Original Article

Causes and Consequences of Increasing Herbicide Use in Mali

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Abstract This paper examines the origins and impact of rapid recent growth of herbicide use in Mali. Primary data come from interviews with herbicide importers and distributors and from a 2014/2015 survey of farm households in Mali's Sudanian Savanna zone. Results suggest that a series of major supply-side changes are driving growth in Mali's herbicide markets, most conspicuously a proliferation in the number of sellers and herbicide brands marketed, a shift to low-cost suppliers in China and India, and consequently falling herbicide prices. At the farm level, herbicides cost on average 50 per cent less than hiring weeding labor. Despite low econometric estimates of damage abatement, herbicide adoption rates reach 25 per cent in remote rural zones and 75 per cent in more accessible rural areas. Key factors affecting adoption include spatial variation in herbicide prices and rural wage rates. At current levels, herbicide use reduces peak season rural labor demand by roughly 14 per cent.

Cette étude examine l'augmentation rapide de l'utilisation des herbicides au Mali, ses origines et son impact. Les données primaires utilisées dans l'étude proviennent des entretiens auprès des importateurs et distributeurs d'herbicide, et aussi d'une enquête en 2014-2015 auprès des ménages agricoles dans la zone Malienne du Savannah Soudanien. Les résultats indiquent que la croissance du marché des herbicides au Mali est dû à des changements dans l'offre des herbicides, en particulier à une prolifération du nombre de vendeurs et des marques disponibles, au déplacement des sources de herbicides a des fournisseurs bas coût en Inde et en Chine, et à une conséquente chute des prix des herbicides. Au niveau des fermes, l'utilisation des herbicides implique des couts 50% inferieurs à ceux assumés en embauchant des travailleurs pour désherber. En dépit des faibles réductions de dégâts, estimés économétriquement, l'adoption des herbicides touche le 25% dans les zones rurales les plus éloignées, et le 75% dans les zones rurales plus accessibles. Les facteurs-clé affectant l'adoption des herbicides comprennent la variation spatiale du prix des herbicides, et les salaires ruraux. Au niveau actuel des prix et des salaires, l'utilisation des herbicides réduit la demande de travail agricole d'un 20% pendant la haute saison horticole.

The European Journal of Development Research (2017) **29,** 648–674. doi:10.1057/s41287-017-0087-2; published online 2 June 2017

Keywords: herbicides; damage abatement; employment; environment; Mali

Introduction

Herbicide use has grown rapidly in Mali over the past decade and a half. Quantities imported have more than doubled since the year 2000, while unit prices have fallen by 50 per cent in

Table 1: Trends in herbicide imports* into Mali, 2000–2014

Herbicide imports	*2000*	*2005*	*2010*	*2014*	*Change (per cent)*
Quantity (tons)	1132	1037	1420	2660	135
Price					
000 CFAF/liter	3.9	2.9	2.1	1.9	−50
US dollars/liter	5.44	5.55	4.27	3.91	−28

* 3-year moving averages.
Source: Camara *et al* (2003), Institut National de la Statistique du Mali (INSTAT).

local currency and nearly 30 per cent in dollar terms (Table 1). Unlike fertilizer, which receives a 50 per cent government-financed price subsidy, herbicide users pay full commercial price (Thériault *et al*, 2015). While large-scale government tenders and public subsidies have fueled recent increases in fertilizer availability, rapid growth in herbicide use has emerged as a result of purely private sector supply systems meeting growing on-farm demand.

This recent, spontaneous technology innovation and diffusion merits close examination. From a policy perspective, it is important to understand the sources of private sector innovation that have enabled rapid expansion of this low-cost herbicide-based technology for weed control. Analytically, most work on farm intensification in the presence of rising labor costs has focused on mechanization. Yet herbicides provide a less costly, more easily divisible technology that has increasingly attracted interest from Malian farmers, large and small, male and female. Without public support or intervention, private sector agribusinesses have developed and delivered an increasing array of herbicide products that attract growing interest among Malian farmers.

The proliferation of herbicide products now available in Mali offers farmers a new set of tools for responding to growing weed pressure. Across Africa, weed losses amount to 15–23 per cent of potential cereal output, exceeding losses due to insect damage, and animal and pathogenic pests (Oerke, 2006; Rodenburg and Demont, 2009). Invasive weeds, such as *Striga and Oriza logistaminata*, have become increasingly difficult to control through hand weeding and plowing (Gebretsadiz *et al*, 2014; Soungalo 2016). In traditional maize cropping systems, agronomic studies suggest that weed pressure, more so than soil fertility losses, leads many farmers to abandon cultivated parcels after 3–4 years (CIRAD, 2012, p. 785). Continued expansion of cultivated area makes weed management increasingly important for Malian farmers, as population growth and declining soil fertility propel area expansion. At the same time, competition for rural labor, in gold mines and urban areas, has led to a growing scarcity of rural labor. This scarcity, in turn, makes traditional hand weeding increasingly expensive as a weed control strategy. Hence the emergence of broad-based farmer interest in the new, inexpensive weed control technology supplied by Mali's growing legion of private herbicide traders.

This paper examines the causes and consequences of rapid recent growth of herbicide use among Malian farmers. In doing so, it fills a gap in our understanding of the forces driving farm intensification by exploring, for the first time, the scale, causal forces, and impact of the ongoing spontaneous expansion of herbicide use in Mali. On the supply side of this growing market, the paper examines recent product innovation, the changing structure of private sector production and distribution systems, key intellectual property and regulatory events, and the commercial branding strategies that have combined to foster increased competition, falling prices, and rapid expansion of herbicide supplies in recent years. On the demand side of the herbicide market, the paper examines factors affecting on-farm adoption and use levels, including prices of herbicides relative to competing weed control inputs, area expansion, the marginal productivity of herbicide applications, and structural features such as household asset endowments, labor supply, and gender.

In terms of potential impact, growing herbicide use holds implications for farm productivity, labor demand, and the environment. Because herbicides limit damage rather than raising productivity (Lichtenberg and Zilberman, 1986), the analysis below investigates the effect of herbicide use on smallholder production of sorghum and maize by estimating a production function with and without damage control. Rising herbicide use likewise implies potentially significant reduction in employment opportunities given that agriculture employs over half of Mali's workforce and that peak season weeding provides the single largest labor demand in many cropping systems (Gianessi and Williams, 2011). Potential environmental spillovers raise parallel concerns about farm worker safety, possible herbicide resistance, and unintended disruptions in plant and animal populations. As a result, crucial tradeoffs may emerge between farm productivity gains, environmental spillovers, and aggregate employment losses. This paper examines these three major implications of expanding herbicide use in Mali.

The paper begins, in Sect. 2, with a review of data and methods. The dynamics of herbicide supply systems form the focus of Sect. 3, while Sect. 4 focuses on herbicide demand among sorghum and maize farmers in southern zones of Mali. Section 5 provides an assessment of the impact of herbicide use on farm-level productivity, employment, and the environment, while the concluding section outlines key analytical and policy implications.

Data and Methods

Supply System Structure and Dynamics

Data for exploring these issues come from a variety of sources. Time-series price information in local markets comes from ongoing monitoring of 10 agricultural markets by Mali's Observatoire du Marché Agricole (OMA), while a 2015 survey of 16 major input markets across Mali provides a recent snapshot of retail distribution density across farming zones (Diarisso and Diarra, 2015). Trends in import quantities and prices come from trade figures tabulated by Mali's national statistical agency. Complementing these statistical data, our detailed compilation of regulatory filings at the Comité Sahélien des Pesticides (CSP) has provided a valuable trove of information about the timing of new herbicide releases, the introduction of new brands, product renewal decisions, as well as withdrawals from the market.

In order to understand supply system trajectories, turning points, and key causal forces governing herbicide availability, utilization, and pricing, the authors conducted interviews with regulators and with herbicide importers, distributors, and retailers in Mali's major agricultural markets during May, June, and July of 2016 (Haggblade *et al*, 2016, 2017). These qualitative interviews enable us to trace changes in market structure and behavior over time, focusing particularly on key actions shaping commercial strategies, product innovation, branding, packaging, pricing, and marketing that are driving rapid recent changes in Mali's herbicide markets.

Farm-Level Adoption and Productivity Impact

Adoption

By far the largest body of adoption literature related to herbicide use in developing countries concerns herbicide-tolerant soybeans or maize (see, for example, the meta-analysis by Klumper and Qaim, 2014). However, two recent studies of herbicide adoption in Sub-Saharan Africa are particularly pertinent to understanding the growing use of herbicides in Africa purely as a weed control technology independent of GMO seed packages. Applying a Probit model to data from Ghana and Zambia, Grabowski and Jayne (2016) find that increased adoption of herbicides depends primarily on product awareness, availability, and demand but not on agricultural wage rates. In contrast, Tamru *et al* (2017, in this special issue) show a strong relationship between herbicide use, rural wage rates, and proximity to markets and cities. Their work applies a double-hurdle model to large-scale survey data on teff in Ethiopia. The analysis below contributes to this emerging body of evidence on herbicide adoption in Africa.

To explore farm-level determinants of herbicide adoption, we analyze data from a 2014/2015 survey of 700 farm households in the high-productivity Sudan Savannah zone (Smale *et al*, 2015). Within these households, we deliberately sampled collective and individual plots managed by women and men from the inventory of all plots worked by the household in order to compare variations in management practices and outcomes. Overall, our sample includes plot-level farm data from 1305 maize and sorghum plots, enabling us to explore spatial and gender differences in herbicide use as well as the profitability of herbicide use compared to alternate weed control strategies.

To formally test determinants of herbicide use, we estimate two types of corner-solution models. Because over one-third (39 per cent) of all plots surveyed did not receive herbicides, our sample included a large concentration of zero adoption values. Under these conditions, a non-linear "corner-solution" model is more appropriate than a linear model for testing the determinants of use. The well-known Tobit model treats the binary decision to use herbicide (0,1) and the amount of herbicide used (>0, conditional on use) as determined by the same underlying process. Like Tamru *et al* (2017, in this issue), we apply a double-hurdle model. The Cragg model (Cragg, 1971; Burke, 2009) relaxes the assumption of common process by allowing the vector of regression parameters to differ between the two aspects of the adoption decision. The Tobit is nested in the Cragg model, which allows estimation of the use and intensity decisions in two stages, through the use of a Probit regression in the first stage followed by a truncated regression in the second stage. We use a log-likelihood ratio test of the restricted (Tobit) vs. the unrestricted (Cragg) regression to determine which model better fits the underlying data-generation process. The Cragg model assumes independence between the two decisions, which is relaxed in later double-hurdle specifications. We use the standard Cragg model because of our focus on adoption determinants rather than average partial effects. For robustness, we also estimate the model using ordinary least squares.

We are guided in our specification of adoption determinants by the model of the agricultural household, which portrays the choice of inputs as an endogenous response affected not only by observed prices but also by the household-specific endowments that influence the costs of market transactions. We include herbicide price and the price of the substitute input, labor, as the daily weeding wage. Village medians were included for missing values since values were reported only when paid. Endowments are measured by household wealth in terms of assets and transfers from absent family members, which relieve cash constraints. To control for household labor supply, we use the total number of active adult household members in the EAF. We also control for plot characteristics, since the crop planted and the size of the plot are likely to affect quantities of herbicides used, while the distance from the house to the plot could affect transaction costs. Consistent with the broad adoption literature, we hypothesize that formal education may affect capacity to assimilate information about new agricultural practices. Reflecting the organization of farm production in our study region, and our interest in gender considerations, we also test for the influence of female plot management (Theriault *et al*, 2017).

Productivity Impact and Damage Control

To measure the productivity impact of herbicides, we use the same farm household dataset to estimate a production function with and without damage control. Unlike conventional inputs (such as land, labor, and fertilizer), damage control agents (such as insecticides, fungicides, and herbicides) do not increase potential output but rather reduce potential output losses. As a result, use of a standard production function to estimate the effect of damage control agents on productivity may lead to biased estimates. In their seminal work, Lichtenberg and Zilberman (1986) addressed potential upward bias by incorporating a damage control abatement function into the standard production function. However, the direction of the bias has been debated (Pandey, 1989). Hall and Moffitt (2002), for example, demonstrate the potential downward bias resulting from estimating a damage control model based solely on economic variables in the absence of actual data on pest populations.

Most research using a damage control abatement model has focused on insecticides, including research on Bt crops (e.g., Saha *et al*, 1997; Chambers *et al*, 2010; Shankar and Thirtle, 2005; Kouser and Qaim, 2014). Herbicides, as a single damage control agent, have received less attention. Previous herbicide studies have instead focused mostly on the economics of herbicide resistance (e.g., Beltran *et al*, 2011; Weersink *et al*, 2005) and weed resistance to herbicides (e.g., Owen and Zelaya, 2005).

In this paper, we estimate a production function with damage control to examine the effect of herbicide use on sorghum and maize production, following the original specification of Lichtenberg and Zilberman (1986) and the example of Carrasco-Tauber and Moffitt (1992). Following their example, we define the damage control function as $Y = F[(Z), G(\mathbf{X})]$, where Y represents output value and the vector $\mathbf{Z}$ includes inputs of the standard production model. The vector $\mathbf{X}$ consists of control inputs. $G(\mathbf{X})$ is increasing in $\mathbf{X}$ and approaches an upper limit of 1, where $Y = F(\mathbf{Z})$. As $\mathbf{X}$ decreases, $G(\mathbf{X})$ and $Y = F(\mathbf{Z}, 0)$ approach the lower limit of 0, or a level that represents maximum destructive capacity. In most applied work, researchers specify the function multiplicatively as $Y = F(\mathbf{Z})G(\mathbf{X})$. The damage abatement effect represents the proportion of the destructive capacity (modeled as a cumulative density function valued between 0 and 1) offset by utilizing a given amount of a control input. In empirical work, researchers typically estimate the cumulative distribution function $G(\mathbf{X})$, which lies in a [0,1] interval, as Weibull, exponential, or logistic functions. $F(\mathbf{Z})$, thus, represents the maximum yield attainable with zero pest damage or maximum pest control.

We chose the Cobb–Douglas functional form for the production model ($F(\mathbf{Z}) = \beta_0 \prod_i \mathbf{Z}_i^{\beta_i}$). The form has been extensively used in damage control analyses and is parsimonious relative to more flexible forms. We estimate the production function with damage abatement using non-linear least squares, which imposes some restrictions on the choice of functional forms. In testing quadratic functions, which have also been applied in the literature, we obtained coefficients largely similar to those of the Cobb–Douglas formulation but statistically insignificant due to high degrees of collinearity. In estimating the $G(Z)$ functions, we tested Weibull, logistic, and exponential functional forms. Of these, only the regressions with the logistic functional form converged, suggesting a better fit to the data. Full-variable descriptions and results follow in the analysis below.

Employment and Environmental Impact

In order to measure aggregate labor displacement resulting from widespread herbicide adoption, the analysis below compares changes in labor demand with expected labor supply levels. Data on farm labor demand – with and without herbicides – come from a series of farm budget studies conducted by Mali's Institut d'Economie Rurale (IER), the Compagnie Malienne pour le Developpement du Textiles (CMDT), the Office du Niger, and from our own farm household survey in southern Mali (Tefft, 2010; Office du Niger, 2012; Diarra *et al*, 2014; Smale *et al*, 2015; Kergna, 2016, Assima *et al*, 2017). Labor supply estimates rely on the demographic and labor supply modules from Mali's 2009 population census, which include age- and gender-disaggregated demographic pyramids and economic participation rates (CPS/SDR, 2010).

Environmental impacts from herbicide use can potentially affect farm worker safety (through direct exposure during application), consumer health (from plant residues consumed), water quality, animal populations (including fish as well as soil bacteria), weed populations, and other plant species (see Wesseler *et al*, 2011; Waterfield and Zilberman, 2012). Given the complexity and time scale required for measuring environmental impacts, this study has not attempted to collect primary data on these issues. Instead, we rely on a series of studies conducted by regional regulatory bodies and local researchers (Keita, 1992; Camara *et al*, 2003; MIR Plus, 2012).

Marketing and Supply System Transitions

Herbicide Products

Glyphosate, the world's top-selling herbicide, accounts for the majority of herbicide sales in Mali as well. Developed by Monsanto and first released commercially in 1976 under the trademark name Roundup, glyphosate is a broad-spectrum herbicide that kills both grasses and broad-leaf weeds (Charles, 2001). Malian importers and agricultural input retailers consistently identify glyphosate as their top-selling herbicide. Offering a rough order of magnitude, farm survey data from southern Mali suggest that glyphosate accounts for about two-thirds of herbicide volumes used, while selective herbicides (used primarily on cotton, maize, and rice) account for the remaining one-third (Table 2).

Over time, the number of herbicide products registered for sale in Mali has expanded rapidly. Following registration of only a handful of cotton-selective herbicides for sale in 1995, the number of herbicide products has increased to 49 as of December 2015 (Figure 1). The period since 2010 has witnessed an unusually large jump in the herbicide brands proposed and registered for sale in Mali. This proliferation of products has accompanied substantial changes in the structure of the herbicide supply system.

Supply System

Imports supply the entirety of the Malian herbicide market, with six major importers dominating the herbicide trade. The largest of these, Mali's parastatal cotton company, the Compagnie Malienne pour le Développement du Textile (CMDT), purchases large volumes of pesticides (primarily insecticides but also herbicides) through tender then sells them through local cooperatives to Mali's roughly 180,000 cotton farmers (Tefft, 2010). Our field visits indicate that small volumes of CMDT-supplied inputs reach local markets as a result of cotton farmers reselling small volumes on the open market. Far larger quantities of herbicides sold in local markets come through the five other large commercial importers – Louis Dreyfus

Table 2: Farmer use of registered and unregistered herbicides on maize and sorghum plots in southern Mali, 2014/2015

Herbicide type	*Herbicide registration*		
	Registered	*Uncertain*	*Total*
Percent of plots using herbicide			
Glyphosate*	34	40	74
Selective**	20	7	27
Total	53	47	100
Percent of herbicide volume used			
Glyphosate*	31	36	67
Selective**	24	9	33
Total	55	45	100

* Non-selective, total herbicide.
** Nicosulfuron, pendimethalin, atrazine, isoxaflutole, 2,4-D.
Source: Smale *et al* (2015) survey data analysis.

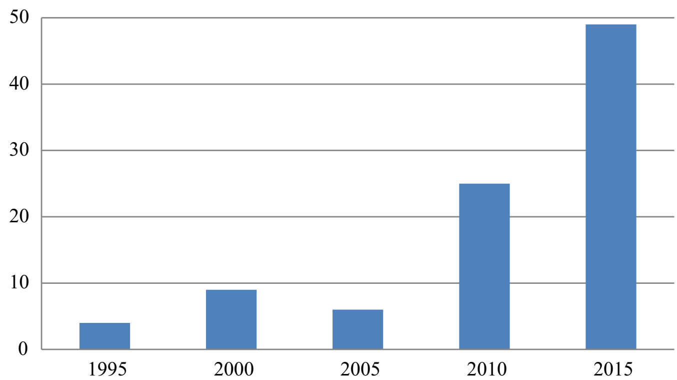

Figure 1: Trends in the number of herbicide products authorized for sale in Mali*.
(* Includes non-selective herbicides as well as selective herbicides used on cotton, maize and rice).
Source: Comité Sahélien des Pesticides (CSP).

Commodities (LDC), Mali Protection Cultures (MPC), Datong Enterprises (DTE-Chine), Société Générale Agricole (SOGEA), and Toguna Agro Industries. Another 20 smaller registered importers compete in this space along with an unknown but likely much larger number of unregistered small traders and smugglers who import off-brand herbicides regionally from Guinea, Ghana, and Côte d'Ivoire.

At the retail level, thousands of small vendors sell herbicides directly to farmers in markets all across Mali. Market surveys conducted during 2015 in 16 agricultural markets across Mali indicate that over two-thirds of agro-dealers in Mali supply herbicides to farmers, slightly more than sell fertilizer and significantly more than sell seeds (Table 3). Geographically, herbicide sales are most prevalent in the cotton zones of southern Mali and in farming areas that lie close to major urban centers. Spatial data from farm household surveys reinforce these findings on the link between urban proximity and herbicide use (see Sect. 4.2 below). Qualitative interviews with agro-dealers confirm that herbicides constitute a growing share of their sales, as farmer demand continues to grow.

Table 3: Prevalence of agricultural inputs sold in 16 markets across Mali*

Zones		*Percent of retailers selling specific inputs*		
		Herbicides (per cent)	*Fertilizer (per cent)*	*Seeds (per cent)*
Served by parastatal marketing agencies				
1	Cotton zone (CMDT, OHVN)	76	61	48
2	Irrigated rice zone (ON)	61	73	50
Without parastatal marketing companies				
3	Accessible zones	72	60	72
4	Remote areas	58	73	32
All markets surveyed		68	66	51

* Markets included in each zone include the following:
(1) Compagnie Malienne de Dévéloppement des Textiles (CMDT): Sikasso, Koutiala, Fana and Organization of the Upper Niger Valley (OHVN): Ouéléssebougou.
(2) Office du Niger: Niono, Ségou, Macina, Kolongotomo.
(3) Accessible zones without parastatals: Mopti, Kati, Banamba, Diéma.
(4) Remote areas without parastatals: Nara, Tominian, Kéniéba, Koro.
Source: Diarisso and Diarra (2015).

Seasonally, large numbers of temporary and itinerant traders enter into the herbicide trade. Agro-dealers we interviewed in a range of local markets suggest that temporary and itinerant peak season herbicide retailers often outnumber permanent sellers by a factor of 10.

Regulatory Framework

Since the 1990s, following a series of coordinated efforts to control major insect infestations across the Sahel, the Sahelian countries of West Africa have regulated pesticides regionally. In 1994, the Comité Permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel (CILSS) established a regional regulatory body, the Comité sahelien des pesticides (CSP), to review and certify all pesticide products sold throughout the nine member countries[1] (Diarra, 2015). Under these rules, any pesticide passing CSP efficacy and safety reviews and registered for sale in one member country becomes automatically authorized for sale throughout all nine member countries. By centralizing this regulatory review, the CSP provides a one-stop-shop for manufacturers and importers, facilitating the review process and reducing administrative costs by standardizing and centralizing review procedures. Rather than preparing nine separate dossiers for review in nine separate countries, prospective suppliers deal with a single regulator whose approval authorizes sales across a multi-country regional market (Traoré *et al*, 2011).

Marketing and Branding

Since the introduction of the CILSS regional regulatory system, the number of herbicide brands registered for sale by the CSP has grown rapidly, particularly in the period since September of 2000 when Monsanto's patent protection for Roundup expired (Zimdahl, 2016). Expiration of the Roundup patent has unleashed a parade of new glyphosate brands – worldwide as well as in Mali. Major international agrochemical companies (including Syngenta, Dow and Bayer) have introduced their own glyphosate brands, sold in Mali under trade names such as Mamba Dominator and Touchdown.

More recently, West Africa-based traders have begun to introduce their own "house brands" of herbicide products (Table 4). In 2008, a Guinean firm registered a new brand of glyphosate,

Table 4: Trends in number of glyphosate brands registered for sale within Mali

5-year intervals beginning in	*Number of brands registered*	
	*International**	*Regional***
1995	0	1
2000	4	5
2005	2	5
2010	1	16
2015	0	5

* International brands include those produced by the Big Six international pesticide companies: Bayer, BASF, Dow, Dupont, Monsanto, and Syngenta.
** Regional brands include those registered by local trading firms.
Source: Comité Sahélien des Pesticides (CSP).

called Glycel, for sale across the CILSS member countries. The Guinean firm, Topex Agro Elevage, commissions Glycel production through an Indian manufacturer based in Mumbai. In a stark departure from the early Roundup imitators, Glycel shifted packaging from the standard Roundup white and green colors to a yellow bottle with a red cap (Figure 2). Marketed as the “Red Beret” – with rough-and-ready, Special Forces power – Glycel has become one of the dominant glyphosate brands sold in Mali.

A rash of imitators has copied Glycel’s Red Beret packaging by enlisting an array of low-cost suppliers in China and India to manufacture and package similar-looking glyphosate products (Figure 2). In June 2016, our survey teams identified a total of 25 brands of glyphosate for sale on the Malian market. Of these, roughly half have received regulatory approval (11 by the CSP, 1 by Ghana and 1 from Guinea) while the remaining half have not. The explosion of newly registered regional brands – with its welter of unregistered imitators – has led to widespread smuggling, customs, and regulatory evasion. As a result, regulators and registered importers have raised increasing concerns about herbicide quality and safety (MIR Plus, 2012).

Glyphosate prices have fallen in recent years as a result of expiring patent protection for Roundup, increased competition from alternate brands, a move to low-cost Asian manufacturers, and increasing efforts by unregistered brands to evade regulatory costs and formal customs duties. Since 2008, Mali’s Observatoire du Marché Agricole (OMA) has tracked herbicide prices across ten major agricultural markets in Mali. The OMA market monitoring data indicate that glyphosate prices have fallen by about 35 per cent in local currency (50 per cent in dollars) among the newer glyphosate brands (such as Kalach), while Roundup prices have declined only slightly in CFA francs (Table 5). Softening prices, in turn, make herbicide uptake increasingly profitable at the farm level, as the following discussion demonstrates.

Farm-Level Demand

Weed Management Options

Malian farmers have historically controlled weeds by hand weeding and by full soil inversion (plowing) during land preparation. During the 2014/2015 cropping season, smallholder farmers in southern Mali applied herbicides on slightly over 60 per cent of their maize and sorghum

a Roundup and imitators (above)

b Glycel and imitators (above)

Figure 2: Registered and Unregistered Brands of Glyphosate Sold in Mali, June 2016.

Table 5: Glyphosate retail price trends: average annual retail price in 12 markets tracked by Mali's Observatoire du Marché Agricole (OMA)

Brand	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*Change (per cent)*
Price in CFAF/liter									
Kalach 360	4833	4313	4313	2804	2958	3164	3375	3125	−35
Roundup 360	4833	5250	4938	6000	5000	4458	4479	4375	−9
Price in US dollars/liter									
Kalach 360	10.8	9.1	8.7	5.9	5.8	6.4	6.8	5.3	−51
Roundup 360	10.8	11.1	10.0	12.7	9.8	9.0	9.1	7.4	−31

Source: Observatoire du Marché Agricole (OMA).

plots (Table 6). Among those using herbicides, glyphosate accounted for about two-thirds of the total volume of herbicides applied (Table 2).

Herbicides cost less than half as much as hiring hand weeding labor, on average, in the zones studied. Our survey of sorghum and maize farmers in southern Mali indicates that farmers who applied herbicides spent an average of $23 per hectare on herbicides. Had they hired weeding labor instead, they indicate that they would have had to spend $52 per hectare, over twice as much.

Table 6: Gender differences in herbicide adoption and rates of application

Plot manager	*Plot type*	*Crop grown*		
		Sorghum	*Maize*	*Total*
Number of observations				
Household head	Family	565	567	1132
Woman	Individual	197	0	197
Man	Individual	20	10	30
Total		782	577	1359
Percent of plots using herbicides				
Household head	Family	47	69	58
Woman	Individual	79		79
Man	Individual	90	60	80
Total		56	69	61
Herbicide application rate (L/ha)				
Household head	Family	1.1	1.7	1.4
Woman	Individual	2.6		2.6
Man	Individual	3.3	2.5	3.1
Total		1.6	1.7	1.6

Source: southern Mali farm survey analysis; see Smale *et al* (2015) for survey details.

Spatial Differences in Adoption

The profitability of herbicide use varies substantially by location, since the relative prices of weeding labor and herbicides both vary spatially. In general, herbicide prices increase in remote areas because of high transport costs and limited competition. Since most herbicides enter Mali through depots in Bamako, prices typically increase along with distance from the capital city. In zones nearby Bamako, farmers pay about \$7 per liter for herbicides. However. in rural communities 400 km away, this price increases to nearly \$14 per liter (Figure 3a).

Wage rates move in the opposite direction. Given greater opportunities for non-farm earnings in peri-urban and semi-rural areas, the opportunity cost of farm labor increases along with urban proximity. As a result, farmers within 100 km of Bamako pay over \$3 per day for adult male weeding labor, while growers in zones 400 km away pay about \$2 per day (Figure 3b).

The scissors effect – of lower herbicide prices and higher farm wages in nearby zones – leads to higher profitability of herbicide use in more accessible rural areas. In farming communities within 100 km of Bamako, over 75 per cent of farmers apply herbicides on their sorghum and maize plots, while in villages 400 km away, only 25 per cent apply herbicides (Figure 3c). Application rates likewise fall off as distance from major urban centers increases. While farmers within 100 km of Bamako apply over 2 L of herbicides per hectare, their counterparts living 400 km away apply only half a liter per hectare (Figure 3d).

Gender Differences in Herbicide Adoption

Using hand hoes, weed control requires heavy labor inputs at multiple points throughout the cropping season. In contrast, use of herbicides for weed control requires less labor but additional input financing. Differences in gender responsibilities, labor resources, and access to cash suggest that both adoption and impact of herbicide use may differ between male and female farmers. Yet few prior studies have examined gender differences in the adoption of yield-protecting inputs such as herbicides (see Nyanga *et al*, 2012; Theriault *et al*, 2017).

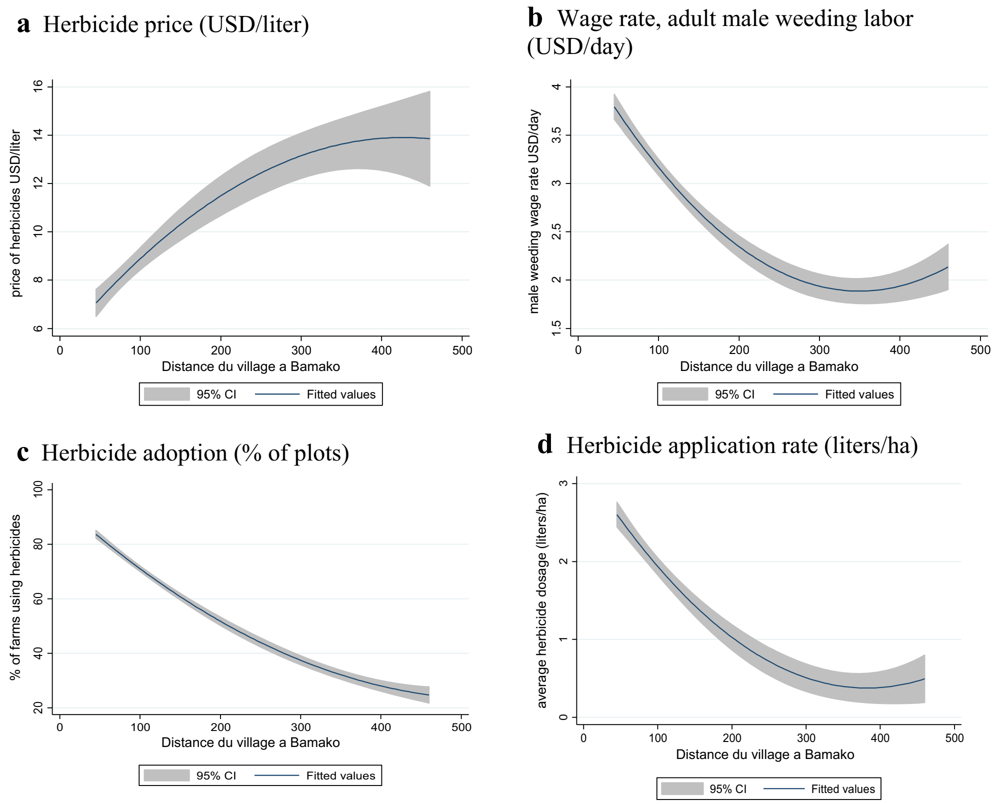

Figure 3: Spatial difference in herbicide prices, wage rates, and herbicide adoption.
Source: Fitted quadratic plots with 95 per cent confidence intervals, computed from 2014/2015 farm household survey described in Smale *et al* (2015).

In southern Mali, women manage about 25 per cent of sorghum plots, though none of the maize plots in the 58 villages we surveyed (Table 6). Family fields managed by the household head, which ensure basic food security for the extended family, account for 80 per cent of all sorghum plots and over 95 per cent of maize plots (Table 6). Typically, the head of household or his designated “chef de travaux” (usually one of his grown sons), manage these common fields, enlisting labor from the extended family as required.

In addition to managing family fields, the household head allocates other plots of land to adult members of the extended family, including sons and their wives, for individual management. The plot managers control proceeds from these fields, which they utilize to meet their own personal needs and those of their children. Adult men rarely grow coarse grains on their individual plots, preferring higher value cash crops. In order to supplement food for their children, adult women, in contrast, do request individual plots for growing sorghum which they often intercrop with cowpea or groundnuts.

Women apply herbicides on nearly 80 per cent of the individual sorghum plots they manage, compared to under 50 per cent of male-managed family sorghum plots (Table 6). Women likewise apply herbicides at over twice the rate, 2.6 L per hectare compared to 1.1 L on the family sorghum plots. Male-managed individual plots similarly apply herbicides more frequently and at higher doses than the male-managed family fields.

Determinants of Herbicide Adoption

Table 8 presents Cragg model estimates of factors affecting herbicide use among sorghum and maize farmers in southern Mali while Table 7 defines the variables used. OLS and Tobit formulations of the adoption decision produce qualitatively similar results (Table A1). The Cragg model results confirm differences between determinants of the decision to use herbicides and extent of their use. Statistically, the likelihood ratio test favors the unrestricted (Cragg) model over the Tobit model.

Table 7: Variable definitions

Name	*Definition*
Adoption	
Use herbicide	1 = use herbicide, 0 else
Extent of herbicide use	Liters used
Adoption determinants	
Prices	
Herbicide price (USD)	Unit price paid by farmer in USD, village median for missing
Daily weeding wage (USD)	Daily weeding wage paid by farmer in USD, village median for missing values
Manager	
Female manager	Plot managed individually by female who is not the EAF head or designate = 1, else 0
Manager has primary education	Plot manager attended primary school = 1, 0 else
Plot characteristics	
Sorghum plot	1 = sorghum planted, 0 = maize
Plot size	Hectares measured by GPS
Distance plot to house	Time in minutes to travel from home to the plot
Household characteristics	
Labor supply per EAF	Number of adults in EAF between 12 and 55 years of age (inclusive)
Asset value of EAF (USD)	Total value of household assets, excluding livestock (ln USD)
Transfers to EAF (USD)	Transfers in USD from absent family members in previous 12 mos
Production function [F(Z)]	
Plot size	Log of hectares measured by GPS
Sorghum plot	2 = sorghum planted; 1 = maize
Kati	2 = village located in Cercle of Kati; 1 = else
Dioila	2 = village located in Cercle of Dioila; 1 = else
Labor	Log of total days of labor used
Fertilizer	Log of total kgs of fertilizer
Manure	2 = manure applied; 1 = else
Seed	Log of total kgs of seed
Machinery	Log of hours of machinery use
Damage function [G(X)]	
Plowing	Log of total hours of plowing
Total herbicides	Log of total liters of herbicide
Herbicides (early)	Log of liters of herbicide applied before planting
Herbicides (middle)	Log of liters of herbicide applied within 10 days of planting
Herbicides (later)	Log of liters of herbicide applied more than 10 days after planting

Table 8: Cragg model explaining herbicide use on maize and sorghum plots in the Sudan Savanna of Mali

Explanatory variables	*Decision to use (0,1)*	*Liters, if used (>0)*
Prices		
Herbicide price (USD)	−0.041***	−0.101***
	(0.010)	(0.020)
Daily weeding wage (USD)	0.248***	0.060***
	(0.030)	(0.018)
Manager		
Female manager	0.964***	−0.635***
	(0.142)	(0.233)
Manager has primary education	0.382***	−0.480**
	(0.113)	(0.195)
Plot characteristics		
Sorghum plot	−0.671***	0.073
	(0.090)	(0.174)
Plot size	0.134***	0.788***
	(0.035)	(0.067)
Distance plot to house	−0.004*	0.009**
	(0.002)	(0.004)
Household characteristics		
Labor supply per EAF	−0.000	−0.015
	(0.009)	(0.017)
Asset value of EAF (USD)	0.180***	0.456***
	(0.049)	(0.100)
Transfers to EAF (USD)	0.000***	0.000
	(0.000)	(0.000)
Constant	−0.660*	−1.738**
	(0.394)	(0.831)
Observations	1205	1205
Value of log-likelihood function	−1945.457	

Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The first column in Table 8 examines factors affecting the decision to use or not to use herbicides. These results suggest several clear conclusions. First of all, price variables strongly shape incentives. Low herbicide prices and high wage rates[2] both significantly increase the probability of herbicide use. Female managers of individual plots are also more likely to use herbicides than male managers of family common plots. This result may stem from women's weaker claims on family weeding labor or high perceived opportunity cost of labor by female plot managers. Although this result also holds for male managers of individual plots compared to family common plots, women account for 90 per cent of all individually managed plots (Table 6). Sorghum plots receive less frequent herbicide application than maize. This may occur because of the frequency of maize cultivation by cotton farmers, who receive inputs (including herbicides) from the CMDT. Household wealth and income transfers also significantly increase the likelihood of herbicide use. In addition to relieving cash constraints, they may signal a shortage of rural labor (temporary migration) or serve as a proxy for non-farm earning opportunities.

In terms of quantities of herbicides used (liters per plot), prices also strongly shape herbicide use. As in the adoption decision, application rates increase with weeding labor costs and as herbicide prices fall (Table 8, column 2). Plot size clearly influences total amounts used, since larger plots require higher input volumes. However, female plot managers use less total herbicides per plot simply because their plots are much smaller. While household wealth significantly influences total herbicide quantities used, income transfers do not. Similarly, and surprisingly, household labor supply does not appear to significantly influence either decision. Although primary education appears to increase the likelihood that a plot manager uses herbicides, it is negatively related to the extent of use. This may stem from larger quantities being used on the larger plots managed by household heads, who tend to be the most senior and least educated household members.

Future Expectations

Looking forward, expected upward pressure on rural wage rates foreshadow continued growth in herbicide demand by Malian farmers. Strong labor demand in Mali's gold mines (and in neighboring Guinea) along with continued rapid urbanization seem likely to draw away rural labor and maintain upward pressure on rural wage rates.

Changing weed populations add further pressure for farmers to increase herbicide use. In the large irrigated farming perimeters of Mali's Office du Niger (ON), pressure from wild rhizomatous weeds (such as *Oriza logistaminata*) have spurred increasing farmer interest in herbicides, particularly glyphosate. Agronomists in the Office du Niger report that flooding and hand weeding no longer suffice for controlling these creeping invasive weeds. Increasingly, early-season glyphosate application offers the most effective means of systemic killing of these rizhomes (Soungalo, 2016). Early adopting farmers report added benefits of increased organic matter as the dead weeds and rhizomes decompose in their paddy fields. As a result, both economic and environmental forces appear poised to promote increased herbicide use in coming years.

Impact of Herbicide Use

Damage Abatement in Farm Production

Damage control agents (such as insecticides, fungicides, and herbicides) do not increase potential output but rather reduce potential output losses. Building on Lichtenberg and Zilberman (1986), we develop a damage control abatement function $G(X)$ that we incorporate into a standard Cobb–Douglas production function $F(Z)$ to examine the effect of herbicide use on sorghum and maize production. The damage function $G(X)$ includes total herbicides used (liters), timing of herbicide application (early, during, late), and plowing (hours). Models that included weeding days did not converge – perhaps because of high correlations. Table 7 presents a full list of the variables used in this estimation, while Table 9 presents the production function estimates, with and without the damage control abatement functions.

Table 9 presents four production models. The standard production function in model (1) includes only inputs that enhance productivity potential. In model (2), we test the effect of total herbicides applied, treating these as we would conventional inputs in the Cobb–Douglas model. Models (3) and (4) present production models with damage abatement. Model (3) treats total herbicide usage as damage abating, while model (4) disaggregates herbicide volumes by time of application. Both models (3) and (4) include plowing as a damage abating variables, because early season soil inversion exerts a strong pre-emptive effect on weeds.

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Table 9: Cobb–Douglas production function with damage abatement, sorghum and maize, Sudan Savanna, Mali

	Production function		*Production function with damage abatement*	
	(1)	*(2)*	*(3)*	*(4)*
Constant	4.300***	4.300***	7.970	8.746
	(0.349)	(0.350)	(0.000)	(0.000)
Plot size	0.288***	0.292***	0.468***	0.569***
	(0.051)	(0.052)	(0.079)	(0.082)
Kati	−0.717***	−0.702***	−1.287***	−1.429***
	(0.089)	(0.094)	(0.177)	(0.194)
Dioila	0.015	0.021	0.079	0.007
	(0.082)	(0.082)	(0.157)	(0.166)
Sorghum	−0.780***	−0.779***	−1.311***	−1.560***
	(0.106)	(0.106)	(0.121)	(0.124)
Labor	0.473***	0.472***	1.179***	0.972***
	(0.085)	(0.085)	(0.146)	(0.165)
Machinery	0.167**	0.167**	0.251***	0.309***
	(0.072)	(0.072)	(0.096)	(0.111)
Fertilizer	−0.009	−0.008	0.003	−0.022
	(0.022)	(0.023)	(0.037)	(0.039)
Manure	0.165**	0.167**	0.263**	0.328**
	(0.071)	(0.070)	(0.134)	(0.142)
Seed	0.210***	0.211***	0.335***	0.423***
	(0.043)	(0.043)	(0.070)	(0.075)
Total herbicides		−0.016	0.001	
		(0.042)	(0.012)	
Herbicides (early)				−0.001
				(0.017)
Herbicides (middle)				0.002
				(0.015)
Herbicides (late)				0.007
				(0.021)
Plowing			0.004	0.004
			(0.006)	(0.006)
Observations	1172	1172	1172	1172
R-squared	0.607	0.607	0.634	0.634

Robust standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
Note: Dependent variable is logarithm of production (kgs).
Machinery variable in damage abatement model is net of plowing.

The standard production function in model (1) confirms that labor, machinery, seed, and manure raise expected production levels. Larger plot sizes, likewise, produce larger harvests, other factors held constant. Labor generates the highest production elasticity and overall returns seem to be increasing since elasticities sum to more than unity. Sorghum plots, on average, produce less grain than maize plots. When we control for crop by including the sorghum dummy, fertilizer has no significant effect on expected production; yet when both crops are combined, the effect becomes strongly significant. Small crop-specific subsample sizes prevent us from running separate regressions with the non-linear damage abatement model.

Model (2), which introduces herbicides naively into a conventional production function, generates a negative, though insignificant estimate of herbicide productivity. Other production function coefficients remain unaffected. Because farmers apply herbicides in response to weed pressure, and because we have no good measure of weed pressure on the right-hand-side of this equation, this omitted variable likely leads to a spurious negative correlation between herbicide use and output.

The damage control function in model (3) suggests that total herbicide quantities generate a positive but small and statistically insignificant impact on output. Similarly, the temporal breakdown in model (4) reveals positive though insignificant productivity impact of planting season and late-season herbicide use. Pre-planting herbicide application produces a small but negative and statistically insignificant coefficient. Consistent with the findings of Hall and Moffitt (2002), these results suggest that econometric estimates of this sort require plot-level data on weed pressure, the omission of which complicates efforts to measure the pure productivity of herbicide use on plots experiencing low and high weed pressure. In future work, controlled agronomic trials offer a still better means of assessing the damage control and productivity impact of herbicide use.

Employment Impacts of Herbicide Use

Malian farmers control weeds multiple times throughout the season, first at plowing time with full soil inversion during land preparation. After planting, they typically hand weed their fields twice. Hand weeding, at the normal rate of 12 man-days per hectare, accounts for between 30 and 40 per cent of on-farm labor demand in dryland production of coarse cereals (see Table A2). That share falls to 10–15 per cent of farm labor use under irrigated rice production (because of high additional labor demands for preparation of seedling nurseries, transplanting, and bird scaring) and cotton production (given repeated, heavy labor demand for insect scouting, insecticide spraying, and mandatory multiple passes under hand harvesting of only fully ripe bolls).

In contrast, herbicide application requires far less labor than hand weeding. Crop budgets suggest that hand weeding requires roughly 12 man-days per hectare compared to only 1–2 man-days with herbicides, saving 10 man-days per hectare (Table 10). Econometric estimates of labor savings from herbicide use in Mali project similar results: a decrease of 7.9 man-days and 2.0 child days of weeding labor per hectare for farmers using registered (and presumably good quality) herbicides. With unregistered herbicides, however, labor savings fall roughly in half (Assima *et al*, 2017). Adjusting for adult male labor equivalents and relative shares of registered and unregistered herbicides, the econometric estimates project an aggregate savings of 7.2 person-days per hectare for farmers using herbicides (Table 10).

As a share of total agricultural labor supply, a wholesale shift to herbicides would free up between 17 and 23 per cent of the peak season rural labor force (Table 10). Currently, if herbicide adoption rates nationally attain the 60 per cent average found in southern Mali, this would imply a reduction of 10–14 per cent in peak season agricultural labor demand.

Farmers in most areas of Mali complain about tight seasonal labor supplies, which they attribute to rapid urbanization and large-scale outmigration of young males seeking work in the goldmines of Mali and neighboring Guinea. Demographic pyramids and age-cohort workforce participation rates from rural Mali confirm the large net outmigration among males aged 20–39 (CPS/SDR 2010, p. 23). Comparison of male and female labor force age cohorts suggests that roughly 20 per cent of males aged 25–34 have left rural areas to work elsewhere (Table A3). Viewed from a labor market perspective, growing farmer demand for herbicides suggests keen interest in reducing on-farm labor requirements (Foltz, 2010).

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Table 10: Weeding share of agricultural labor demand in Mali, 2015

1. Area cropped in cereals, pulses and oilseeds (millions of hectares)	6.0			
		person-months		
2. Agricultural labor force (millions)	people	annual	peak season	
a. annual full-time adult male equivalents (FTEs)	4.1	49.3	12.3	
b. economically active population (EAP)	5.5	66.3	16.6	
c. total population	10.6			
	Crop budget estimates			Econometric estimates
3. Weeding labor requirements	hand weeding	herbicides	savings	savings
a. per hectare (mandays/ha)	12	2	10	7.2
b. mandays per year (millions)	71.6	11.9	59.7	43.1
c. man-months per year (millions)	3.4	0.6	2.9	2.1
4. Weeding labor as a share of agricultural labor force (percent)	hand weeding	herbicides	savings	savings
a. Peak season labor share (June, July, August)	28%	5%	23%	17%
b. Annual labor share (January - December)	7%	1%	6%	4%

Source: Tables A2–A3.

Environmental Impact

Environmental concerns about the impact of repeated, concentrated insecticide applications motivated the establishment of a Sahel-wide regional pesticide regulatory body several decades ago (Diarra, 1998; Abiola *et al*, 2004). Major locust invasions in 1974–1975 and in 1986–1989 triggered a series of large-scale regional spraying programs as well as the emergence of localized stockpiles of highly toxic chemical insecticides. Scattered reports of poisoning among humans, birds, fish, and bees raised growing fears about both human safety and environmental impact (OTA, 1990). Over time, large-scale insecticide application has continued annually on Malian cotton farms beginning in the 1960s. Growing insect resistance, in turn, has forced Mali's CMDT to supply an evolving cocktail of insecticides to their contract cotton farmers (Tefft, 2010). During the 1990s, the volume of insecticides applied on cotton fields doubled, exacerbating worries about toxicity in humans (Keita, 1992; Camara *et al*, 2003). Ultimately, these concerns about insecticide impact on human health and the environment led the regional grouping of Sahelian countries to establish a pesticide regulatory body for the nine member states of the Club Inter-Etat de Lutte Contre la Sécheresse au Sahel (CILSS). In March 1994, CILSS established the Comité Sahélien des Pesticides (CSP) as the legal body regulating all pesticides, including insecticides, fungicides, and herbicides.

In Mali, as elsewhere, herbicides fall under the same regulatory rules as insecticides. Nevertheless, differences in time frames, toxicity, and environmental impact frequently emerge. While heavy insecticide use has occurred since the 1960s in Mali, widespread farmer adoption of herbicides has emerged only since 2005 (Figure 1). Given this very recent uptake of herbicides by Malian farmers, weed resistance has not yet emerged as a significant issue. Malian weed scientists, nonetheless, indicate that they have begun to observe episodic cases of resistance, specifically resistance of the weed *Echinochloa* to 2, 4D herbicides (Soungalo, 2016). Going forward, as herbicide adoption and application rates increase, monitoring for potential weed resistance will assume greater importance.

Glyphosate, which accounts for two-thirds of the volume of herbicides used in Mali, has historically been considered one of the world's least dangerous herbicides due to its low reported toxicity in mammals and low retention in soils (Franz *et al*, 1997). Recently, however, the EU has placed glyphosate under active review due to a 2015 finding by the WHO's International Agency for Research on Cancer (IARC) which reclassified glyphosate from a Class 3 (slightly hazardous) to a Class 2a (moderately hazardous) pesticide with potentially carcinogenic impact on humans. This revised rating remains controversial (WHO, 2009; Bonanno *et al*, 2017). In general, other herbicides pose greater dangers to human health and to the environment. As a result, the CSP has formally banned two herbicides – paraquat and atrazine. Despite this legal ban, our survey teams found both products available in small quantities in local markets. As an order of magnitude, our farm survey in southern Mali suggests that these two banned herbicides account for roughly 5 per cent of herbicide volumes applied by farmers.

CSP regulators require that firms proposing to sell a new herbicide product in Mali supply detailed information about the active ingredients as well as biological testing and toxicity results. Agricultural researchers at Mali's national research institute (IER) conduct field trials to assess biological efficacy and selectivity of each proposed herbicide, at a cost of roughly $8000 to the proposing firm (IER, 2013). Required toxicity testing takes place in Burkina Faso. After provisional approval by the CSP, firms have three to six years to supply more detailed information on herbicide behavior in the environment (including rates of degradation and mobility in both soil and water), its impact on non-target organisms (including humans, fish, reptiles, algae, birds, bees, and soil invertebrates), and residue analysis of affected foods (CSP, 2015).

In practice, however, the high cost of environmental testing coupled with an absence of certified local testing laboratories results in only cursory assessment of environmental impacts (Cissé, 2012). A small number of studies has examined insecticide impacts on human health and the environment (Keita, 1992; Camara *et al*, 2003). To our knowledge, no studies of the environmental impact of herbicides have taken place in Mali. Instead, international evidence on glyphosate and major selective herbicides provides the environmental evidence and guidelines on which Sahelian regulators rely. Looking forward, ongoing concern about insecticide use (particularly in cotton production and in malaria and locust control) appears likely to increase pressure for improved environmental impact monitoring of all pesticides, including herbicides.

Conclusions and Policy Implications

Steady increases in herbicide availability in Mali, over the past decade and a half, have dramatically altered farmer options for managing weeds. Falling herbicide prices have made weed control via herbicides increasingly viable compared to hand weeding. Profitability of herbicide use varies spatially, depending critically on the unit price of herbicides (which increases with distance from the major import depots in Bamako) and the opportunity cost of labor (which increases with proximity to major urban centers). Across a broad swath of southern Mali, our survey results suggest that farmers using herbicides can control weeds at roughly 50 per cent of the cost of hiring weeding labor. As a result, rather than hand weeding, a majority of Malian farmers have begun to use herbicides to control weeds. Together, these findings highlight a series of research and policy implications going forward.

Drivers of Herbicide Intensification

Rapid changes in private sector supply systems are driving growth in herbicide use among small farmers in Mali. Since Monsanto's Roundup went off patent in 2000, international agrochemical firms and regional commodity traders have released a series of new glyphosate brands accompanied by new packaging, branding, and marketing efforts that feature extensive advertising – on radio, television, through dealers, and privately financed on-farm demonstrations. Increased competition among herbicide brands and suppliers, coupled with a broad move to new low-cost production sites in Asia, has resulted in declining herbicide prices.

From a policy perspective, this purely private sector driven herbicide growth stands in stark contrast with Mali's fertilizer policy, which relies on 50 per cent price subsidies. Like African governments more generally, who have spent $1 billion on fertilizer subsidies over the past decade, Mali's government spends heavily on fertilizer subsidies (Jayne and Rashid, 2013). In 2015, fertilizer subsidies accounted for 25 per cent of Mali's annual agricultural budget (Thériault *et al*, 2015). Given tepid productivity results reported to date from Mali's large-scale fertilizer subsidies, the counter-example provided by Mali's private-led herbicide surge offers a possible opportunity for exploring less costly models for promoting input intensification.[3]

Peak season labor shortages, likewise, contribute to growing farmer demand for herbicides. Despite widespread concerns about Sub-Saharan Africa's demographic bulge and impending youth unemployment, Malian farmers appear to be coping, instead, with labor shortages, particularly during the peak agricultural season (Foltz, 2010; IFAD, 2014; Loch *et al*, 2014). In part, rapid recent success in raising primary school enrollment rates in Mali, from under 30 per cent in 1990 to over 80 per cent today, may have softened, or at least delayed, the anticipated labor supply surge (World Bank, 2010). Outmigration to urban areas and to gold mines, by roughly 20 per cent of the rural males aged 25–34, also contributes to current labor shortages in rural areas. Underlining farmer concerns about labor scarcity, our econometric results point to labor costs as a major factor (along with herbicide price) governing herbicide use by Malian farmers. From a research perspective, more careful evidence on the opportunity cost of rural labor, particularly female labor, will offer important insights into economic alternatives available to rural laborers of different sexes and in different locations and seasons.

Impact of Growing Herbicide Use

Malian farmers – even female farmers managing very small plots – voluntarily pay full commercial price for herbicides. Among the benefits, they achieve higher profits (cutting weed control costs in half compared to hand weeding), reduce peak season labor bottlenecks, and consequently improve timing of other on-farm operations. Complementarities also arise between herbicide use and fertilizer productivity, since improved weed control serves to focus fertilizer-induced productivity gains on food crops rather than on weeds (Barrows *et al*, 2014, Wesseler and Smart, 2014). Looking forward, agronomic work on minimum tillage systems, in which herbicides reduce land preparation requirements, may offer further savings (Zindahl, 2007).

Despite broad enthusiasm from farmers, our econometric measurement of damage abatement generates insignificant (though positive) results, likely because of our inability to control statistically for weed pressure on individual plots. This key omitted variable influences both farm output (negatively) and levels of prophylactic herbicide application (positively), leading to spurious negative correlation. Future empirical work will require careful information on plot-level weed pressure, preferably direct measurement rather than recall-based farm surveys. For this reason, controlled agronomic experiments under farmer conditions will likely offer the best prospects for accurately assessing the impact of herbicide use on farm production.

Environmental impacts of herbicide use remain largely unmonitored in Mali. Yet the growing numbers of unregistered and counterfeit herbicide products available on the market lead to mounting concerns about product quality and safety. Looking forward, policy makers will increasingly require better monitoring of pesticide product quality and environmental impact. The CILSS model of regional regulatory review, which economizes on scarce scientific personnel and laboratory facilities, has proven efficient in vetting herbicide products prior to release. Regional sampling and studies across common Sahelian agro-ecological zones could perhaps offer parallel economies in environmental monitoring.

Employment impacts of herbicide use appear substantial. At current rates of herbicide application, farmers are able to reduce peak season labor use by 10–14 per cent. Our estimates suggest that full-scale adoption could potentially reduce peak season labor demand by as much as 20 per cent. Going forward, policy makers will want to learn more about what alternatives women and men farmers pursue when herbicides free up labor time they would otherwise spend weeding.

Notes

1. The original nine CILSS member countries included Cape Verde, Senegal, Gambia, Guinea-Bissau, Mauritania, Mali, Burkina Faso, Niger, and Chad.

2. We have tested these models using two different measures of weeding wage rates: (a) farmer estimates of hired labor cost; and (b) village-level focus groups which generated a uniform village-level wage rate. The two sources produce similar mean wage rates – $3.26 and $2.89, respectively, for adult males – as well as comparable econometric results. Tables 8 and A1 report results from the farmer-based wage estimates.
3. Ariga and Jayne (2009) present a similar alternative model for promoting increased fertilizer use.

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Appendix A

Table A1: OLS and Tobit adoption models explaining herbicide use (liters per plot) on maize and sorghum plots, Sudan Savanna, Mali

Explanatory variables	*OLS*	*Tobit*
Prices		
Herbicide price (USD)	−0.083***	−0.122***
	(0.013)	(0.019)
Daily weeding wage (USD)	0.093***	0.147***
	(0.015)	(0.022)
Manager		
Female manager	0.430***	1.084***
	(0.157)	(0.235)
Manager has primary education	0.006	0.244
	(0.131)	(0.196)
Plot characteristics		
Sorghum plot	−0.632***	−1.140***
	(0.110)	(0.170)
Plot size	0.430***	0.552***
	(0.044)	(0.066)
Distance plot to house	0.001	–0.002
	(0.003)	(0.004)
Household characteristics		
Labor supply per EAF	−0.006	−0.009
	(0.011)	(0.017)
Asset value of EAF (USD)	0.357***	0.564***
	(0.061)	(0.094)
Transfers to EAF (USD)	0.001***	0.001***
	(0.000)	(0.000)
Constant	−0.337	−1.925**
	(0.487)	(0.756)
Observations	1205	1205
R-squared	0.188	
Value of log-likelihood function		−2084.162

Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A2: Weeding labor requirements by crop

Crop	*Labor (man-days)*				*Weeding share*	
	Weeding	*Other on-farm*	*Post-farm*	*Total*	*On-farm labor*	*Total*
Sorghum	12	18	8	38	0.40	0.32
Millet	10	20	12	42	0.33	0.24
Maize						
Hand shelled	12	20	13	45	0.38	0.27
Mechanical shelling	12	20	3	35	0.38	0.34
Rice						
Irrigated, transplanted	12.5	63.5	23	99	0.16	0.13
With bird scaring	12.5	134.5	23	170	0.09	0.07
Cotton						
CMDT	12	67	3	82	0.15	0.15
IER	12	94	3	109	0.11	0.11

Sources: Tefft (2010), Office du Niger (2012), Kergna (2016).

Table A3: Agricultural population and rural economic activity rates

Age cohorts	*Agricultural population (2009, thousands)*			*Participation rate (per cent)*		*Economic active population (thousands)*			*Adult male equivalency rates*		*Adult male full-time equivalents (FTEs)*		
	Male	*Female*	*Total*	*Male*	*Female*	*Male*	*Female*	*Total*	*Male*	*Female*	*Male*	*Female*	*Total*
0–4	816	741	1557	0	0	0	0		0	0	0	0	0
5–9	788	729	1517	41	35	323	255		0.10	0.10	32	26	58
10–14	592	479	1071	73	64	432	307		0.85	0.65	367	199	567
15–19	490	450	940	78	65	382	293		1.00	0.80	382	234	616
20–24	339	363	702	77	65	261	236		1.00	0.80	261	189	450
25–29	264	348	612	78	65	206	226		1.00	0.80	206	181	387
30–34	221	267	488	82	62	181	166		1.00	0.80	181	132	314
35–39	201	225	426	82	64	165	144		1.00	0.80	165	115	280
40–44	189	202	391	72	63	136	127		1.00	0.80	136	102	238
45–49	137	134	271	80	67	110	90		1.00	0.80	110	72	181
50–54	134	122	256	75	62	101	76		1.00	0.80	101	61	161
55–59	109	81	190	82	63	89	51		0.65	0.45	58	23	81
60–64	106	83	189	81	44	86	37		0.65	0.45	56	16	72
65–69	67	39	106	74	35	50	14		0.65	0.45	32	6	38
70+	118	79	197	58	18	68	14		0	0	0	0	0
2009 Total	4571	4342	8913	57	47	2590	2034	4624			2087	1356	3443
Annual population growth rate			0.03										
Estimated totals, 2015			10,643					5521					4111

Source: ILCA (1990), CPS/SDR (2010).