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Fraudulent pesticides in West Africa: a quality assessment of glyphosate products in Mali

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ABSTRACT

Pesticide markets have grown far faster than regulatory monitoring capacity in West Africa. As a result, fraudulent pesticides (unregistered and counterfeit) have become widely available. This paper focuses on glyphosate, the region's most widely used pesticide. Purchase of 100 glyphosate samples from 50 different retailers across Mali found that 45% were fraudulent. Laboratory testing revealed that fraudulent glyphosate products contained 8-10% less active ingredient than registered products. Together, variable quality and widespread underdosing raise serious risks of accelerating weed resistance. These results suggest a clear need for more aggressive monitoring of pesticide markets, product quality and resulting environmental impacts. For practical purposes, farmers can protect themselves by purchasing only products duly registered by Mali's regulator, the Comité Sahélien des Pesticides (CSP).

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Pesticides; Fraudulent; West Africa; glyphosate; quality; testing

1. Introduction

1.1. The setting

Pesticide markets have grown rapidly in West Africa over the past decade and a half (Figure 1), in tandem with the rising use of pest control products throughout Sub-Saharan Africa (Sheahan and Barrett 2017). Sales of the herbicide glyphosate – the most widely sold pesticide in West Africa – have led this rapid growth, driven by rising farm wage rates and falling prices of a growing number of generic glyphosate brands (Haggblade, Smale, et al. 2017). Following the expiration of Monsanto's international patent protection for glyphosate, at the end of the year 2000, the number of registered generic glyphosate products available for sale has exploded. As of 2018, the joint regional regulator for nine Sahelian West African countries had approved 38 different glyphosate products for sale. In the much larger coastal market of Côte d'Ivoire, regulators have registered over 140 different glyphosate products for sale (Diarra and Haggblade, 2017).

Sales of fraudulent[1] pesticides have increased as well, primarily because regulatory capacity has not kept pace with this rapid market growth (Figure 2). Though notoriously difficult to measure precisely, levels of fraud clearly vary widely across countries (MirPlus 2012; Rodenburg 2019). An indicative study of the eight largest West African pesticide markets provides ballpark estimates for individual countries. Taking a market-weighted average, their estimates suggest that fraudulent pesticides in West Africa account for roughly 34% of regional pesticide sales, 27% of them unregistered and 7% counterfeits (MirPlus 2012).

In the face of widespread fraud, farmers frequently complain about low and variable input quality (Ashour et al. 2018; Assima et al. 2017b). The limited available empirical analysis suggests that farmers have good reasons to doubt pesticide quality. In Gambia, analysis of 128 pesticide products on sale in local markets revealed that only 10% were properly labeled in original containers; fully 90% had been repackaged and were on sale in unlabeled bags and bottles. Among the 90% unlabeled, 28% contained banned substances, primarily highly toxic insecticides (Murphy et al. 2012). In Uganda, laboratory analysis of commercial glyphosate samples found that one-third of products tested contained below 75% of the stated concentration of active ingredients. Preliminary quality assessments in Mali, based on farmer estimates of input use and output produced, found that registered herbicides reduce labor requirements for weeding by twice as much as unregistered products, suggesting significantly higher quality of registered herbicides (Assima et al. 2017a).

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Over the past 15 years, studies in Ethiopia and across half a dozen countries in West Africa suggest that herbicide markets have grown far faster than regulatory capacity (Diarra and Haggblade, 2017; Tamru et al. 2017). In this environment of rapid market growth and weak regulatory monitoring capacity, quality problems seem likely to increase.

1.2. Objectives

This paper examines pesticide quality in West Africa as well as key implications for farmers, regulators and the environment. Because glyphosate dominates among pesticides used in the region, laboratory testing of this single active ingredient offers an unusual opportunity to verify the range of quality currently available to farmers in both registered and fraudulent products.

Beyond its obvious importance to farmers and regulators, this assessment of pesticide quality holds wider significance as well. Quality problems plague many major agricultural inputs across Africa, including fertilizer, insecticides, seeds and herbicides (Sheahan and Barrett 2017; Ashour et al. 2018). Uncertainties about stated dosages and concentration levels lead to potentially high variability in on-farm outcomes as well as inefficiencies stemming from under- and over-dosing of plots (Assima et al. 2017b; Perry et al. 2019). These uncertain outcomes, in turn, affect farmer perceptions of product quality and tend to depress demand for productivity-enhancing purchased inputs (Bold et al. 2017; Ashour et al. 2018). As a result, the success of broad efforts to raise agricultural productivity in Africa will depend, in part, on effective policy and regulatory systems for ensuring quality inputs of known, reliable dosages. Even more problematic, the uncertain quality of pesticides sold poses largely unmonitored and unmeasured environmental and human health risks.

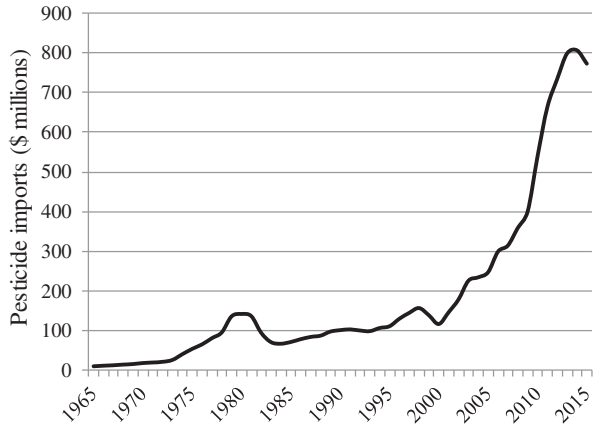

Figure 1. Trends in pesticide imports into West Africa (millions of US dollars, 3-year centered moving averages).
Source : FAOSTAT (2019).

(a) Roundup and imitators (above)

(b) Glycel and "Red Beret" imitators (above)

Figure 2. A partial display of the profusion of glyphosate brands sold in Sahelian West Africa.
a. Roundup and imitators (above).
b. Glycel and "Red Beret" imitators (above).

Figure 3. Packaging similarities between registered and unregistered herbicides sold in Mali.
a. Roundup and imitation.
b. Glycel and imitation "Red Beret".

The empirical work reported here centers on glyphosate samples collected in Mali, whose capital city serves as the headquarters for the Sahel-wide regional pesticide regulator, the Comité Sahélien des Pesticides (CSP). Following a description of the data and methods used, the paper reports laboratory testing results from 100 glyphosate samples purchased in four major markets across Mali. The resulting sample included 33 different glyphosate brands, representing most of the major glyphosate brands sold throughout the region. The discussion and conclusions explore key implications for regulators, pesticide suppliers and farmers.

2. Materials and methods

2.1. Study design

This study design builds on recent pesticide market and regulatory reviews in six different West African countries[2]. From among many hundreds of pesticide active ingredients sold throughout the region, the study elected to focus on glyphosate, far and away the most widely sold pesticide in West Africa (Diarra and Haggblade 2017). Since 2000, when Monsanto's last international patent on Roundup expired, a proliferation of generic glyphosate brands has flooded markets worldwide, including West Africa (Haggblade, Minten et al. 2017). Given its widespread availability in numerous registered and fraudulent formulations, glyphosate provides an ideal initial candidate for testing pesticide quality.

As a study site, the team sought a country with high levels of fraudulent products as well as receptivity to regulatory reform. Mali offered good prospects on both counts. A series of studies has identified generally high levels of fraudulent pesticides in Mali (Assima, Haggblade and Smale 2017; MirPlus 2012; Haggblade, Diallo, et al. 2017). Moreover, Mali's capital city of Bamako houses the technical secretariat and headquarters for the CSP, the collective body through which nine Sahelian member countries jointly review and register pesticides for sale throughout the region (Abiola et al. 2004). Since 1994, the CSP has served as a one-stop-shop registering pesticides for its nine Sahelian member countries. Once registered by the CSP, a pesticide can be sold in any of the member countries. Because the CSP staffs only a small technical secretariat in Bamako, national authorities retain responsibility for post-registration monitoring of pesticide markets and product quality in their respective countries. Conduct of this study in close proximity to the CSP headquarters, coupled with their strong interest in assuring pesticide quality, raises the visibility of the results in all nine-member countries and, hence, improves prospects for improved regulatory enforcement efforts throughout the region.

2.2. Glyphosate sample selection

In order to assess glyphosate quality across a range of different agro-ecological and cropping zones, sample collection took place in four major market centers: *Bamako*, Mali's capital city and the site of most major import warehouses; *Niono*, a major agricultural market town in the irrigated rice zone of central Mali 340 km north of Bamako, along the Niger River; *Koutiala*, a cotton-growing zone and horticultural hub 316 km east of Bamako; and

Table 1. Profile of glyphosate samples collected in Mali.

Sample characteristics		Sample characteristics	
Categories	Sample size	categories	Sample size
		Glyphosate level, as stated on bottle	
Purchase location		41%	2
Bamako		356	1
central market	27	360	43
other markets	13	450	12
Niono	30	480	37
Sikasso	16	500	5
Koutiala	14	total	100
total	100		
		Formulation	
		salt	44
Country of fabrication		acid	42
China	63	not indicated	14
Belgium	12	total	100
France	6		
India	2	Registration status	
Ghana	1	CILSS	55
Mexico	1	other	6
not indicated	15	none	39
total	100	total	100

Table 2. Summary values of key sample characteristics.

Sample characteristics glyphosate levels (g/L)	mean	s.d.	min	max
Stated on bottle	425	59	356	500
Acid equivalent	376	40	356	489
Price				
CFAF/liter	3,830	985	2,500	8,000
USD/liter	$6.96	$1.79	$4.55	$14.55
Date of fabrication	12-Jul-15	377	1-Feb-09	24-Dec-16

Sikasso, market center for the high-rainfall southern zone of Mali, 380 km southeast of Bamako. Among Bamako's many markets, the team selected the central market in the river quarter as well as smaller markets of Bozola and Kati. Niono, Koutiala and Sikasso purchases took place from the main market in each town. The team targeted procurement of 40 sample products from Bamako and 60 from the other market centers.

In each location, the team consulted with the local agro-dealers' association to obtain a list of all registered farm input retailers. From this listing, the team selected 10 distributors at random. In December 2016, one team member then visited each shop, posing as a farmer, and asked the shop owner to recommend two glyphosate products for him to try on his fields – the best quality product in stock as well as the cheapest. The buyer then purchased two one-liter bottles from each supplier. This procurement protocol aimed to capture a range of glyphosate brands and qualities.

The resulting distribution of samples included 40 from Bamako, 30 from Niono, 16 from Sikasso and 14 from Koutiala (Table 1). Among the 100 glyphosate samples, 63 came from China, 18 from Europe, 2 from India, 1 from Ghana, and 1 from Mexico, while 15 failed to indicate their provenance. Prices ranged considerably, from $4.55 to $14.55 per liter (Table 2). Manufacturing dates likewise suggested a wide range of time in inventory prior to sale. The oldest product listed a fabrication date of February 2009, compared to the most recent one manufactured in December 2016 (Table 2). Given a mean production date of July 2015, the samples averaged one and a half years old.

In terms of regulatory approval, slightly over half of the products purchased (55 out of 100) had passed regulatory review by the CSP. Another 6 products were registered elsewhere (mostly in Ghana or Guinea) and then smuggled into Mali. Though not registered by the CSP, they did undergo regulatory review in these neighboring countries through their respective national review systems.[3] The remaining 39 glyphosate products purchased had not undergone regulatory review anywhere (Table 1). Overall, fraudulent products accounted for 45% of the samples tested, 39% unregistered anywhere and 6% registered outside of the CSP zone and then smuggled in.

2.3. Sample preparation

Materials used for sample preparation included 20 mL pipettes, 100 mL high-density polyethylene (HDPE) containers with locking caps, and safety materials including face mask and laboratory gloves. A senior chemist from Mali's Central Veterinary Laboratory set up a work station with clean sheets on a shaded and well aerated veranda. He vigorously shook each one-liter glyphosate bottle, then drew five 20 mL pipettes, transferred them to the 100 mL pre-labeled HDPE containers and used locking caps to hermetically seal the HDPE sample containers (Figure 4). Two samples were prepared from each bottle, one set for testing locally in an African analytical laboratory and the other set for testing in the USA. All samples were kept in darkness at ambient temperature between the time of sample purchase in December 2016 and their shipment to the testing laboratories.

The research team labeled each 100-mL container with an alphanumeric code to identify the location of purchase as well as the specific bottle of glyphosate being evaluated. The laboratories received only the sample code numbers. They had no knowledge of the individual brand names, locations of purchase, price, registration status or manufacturing location. The laboratories conducted their analyses blind, knowing only the sample code numbers. The wide range of colors found among the 100 glyphosate samples tested suggested clear differences in the various glyphosate formulations sold (Figure 4).

2.4. Blind duplicates

Among the 100 samples submitted to each laboratory, 10 pairs (that is, 20 individual samples) were

Figure 4. Glyphosate samples: a color spectrum of products tested.

duplicates. For each duplicate, the laboratory received two separate samples drawn from the same bottle of glyphosate and submitted in two separate specimen bottles under two different identification numbers. The laboratory did not know about the duplicates. As a result, the labs treated each duplicate as a separate submission. Upon receipt of the results from the laboratory, comparison of the blind duplicate results provided a check on the reliability of the laboratory dosage estimates and their calibration procedures.

2.5. Laboratory selection

Mali has no laboratory accredited for formulation verification testing under the relevant international testing standard ISO 17025. Therefore, laboratory testing of the 100 glyphosate samples took place at laboratories outside of Mali. Our team initially selected two analytical laboratories for this purpose, one in West Africa and one in the USA.

To identify a suitable laboratory in West Africa, we consulted with the CSP regulators and major private sector importers to see if they could identify a laboratory accredited for formulation verification analysis in any of the surrounding countries. Based on recommendations from our Malian colleagues, we selected a large government laboratory nearby that has begun the international accreditation process. In late February 2017, we shipped one set of 100 mL samples overland to this regional lab in West Africa accompanied by one of our staff members.

To select a suitable, accredited laboratory in the USA, our team contacted three private testing laboratories suggested by Michigan State University's Department of Crop Sciences. Following a review of each laboratory's experience, testing protocols and facilities, our team selected one of them to conduct the second round of testing. To export the samples to the USA by air, we required an export permit from the Government of Mali as well as an import permit from the US Environmental Protection Agency (EPA). After obtaining the necessary permits, we shipped the second set of glyphosate samples to the USA by air in May 2017.

Following receipt of the test results, disparities between the two initial sets of laboratory test results prompted selection of a third laboratory to retest the samples from Laboratory 2. In June 2018, the initial USA testing laboratory (Laboratory 2) sent the samples by truck to Laboratory 3.

Comparison of the blind duplicate results from each laboratory revealed that only Laboratory 2 produced results within acceptable reliability ranges. Under strict quality control procedures, the same laboratory using the same technique and equipment to test repeat samples pulled from the same bottle should report comparable results. At most, we expected deviations within 5% to 10% of each other. Laboratory 2 came closest to meeting this standard; only 1 out of 10 duplicate pairs differed by more than 10%. In contrast at Laboratory 1, 3 of the 10 blind duplicate pairs differed by more than 10% and 2 differed by over 20%, well outside normal quality control standards. The results from Laboratory 3 revealed even larger differences, with 6 of the 10 duplicate pairs differing by over 20%, clearly outside acceptable ranges.[4] For this reason, the discussion below reports only the results from Laboratory 2, an ISO 17025 accredited laboratory in the USA.

2.6. Expected dosage of glyphosate formulations

The potency of any given glyphosate product depends on the quantity of glyphosate acid supplied. Typically, manufacturers rate dosage in grams of glyphosate *acid-equivalents* (ae) per liter of formulation (g/L ae). In addition to glyphosate acid, most formulations include salts and other co-formulants designed to improve product characteristics such as adherence to plant foliage. The classic original Roundup formulation included 360 g/L of glyphosate acid plus an additional 120 g/L of isopropylamine (IPA) salts (Dill et al. 2010). In terms of acid-equivalents, this results in a dosage of 360 g/L ae. Some suppliers of generic glyphosate products advertise

Table 3. Formulation conversions to acid equivalents.

Category	Sample Size	Bottle label information		Conversion ratio*		Acid equivalent (g/L)		
		Formulation	g/L	Min	Max	Min	Max	Best guess
1	31	acid equivalent	360	1	1			360
2	11	acid equivalent	450	1	1			450
3	33	IPA salt	480	1.35	1	356	480	356
4	2	IPA salt 41%	480	1.35	1	356	480	356
5	3	IPA salt	360	1.35	1	267	360	360
6	1	IPA salt	356	1.35	1	264	356	356
7	5	potassium salt**	500	1.23	1	408	500	489
8	9	not indicated	360	1.35	1	267	360	360
9	1	not indicated	450	1.35	1	333	450	450
10	4	not indicated	480	1.35	1	356	480	356
total	100							

*Acid equivalent computed from molecular weights: glyphosate acid 169.07, potassium salt 207, IPA salt 228.19 g/mole.
Converting to acid-equivalent dosages results in conversion ratio of 228.19/169.07 = 1.35 for IPA formulations and to 207.153/169.07 = 1.225 for potassium salt formulations.
**Potassium salt listed as 36.5% acid @ 1.34 specific gravity; 1,340 g/L * 36.5% = 489 g/L acid.

this same formulation as containing 480 g/L of *active ingredients* (glyphosate acid plus salt). Not surprisingly, these labelling differences can quickly become very confusing for pesticide users.

Unfortunately for farmers, product labels do not always clearly specify each product's acid-equivalent dosage. As generic products have entered the market, a considerable amount of confusion has arisen due to differing labeling practices. Many generic glyphosate products continue to sell the classic original formulation. Yet they often label the contents differently, even for the same formulation (Rolando et al. 2017). As a result, different suppliers may variously report the dosage of this same classic formulation in the following different ways:

- 360 grams/liter of *acid-equivalent* glyphosate
- 480 grams/liter of *active ingredient* (glyphosate plus IPA salts)
- 31% weight/weight *acid equivalent*
- 41.9% weight/weight *active ingredient*.

A newer generation of higher dosage Roundup offers 450 g/L acid equivalent (ae) glyphosate. This leads to the confusing situation where a bottle with a 480 (ai) label offers lower acid-equivalent (ae) dosage (only 360 g/L acid equivalent) than a 450 g/L (ae) product. An additional source of confusion stems from rounding differences in imperial to metric conversions, resulting in some ae formulations listing 356 g/L with others reporting 360 g/L.

As a marketing tool, many generic glyphosate products report the 480 number prominently on their label, often without clearly specifying whether this refers to active ingredient (ai) or acid-equivalent (ae). Most farmers expect that a 480 g/L dosage must be more powerful than a 360 g/L product. Yet, in fact, these two different numbers refer to the identical dosage in term of acid-equivalent glyphosate.

Taken altogether, these product labeling differences cause considerable confusion and frustration among farmers. Although most product labels contain dilution instructions, farmers find the variety of dosage numbers on the product labels highly confusing. Indeed, the logos sometimes appear to be deliberately misleading, as in the case of generic products touting 480 g/L of active ingredient. Given weak regulatory enforcement, only a handful of products properly color-code their product labels and warning bands. All products contain the name "glyphosate" somewhere on the label, often in small font, with the generic brand name in much larger font. Often these trade names emphasize the product's weed-killing properties in local languages. Mostly illiterate, Mali's farmers frequently use packaging color schemes and logos to identify their preferred herbicides; hence the ascendance of the Red Berets, with pest-killing power allegedly equivalent to that of the elite special forces of the French army. In addition, some of the large pesticide suppliers use company-specific colored logos on their labels – a blue stork, a blue eagle, an elephant or a lion – to provide farmers with a visual symbol of the firm and of the quality control they provide. Since most retailers supply multiple generic brands of glyphosate, any farmer returning to ask for a better product will find a multitude of alternative generic brands available.

2.7. Product groupings

After sorting, the purchased samples fell into one of ten different categories (Table 3). To determine the acid-equivalent (ae) dosage for each category, the team first studied the product labels and their fine print carefully. A total of 42 samples, those in Categories 1 and 2, clearly and unambiguously stated glyphosate dosage in acid-equivalent (g/L ae). A further 44 samples, in Categories 3 through 7, contained product labels that did not clearly specify whether the dosage referred to ae or ai. In these instances, the team consulted manufacturer information sheets in order to determine the correct

Table 4. Four major groups of glyphosate products.

Group**	Label information: Dosage	Label information: Formulation	Acid-equivalent Dosage*	Sample Size
Group 1	480	IPA salt	356	40
Group 2	360	IPA salt	360	43
Group 3	450	IPA salt	450	12
Group 4	500	K salt	489	5
average dosage			376	100

*Glyphosate acid-equivalent (ae) dosage (g/L ae).
**Group 1 = Categories 3,4,6 and 10.
Group 2 = Categories 1,5 and 8.
Group 3 = Categories 2 and 8.
Group 4 = Category 7.

formulation and conversion ratio. Labels on the final 14 products, those in Categories 8 through 10, contained only a number and the word "glyphosate" with no indication of the formulation. Nor did they contain any clear manufacturer or distributor information. In these cases, the team had to make an educated guess as to the expected dosage. Given the standard industry formulations, we have a high degree of confidence that 360 g/L refers to the classic Roundup formulation, 450 g/L refers to the newer generation and 480 corresponds to the classic formula described in active ingredient, rather than acid equivalent, terms.

In the end, these ten product categories can be grouped into four acid-equivalent (ae) dosage levels (Table 4). Groups 1 and 2 both contain the standard Roundup dosage of 360/g/L ae. However, their labeling differs, with Group 1 reporting 480 g/L of *active ingredient* (glyphosate plus IPA salts) while Group 2 markets the same formulation as containing 360 g/L glyphosate *acid-equivalent* (ae). Group 3 contains 450 g/L ae, while Group 4 contain 489 g/L ae in a potassium (K) salt formulation. The ensuing analysis reports glyphosate dosage measurements in acid-equivalents for the combined sample as well as separately for these four groups.

2.8. Methods of data analysis

The key dependent variable of interest in this analysis is the level of under-dosage of each sample, expressed in percentage terms. We computed this percentage as the actual acid-equivalent glyphosate concentration, as measured by the testing laboratory, compared to the concentration promised by the manufacturer. Simple correlation coefficients provided an initial screening of the many potential causal factors associated with under-dosing. Key independent variables that stakeholders believe may affect under-dosing include product registration status, characteristics of the supplying firms, manufacturing location, date of production and price. Given the high levels of correlation among these hypothesized causal variables, the statistical analysis below centers on multiple regression using ordinary-least squares, which enables measurement of the effect of each individual independent variable on the level of under-dosing.

Table 5. Glyphosate dosage of 100 samples tested from Mali (laboratory measurement / stated dosage on the bottle).

Summary statistics	Dosage (lab/label)
average	0.87
standard deviation	0.11
minimum	0.59
maximum	1.03
Distribution of dosage ratings	% of samples
<75%	18
75–89%	32
90–110%	50
total	100

3. Results

3.1. Dosage measurements

The laboratory test results enable comparison of actual glyphosate dosage (in acid-equivalent) with the expected dosage as reported on the product labels. In the results reported below, a dosage rating of 1.00 means that the laboratory measured exactly the same acid-equivalent glyphosate dosage as promised on the product label, while a dosage rating of 0.75 indicates that the product contained only 75% of the promised dose of glyphosate acid.

Overall, the testing results revealed that quality varies substantially among the various glyphosate products evaluated. Actual dosage as measured by the laboratory ranged from a minimum of 59% to a maximum of 103% of manufacturer's stated value. On average, the test results measured glyphosate dosage at 87% of the manufacturers' stated value. While 50% of the samples tested fell into the normal expected range, between 90% and 110%, at the low end of the quality spectrum, 18% of the samples tested contained extremely low dosages, below 75% of advertised levels (Table 5).

3.2. Hypotheses about factors affecting underdosage

Regulators, traders and farmers we spoke with suggested a variety of factors that might contribute to underdosage of different glyphosate formulations. *Registration status.* Most consider unregistered products – which accounted for 39% of our sample purchases – most likely to scrimp on active ingredients and quality controls. *Suppliers.* Likewise, some suppliers and brands have strong reputations for providing quality products and service. To test this hypothesis, the statistical analysis below breaks down supplying firms into two groups: (a) large international agro-chemical firms who develop, formulate and test their products and (b) a growing

Table 6. Correlation matrix: potential factors affecting formulation dosage.

	1 Share	2 CSP	3 Unreg.	4 Other	5 Firm	6 Group 1	7 Group 2	8 Group 3	9 Group 4	10 Europe	11 China	12 Elsewhere	13 Price	14 Date
Estimated glyphosate dosage														
1 share (lab/bottle)	1.00													
Registration status														
2 CSP	0.40	1.00												
3 Unregistered	−0.33	−0.87	1.00											
4 Other registration	−0.15	−0.30	−0.22	1.00										
Supplier														
5 International R&D firm	0.30	0.66	−0.60	−0.13	1.00									
Formulation groups														
6 Group 1. 356 g/L IPA	−0.38	−0.72	0.66	0.14	−0.63	1.00								
7 Group 2. 360 g/L IPA	0.39	0.50	−0.49	−0.05	0.56	−0.72	1.00							
8 Group 3. 450 g/L IPA	−0.02	0.19	−0.14	−0.10	−0.07	−0.31	−0.31	1.00						
9 Group 4. 489 g/L K	−0.02	0.20	−0.18	−0.06	0.27	−0.19	−0.19	−0.08	1.00					
Production location														
10 Europe	0.29	0.24	−0.25	0.02	0.29	−0.34	0.27	0.17	−0.09	1.00				
11 China	−0.27	−0.14	0.25	−0.20	−0.14	0.23	−0.01	−0.13	−0.32	−0.58	1.00			
12 Other	0.07	−0.04	−0.07	0.22	−0.09	0.03	−0.23	0.01	0.46	−0.20	−0.69	1.00		
Retail price														
13 Price	−0.04	0.15	−0.19	0.07	0.13	−0.18	−0.33	0.31	0.72	0.21	−0.48	0.39	1.00	
Manufacturing date														
14 Date	−0.09	−0.10	0.19	−0.16	−0.21	0.30	−0.25	−0.09	0.01	−0.42	0.34	−0.03	−0.19	1.00

number of small local and regional trading firms with limited technical expertise and shorter commercial histories working with agro-chemicals. *Formulation groups.* Market watchers worry about possible underdosage among the large number of mostly Red Beret formulations in Group 1, many of them smuggled into Mali from Ghana (Figure 2b). These formulations advertise 480 g/L IPA salt, which is equivalent to 356 g/L of glyphosate acid. *Production location.* Historically, large international agro-chemical firms produced glyphosate products in the USA or Europe before shipping to West Africa. However, in the years since 2005, Asian producers have come to dominate the market (Haggblade, Diallo, et al. 2017; Huang et al. 2017). Even the international research and development (R&D) firms now produce mainly in China. In addition, all of the small regional trading firms commission production in China. These most recent market entrants supply a wide array of house-brand generic glyphosate products (Figure 2). Yet their more limited technical capacity makes it far more difficult for them to monitor and ensure product quality from their Asian suppliers. *Price.* Among our purchased samples, glyphosate prices ranged from roughly $5 to $15 per liter (Table 2). As a general rule, Monsanto-branded Roundup typically sells for about 20% more than the major generic brands according to monthly price data collected by Mali's market information service, the Observatoire du Marché Agricole, or OMA (Haggblade, Smale, et al. 2017). Since the major agro-chemical firms who supply brand-name products also incur the higher costs associated with regulatory compliance, distributor training and support, many observers expect that higher price may offer a good indicator of high-quality products. *Date.* Among the 100 samples purchased for testing, manufacturing dates ranged from February 2009 to December 2016. Given this range, most stakeholders expect that older inventory may lose potency over time, particularly under poor storage conditions practiced by many informal traders.

Simple correlation coefficients suggest a strong relationship between dosage shares and the first four hypothesized factors: registration status, suppliers, formulation and production location. Products registered by Mali's designated regulator (the CSP) are positively correlated with dosage levels, while unregistered products correlate negatively dosage levels (Table 6). Products supplied by international R&D firms tend to have higher dosages than products supplied by small local and regional trading firms. The R&D firms are also most likely to comply with the CSP registration requirements and to supply Group 2 (advertised at 360 g/L) products rather than Group 1 (those that advertise 480 grams of acid plus salts). Among formulation groups, the Group 2 products (advertised at 360 g/L ae) tend to be correlated with high dosages, while Group 1 formulations (those that advertise 480 grams of acid plus salts) are correlated with low dosages. Production location signals a positive correlation between glyphosate dosage and European manufacture and a negative correlation with Chinese-produced products. Although many Chinese products are of very high quality, most of the fraudulent products found on the Malian market are produced in China, resulting in a mixed record for the Chinese-supplied products. Given these strong inter-relationships, the following analysis aims to separate out key relationships statistically.

Statistical testing of multiple relationships using ordinary least squares indicates that CSP registration status proves to be the strongest determinant of dosage levels (Table 7). Across a range of different specifications, products properly registered by Mali's regulatory authority (the Comité Sahélien des

Table 7. Regression results: factors affecting glyphosate dosage.

Independent variables	Model 1 Coeff. sig	Model 2a Coeff. sig	Model 2b Coeff. sig	Model 2c Coeff. sig	Model 3 Coeff. sig	Model 4 Coeff. sig	Model 5 Coeff. sig
Registration status (0 = CILSS)							
Unregistered	−0.08 ***	−0.07 ***	−0.07 ***	−0.06 *	−0.07 ***	−0.08 ***	−0.09 ***
Other_reg	−0.10 **	−0.11 **	−0.09 **	−0.08 *	−0.11 ***	−0.11 ***	−0.10 **
Fabrication location (0 = China)							
Europe		0.06 **			0.09 **	0.10 ***	
Other		0.04 **			0.07 ***	0.07 **	
International firm			0.01	−0.01			
Formulation (0 = group 1)							
Group 2. 360 g/L				0.07 *			
Group 3. 450 g/L				0.01			
Group 4. 489 gL				0.00			
Price (CFAF)					−0.000028 ***	−0.000030 **	0.00
Date of fabrication						0.00	0.00
Constant	0.91 ***	0.88 ***	0.90 ***	0.87 ***	0.98 ***	0.68	1.91
n	90	90	90	90	90	85	85
adj R2	0.138	0.175	0.130	0.163	0.214	0.212	0.133

Significance levels.
***99%.
**95%.
*90%.

Pesticides, or CSP) have significantly higher dosage of acid-equivalent glyphosate than the fraudulent products which are unregistered or smuggled in from neighboring countries. On average, the fraudulent products contained 8-10% less active ingredient than the registered brands.

Other potential quality indicators – such manufacturing date and price – do not appear to offer reliable indicators of product quality. Given the chemical stability of common glyphosate formulations, manufacturing date was statistically insignificant as a determinant of product quality. With price, the absolute effect, though statistically significant, was extremely small. A 2 dollar (1,000 CFAF) price increase per liter would affect dosage by only 2.8%. Surprisingly, a *lower* price results in a *higher* dosage, exactly the reverse of the high-quality-high-cost hypothesis. The discussion below explores these price signals in more detail.

4. Discussion

National regulators charged with monitoring pesticide markets and product quality in West Africa face acute resource constraints (Diarra and Haggblade 2017). The following discussion explores ways in which they can deploy their limited manpower and testing budgets most effectively.

Farmers, of course, face even greater constraints, not only limited budgets but also negligible command of the technical chemistry required to asses pesticide product quality. The discussion below suggests several simple decision rules that will improve their chances of procuring pesticides of reliable quality.

4.1. Registration status

Statistically, proper review and registration with the CSP offers the strongest indicator of glyphosate quality (Tables 6 and 7). On average, glyphosate products registered by the CSP contained 9% more active ingredient than the unregistered, fraudulent products (Table 8). While 38% of the fraudulent glyphosate products contained dosages less than 75% of the manufacturers stated value, only 4% of the CILSS-registered products fell below that threshold. Looking at the full distribution of dosage levels, Figure 5 reveals the stark difference between products duly registered by Mali's designated regulator, the CSP, and the many fraudulent products smuggled into Mali and unregistered by the legally designated regional regulator.

Table 8. Glyphosate dosage, by registration status.

Registration Status	Laboratory dosage / stated dosage: Average	Distribution: <75%	75–89%	90–110%
Fraudulent*	0.82	38	30	32
Registered by CSP	0.91	4	32	64
total	0.87	18	32	50

*Fraudulent products include the 39% unregistered anywhere and the 6% registered in neighboring countries and then illegally smuggled into Mali.

For farmers, the simple precaution of purchasing only CSP-registered products would insulate them from the most egregious downside risk of under-dosage. For regulators, initial monitoring efforts focused on the seizure of fraudulent products and fining of retailers selling them would appear most likely to clean up currently widespread glyphosate quality problems.

Registration status serves as a good indicator of product quality because it identifies firms with the professionalism and chemical expertise to ensure quality control from its suppliers. The registration process imposes costs, since firms submitting new pesticide products for approval pay roughly $8,000 in testing fees to agencies authorized to conduct

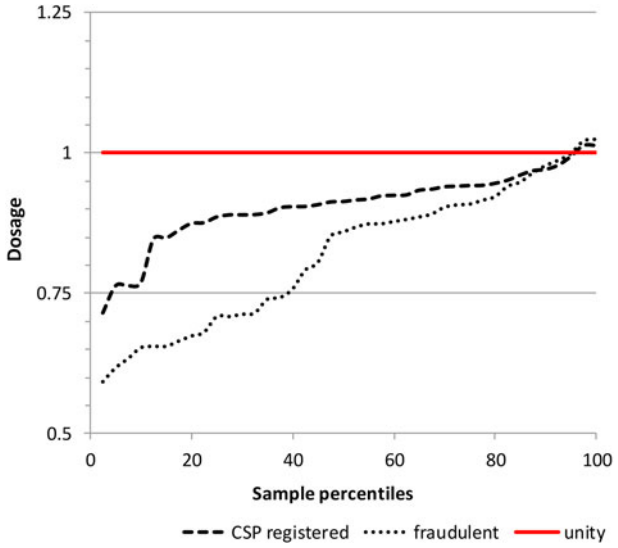

Figure 5. Glyphosate dosages for registered and unregistered products (laboratory estimate compared to manufacturers stated concentration).

CSP-mandated testing. In addition, the firms must pay registration review fees of $1,200 to $6,000 to the CSP when they submit new products for regulatory review. Thereafter, the CSP imposes an annual fee of $200 for each pesticide registered for sale (Diarra and Haggblade 2017). Firms that incur these costs do so to comply with regulatory requirements, to preserve their professional reputations and to ensure the safety of the products they bring to market. In contrast, many smaller and non-specialist trading firms avoid these regulatory costs, in part simply to boost profits and in part because they have neither the technical staffing nor the financial strength to comply.

Despite the generally higher quality of registered glyphosate products, Figure 5 reveals that about 10% of the CSP-registered samples tested contained only 75% of advertised dosage. Industry sources and regulators advanced two possible explanations. Some believe that counterfeiting may explain these low-side outliers, though others note that profitable counterfeiting typically focuses on high-value products rather than bulk generics such as glyphosate. Alternatively, the presence of a handful of underdosed registered formulations suggests that firms importing duly registered products will need to improve quality control of their international suppliers.

Since product registration status provides the clearest quality signal for farmers and regulators, Table 9 explores the characteristics of registered and unregistered products. International agro-chemical firms registered 95% of their products, 93% through the CSP and 2% through coastal regulators. The remaining 5% were possibly counterfeits. Local trading firms, in contrast, registered only about one-third of their products, with nearly two-thirds of them unregistered anywhere.

Table 9. Registration status.

	Registration status			
	CSP	None	Other	Total
Supplying firm type				
International R&D	93%	5%	2%	100%
Local trading	28%	64%	9%	100%
Manufacturing location				
Europe	83%	11%	6%	100%
other	47%	37%	16%	100%
China	49%	48%	3%	100%
Formulation				
Group 1. 356 g/L	10%	80%	10%	100%
Group 2. 360 g/L	84%	12%	5%	100%
Group 3. 450 g/L	83%	17%	0%	100%
Group 4. 489 g/L	100%	0%	0%	100%
All samples	55%	39%	6%	100%

Among the four groups of glyphosate products, suppliers of Groups 2, 3 and 4 registered over 80% of their products. In contrast, only 10% of Group 1 products were registered for sale in Mali by the CSP. Another 10% were registered elsewhere and smuggled into Mali, while fully 80% were not registered anywhere (Table 9).

4.2. Formulation groups

Given the predominance of unregistered products in Group 1, these products not surprisingly provided the lowest average dose of any product group – only 82% of the acid-equivalent glyphosate concentration promised on the label (Table 10). In fact, fully 40% of all samples from Group 1 provided less than 75% of the promised dosage. In contrast the chemically identical but differently labeled products in Group 2 offer the highest dosage of 92%, with only 2% of samples falling below 75% of the promised 360 g/L of acid-equivalent (ae) glyphosate.

This evidence suggests that farmers and regulators should be wary of Group 1 products, that is those that promise 480 g/L of active ingredients. These generics advertise the number 480 in large font, evidently hoping that farmers will mistakenly conclude that these products offer higher dosage than the standard 360 g/L formulations. In reality, they promise only 356 g/L of glyphosate acid equivalents. Even more disconcerting, they deliver only 82% of the promised dosage, the lowest of any of the four product groups (Table 10). Prominent placement of the number 480 on the label appears aimed at fooling farmers with big-but-misleading numbers that include the weight of the co-formulant salts. The many "Red Berets" smuggled into Mali from Ghana fall into this category. This finding suggests that formal discussions with Ghanaian regulators may prove necessary to clean up Malian pesticide markets.

4.3. Supplying firms

As pesticide markets have grown in West Africa, a flood of small trading companies has emerged to

Table 10. Dosage levels by group.

	Laboratory dosage / stated dosage			
		distribution		
Group	average	<75%	75–89%	90–110%
Group 1	0.82	40	30	30
Group 2	0.92	2	26	72
Group 3	0.86	17	41	42
Group 4	0.86	0	80	20
total	0.87	18	32	50

*Glyphosate acid equivalent (ae) dosage (g/L ae).

compete with the large international agro-chemical firms by importing generic pesticides directly from China. In Côte d'Ivoire, for example, the number of firms importing pesticides has increased from 12 firms in 2000 to 67 in 2016 (Traoré and Haggblade 2017a). As generic pesticides have become widely available globally, entrepreneurial employees – often those working in the marketing departments of the large international agro-chemical firms – have quit in order to start their own, rival pesticide import businesses. These new entrants import directly from one of several dozen Chinese firms that produce generic house-brands of glyphosate on special order for African importers. Typically, the new and smaller importers order single container loads of pre-packaged one-liter bottles using labels mocked up to imitate well-known brands (Figure 3). Nearly every visit to Mali's major agricultural input markets reveals new unregistered generic brands on sale.

Although some of the new firms comply with registration requirements, many of the smaller newcomers shirk regulatory review and shamelessly imitate the packaging of well-known high-quality brands (Figure 3). While the large international agro-chemical firms register 95% of their products, the smaller local trading firms, in contrast, register only about one-third of their products, with two-thirds of them unregistered anywhere (Table 9). The smaller firms, often general importers with little technical background in agricultural chemicals, frequently lack the technical expertise required to ensure quality control of products received from their Asian suppliers.

4.4. Manufacturing location

On average, European manufactured glyphosate offers dosage rates 7-10% higher than those manufactured in China (Table 7). Despite the availability of many high-quality Chinese products, most of the fraudulent products found on the Malian market are also produced in China, resulting in a very mixed record for the Chinese-produced products. Industry sources suggest that these variable outcomes depend, in part, on the vetting and quality control procedures adopted by importing firms. The large international agro-chemical firms, as well as others with solid technical staffing, commission and receive high quality products from China. In contrast, the many smaller newcomers in the pesticide import business, particularly those without strong research or technical staffs, face a serious risk of receiving low quality glyphosate products with no way of verifying quality.

Production location, though statistically significant, seems unlikely to offer useful purchasing guidance for farmers given that the few remaining high-quality European products available on the market are rapidly being displaced by Asian manufacturers who can supply this generic pesticide at much lower cost. Chinese products in our sample were, on average, one year and four months newer than the European products. Indeed, while over 40% of the Chinese products in our sample were manufactured in 2016, the samples contained no European products manufactured after January 2016. These findings reinforce traders' assertions that the few remaining European-manufactured glyphosate samples found on the market constitute legacy inventory that they are rapidly phasing out. Even the major international agro-chemical firms are moving pesticide production to China to take advantage of the enormous economies of scale and investment by Chinese firms in glyphosate production capacity over the past decade and a half (Huang et al. 2017). Over the coming decade, Malian farmers will be choosing from among various generic brands of Chinese-produced glyphosate. The key to selecting good quality products will center on registration status coupled with the supplier's reputation and support.

Importing firms can benefit by working only with good quality Chinese suppliers, while regulators will want to ferret out the less reputable manufacturers. Our 100 samples list 22 different manufacturing firms, 13 of them Chinese. Of the 13 Chinese firms, 6 supply only properly registered CSP products, while 7 supply primarily unregistered pesticides to the less discriminating traders. This disparity suggests the existence of both "good actors" and "bad actors" among the various Chinese manufacturers. The good actors among the Chinese suppliers produce high-quality products at low cost. Since most West African importers are moving towards Asian-based production of generic products such as glyphosate, an important component of regulatory monitoring will involve identification and rewarding of the good actors and sanctioning of the bad.

4.5. Price

Even though glyphosate prices vary widely, price does not serve as a good guide to product quality. Formulation Groups 1 and 2 both promise 360 g/L ae glyphosate; yet their per liter prices do not differ significantly from one another (Table 11). Nor do their prices per acid-equivalent differ, at advertised

Table 11. Glyphosate prices, by formulation group.

Group	Advertizedosage	Price (USD/ liter)	Price difference compared to	Price per acid-equivalent (US cents/ae)	
			Group 2 significance	Advertized dosage	Actual dosage
1	356	6.17	0.22	1.7	2.1
2	360	5.95	0.00	1.7	1.8
3	450	8.12	2.16 ***	1.8	2.1
4	489	11.97	6.01 ***	2.4	2.9

Statistical significance.
***99%.
**95%.
*90%.

Table 12. Differences in glyphosate pricing, by registration status.

Registration status	n	Price (USD/liter)	Price difference compared to	
			CSP	significance
CSP	36	5.91	0.00	
other	6	6.97	1.06	***
none	32	6.08	0.18	

Statistical significance.
***99%.
**95%.
*90%.

dosage levels. Given that actual dosage in Group 1 is 10% lower than that in Group 2, Group 2 products offer better value for farmers in the form of lower cost per glyphosate acid-equivalent.

The higher dosage products in Group 3 charge higher per-liter prices; yet cost per acid-equivalent at advertised dosages remains the same as Groups 1 and 2. Only the highest-dosage Group 4, with its very limited (5%) market share and potassium salt formulation, charges higher price per ae than the other groups. Possibly the potassium salt formulation contains special co-formulants that provide value over and above the glyphosate acid.

Formal testing for price differences within Groups 1 and 2 revealed that the price of unregistered products (Registration status "none") did not differ statistically from the price of the CSP-registered products (Table 12). In other words, the market currently provides no quality premium for the higher quality, registered products, presumably because of lack of farmer awareness of this quality difference. To address this information problem, an upcoming extension campaign with the local regulators aims to improve farmer understanding of the quality premium afforded by CSP-registered products.

The higher cost of "other" glyphosate products registered in Ghana and Guinea, but not in the Sahel, likely stems from the costs incurred for completing registration formalities plus the added cost of smuggling goods into Mali (Table 12).

5. Practical implications for stakeholders

For farmers, these results suggest a simple decision rule for improving the quality of glyphosate products they purchase and apply on their fields. Farmers can improve input quality by purchasing only products duly registered by Mali's regulator, the Commité Sahélien des Pesticides (CSP). Currently, the CSP has approved and registered 38 generic glyphosate brands for sale throughout the Sahel, resulting in a wide array of good choices. A second, complementary decision rule can help as well. Since 90% of the glyphosate products in Group 1 are fraudulent, farmers would also be well advised to avoid glyphosate formulations advertising 480 g/L on their label.

These findings underscore the important quality control function performed by the Sahelian regional regulatory authority (the CSP) and the scores of "good actors" in the industry who duly comply with the CSP-mandated testing and review process. The findings from this study suggest that firms who respect these regulatory requirements supervise their Asian manufacturers more carefully than the less specialized, often smaller importers and, as a result, supply higher quality pesticides to their local distributors and retailers. Yet even among the suppliers who comply with regulatory requirements, approximately10% of samples tested contained only 75% of advertised dosage. Pesticide importers with whom we have shared these results in a series of outreach events across Africa react with concern to this evidence of low-side outliers, concluding that they will need to review quality control processes in their international supply chains and simultaneously ramp up anti-counterfeiting efforts.

For regulators, the widespread prevalence of fraudulent glyphosate products in Mali and elsewhere raises serious concerns (MirPlus 2012). Fully 45% of the glyphosate samples purchased for this study proved to be fraudulent. Of these, over two-thirds were under-dosed: one-third contained less than 90% of the promised glyphosate acid, while a further one-third contained less than 75% of the promised dosage. The widespread prevalence of low-quality, fraudulent products suggests a clear need for more aggressive monitoring of pesticide markets and product quality. Since post-registration monitoring remains the province of individual national governments, and not the CSP, national

regulatory bodies will need to step up their efforts to monitor markets as well as the quality of pesticide formulations currently on sale. At a regional level, the scarcity of quality testing laboratories poses a fundamental constraint that will likely require additional attention and investment.

Large-scale underdosage, of the magnitude identified in Mali and in Uganda (Ashour et al. 2018), raises the specter of accelerating weed resistance to key, widely used active ingredients. As a result, environmental impacts, largely unmonitored to date, will merit careful empirical scrutiny going forward.

Notes

1. Fraudulent products include both counterfeits and unregistered generics. Counterfeiters strive to pass off their products as originals by using packaging identical to well-established registered brands. In contrast, suppliers of unregistered products produce low-cost generic products by short-circuiting regulatory controls in order avoid the costs associated with regulatory testing and registration requirements. Unregistered products often imitate the packaging of market leaders, though not precisely (see Figure 3).
2. The country studies include Côte d'Ivoire (Traoré and Haggblade 2017a), Gambia (Diallo and Oyinkan 2017), Ghana (Diarra and Tasie 2017), Guinea (Traoré and Haggblade 2017b), Mali (Haggblade et al. 2017) and Senegal (Diarra and Diallo 2017).
3. The eight coastal West African countries are currently working to establish a single regional regulator for the humid coastal zone, modeled on the Sahelian CSP (ECOWAS 2008; Traoré et al. 2011; Diarra and Haggblade 2017).
4. Baker (2016) has highlighted the pervasive problem of reproducibility in scientific research. The unreliability of blind duplicate results from two of our three testing laboratories raises similarly serious practical problems for regulators, farmers and researchers trying to monitor and ensure pesticide quality. To address these technical issues directly, our team has prepared a separate technical paper providing full details of the chemical analysis, including differences in laboratory equipment, procedures and quality control procedures. Full details are available on request from the authors.

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