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Optimisation of major nutrients (N, P and K) for lowland rice production in Eastern Uganda

I. Wanyama[1], V.A. Ochwoh[2*], E. Nankya[3], P.J.A. Van Asten[4]

[1]*Consutative Group on International Research; International Institute of Tropical Agriculture (IITA); Nairobi, Nairobi Area, Kenya*

[2]*Directorate of Graduate Studies, Research and Innovations, Busitema University, P.O. Box 236, Tororo, Uganda*

[3]*Buginyanya Zonal Agricultural Research and Development Institute (BugiZARDI)-NARO; P.O. Box 1356-Mbale, Uganda*

[4]*International Institute of Tropical Agriculture (IITA), Uganda*

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Abstract

Demand for rice in Uganda surpasses the supply and results in importation of over 30% of the rice consumed. Actual rice yields are still very low (1.5 t ha^{-1}) compared to the potential yield (8 t ha^{-1}). Therefore, this study aimed at establishing the major limiting nutrients and estimation of optimum fertilizer requirements for lowland rice for increased and sustainable production. The study was conducted in two seasons Eastern Uganda. Two sets of trials were conducted; nutrient omission trial for estimating indigenous nutrient supply of the major nutrients and response function and the recovery efficiency trial for estimating recovery of applied Nitrogen. Both experiments were laid in a RCBD, where the first one involved 8 treatments of NPK (t0, t1, t2, t4, t5, t6, t7 and t8) each at different rates. While the second experiment involved two treatments (t0 and t1) of N fertilizer. Applications of nitrogen significantly increased yield components and consequently the grain yield of rice. The major limiting nutrient for lowland rice production is nitrogen and the soil nitrogen supplying potential can support yield target of 2.8 t ha^{-1}. Whereas, the indigenous Phosphorus and Potassium supply can support yield target of up to 9 t ha^{-1} and therefore, not limiting at achievable yield targets of 6 tha^{-1}. Use of internal efficiencies was promising in analysis of nutrient status and nutrient requirement to achieve the specific yield targets. 65 kg N ha^{-1} is the optimum rate for lowland rice and this corresponds to a target yield of 5 t ha^{-1}.

* **Corresponding Author**: V.A. Ochwoh ✉ ochwokangah@gmail.com

Introduction

Rice is a staple food of over half of the world's population (IRRI, 2008). Rice is the most rapidly growing food source in Africa and it is of significant importance to food security in an increasing number of low-income, food-deficit countries (FAO, 2004). In Uganda, rice is gaining importance as both a commercial and food crop, especially among the rural peasant farmers (Kibwika *et al.*, 2002). The area under rice cultivation in Uganda increased by 30 % between 1997 and 2007 (FAOSTAT, 2014), consequently, the quantity of rice produced increased by 29% between 1997 and 2007 hence the increase in rice produced is attributed to putting more land under rice production. The actual farm yields are still very low; 1.5 t ha^{-1} (FAO, 2004), 2.2 t ha^{-1} (Kaizzi *et al.*, 2002) for lowland and 1.72 t ha^{-1} for upland (Kijima *et al.*, 2006) compared to the potential for lowland rice (7 t ha^{-1}) and the water-limited potential for upland rice (4.5 t ha^{-1}) (Kamwezi *et al.*, 1997; Takeshi, 2005). Rice imports into the country quadrupled between 1994 and 2004. In 2007 alone, Uganda imported around 70,000 tonnes of rice costing us $ 20M (FAOSTAT, 2014). In addition the world rice price is increasing; hence, more money will be spent on rice imports. Amidst the increasing world price and increasing foreign exchange spent on rice imports in Uganda, the demand for rice is increasing. Low soil fertility is recognised as one of the attributors to low lowland rice yields in Uganda (Kaizzi *et al.*, 2002). However, the specific major nutrients and their respective optimum rates have not been established. There is need to increase on quantity of rice at farm levels in order to scale down the rice imports as well as meet the increasing rice demands. This study was carried out in Doho rice scheme, one of the largest rice irrigation schemes in Eastern Uganda. This study aimed at quantifying nutrient constraints and crop response in researcher-managed and farmer managed trials. The Site Specific Nutrient Management Strategy (SSNM) approach was used to estimate fertilizer requirement for a given yield target given the soil indigenous nutrient supply and recovery efficiency.

The Nutrient Omission Technique for Estimation of Soil Indigenous Nutrient supply

This technique is used to estimate indigenous nutrient supplies (IS) as described by Janssen *et al.* (1990). The IS represents the cumulative amount of a nutrient originating from all local sources that circulate in the soil solution surrounding the entire root system during one complete crop cycle (Doberman and Farihurst, 2000). It can be measured as plant nutrient accumulation or as grain yield measured at crop maturity in a nutrient omission plot under well-managed field conditions, i.e., when all other nutrients except one are amply supplied and other limitations to growth such as water or pests are absent (Janssen *et al.*, 1990). This technique has been found to be the most promising in determination of IS relative soil tests (Dobermann and White, 1999). Soil tests have been found to be inaccurate in predicting IS for the following key reasons; inherent soil fertility variation, variation in fallow periods, tillage methods and depth, water and crop residue management that affect microbial activity, SOM quality and turnover, chemical soil processes, and root growth (Mokwenye *et al.*, 1997;Buresh *et al.*, 2001; Twongyirwa *et al.*, 2013), non-symbiotic biological N fixation at rates of up to 50 kg N ha^{-1} per crop (Roger, 1996), variable nutrient input through irrigation and sediments (Dobermann *et al.*, 1998), and fixation and release of NH_4^+ and K^+ (Wen and Cheng, 1997, Viek and Craswell, 2015) as well as enhanced P availability under submerged conditions.

Crop-based indices of IS are therefore likely to be a key component of Site Specific Nutrient Management (SSNM) at high yield levels of rice. The key advantage of crop-based IS measurement is that it integrates the supply of truly plant available nutrient forms across the effective rooting depth under field conditions. This includes readily available nutrient pools and nutrient pools that are typically extracted with soil tests but also more slowly available nutrient pools and nutrients supplied from other indigenous sources in flooded rice fields. They also account for plant-mediated processes to acquire nutrients through chemical and microbial processes in the rhizosphere, which play an important role in nutrient uptake by rice (Kirk and Saleque, 1995; Kirk, 2001). To estimate the IS of a given major nutrient (N, P or K) in an omission trial, two of the major nutrients are supplied other than the nutrient in question. The indigenous N supply (INS) can be measured as plant N accumulation in a 0-N plot, which receives P, K and/or other nutrients but no fertilizer N. Likewise, indigenous P supply (IPS) can be measured as plant P accumulation in a 0-P plot, which receives N, K, and/or other nutrients, and indigenous K supply (IKS) can be measured as plant K accumulation in a 0-K plot, which only receives N, P, and/or other nutrients. This is based on the principle that when the supply of a particular nutrient is inadequate in relation to other nutrients, the whole supply of that nutrient will be taken up by the crop (Janssen *et al.*, 1990).

Knowledge of indigenous nutrient supply is fundamental in fertilizer rates calculations according to the general equation (Dobermann and Cassman, 2002).

$$Y = f(Ym, Ux) \quad (1)$$

$$Fx = (Ux - ISx)/Rx \quad (2)$$

Where Y= Target yield, Ym= climatic and genetic yield potential, Ux = amount of nutrient x that has to be accumulated in the plant to achieve Y; Fx = amount of fertilizer for nutrient x that needs to be applied to achieve Y, ISx = indigenous supply for nutrient x, Rx = fraction of fertilizer nutrient x recovered in the plant.

Nutrients in the crop are derived from the soil and added nutrient inputs. Nutrients in crop, soil and input are mutually related. When two of the three attributes are known, the third one can be calculated; if soil indigenous nutrient supplying power and the corresponding target yield are known, then required nutrient input can be determined (Janssen and de Willigen, 2006). This is the principle applied in the SSNM.

Material and methods

Location of the study

The study was carried out on an undifferentiated alluvial in Doho rice scheme, Butaleja district. The rice is cultivated in irrigated lowlands. Irrigation water comes from River Manafwa, originating from Mt. Elgon ranges. The area receives mean annual rainfall of about 1,495 mm and the district is generally hot with mean annual temperature of over 25°C. The study was conducted on farmers' fields during the first and second rainy seasons.

Soil characterisation

Soil samples were taken from a depth of 0-20 cm prior to planting following methods by Okalebo *et al.* (2002). Parameters tested were; pH, Total N, exchangeable K, organic matter, Ca, texture and Bray 1 P (Available P). Analysis was done according to methods by Okalebo *et al.* (2002).

Nutrient omission trial

The aim of these trials was to determine the soil nutrient supplying power and nutrient response curve. Eight treatments (Table 1) were assigned to plots each of dimensions 4 m × 5 m with 1 m-wide separating ridges in Randomized Complete Block Design (RCBD). The trial involved 5 farmer's fields and each farmer was considered as a replicate.

Recovery Efficiency trial

These were used to capture variability in recovery efficiencies for N in lowland rice ecologies. K 98 rice variety was used in these trials, two treatments, namely, T0 with no fertilizer and T1 with ample fertilizer (60 kg N ha^{-1}) in plots of dimensions 4 m × 5 m. A total of 30 farm field was used.

Trial management

K98 lowland variety was used, 21 days old rice seedlings were transplanted at a recommended spacing of 25 cm × 15 cm. Urea, Triple Super Phosphate (TSP) and Potassium chloride (Muriate of potash) were used as sources of N, P, and K, respectively. Phosphorus was applied once as a basal application at a distance of about 5 cm from the plant rows. The N and K sources being very soluble were applied in 3 allotments with the first dose (40%) at 2 weeks after transplanting, the second dose (40%) at tillering and the third dose (20%) at panicle initiation. The fields were drained two days before fertilizer application. The fertilizers were then covered slightly with a layer of soil and water was allowed in the field 2 days later. Weeding, disease and pest control/bird-scaring were carried out as required.

Experimental parameters

In both the nutrient omission trials and recovery efficiency trials, the standard procedure for determining straw yield, grain yield, components of yield and plant nutrient concentration (Witt *et al.*, 1999) were applied at all sites. Grain yield was taken at harvestable maturity (HM) from a central area of 6 m^2 and adjusted to a standard moisture content of 14% dry weight. Straw yields were estimated from the oven-dry grain yield of the 6 m^2 harvest and harvest index according to the equation below.

Straw yield = (Grain yield/Harvest Index) – Grain yield

In the equation above, straw and grain yields were based on 3% moisture content (Kenneth and Hellevang, 1914).

A 12 hill plant sample was taken at HM with 3 hills from each of the corners of the central 6-m^2 area. From the hills, yield component determination was done and above ground biomass nutrient accumulation (N, K, P) determined. The samples were oven-dried to constant weight at 70 ^{o}C for 48 hours, weighed and ground for nutrient analysis. All directly measured plant parameters were based on oven-dried plant material with a residual moisture content of approximately 3% except for grain yield, which was adjusted to 14% moisture content.

The harvest index (grain yield as a proportion of above ground biomass) was determined from 12 hill sub sample. The nutrient harvest index was computed as the ratio of nutrient accumulation in the grain to the total nutrient accumulation in above ground biomass. The internal efficiency of a nutrient was computed as the grain yield produced per kg of plant N, P or K accumulation in above ground biomass.

Statistical data analysis

Treatment effects were subjected to analysis of variance (ANOVA) for determination of means of samples and treatments using GenStat, version 14. The Least Significant Differences (LSD) at 5% probability level was used to determine differences among significant treatment means.

Fertilizer rates required to achieve a given target yield of lowland rice were calculated as follows;

Fx = (Ux – ISx) / Rx3 (Dobermann and Fairhurst, 2000).

Where Fx = amount of fertilizer that has to be applied to achieve target yield Y, Ux = amount of nutrients that need to be accumulated in the plant to achieve Y, ISx = indigenous nutrient supply, and Rx = fraction of fertilizer nutrient recovered in the plant, and x signifies each of the major nutrients.

Results and discussion

Soil characterisation

Lowland rice was cultivated on heavy textured clay loam with high SOM and adequate total N, Bray 1 P, exchangeable K and Ca (Table 2). However, these results may give a false impression because the soil samples were first dried before analysis yet they are under submerged conditions in the field. Under submerged conditions, the pH of acidic soils increases towards the neutral range (6.5) as SOM is oxidized by iron (Sahrawat, 2005). Consequently, P is made more available through a variety of mechanisms including reduction of ferric (Fe^{3+}) to ferrous (Fe^{2+}) phosphate, with attendant release of P from insoluble Fe and Al compounds; desorption of P from clay and oxides of Al and Fe (de Datta, 1981); and through release of occluded P (Patrick and Mahapatra, 1968). Through irrigation water, P, Ca, Mg as well as SiO_2 are supplied (Tyler *et al.*, 2014) to lowland as sediments, as may be the case at Doho irrigation scheme.

Grain yield and yield components in the nutrient omission trial

The 3 treatments with the highest N rate (T2, T4, and T7) produced significantly ($p<0.05$) higher straw yield than the rest of the treatments. This implies that nitrogen plays a vital role in improving rice yield. This is in agreement with studies of Hollena *et al.* (2008), when the researchers studied the effects of nitrogen fertilization management practice on the yield and straw nutritional quality of commercial varieties. Consequently, Harvest index was significantly ($p<0.05$) lower in T2, T4 and T7 than for the rest of the treatments, implying that yield is affected by excessive nitrogen uptake and this could probably be due to impairment of plant physiological processes such as metabolism. Similar results were obtained by Mojtaba *et al.* (2009), during studies of the effects of irrigation and nitrogen management on yield and water productivity of rice. Similar trends were observed for grain yield (Table 3) This is an indicator that the optimal N application rate is between 60 kg ha^{-1} and 150 kg ha^{-1} or other limiting factors other than N limit further increase grain yield (Mojtaba *et al.*, 2009).

Table 1. Treatments for nutrient omission trial.

Treatment	N dose (Kg ha^{-1})	P dose (Kg ha^{-1})	K dose (Kg ha^{-1})	Objective of the treatment
T0	0	0	0	Control
T1	150	30	50	Maximum yield
T2	150	10	50	Steep part of response curve for P
T3	0	30	50	Soil N supply
T4	150	0	50	Soil P supply
T5	60	10	50	Response curve
T6	60	30	50	Part of response curve for N
T7	150	30	0	Soil K supply

Table 2. Soil analytical results for soil properties.

n	Soil characterisation						
	pH	OM %	N	Bray 1 P mg kg^{-1}	K cmol(+)kg^{-1}	Ca	Textural class
18	5.2	9.70	0.21	30.0	1.10	5.6	Clay loam
Critical values	5.5	3.00	0.20	10.0	0.22	0.9	

Critical value are quoted from Okalebo (2002), n = number of soil samples.

Grain yield was significantly ($p<0.05$) and positively correlated to number of panicles m^{-2} with a coefficient of determination of 0.888. In spite of the increase in number of panicles m^{-2} with fertilizer application, increasing P rate from 10 to 30 kg P ha^{-1} did not significantly ($p<0.05$) increase grain yield at both 60 and 150 kg N ha^{-1} rates. Application of either P or K to plots where 150 kg N ha^{-1} was applied did not significantly ($p>0.05$) change grain yield (Table 3) indicating that there was no response to either P or K. This could be attributed to the high inherent supply of P and K (Peter *et al.*, 2015). This high inherent supply could be attributed to the availability of P under submerged conditions (Asmare *et al.*, 2015) and deposition of P and K through sediments carried down by the river.

Indigenous nutrient supply in lowland rice soil ecology

Nutrient uptake of rice significantly ($p<0.05$) influences yields directly (Table 4). The average indigenous N supply (INS) ranged from 30.5 to 53.1

kg ha^{-1}, P supply (IPS) capacity ranged from 17.7 to 35.7 kg ha^{-1}, indigenous K supply (IKS) capacity ranged from 112 to 308 kg ha^{-1}., implying significant nutrient use efficiency by rice crops. Studies of Das *et al.* (2015) showed that nutrient uptake (Phosphorus and Potassium) increased rice yields under integrated plant nutrition system.

Lowland rice grain yield and yield component in trial two

Grain yield, straw yield, Harvest Index and number of panicles m^{-2} were significantly different ($p< 0.05$) between the control and fertilized treatments. Application of 60 kg N ha^{-1} increased grain yield from 2930 kg ha^{-1} in control plots to 5100 kg ha^{-1} (Table 5) translating into a 43% grain yield.

Table 3. Grain yield and yield components in the nutrient omission trial.

Treatment	Mean grain yield (kg ha^{-1})	Mean harvest Index	Mean straw yield (kg ha^{-1})	Mean panicles number m^{-2}
T0 ($N_0P_0K_0$)	3342	0.50	3520	204.9
T1 ($N_{150}P_{30}K_{50}$)	5622	0.54	4476	349.9
T2 ($N_{150}P_{10}K_{50}$)	5497	0.44	7058	320.3
T3 ($N_0P_{30}K_{50}$)	3488	0.53	3202	245.2
T4 ($N_{150}P_0K_{50}$)	5428	0.40	7858	348.4
T5 ($N_{60}P_{10}K_{50}$)	4818	0.51	4035	290.7
T6 ($N_{60}P_{30}K_{50}$)	5167	0.52	4476	300.9
T7 ($N_{150}P_{30}K_0$)	5257	0.42	7260	351.5
$LSD_{0.05}$	845	0.07	2416	71.4

*Terms in parentheses are treatment descriptions in terms of the nutrient (N, P and K for nitrogen, phosphorus and potassium, respectively) and the nutrient rate (kg ha^{-1}) as the subscript; $LSD_{0.05}$= least significant difference at 95% level.

Similarly, nitrogen application significantly ($p<0.05$) increased the straw dry matter yield relative to that for the control. Straw yield in the fertilized treatment varied from 2300 to 10031 kg ha^{-1} while that for the control ranged from 1689 to 10,314 kg ha^{-1}, their respective averages was 4981 and 5028 kg ha^{-1} respectively. In addition, application of 60 kg N ha^{-1} increased HI by 25%. This may have been due to increase in accumulated N in rice crop. It is N availability and the relative priority given to grain production that influences Harvest Index (Sinclair, 1998).

Table 4. Indigenous nutrient supply of lowland rice ecology.

Parameter	n	Mean ($kgha^{-1}$)	SD	Minimum ($kgha^{-1}$)	Maximum ($kgha^{-1}$)
INS	6	40.65	7.2	30.5	53.1
IPS	6	27.7	8.1	17.7	45.6
IKS	6	184.5	84.2	112	309

From the results (Table 5), the increase in grain yield as a result of application of 60 kg ha^{-1} surpassed the increase in straw yield, indicating that most of the applied N was allocated for grain production other than vegetative production, this relates to the increase in Harvest Index observed during the two seasons. Accumulation of high levels of N is essential for high grain yield, and, thus, high levels of nitrogen are commonly associated with crops having high harvest indices. Under conditions where N is limiting, plants allocate most of the N for vegetative growth consequently resulting in a low HI (Sinclair, 1998). This perhaps explains why the HI of the control was lower than that for the fertilised treatment in the farmers' field trials.

Nitrogen recovery efficiencies in farmer field trials

The mean N recovery fraction was 45% (range: 4.9% to 86%). The overall average recovery efficiencies of 45% (Table 6) implies that on average, 55% of the applied N was lost through means such as leaching, de-nitrification, ammonia volatilization and surface runoff. Graeme and NSW (2014) also observed similar results. In addition, N is rendered unavailable to plants through immobilization and ammonium fixation. The overall nitrogen recovery efficiency (45%) recorded in this study was slightly higher than the 36% achieved in farmers-managed fields in West Africa (Haefele *et al.*, 2003) and 31% determined by Dobermann *et al.* (2002) in Asia. Higher N recovery efficiencies have been observed in researcher-managed trials. For instance, recovery efficiencies of 56%- 66% were reported in West Africa (Wopereis *et al.*, 1999) and a mean of 57% was recorded in Asia (De Datta and Buresh, 1990) indicating that recovery efficiency is principally a function of management.

Table 5. Lowland rice yield and yield components on farmers' fields.

Parameter	n	Control (+0 kg N ha^{-1})				Fertilized (+60 kg N ha^{-1})			
		Mean	Sd	Min	Max	Mean	Sd	Min	Max
Grain yield (kg ha^{-1})	58	2930	1180	1140	5360	5100	1480	3000	8200
Harvest index	58	0.39	0.018	0.15	0.38	0.52	0.075	0.31	0.74
# of panicles m^{-2}	58	188	64.5	60.8	309	289	52.6	183.9	408.3
Straw yield (kg ha^{-1})	58	4981	1689	1332	10314	5028	1315	2300	10031

n = Number of observations; SD = standard deviation; # = Number; Min = Minimum; Max = Maximum.

The N agronomic efficiency ($AE_{(N)}$) or additional yield produced per kg of N applied was 45% ranging from 4.9% to 86%. The overall average $AE_{(N)}$ 45 kg grain yield kg^{-1} applied N implies that for each kg of applied N, rice grain yield increased by 45 kg. This was higher than the $AE_{(N)}$ of 10 to 25 kg grain kg^{-1} N observed in most farmers' fields in Asia (Doberman and Fairhurst, 2000). It is probable that in the study by Doberman and Fairhurst (2000), fertilizers were used at levels where the relationship between grain yield and fertilizer rates was no longer linear. The observed high $AE_{(N)}$ could be attributed to sufficient amounts of P and K in the study such that any applied N application resulted in a high increase in grain yield thus a high $AE_{(N)}$.

Table 6. N recovery efficiencies in farmers' fields.

Parameter	n	Mean	Sd	Min	Max
Recovery efficiency	58	45%	19%	4.9%	86%

n = number of plots.

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The model variables that made significant contribution to the regression and the respective coefficients (Table 7).

Lowland rice yield response to N perfectly fitted a quadratic equation (Equation 5 form) with 99.83% of the variance in the grain yield presented in Table 7.

$$y = a + bN + cN2 \quad (5)$$

Where y = grain yield (kg ha^{-1}); N = fertilizer nitrogen rate (kg N ha^{-1}); a, b and c = constants.

The solution to equations 5 gave optimum nutrient estimate. The optimum N rate for lowland is 375 kg ha^{-1} corresponding to a target grain yield of 10 t ha^{-1}. However, during the research, N was applied at150 kg N ha^{-1} and this resulted into only 5.7 t ha^{-1} grain yields yet according to Fig. 7, this was however supposed to produce 6.4t ha^{-1}. This could be as a result of other limiting factors other than N, P and K and/ or low N recovery efficiencies observed in treatments with the N rate (150 kg N ha^{-1}). There is a lot of risk associated with fertilizer rate of 375 N ha^{-1} as it may not be possible to achieve the corresponding target yield from the fertilizer rate as for the case of 150 kg N ha^{-1}. It is therefore important not to consider fertilizer rates whose corresponding yield levels are not achievable to avoid exposing farmers to financial losses. From the trails, the optimum N rates lies between 60 and 150 kg ha^{-1}. It is therefore important to consider yield targets which can be achieved and their respective nitrogen requirement under our conditions. From N response curve generated from the omission trials, the optimum N requirement is to a yield target of 5 t ha^{-1}. This could be achieved under the prevailing biophysical conditions.

Table 7. Lowland rice nitrogen response function parameters and coefficients.

Parameter	Coefficients (kg ha^{-1})	Standard error (kg ha^{-1})
a (control)	2826*	61.7
b	34.2*	0.95
c	-0.0039*	0.003

*Significant at p<0.05 May you describe what the stars represent, in the foot note

$Y=a + bN + cN^2 + dP + eP^2$.......6

Where y = grain yield (kg ha^{-1}); N = fertilizer nitrogen rate (kg N ha^{-1}); a, b and c = constants.

To achieve a target yield of 5 t ha^{-1}, 65 kg ha^{-1} nitrogen is required. For lowland rice, the optimum N rate is 60 kg ha^{-1} and optimum P rate is 20 kg ha^{-1} for a grain yield target of 4 t ha^{-1}, this yield target can be achieved in the study area if good agronomic management practices are carried out.

Conclusion

The major limiting nutrients for lowland rice production is nitrogen and the soil nitrogen supplying potential can support yield target of 2.8 t ha^{-1}. Whereas, the indigenous Phosphorus and Potassium supply can support yield target of up to 9 t ha^{-1} and therefore, not limiting at achievable yield targets of 6 tha^{-1}. Use of internal efficiencies was promising in analysis of nutrient status and nutrient requirement to achieve the specific yield targets. 65 kg N ha^{-1} is the optimum rate for lowland rice and this corresponds to a target yield of 5 t ha^{-1}.

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