

Article

Bulb Yield Stability Study of Onion Lines over Locations and Seasons in Ghana and Mali

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Abstract: Onion is one of the most economically and nutritionally important vegetable crops in West Africa. However, high-yielding varieties that are accessible to farmers remain scarce. Onion lines from the World Vegetable Center's Allium program were evaluated during the cool and dry season from September to March for three years to identify adapted onion lines suitable for sustainable intensification of production systems in Northern Ghana and Southern Mali. Trials were implemented in the Upper East and Northern Regions of Ghana and in two districts in the Sudan savanna zones of Mali (Bougouni and Koutiala). Nine onion lines, including a check variety were assessed for yield stability using a randomized complete block design. The trials were carried out in "technology parks" under the joint management of farmers and researchers. Onion bulb weight was recorded for each plot after harvest. Separate analyses of variances were performed for each location and season. Analysis of variance of combined locations, seasons and lines was made to determine the most stable varieties using the line-superiority measure and ecovalence stability coefficients. Results indicated that lines AVON1310 and AVON1325 were most stable for yield performance over locations and seasons. From the genotype main effects and genotype-by-environment interaction (GGE) biplot, the best performing lines were AVON1310 (33.32 t.h⁻¹), AVON1308 (28.81 t.h⁻¹) and AVON1325 (31.68 t.h⁻¹). These lines are potential candidates for sustainable intensification of onion production in Ghana and Mali.

Keywords: multilocation; AMMI; GGE; vegetable; *Allium cepa*;

1. Introduction

Onion (*Allium cepa*) is among the oldest cultivated crops and one of the most economically important vegetable worldwide [1]. This plant is a nutrient-rich crop [2], which has been used as both a food and a medicinal plant since ancient times [1,3,4]. Onion is thus used in the treatment and/or prevention of many illnesses, such as cancer, coronary heart disease, obesity, hypercholesterolemia, type 2 diabetes, hypertension, cataract and disturbances of the gastrointestinal tract [1,3,5,6]. Due to its shelf life and resilience during shipping, onion bulbs have been traded and consumed very widely across the world and have been accommodating with many dishes, traditions and cultures [1,7,8]. In West Africa, onion has become a "must have" vegetable that is consumed daily in most households in variable forms and recipes [9,10]. Therefore, onion production can be very profitable, especially when the produce is stored up to off-season [11,12].

Onion growing areas and productivity vary depending on countries and the production systems. While production-intensive countries achieve yields of 50 t.h⁻¹ or more, onion mean yield in West Africa remains on average below 10 t.h⁻¹ [13]. In the sub-

region, onion supply is highly subject to high seasonality, post-harvest losses of about 40%, and various production-side constraints [11], which make it hard to cover the year round needs of consumers [9]. The low productivity this important vegetable crop is often attributable to poor application of appropriate farming techniques and poor access to agricultural inputs [12,14]. Yet, soils and climatic conditions during the crop growing season (dry and cool) are very conducive to onion production [14]. Thus, Sahelian countries appear to produce more onion than coastal and humid areas, and achieve important exportations towards high-demanding countries such as Cote d'Ivoire and Ghana [4,15]. Besides onion trade within the sub-region, huge quantities of onions continue to be imported from Northern Africa and Europe to face the demand [9,16]. Despite such economic and cultural importance of onion, second most produced vegetable in West Africa after tomatoes [11,12,17,18], not many studies were conducted to unravel its agronomic stability across the region.

Furthermore, important genetic diversity was reported in West African onions [19]. However, the maintenance and management of genetic resources remains a major difficulty in national agricultural research systems [20], resulting in continuous decline of on-farm diversity of cultivated onions over the years. Also, usually offering good level of resistance to biotic and/or abiotic stress, local onion varieties may present poor agronomic performance. Yet, although some elite varieties may exist with private seed companies, their cost hinders accessibility to farmers. Therefore, it is crucial to develop and select high-yielding cultivars, which ought to be easily accessible and presenting sufficient stability across West Africa to sustain onion production.

Crop traits' stability is known to be influenced by factors including the environment (E), genotype (G) and their interaction (GxE) [21]. Previous studies reported that onion sowing date, seedling size at transplanting and fertilisation can significantly affect the bulb size at maturity [22-24]. Therefore, GxE interaction may result in significant variation in cultivar performance from one location to the other, and so can it mislead the plant breeder if an appropriate statistical tool is not used [25,26]. The assessment of GxE interaction is crucial to optimize the breeding strategy leading to releasing cultivars adequately adapted to target environments [26,27]. In this way, multilocation yield trials analysed through the lenses of GxE interaction are very important to evaluate, and support decisions in the process of selection and recommendation of crop varieties [26,28,29].

The AMMI, Additive Main effects and Multiplicative Interaction, is one of the many statistical tools commonly used to detect crop phenotypic stability over multiple locations [29,30]. This approach provides an estimate of the crop adaptability, especially for quantitative traits such as agronomic yields, which often present $G \times E$ interaction [25,31]. The common analysis of variance is known to highlight differentiation in fixed and random effects such as genotype, replication and environment [32]. However, this approach cannot discriminate genotype variances in a non-additive manner as $G \times E$ interaction [21,27,33]. By combining ANOVA with principal *components* analysis (PCA), the AMMI model extirpates, first, the main effects of varieties and environments, and then, presents the GxE interaction through a PCA [29,34]. From there, performance of genotypes as well as the extent of divergence between varieties and optimum environments can be appreciated [25,30,31]. In practice, it appeared that the GGE biplot and the AMMI graphs can be complementary in explaining the stability of genotypes and describing mega-environments [33,35].

The objective of the present study was to identify adapted onion genotypes for a sustainable production in Northern Ghana and Southern Mali. To this extent, we assessed the adaptability of nine onion varieties, their yield potential and stability across Northern Ghana and Southern Mali. This evaluation was important to provide varieties suitable either for specific sites, or stable across the subregion. Results revealed two varieties that proved to be very stable across the study environments. Additionally, the top three performing varieties showed potential yields above 28 t.h⁻¹. Such high-

performing lines are potential candidates for release in Ghana and Mali to contribute to sustainable intensification of onion production in West Africa.

2. Materials and Methods

2.1. Plant material

To conduct the trials, eight onion lines from the World Vegetable Center's Allium program and one commercial check (Table 1) were evaluated during the cool and dry season from September to March for three years (2018, 2019 and 2020) in Northern Ghana and Southern Mali. These lines included two varieties previously released in Mali (AVON1073, AVON1074) and five lines newly introduced for testing in West Africa (AVON1023, AVON1308, AVON1310, AVON1314, AVON1317, AVON1325) (Table 1). Onion seedlings were produced for forty days in 1 m x 5 m nurseries before transplantation into the experimental plots.

Table 1: List of onion varieties used in the present study

Genotypes	Duration ^a	Origin
AVON1323	125	Bulk selection - Local
AVON1073	142	Released in WCA by WorldVeg
AVON1074	137	Released in WCA by WorldVeg
AVON1308	120	Bulk selection - Local
AVON1310	130	Bulk selection - Local
AVON1314	125	Bulk selection - Local
AVON1317	120	Bulk selection
AVON1325	120	Bulk selection
Check (Gebugo)	90	Local

(a): Average number of days from planting to maturity

2.2. Trial locations and implementation

The trials were implemented in the Upper East and Northern Regions of Ghana and in two districts in the Sudan savanna zones of Mali (Bougouni and Koutiala) (Table 2). These locations in Ghana and in Mali were technology parks under the joint management of farmers and researchers. Eight onion lines and a hybrid check 'Gebugo' (Table 1) were assessed for yield stability in Ghana and/or Mali and at least, in two locations or years from 2018 to 2020 (Table 2). The trial field was ploughed and harrowed, and a chemical fertilizer (NPK, 15-15-15) was applied at 200 kg/ha. Sulphate of ammonia (100 kg/ha) was applied as a top dressing 5-6 weeks after planting. Each experimental plot was 2 m x 2 m in size, containing 10 rows spaced by 20 cm. Seedlings planted on rows were spaced by 15 cm, resulting in about 133 plants per plot. Hand weeding was carried out two and five weeks after planting. Field planting and maintenance operations occurred each year from October to January.

Table 2: Climatic characteristics of trial locations

Location		GPS coordinates	Average rainfall	Temperature	
Country	Region/district			Min (°C)	Max (°C)
Ghana	Northern Region (NR)	9° 24' 3"N; 0° 50' 21"W	1,034 mm	24	40
	Upper East (UER)	10° 53' 44"N; 1° 5' 32"W	1024 mm	23	42
Mali	Bougouni	11°25'07.4"N; 7°28'53.2"W	1061 mm	18	38
	Koutiala	12°22'53.2"N; 5°28'01.7"W	889 mm	19	39

2.3. Data collection and analyses

The only variable measured concerned the bulb yield of onion genotypes. Thus, bulbs harvested after plant maturity, were weighted for each plot. All statistical analyses were performed using the GenStat software. Separate analysis of variances was performed for each location and season. Then, analysis of variance of combined locations, seasons and lines (sites x year x genotypes) was performed to determine the most stable varieties using the AMMI model [21,26]. This model was also used to show the level of similarity between locations and interaction patterns between genotypes and locations. The AMMI model equation is:

$$Y_{ij} = \mu + G_i + E_j + \sum \lambda_k \alpha_{ik} \delta_{jk} + R_{ij} + \varepsilon$$

Where Y_{ij} is the value of i^{th} genotype in the j - environment; μ is the grand mean; G_i is the deviation of the i^{th} genotype from the grand mean; E_j is the deviation of the j environment from the grand mean; λ_k singular value for PC axis k ; α_{ik} and δ_{jk} are the PC scores for axis of k of the i^{th} genotype and in the environment; R_{ij} and ε residual and error term [26].

To detect stability indices of genotypes and support decision making for varietal selection, we further performed Genotypes + Genotype x Environment interaction (GGE) biplot [36], which was computed as:

$$Y_{ij} - E_j = \sum \lambda_k \alpha_{ik} \delta_{jk} + R_{ij}$$

Where Y_{ij} is the value of i^{th} genotype in the j environment; E_j effect of environment; λ_k singular value for PC axis k ; α_{ik} and δ_{jk} are the PC scores for axis of k of the i^{th} genotype and j^{th} environment; R_{ij} residual [36].

Furthermore, measures of ecovalence stability and line-superiority coefficients were computed to assess the consistency of genotypic performance [37]. The ecovalence stability coefficient, W_i , is a measure of genotypes stability over locations and is computed as:

$$W_i = \sum_j (y_{ij} - Y_i - Y_j + \mu)^2$$

Where y_{ij} is the mean performance of genotype i in the j^{th} environment; Y_i is means of i^{th} genotype across environments and Y_j is means of j^{th} environment across all genotypes and μ is the grand mean [26].

To the same extent, line superiority index is evaluated with the formula:

$$P_i = \left[n(X_i - M \dots)^2 + \left(\sum_{j=1}^n (X_{ij} - X_i - M_j + m \dots)^2 \right) \right] / 2n$$

Where P_i is superiority index of the i^{th} genotype, X_{ij} is the average response of the i^{th} genotype in the j^{th} environment, X_i is the mean deviation of the genotype i ; M_j is the genotype with maximum response among all the genotypes in the j^{th} environment; M is maximum response among all the genotypes over the environments; n is number of environments. Smaller value of P_i indicates less distance and maximum yield resulting in better and stable genotype [26].

3. Results

3.1. Additive Main effect & multiplicative interaction

The ANOVA showed a significant variability among genotypes and significant interactions between years, locations, and varieties (p -value < 0.001 , Table 3). That is, environments diverged for bulb yield of genotypes, which performed differently depending on environments. Then, five lines performed better than the commercial check (Gebugo) with average yields higher than 25.2 t ha⁻¹. However, only one line,

AVON1325, yielded (31.68 t ha^{-1}) above average of trialled varieties (25.61 t ha^{-1}) (Table 3).

To visualise the relationship between genotypes and environments, a biplot was generated from AMMI analysis for onion bulb production (Figure 1). This revealed that three genotypes (AVON1325, AVON1323 and AVON1317) were the most stable lines, since their scores of interaction principal components 1 (PC1) and 2 (PC2) were the closest to zero (Figure 1). The principal components (PC1 and PC2) accounted for 65.78% and 14.02% of the variation, respectively, making a total of 79.80% of the variance among the stability factors (Figure 1).

Table 3: G x E interaction (AMMI) for yield performance (t.ha⁻¹) of onion varieties over years and locations in Ghana and Mali – 2018-2020

Genotypes	GHANA			MALI				Mean	Rank	
	UER		NR	KOUTIALA		BOUGOUNI				
	2018	2020	2020	2019	2020	2019	2020			
AVON1310	32.38	34.81	33.64	34.81	-	-	-	-	33.32	1
AVON1325	28.04	-	-	-	-	35.31	-	-	31.68	2
AVON1308	33.16	33.88	36.73	33.88	29.00	27.81	26.47	10.35	28.81	3
AVON1074	26.65	31.56	27.56	31.56	25.67	35.00	20.93	11.93	25.48	4
AVON1314	27.69	30.75	25.08	30.75	28.50	-	20.73	-	25.47	5
Gebugo (Check)	28.04	26.50	23.36	26.50	-	-	-	-	25.02	6
AVON1073	25.26	28.12	28.34	28.12	27.17	28.75	21.00	5.62	24.29	7
AVON1323	-	27.88	23.31	27.88	26.33	31.56	23.13	10.50	23.68	8
AVON1317	-	-	-	-	-	27.19	-	12.13	19.66	9
Mean	28.75	30.50	28.29	30.50	27.33	30.94	22.45	10.10	25.61	
SE	1.47	0.91	0.69	0.91	0.87	1.20	0.84	0.73	-	
Year x Loc x Var. (p-value)	<0.001 **									

UER: Upper East Region, NR: Northern Region; SE: Standard error; Loc: location; Var: Varieties.

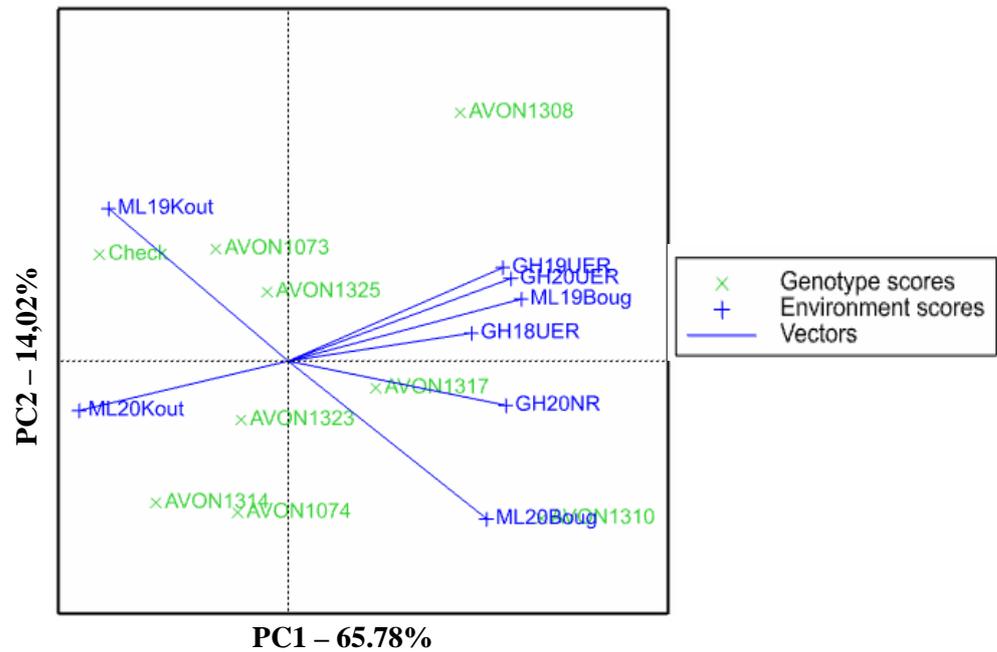


Figure 1: Vector view of the AMMI biplot (PC1 and PC2) of onion yield showing the relationship between tested varieties and environments. GH19UER, Upper East Region, 2019; GH20UER, Upper East Region, 2020; GH20NR, Northern Region; ML19Kout, Koutiala 2019; ML20Kout, Koutiala 2020; ML19Boug, Bougouni 2019; ML20Boug, Bougouni 2020. Dotted vertical and horizontal lines indicate points where the PC1 and PC2 axes had respective values of zero

4.2. Genotype + GxE interaction (GGE) biplot

Two mega-environments emerged from the GGE biplot model analysis of locations and years (Figure 2). Mega-environments represent the graph sectors comprising one or more locations. Irrespective of the year and counterintuitively, the first mega-environment included the two locations in Ghana and one of the locations in Mali (Bougouni); whereas the second mega-environment was represented by only one location in Mali (Koutiala). The locations forming the first mega environment (Northern (NR), Upper East (UER) regions in Ghana and Bougouni in Mali) were significantly and positively correlated (Figure 2). In that first mega environment, AVON1308 produced the highest average yields (Figure 3a), and thus was the best performing variety across locations and years. Onion lines AVON1074 and AVON1325 were considered as stable, due to their positions near the origin of the GGE bi-plot (Figure 2). AVON 1314 was the winning variety over two years in the mega-environment 2 (Koutiala, Mali).

Furthermore, Wricke's ecovalence stability coefficients revealed genotypes AVON1310, AVON1325, Gebugo (check) and AVON1317 as the most stable varieties due to their lowest W_i values (Table 4). Of these, AVON1310 (Figure 3b) and AVON1325 showed superior performance, by yielding more than the average ($25.61 \text{ t}\cdot\text{ha}^{-1}$). Additionally, based on the model of Lin and Binns Superiority measure, genotypes AVON1310, AVON1308 and AVON1325 were found to be the most stable varieties, with the smallest W_i values and the highest yields (Table 5).

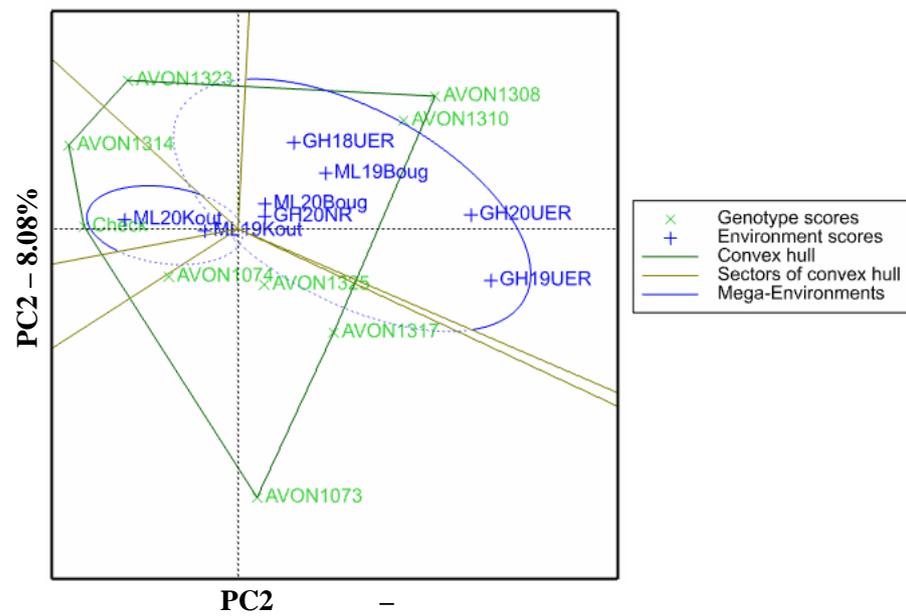


Figure 2: Genotype + GxE interaction (GGE) biplot showing which genotypes performed best in which environment (“which won where”). Dotted vertical and horizontal lines indicate points where the PC1 and PC2 axes had respective values of zero. Vertices of the polygon indicate superior genotypes in each sector. See codes of genotypes in Table 1 and 4. GH19UER, Upper East Region, 2019; GH20UER, Upper East Region, 2020; GH20NR, Northern Region; ML19Kout, Koutiala 2019; ML20Kout, Koutiala 2020; ML19Boug, Bougouni 2019; ML20Boug, Bougouni 2020.

Table 4: Wricke's ecovalence stability Coefficients W_i

Genotype	W_i	Bulb yield (t.h ⁻¹)
AVON1310	2.20	33.32
AVON1325	11.60	31.68
AVON1308	91.94	28.81
AVON1074	36.90	25.48
AVON1314	36.01	25.47
Check	13.99	25.02
AVON1073	41.28	24.29
AVON1323	29.46	23.68
AVON1317	14.45	19.66
Mean		25.61

Table 5: Lin and Binns Superiority measure of genotype performance (Pi)

Genotype	Stability superiority coefficient (Pi)	Bulb yield (t.ha-1)
AVON1310	1.32	33.32
AVON1325	6.56	31.68
AVON1308	3.77	28.81
AVON1074	15.78	25.48
AVON1314	32.03	25.47
Check	49.1	25.02
AVON1073	19.09	24.29
AVON1323	25.99	23.68
AVON1317	16.50	19.66
Mean		25.61

**Figure 3:** Photos of two high performing and stable onion varieties. (a) light red-colored bulbs of variety AVON1308; (b) light red-colored bulbs of variety AVON1310.

4. Discussion

The present study was designed to identify high yielding and stable onion varieties for production in Ghana, Mali, and possibly in West Africa at large, through the assessment of eight lines in different environments. It appeared from AMMI analysis that the evaluated onion varieties were significantly influenced by locations, probably due to the diversity of soil types, rainfall and other climatic conditions [22-24]. The differential response of onion genotypes to environments translated into significant GxE interactions ($P < 0.001$), which could influence about 80% varietal performances. Highly significant differences in locations, years, and genotypes may be due to variable environmental conditions between locations and/or diversity of the genetic makeup of tested lines that may respond differently to locations [38,39]. Our result is consistent with many previous studies that reported significant GxE effects not only in onion [28], but also in other crops [33,38,40]. However, the magnitude of GxE interactions was

higher in the present study than in earlier works. This may be attributed to the geographic distances between trial sites in Ghana and Mali, some of which were near 1000 kilometers apart.

From the GGE biplot analysis, two mega environments emerged, the first one overlapping Ghana and Mali, and the second represented by a single location in Mali. Environmental conditions are not always under control and can thus affect cultivar performance, despite the standardisation of experimental design and conditions across locations (plant density, fertilisation, experimental design [41]). Nevertheless, it was counterintuitive to have locations this far apart, within the first mega environment. This may be attributable to two possible reasons: 1) agro-environmental conditions may be similar in the concerned locations and 2) the top varieties boast adaptability to a wide range of environmental conditions, including soil types, fertility levels, moisture, temperature and even cropping systems [22,41,42].

In mega environment 1, the most stable genotypes were AVON1308 and AVON1325 with yields above average (25.61 t.ha⁻¹); whereas AVON1308 (28.81 t.ha⁻¹) and AVON1310 (33.32 t.ha⁻¹) were the top performing and stable genotypes in the mega-environment 2 (2019 and 2020). Of these, AVON1308 revealed to be the most stable genotype with high yield performance across all environments (Ghana and Mali) and, AVON1310 and AVON1325 were the most stable varieties for yield performance over locations and seasons (Figure 1). Furthermore, the genotype main effects and genotype-by-environment interaction (GGE) biplot enabled the identification of the best performing genotypes among the tested cultivars, viz. AVON1310 (33.32 t.h⁻¹), AVON1308 (28.81 t.h⁻¹) and AVON1325 (31.68 t.h⁻¹). Since GGE biplot was reported as the best approach to discovers mega environments and winning cultivars [35], therefore, the lines that were identified through this approach can be confidently proposed for release in Ghana and Mali. Interestingly, the best lines evoked in this study outperformed most of the varieties released hitherto, and thus are suitable to contribute to sustainable intensification of onion production in the target environments.

5. Conclusions

This study revealed that varieties AVON1310 and AVON1325 were the most stable for yield performance over locations and seasons. From the genotype main effects and genotype-by-environment interaction (GGE) biplot, the best performing lines among the tested cultivars were AVON1310 (33.32 t.h⁻¹), AVON1308 (28.81 t.h⁻¹) and AVON1325 (31.68 t.h⁻¹). These lines are potential candidates for release in Ghana and Mali to contribute in this way to sustainably intensify onion production in the region. Also, AVON1314 showed the best performance in environment 2 and may be deployed as an elite cultivar for production in specific environments.

One of the aspects that could be investigated is the assessment of genotypes response to biotic constraints, which are often key to the long-term success of newly released varieties. Additionally, combining agronomy and crop breeding is essential to improve plant traits and adaptability before commercial release. Therefore, it is desirable that future varietal evaluations take into account the effect of farm management (M) options on crop performance, and so include GxExM interaction in the decision-making process.

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