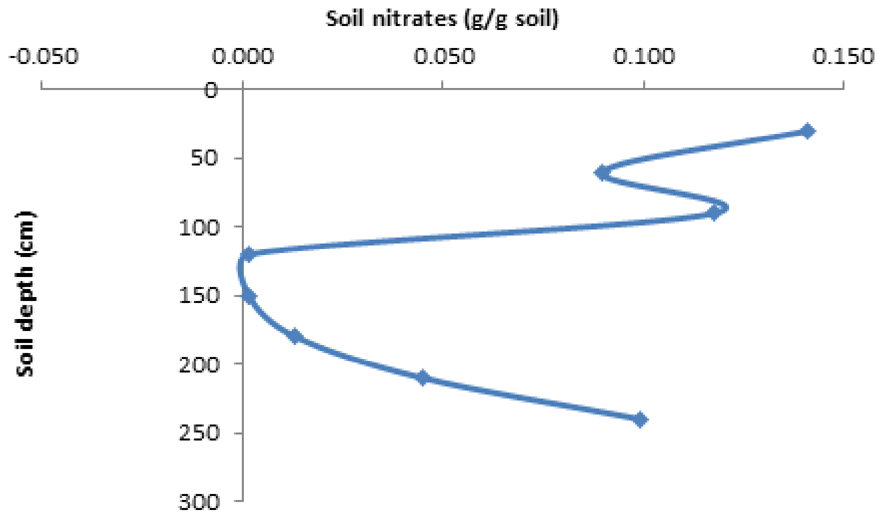

Figure 4. Soil nitrates measured after onset of rainy season, in pit dug down to 240 cm, on position CP-Pit-SP on the northern edge of centre pivot irrigated field.

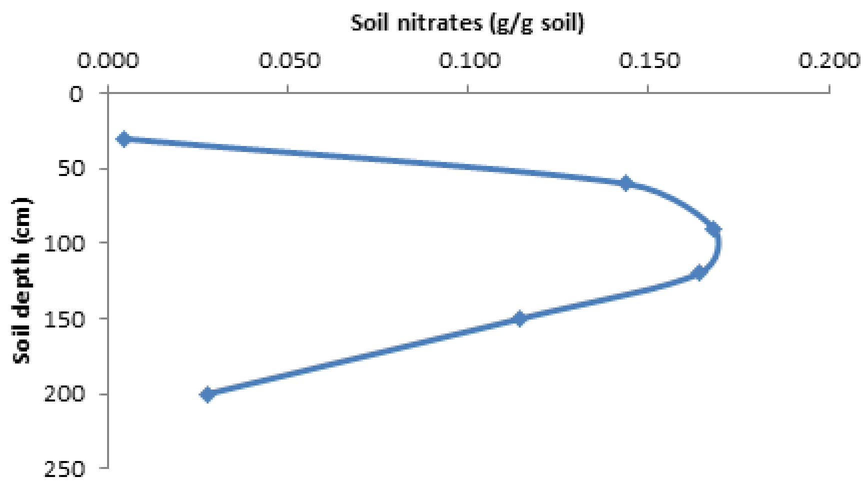

Figure 5. Soil nitrates measured in the vlei before just after the wheat harvest, sampled with an auger down to 200 cm.

summer season, and the agronomic management practices are different, hence for reducing nitrate leaching, different soil fertility and moisture management strategies are required for the two crops. The earlier mentioned strategies for minimizing nitrate losses to leaching are:

Improving the soil properties for higher soil nitrate retention and leaching reduction, and Use of more accurate fertigation schedules; may be complimented with methods that enhance recovery of nitrates and curtail transport of nitrates from the old flood plains into the river's current flood plains. For example, identifying subsurface leachate draining zones between the field's edge and the river's levee, and planting deep rooted crops or tress to take up the nitrates in the drainage flow lines may mitigate nutrient pollution of the Okavango River's ecosystem.

Table 1 showed that after the wheat harvest; nitrates in the top soil were in the range 0.001 to 0.104 g per g soil, and the subsoils nitrate levels ranged 0.001 to 0.02 g per g soil. The lowest nitrate levels were obtained near the middle of the centre pivot irrigated field. The highest soil nitrate concentration was obtained in the low lying northern edge of the field probably due to transportation and deposition of nitrates from upslope to lower lying parts of the field by storm water runoff. The top soil had

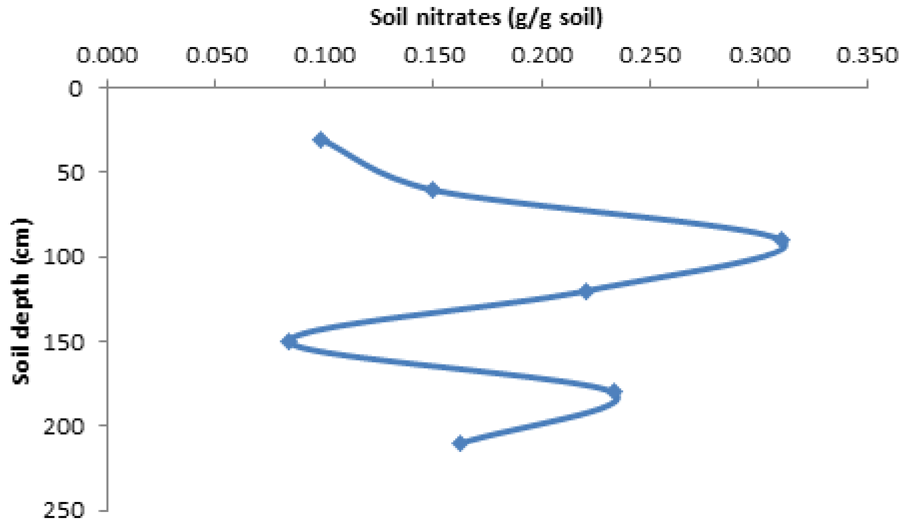

Figure 6. Soil nitrates measured in vlei after the first rains sampled with an auger down to 210 cm.

higher nitrate levels probably due to a higher nitrate retention capacity because of a higher water holding capacity which is usually enhanced by a higher content of organic matter of top soils of the Kalahari sands (Ministry of environment and Tourism, 2000). Also, organic matter provides a source of nitrogen, increases water-holding capacity, and improves nutrient holding and release (McClellan et al., 2014; University of Hawai'i at Manoa, 2015).

The elevated nitrate levels in the irrigated field, the vlei's edge and in the middle of the vlei (ranged 0.004 to 0.311 g per g soil) compared to the control (ranged 0.002 to 0.007 g per g soil) showed that the vlei area's nitrate level was receiving nitrates from the agricultural activities either as overland flow or through groundwater leachate flows. This was indicated by the high nitrates levels in both the top soil and the subsoil of the sampling points at the edge of the vlei, and between the vlei and the field. The control site had lower nitrate levels which were contributed by non-anthropogenic natural sources.

When the irrigated field had a maize crop, the nitrates levels of 0.141 g per g soil were highest in the top soil (0 to 30 cm depth) of the field (as shown in Figure 4), because N fertilizers were applied weekly through fertigation. The relatively high nitrate levels (0.118 g per g soil) in the 60 to 90 cm horizon might be due to nitrates that were transported by percolating water from upper horizons (subsoil), because 82.5 mm of rainfall was received after the maize crop's planting date (11/11/2015), and in particular two consecutive days got heavy rainfall amounts of 30 mm on 16/11/2015 and 23 mm on 17/11/2015. The two consecutive rainfall events caused a long term wetting of the partial impermeable calcrete, which only allow downward water movement when subjected to continuous wet conditions for over three hours (Grigsby, 1992; National Research Council, 1995).

Hence leaching of nitrates could have occurred, and probably aggravated by antecedent moisture from preceding irrigation events. The tests for soil nitrates were done 11 days after the last heavy rainfall of 22 mm on 04/12/2015, and the soil nitrate levels were 0.141 g per g soil in the top soil (0 to 30 cm depth). Zotarelli et al. (2008) measured nitrate levels in 0-30cm depth of a sandy soil (with 97% sand-sized particles) 51 days after planting a zucchini squash crop, 163 and 246 kg/ha N fertilizer had been applied, and the soil nitrate levels were 113 and 274 mg/L in the soil solution. This can be compared to the soil nitrate levels of 1410 mg/L in soil solution (0.141 nitrates per g soil shown in Figure 4). The higher nitrate levels showed that the Mashare farmer applied some nitrogen fertilizer after the heavy rains in order to compensate for possible losses of nitrogen nutrients.

Figure 4 showed that nitrates were almost absent (0.002 g nitrates per g soil) in the light-coloured calcrete layer which dominated the 120 to 180 cm horizon, although the layer overlaid the 180 cm to 240 cm horizon, which had higher nitrate levels (0.013 to 0.099 g nitrates per g soil). This indicated a low nitrate retention capacity of hard light-coloured calcrete layer and the resistance of the hard calcrete layer to capillary movement of the leachate. Therefore the nitrates under 180 cm depth was identified as the leached nitrates and hence lost from the field to the environment because the maize and wheat crops (with less than 100 cm effective root depths) were unable to utilize the nitrates leached below the 180 cm depth. The increased nitrate concentration under the 180 cm horizon corresponded to a change in geological formation from hard light-coloured calcrete to a softer reddish-brown calcrete formation, and the later could have higher water retention capacity due to a higher porosity. The soft reddish-brown calcrete zone could be one of the main geological formations through which the nitrate leachate is transported from the irrigated field into the vlei. Further studies could give details on the effectiveness of the soft reddish-brown calcrete horizon in transportation of leachates from the irrigated fields.

As shown in Figure 5, the dry and cracked top soil (0 to 30cm depth) had low nitrate levels of 0.004 g per g soil which indicated that nitrates could have been lost, probably to the atmosphere through denitrification (Tindall et al., 1995). Generally moist black clay soil has low permeability, but under arid conditions it dries and cracks, and the cracks can conduct water rapidly as preferred pathways downward water flow (Yong and Warkentin, 1975; Mitchell and van Genuchten, 1993). Also, Tindall et al. (1995) stated that clay may only retard leaching of nitrate and leaching loss is significant in both sand and clay. Therefore the vlei's black clay could allow percolation of the nitrate leachate to lower horizons. Figure 5 showed an increased levels of moisture content and nitrate levels in the 30 to 150 cm depths of the vlei, which had a range of 0.114 to 0.168 g nitrate per g soil, while the control site had 0.002 to 0.007 g nitrate per g soil, which showed that the nitrates transported from the field by the leachate and overland flow were being deposited in the vlei.

Generally, denitrification is relatively low in moist clay soils compared to sandy soils, because under unsaturated conditions, the clay has little to no tendency to denitrify due to high moisture content of the clay (Tindall et al., 1995). This explained why the moist horizons of the black clay soil had higher levels of nitrates compared to the dry top soil. The light coloured clayey soils at the 200 cm depth had high amounts of calcrete and calcium silicate stones and lower levels of nitrates despite a higher moisture content compared to upper horizons. The lower nitrate levels at the 200 cm depth showed that the calcrete and calcium silicate stones had probably lost some nitrates through leaching into deeper horizons. As shown in Figure 5 and Figure 6, the nitrate levels in the 120 to 150 cm horizon, before the rains and after the rains remained almost constant (decreased by 0.03 g per g soil), probably because the soil in the 120 to 150cm horizon had a low nitrate retention capacity that got saturated at a level less than 0.12 g nitrate per g soil. Therefore the horizon released excess nitrates to lower horizons. Therefore, if the vlei is hydro geologically connected to the Okavango's main stream the leached nitrates eventually enter the mainstream through groundwater flow channels.

Conclusion

For a target yield of 10.5 t ha^{-1}, more than 286 kg ha^{-1} of N fertilizer was applied to maize crops grown in the rainy summer seasons compared to 170 N kg ha^{-1} application rates recommended internationally for a target yield of 8 t ha^{-1}. Hence maize production might have contributed more leached nitrates compared to the wheat crop produced in the dry winter season, and a yield of 5.5 t ha^{-1} was harvested when the fertilizer application rate was 194.6 kg N ha^{-1}, which was within international recommendations.

Evidence of nitrate leaching was shown by the high nitrate levels in soil horizons at 240cm depths, which were 150 cm deeper than the root zone. The hard light-coloured calcrete had low nitrate levels compared to the underlying soft reddish-brown calcrete horizon located below the 180 cm depth, which might be the most likely horizon and pathway for transportation of nitrate leachate. Evidence of nitrate transport from the irrigated field into the uncultivated riparian zones of the Okavango River were proved by nitrate levels in the vlei which were more than twice the soil nitrate levels of irrigated field and the control site.

The top soil (0 to 30 cm horizon) had higher nitrate levels compared to the subsoil which had higher contents of light-coloured calcrete, and the calcrete contained no nitrates when dry. The nitrate concentration in the soil decreased with increase in depth in the irrigated field and uncultivated fields in all soil horizons containing high calcrete content, showing that the calcrete had low nitrate retention capacity.

Conflict of Interests

The authors have not declared any conflict of interests.

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