Product concentration and usage: Behavioral effects in the glyphosate market☆

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A B S T R A C T

People often ignore or misunderstand information that would help them make better decisions. For products that differ by concentration level, a critical choice concerns the correct dosage rate. We study the effects of changing glyphosate product concentration levels on farmers' glyphosate usage behavior. Glyphosate is the world's most widely used herbicide. After glyphosate went off patent in 2000, product variants with higher concentration levels entered the market. Using detailed farm-level glyphosate use data in U.S. corn and soybeans over the period 1998–2011, we estimate the impact of product concentration levels on glyphosate application rates. We control for prices and other sources of heterogeneity by means of individual and time fixed effects. Our findings indicate that increasing the baseline concentration level by 10% increases the application rate by nearly 6%, despite the fact that labels on more concentrated products provide instructions on how to correctly adjust dosage rates downwards. We attribute part of the concentration effect to rational behavior and part of it to label confusion and/or habit, with smaller farms and late adopters being more likely to resort to habit. A counterfactual simulation predicts that label confusion and/or habit was responsible for a 4.6% increase in total glyphosate use and an additional $59 million per year (4.7%) in glyphosate sellers' revenues.

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1. Introduction

Seemingly innocuous and subtle changes to the formulation and packaging of products may lead to significant changes in consumption behavior (French et al., 2001; Geier et al., 2006). Simply doubling the portion size of a food offering, for example, can increase consumption by as much as 35%, and this effect is even present for less palatable foods (Wansink, 1996; Zlatevska et al., 2014). Although these issues have been explored widely for food consumption decisions, they have received far less scrutiny in other contexts. Notwithstanding, products ranging from detergents, to medications, to various pesticides are subtly differentiated, and companies often change how such products are packaged, formulated, and presented. The concentration level of a product may be particularly important. Anecdotal evidence points to dosing confusion for concentrated detergents (Consumer Reports, 2012), and survey evidence suggests that acetaminophen label confusion can unintentionally

lead to overdosing (King et al., 2011; Wolf et al., 2012). Despite its importance, there is little research into how concentration levels affect product usage.

The effects of product concentration, and product modifications in general, have received even less attention in a production context. This is partly due to the widespread belief, based on "natural selection" arguments (e.g., Friedman, 1953), that market competition disciplines firms' choices by fostering profit maximization. With respect to the narrower question of whether product formulation impacts users' choices, production inputs tend to be more standardized and uniform than consumer goods, suggesting less scope for behavioral effects. Nonetheless, there are many situations in which behavioral biases at the firm level can emerge. However, empirical evidence has mostly come from laboratory or field experiments (Armstrong and Huck, 2010; Hanna et al., 2014). Documenting the presence of such effects in real-world markets can have significant implications for efficiency and the distribution of economic surplus, as well as for regulatory policies intended to address external effects of usage decisions.

In this paper we present empirical evidence on how changes in the formulation of glyphosate products (increased concentration of its key ingredient) impacted U.S. corn and soybean farmers' glyphosate usage behavior. Glyphosate, known to many by its original commercial name of Roundup®, is the most widely applied herbicide in the world, largely due to the widespread diffusion of genetically engineered glyphosate tolerant crops (Perry et al., 2016b). Prior to the year 2000, the U.S. glyphosate market was highly standardized. Virtually all farmers purchased the same glyphosate formulation: Monsanto's Roundup®, which contained 3 lb/gal of the acid glyphosate in the form of an isopropalymine salt. The standard recommended dose for a single application of glyphosate was 0.75 lb/acre. To achieve this rate, the traditional 3 lb/gal product needed to be applied at the rate of 32 fl oz/acre, and indeed this is the rate that the majority of farmers used.

Monsanto's glyphosate patent expired in 2000. Subsequent years saw a large number of new products gradually enter the market. While these new products differed in multiple dimensions, the most significant source of differentiation was the concentration level of the acid glyphosate. Instead of containing the typical 3 lb/gal, some new products had higher concentration levels (e.g., 3.7, 4, and 4.5 lb/gal). As such, the recommended standard dose—the dose required to achieve the standard field rate of 0.75 lb/acre—was lowered on the labels of higher concentration products. As agricultural producers adopted higher concentration products, however, a strong pattern emerged: many were applying them at the pre-patent expiration standard rate of 32 fl oz/acre. The impact on glyphosate use was substantial. Whereas the mean application rate for glyphosate had been flat for several years at about 0.73 lb/acre, between 2002 and 2011 it rose to 0.89 lb/acre, a 22% increase. This begs the question of *why* farmers chose 32 oz/acre so frequently with higher concentration products. Was it due to farmers' complete unawareness that newer products contained more glyphosate? Or were individuals *aware* that new products differed, but consciously chose not to adapt to the new rate and instead resorted to habit or rule of thumb? Both of these strategies have long been noted as characteristic of changing and complex decision environments (Simon, 1959; Wood and Neal, 2009).

A recent and briskly expanding literature has identified a wide range of situations in which individuals do not use information that would help them make better decisions. For instance, bad decision-making has been documented in the realms of personal finance, health insurance, and non-prescription drug choice (Handel and Schwartzstein, 2018). These outcomes may arise in part because an inherently difficult choice is made in a distracting and/or confusing environment (Campbell et al., 2011; Campbell, 2016; Agarwal et al., 2017). More generally, failure to make use of valuable information appears to stem from two sources (Handel and Schwartzstein, 2018): frictions such as rational inattention or search costs (Sims, 2003; Matejka and McKay, 2014); and mental gaps such as an incorrect model of the world. Both factors may have played a role in U.S. farmers' glyphosate application rate choices. The rapid changes in products and formulations that followed the glyphosate patent expiration certainly led to the sort of confusion and uncertainty that could generate heuristic behavior. A cursory search on the worldwide web, for example, reveals a high level of confusion about how to apply new glyphosate products: numerous university extension education webpages have been written to address the differences in concentrations, surfactants, salts, and conversion rates (Nordby and Hager, 2004; Sprague, 2006; Armstrong and Lancaster, undated). Indeed, the nature of pesticide application, in general, could be characterized as complex and often confusing. The pesticide market consists of a large number of subtly differentiated products that come with label instructions sometimes exceeding 50 pages in length. Recently, herbicide label complexity has been cited as a source of confusion by farmers who apply Dicamba herbicide to newly-released Dicamba resistant soybeans (Polansek and Plume, 2017).

Whereas the data we use do not permit identification of the relative influence of each behavioral mechanism—e.g., frictions versus mental gaps, or which type of frictions—it does permit a systematic exploration into whether different concentration levels impacted application rates, as well as whether farmers made use of available label information. There are, however, several challenges to studying the relationship between glyphosate concentration levels and dosing choices. During the same time that new glyphosate products were being adopted and applied, other important events were occurring: glyphosate prices were falling, commodity prices were rising, and some farmers were experiencing weed resistance to glyphosate. Our ability to identify whether higher product concentration levels led to higher application rates, therefore, depends crucially on controlling for other, possibly correlated, factors. Given these issues, in this paper we take a three-pronged approach to exploring the relationship between glyphosate concentration levels and application rates.

First, using a rich farm-level dataset on pesticide use during the 1998–2011 period, we estimate the extent to which observed glyphosate application rates change with the product concentration level while controlling for prices, unobserved farm-level heterogeneity, and several other potentially confounding factors. Importantly, we include both farm- and year-

specific fixed effects. We find that there is a robust and large positive effect of glyphosate concentration levels on the application rate.

The initial estimate we obtain for the concentration effect is subject to certain limitations. One drawback is that we cannot control for all individual and time-varying factors that affect application rates. If such factors were correlated with the choice of which concentration to use, then the model estimates may be biased. For example, when a farmer needs to spray at high rates because of inordinate weed pressure, they may save on storage and transportation costs by using a smaller quantity of more concentrated product. Without controlling explicitly for weed pressure, the coefficient of interest may be biased upwards. More generally, a farmer's choice of which concentration to purchase may be a function of the dosing rate they intend to use. Several robustness checks address these concerns, but some potential biases may persist. Thus, the next two stages of our analysis explore the data in alternative ways that avoid many of these limitations.

As noted, the most frequently chosen application rate for more concentrated products is 32 fl oz/acre, the pre-patent-expiration "usual" rate. This is despite the fact that 32 oz/acre is not explicitly recommended on the labels of these products. The second stage of our analysis, therefore, consists of estimating whether certain farmer characteristics were correlated with the choice of 32 oz/acre. We also consider the relationship between these same factors and the use of the (recommended) standard 0.75 lb/acre rate, which requires knowledge of label information. In short, we find that larger operations and early adopters were significantly less likely to use 32 oz/acre. Conversely, these same types of farmers were *more* likely to use the standard rate of 0.75 lb/acre. These findings reinforce some previous research that points to greater information acquisition in new technologies by early adopters and larger farms (see, e.g., Feder and Slade, 1984; Diederen et al., 2003).

In the third and final stage of our analysis, we look further into the issue of whether there were real benefits to using products that are more concentrated if one were planning to apply glyphosate at higher rates. To do so, we identify a subset of farmers that we term "rationally *attentive.*" These are producers who early in the sample applied new, more concentrated glyphosate products at the recommended standard rate of 0.75 lb/acre. By applying more concentrated products at the standard application rate, these individuals not only demonstrated an awareness of the changes, but also a willingness to learn the new rate and apply that knowledge in the field. We then estimate the relationship between application rates and concentration levels for this subgroup during the 2003–2011 period. We find that even "rationally attentive" individuals use more concentrated products at higher rates. Thus, part of the positive concentration effect appears to be the result of deliberate behavior. However, we also find that the impact of glyphosate concentration on application rates is *significantly* smaller for rationally attentive farmers compared to the rest of the population, which is consistent with the presence of mechanisms such as label confusion and habit. Using the model estimates for the rationally attentive individuals, we simulate a counterfactual scenario in which all individuals are held to be rationally attentive. The simulation predicts that label confusion and/or habit increased farmers' glyphosate expenditures (revenues for glyphosate sellers) by (at least) $59 million per year, the vast majority of which went to Monsanto.

The rest of this paper proceeds as follows. First, we provide further details on the history of glyphosate, market trends following the expiration of Monsanto's patent, and information concerning glyphosate formulations as well as application rates and their relationship to concentration rates. Next we present the basic econometric framework, followed by a description of the data and initial regression results. We then investigate the factors associated with using 32 oz/acre and 0.75 lb/acre. We follow this with the development of a strategy for decomposing the concentration effect. We then report and compare results for rationally attentive and all other individuals, followed by a counterfactual simulation of glyphosate use and revenues. Finally, we provide concluding comments.

2. Glyphosate

Glyphosate was introduced commercially in 1974 by Monsanto Co. as Roundup®. It is a powerful, broad-spectrum herbicide with favorable environmental properties (e.g., low toxicity).[1] As such, it quickly gained commercial success among agricultural producers, but its use was limited by its non-selective properties (i.e., glyphosate was also toxic to crops). Growers primarily used it prior to planting or in circumstances where crop exposure could be avoided (Duke and Powles, 2008). These limitations were lifted with the adoption of genetically engineered glyphosate tolerant (GT) crops, first introduced in 1996. Farmers could now apply glyphosate on fields with GT varieties after the crop had emerged (i.e., post-emergence) without causing crop injury. The incentives for farmers to adopt GT varieties were compelling. Before the advent of GT crops, a typical producer had to use multiple herbicides, each able to treat a small range of weeds, at different stages of the planting process, and often had to supplement those herbicides with mechanical cultivation. By contrast, the GT crop production system was simple and effective: a grower could plant the crop and then rely exclusively on post-emergence applications of a single herbicide (glyphosate).[2] Rapid diffusion of GT crop varieties resulted in a massive expansion of glyphosate use, turning it into the most widely used herbicide in the world. In the United States, where the adoption of GT crops currently exceeds 90% of acres in corn, soybeans, and cotton, total agricultural glyphosate use exceeded 284 million pounds in 2014,

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[1] Widely held beliefs about glyphosate's safety, however, have recently been questioned (Grimwood, 2017; Waldman et al., 2017).

[2] Because mechanical cultivation was less needed with a GT system, adoption of conservation tillage and no-tillage production systems also increased significantly as a result of GT variety adoption (Perry et al., 2016a).

Table 1
Price, use and market structure trends in the U.S. glyphosate market.

Year	Companies	Products	Concentrations	Price[b]	lb/acre[c]	HHI[d]
1998	1	6	4	15.86	0.90	1.00
1999	1	8	4	12.76	0.93	1.00
2000[a]	9	13	5	12.42	0.96	0.977
2001	12	19	5	12.41	1.00	0.866
2002	16	27	7	11.69	1.00	0.655
2003	18	30	5	10.54	1.07	0.509
2004	21	50	7	8.88	1.09	0.385
2005	23	56	7	7.53	1.10	0.346
2006	27	62	8	7.05	1.04	0.331
2007	25	65	9	6.39	1.13	0.280
2008	25	67	9	9.58	1.20	0.353
2009	24	67	8	9.96	1.17	0.227
2010	28	78	7	5.65	1.24	0.197
2011	30	70	6	4.74	1.26	0.319

[a] Glyphosate patent expired.
[b] U.S. average nominal prices ($/lb).
[c] Ratio of total glyphosate use to total corn and soybean acres with at least one glyphosate application.
[d] Herfindahl-Hirschman Index of market concentration.

a more than twenty-fold increase from 1992 (USGS, 2017). Glyphosate use in corn and soybeans alone accounted for about 73% of total US glyphosate use.

In 2000, Monsanto's patent on glyphosate expired, and in the years that followed significant changes took place (Table 1). The number of companies producing glyphosate expanded from one to 30 while the number of products rose from six to more than 70. The number of concentrations rose from four to a maximum of nine in 2007 before settling at six in 2011. Monsanto's hold on the industry declined considerably as well, as evidenced by the fact that the Herfindahl-Hirschman Index (HHI) of market concentration declined from 1.00 in 1999 to a low of 0.197 in 2010. The increased competition, in turn, led to a significant decline in glyphosate prices, from $12.42/lb in 2000 to $4.74/lb in 2011. At the same time, the amount of glyphosate applied per acre increased by over 30%.

2.1. Products and formulations

A glyphosate product formulation has three components: the amount of parent acid (i.e., glyphosate), salt, and proprietary components. A typical product label lists the amount of active ingredient (ai) in lb/gal, the type of salt, and the amount of acid equivalent (ae) (also in lb/gal). The ai/gal differs from the ae/gal because the former includes the salt. The most important component is the ae concentration. Two glyphosate products with different ai concentrations but the same ae concentration will perform essentially the same. Differences in the salt and proprietary components—inert ingredients like surfactants and defoamers—do not seem to generate significant differences in effectiveness (Mueller et al., 2006; Mahoney et al., 2014).[3]

Prior to the year 2000 there was essentially one glyphosate formulation: Monsanto's Roundup Ultra®, which contained 3 lb ae/gal of glyphosate. Upon expiration of its patent, Monsanto introduced Roundup UltraMax®, a new glyphosate formulation with 3.7 lb ae/gal. In subsequent years, Monsanto and their competitors introduced several other formulations. Ultimately, six different concentration levels emerged on the market: 3 lb ae/gal, 3.7 lb ae/gal, 4 lb ae/gal, 4.17 lb ae/gal, 4.5 lb ae/gal, and 5 lb ae/gal (henceforth, when we write "lb/gal", we are referring to ae and not ai).

2.2. Application rates

The glyphosate application rate is defined as the amount (pounds) of glyphosate ae applied per treated acre. The product label for each of the different commercial formulations contains instructions for the recommended application rate. The recommended rate may vary depending on the crop, time of application, weed type, and weed height. For example, the recommended rate for the treatment of taller weeds may be greater than the recommended rate for comparatively smaller weeds.[4] The general standard recommended field rate—the rate recommended for most situations—has historically been 0.75 lb/acre. Because different products may contain different ae concentrations, a farmer needs to appropriately adjust the *product-specific rate*—the rate in fl oz/acre—needed to achieve a particular field rate. The product-specific rate required to achieve the standard field rate of 0.75 lb/acre is given by

$$x = 0.75 \, (\text{lb/acre}) \frac{128 \, (\text{oz/gal})}{\text{concentration} \, (\text{lb/gal})},$$

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[3] Nonetheless, firms rely on proprietary components as a product differentiation strategy in their marketing efforts.

[4] See Table A1 in the Appendix for the recommended label rates of different popular products on the basis of weed height.

Table 2
Comparison of recommended application rates for common glyphosate formulations.

Salt	Glyphosate formulation		0.75 lb ae/acre standard 1x dose	1.13 lb ae/acre 1.5x dose
	lb ai/gal	lb ae/gal	fl oz/acre	
isopropylamine	4	3	32	48
isopropylamine	5	3.7	26	39
dimethylamine	5.07	4	24	36
potassium	5	4.17	24	34
potassium	5.5	4.5	22	32
potassium	6	5	20	30

Source: Armstrong and Lancaster (undated).
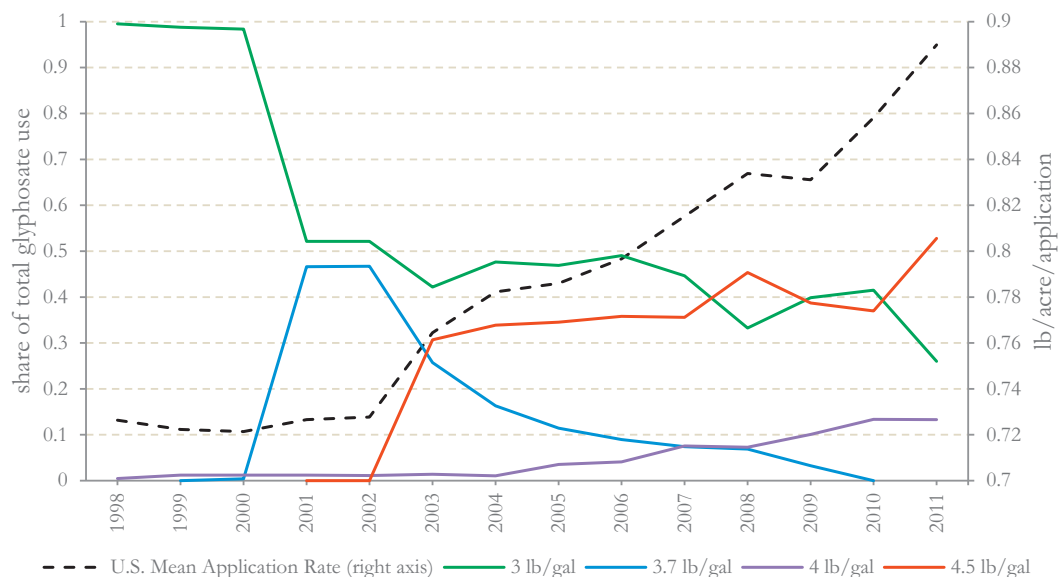
Fig. 1. Glyphosate product concentration shares and mean application rate in U.S. corn and soybeans.
Note: The green, blue, purple, and red lines represent the quantity shares of the respective glyphosate concentrations (lb/gal). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where x is the application rate expressed in fl oz/acre. For example, the product rate for the classic 3 lb/gal formulation is 32 fl oz/acre, and the product rate for a 4 lb/gal formulation is 24 fl oz/acre. Table 2 provides the product rate needed to achieve the standard rate of 0.75 lb/acre and the 1.5 dose rate of 1.13 lb/acre for each of six popular formulations. Note that these numbers reflect what is written on the label and are thus not always an exact conversion to 0.75 lb/acre. Some of the more concentrated products actually recommend rates that imply a slightly higher rate than 0.75 lb/acre – e.g., the recommended rate on 4.5 lb/gal formulations is 22 oz/gal, which implies an acre-rate of about 0.77 lb/acre.

2.3. Different application rates with different concentrations

Without further information, it might be expected that glyphosate application rates would not differ significantly across concentration levels: farmers should adjust their application rates in accordance with label recommendations. However, various patterns in the data suggest that such adjustments were often not made.[5] One indication is the overall trend in application rates. As the market became increasingly saturated with higher concentration products, application rates rose significantly. Between 1998 and 2011, the mean application rate rose from 0.73 lb/acre to 0.89 lb/acre, a 22% increase (Fig. 1). During the same time, the quantity share for products with 3 lb/gal fell from 99% to about 26%.

More detailed evidence on the drivers of these trends is provided in Table 3, which presents mean application rates and mean prices for the three most commonly purchased concentrations from 1998 to 2011. Three stylized facts emerge from these numbers. First, more concentrated products were applied at significantly higher rates and this difference was fairly stable over time. Second, and relatedly, the prices of the different formulations cannot explain these differences. In other

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[5] The tables and figures presented in this section are based on farm-level survey data from GfK Kynetec. Further details about these data are provided in the Results section.

Table 3

Prices and application rates for the three most commonly used glyphosate concentrations.

Year	Overall rate lb ae/acre	Rate (lb/acre) by concentration			Price ($/lb ae) by concentration		
		3 lb/gal	3.7 lb/gal	4.5 lb/gal	3 lb/gal.	3.7 lb/gal	4.5 lb/gal
1998	0.73	0.75			15.88		
1999	0.72	0.73			12.79		
2000	0.72	0.73	0.73		12.44	13.99	
2001	0.73	0.71	0.77		12.95	11.84	
2002	0.73	0.70	0.79	0.95	11.67	11.72	9.48
2003	0.76	0.73	0.81	0.85	9.14	11.75	11.55
2004	0.78	0.73	0.81	0.90	7.16	11.00	10.44
2005	0.79	0.73	0.80	0.90	6.59	9.19	8.53
2006	0.80	0.74	0.81	0.91	6.09	9.28	8.02
2007	0.81	0.74	0.79	0.92	5.66	8.67	7.28
2008	0.83	0.76	0.81	0.91	9.32	10.89	10.28
2009	0.83	0.76	0.83	0.92	8.85	10.43	11.90
2010	0.86	0.80		0.96	4.58		7.19
2011	0.89	0.82		0.97	4.35		5.10
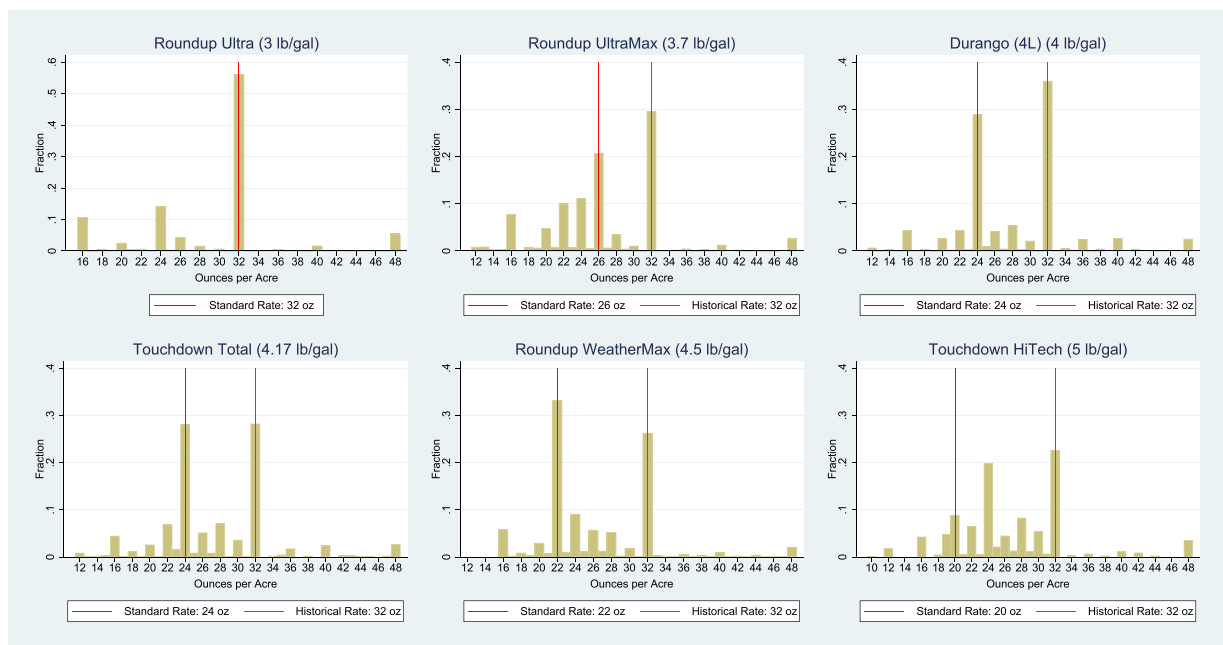
Fig. 2. Selected top commericial glyphosate product histograms, 1998–2011 (*y*-axis: fraction of applications; *x*-axis: application rate (oz/acre)).
Note: Product concentration level in parentheses. The "Standard Rate" is the product specific rate for the standard field rate of 0.75 lb/acre and the "Historical Rate" is the pre-patent expiration standard rate of 32 oz/acre for 3 lb/gal products.

words, for most of the sample, more concentrated products were priced higher per unit acid equivalent. Finally, there is also a general upward trend in application rates for all concentrations over time. This is in part likely due to falling prices, but there is a particularly sharp rise in the final two periods, which may in part be explained by rising crop output prices, which raise the marginal value of yield-enhancing inputs (such as herbicides), and/or the gradual onset of glyphosate weed resistance. The latter refers to weed species that have evolved tolerance to glyphosate, an issue which began to emerge in the mid 2000s and has become increasingly prevalent in recent years (Perry et al., 2016b). Producers have responded by supplementing glyphosate with other herbicides, or in some cases by increasing the glyphosate application rate.

2.4. Historical inertia: 32 fluid ounces

A particularly revealing piece of evidence is the distribution of application rates across different concentrations. Fig. 2 contains histograms of application rates for six of the most popular commercial glyphosate products in our sample. The red line marks the standard application rate – which ranges from 20 to 32 oz/acre - for each product. As expected, there is significant clustering at the standard rate for all products. However, what it is more remarkable is the clustering that occurs at the green line, which marks the rate of 32 fl oz/acre, the historical product rate for a standard application of 3 lb/gal products. This clustering occurs for all products in Fig. 2, and we found it to occur also for virtually every product

not shown here. The clustering is also fairly stable over time. In the Appendix, we present additional histograms for each concentration level over time (Figure A1). For some concentrations, the frequency of 32 ounce applications actually increases over time, and in some cases there is evidence of farmers possibly misapplying products at rates other than 32 ounces. For example, a substantial fraction (∼20%) of farmers applied Touchdown HiTech (5 lb/gal) at 24 oz/acre, which is the standard rate for Touchdown Total (4.17 lb/gal).

What exactly the clustering at 32 fl oz/acre indicates is an open question. At the very least, it indicates that a heuristic or habitual component was present. With the exception of 4.5 lb/gal formulations, the rate of 32 fl oz/acre has no obvious rationale other than that it is what farmers had always used. For all concentrations besides 3 and 4.5 lb/gal products, the annual weed rate tables for different products never explicitly suggest 32 ounces (see Table 2 and Table A1). Whether pure error was involved is hard to establish. Another thing to note is that the clustering occurred early in the 2000s, well before glyphosate resistance was an issue, and before glyphosate prices had drastically fallen. Consider, for example, that the share of applications that exceeded 0.8 lb/acre was 0.14 in 1998, 0.12 in 1999, 0.13 in 2000, and then increased to 0.21 in 2001 and 2002 upon the widespread adoption of Roundup UltraMax® (3.7 lb/gal). This happened concurrently with a slight *increase* in mean prices from 2000 to 2001. Overall, these facts are difficult to reconcile with a full-information, rational model of behavior. Nonetheless, there may be other factors that contributed to the trends in, and clustering of, application rates. In particular, more systematic control is desirable for factors such as unobserved farmer heterogeneity, prices, and weed pressure.

3. Empirical methods

We now examine more systematically whether changes in the concentration level of glyphosate products led to changes in usage behavior. We do so by first estimating how the application rate varies in response to the concentration level, while controlling for prices, individual heterogeneity, generic product dummies, the timing of application, the crop, and time effects.

The unit of observation is an application of a specific glyphosate product to a particular field. A field is defined as a unique combination of the seed planted, the tillage system used, and the sequence of herbicide products used. It is also possible for a field to receive more than one glyphosate application.[6] Denote an application by i, a farmer by f, and a year by t. We estimate regressions of the following form:

$$y_{ift} = g(z_{ift}) + \beta \cdot x_{ift} + \mu_t + \lambda_f + \varepsilon_{ift}, \tag{1}$$

where y_{ift} is the glyphosate application rate (lb ae/acre), z_{ift} is the concentration level of the glyphosate product used in application i (lb ae/gal), and x_{ift} is a vector of controls which include: the price of glyphosate ($/lb), dummy variables for whether or not the product is generic, the type of crop, and whether glyphosate is applied pre-emergence (before the crop sprouts). The "generic" dummy controls for the possibility that farmers perceive generic products as less effective and therefore compensate by increasing application rates. Although peer-reviewed studies find no significant differences in efficacy between generic and non-generic products (Hartzler et al., 2002; Mahoney et al., 2014), anecdotal evidence via web-based forums suggests that some farmers are wary of generic products, particularly those not produced in the United States.[7] As noted, previous work has shown that some individuals are willing to purchase non-generic medications at a price premium, despite having the same ingredients. Lastly, the pre-emergence dummy controls for the fact that post-emergence applications are typically more re-active and thus weed height may tend to be higher, resulting in higher application rates.

The main component of interest is the function of the concentration level, $g(z_{ift})$. We consider two different specifications of this function. First, we postulate a linear relationship between the concentration level and the application rate, that is $g(z_{ift}) = \alpha z_{ift}$. This specification implies that concentration levels do not impact the application rate if α is not statistically different from zero. Alternatively, we estimate the dummy-variable specification $g(z_{ift}) = \sum_j \gamma_j D_{ij}$, where $j \in \{3.7, 4, 4.17, 4.5, 5\}$ indexes the concentration level of the glyphosate product and D_{ij} is a dummy variable equal to one if a product with concentration j was applied on plot i (zero otherwise). In this case, the concentration level is simply a concentration-specific intercept shifter (relative to the base concentration level of 3 lb ae/gal). As such, it is more flexible when compared to the linear specification. Because we set the 3 lb/gal concentration as the reference formulation, higher concentration levels impact application rates if we obtain statistically significant estimates for the respective γ_j coefficients.

The model also includes time and farmer fixed effects (μ_t and λ_f, respectively). Time effects control for unobserved, commonly shared shocks that influence the application rate. Two examples include crop output prices and glyphosate weed resistance. Both potentially increase the application rate and, because they increased later in the sample, are positively correlated with applied concentration levels. Farmer fixed effects control for time-invariant unobserved heterogeneity at the farm level. For instance, they control for the possibility that growers who apply glyphosate at higher field rates prefer to use more concentrated products, perhaps to better manage higher application costs.

The impact of concentration levels on the application rate is identified by variation within farmers' application rates across different products. It is important to be clear about what we are not identifying. We cannot explicitly control for

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[6] For example, if a field receives an application of glyphosate once before the crop emerges and once after the crop emerges, this would constitute two observations.

[7] For further details on these web-based forums, see *Agricultural Web Forums* in the Appendix.

Table 4
Summary statistics for model variables.

Variable	Mean	S.D.	Min	0.25	Median	0.75	Max
Application rate (lb/acre)	0.82	0.29	0.01	0.75	0.75	0.92	4.69
Concentration (lb ae/gal)	3.58	0.66	3	3	3	4.5	5
D_3	0.54	0.5	0	0	1	1	1
$D_{3.7}$	0.1	0.3	0	0	0	0	1
D_4	0.06	0.24	0	0	0	0	1
$D_{4.17}$	0.03	0.18	0	0	0	0	1
$D_{4.5}$	0.26	0.44	0	0	0	1	1
D_5	0.01	0.07	0	0	0	0	1
Price[a] ($/lb ae)	12.61	7.47	2.2	6.57	10.64	18.03	50.96
Corn	0.41	0.49	0	0	0	1	1
Pre-Plant	0.27	0.44	0	0	0	1	1
No-Till	0.47	0.5	0	0	0	1	1
Generic	0.42	0.49	0	0	0	1	1

[a] Prices are converted to 2011 $ by using the USDA crop sector index for prices paid.

unobserved factors that are individual or field specific and that vary over time. Moreover, it may be the case that when producers plan to spray at higher rates, they deliberately use more concentrated products. Why might this be? One possible reason is that, by entailing smaller volumes (ceteris paribus), more concentrated products may have lower storage and/or transportation costs. Alternatively, farmers may simply prefer to adjust their rates through discrete product changes (holding the product rate fixed) rather than through product rate adjustments for a given product. For example, a farmer wanting to use the product rate they have become accustomed to (e.g., 32 oz/acre), but also increase rates, could jump from a 3 lb/gal product to 4.5 lb/gal product.

These possibilities have at least two implications for our analytical framework. First, if there are indeed unobserved factors correlated with both the chosen concentration level and the dosing level, then the estimated concentration coefficients may be biased. Second, even supposing that the estimated concentration coefficients are unbiased, their interpretation is complicated by the possible existence of complementarities (e.g., cost savings) from using more concentrated products at higher rates. In such a case, the estimated coefficients on the concentration variable(s) will potentially reflect both cost savings and farmers not using label information. Some of these issues are addressed through robustness checks in the Appendix. In any event, in the first stage of our initial analysis, our main goal is to establish whether the observed correlations between concentration and dosing rates can be explained by prices, the type of products, or the other controllable factors. Next, in the second stage of our analysis, we avoid some of these issues by focusing on the factors associated with the dosing choices of 32 oz/acre and 0.75 lb/acre. Finally, in the third stage of our analysis, the regression model of Eq. (1) is extended to look further into whether the estimated effect on the concentration variables represent deliberate choices or whether some farmers did not make use of label information.

4. Results

The baseline econometric analysis relies on a large sample of farm-level data on applications of glyphosate in U.S. corn and soybean production over the period 1998–2011. The commercial name of the dataset is AgroTrak®, which was constructed by GfK Kynetec, a unit of a major market research firm.[8] Each year GfK conducts computer-assisted telephone interviews of farmers throughout the United States. The sampling procedure is designed to be representative at the crop reporting district (CRD) level, a multi-county sub-state region identified by the National Agricultural Statistics Service (NASS) of the U.S. Department of Agriculture (USDA). Farmers are surveyed in detail about the pesticide products they used: which ones, how much, when they were applied, on what crops, and the prices paid. Further details about the dataset are provided in the Appendix (see *Data Description* and Tables A2-A5).

While producers report all of the pesticides they used, here we only employ observations in which glyphosate was used. This results in 191,789 observations across an annual average of 5228 farmers. We further trim this dataset in two ways. First, a small share of glyphosate products are pre-mixes (products that contain glyphosate and at least one other herbicide mixed together). Because our focus is on glyphosate as a standalone product, we drop these observations, reducing the dataset to 185,377 observations. We also drop products with concentration levels that were seldom observed (595 observations).[9] Overall, our final dataset consists of 184,782 observations across 31,417 distinct farmers across 284 CRDs. Importantly, for many individuals we observe multiple periods, which allows us to control for unobserved heterogeneity through farmer-specific fixed effects. This feature is also necessary for the second stage of our empirical analysis, where we compare usage rates over time between subsets of individuals.

Table 4 provides summary statistics for the model variables. The mean and median application rates were 0.82 and 0.75, respectively. The latter is consistent with 0.75 lb/acre as the standard rate. The mean concentration level was 3.58 lb/gal,

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[8] The GfK AgroTrak data have also been used, among others, in Thelin and Stone (2013), Mitchell (2014), Perry et al. (2016a, 2016b).

[9] We also run our analysis having included infrequently purchased concentrations and the results are unaffected.

Table 5
Product concentration effect on glyphosate use.

	Specification	
	Linear	Dummy variable
Concentration	0.1431***	
	(0.0031)	
$D_{3.7}$		0.1065***
		(0.0056)
D_4		0.1450***
		(0.0068)
$D_{4.17}$		0.1313***
		(0.0085)
$D_{4.5}$		0.2253***
		(0.0060)
D_5		0.2763***
		(0.0198)
Price	−0.0035***	−0.0034***
	(0.0004)	(0.0004)
Corn	−0.0089***	−0.0087***
	(0.0024)	(0.0024)
Pre-plant	−0.0252***	−0.0252***
	(0.0043)	(0.0043)
Generic	0.0189***	0.0293***
	(0.0042)	(0.0052)
No-till	0.0019	0.0018
	(0.0023)	(0.0023)
N	184,782	184,782
R^2	0.488	0.489

Dependent variable: Application Rate (lb/acre/treatment). Standard errors, in parentheses, are clustered at the CRD level. All regressions include farmer-specific and time fixed effects. The coefficients are estimated using the Stata *reghdfe* package, based on the fixed effects estimator in Correia (2016). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

with a maximum of 5 lb/gal. The dummy variables for each of the different concentrations inform on the frequency with which they were used. The top concentrations were 3 lb/gal at 54% of applications, 4.5 lb/gal at 26%, and 3.7 lb/gal at 10%. For the remaining variables, the mean price, which is deflated by the USDA crop sector index for prices paid by farmers, was $12.61/lb, 41% of applications were on corn, 27% were pre-emergence, 47% were on no-till fields, and 42% of products were generic (i.e., non-Monsanto products).[10]

Table 5 contains results for the two main regression specifications. Overall, the parameters are tightly estimated and the signs for the non-concentration variables are broadly consistent with expectations. The price coefficient is negative and highly significant. Its magnitude implies that a real $10 decrease in the price of glyphosate increases the application rate by 0.034 lbs/acre, or just a bit under 5% of the standard rate. From 1998 to 2011, the mean real price of glyphosate fell by about $24/lb, implying that prices accounted for about 0.08 lb/acre of the increase in application rates. Applications on corn show slightly lower glyphosate use than on soybeans. This can possibly be explained by the fact that early canopy closure in corn helps weed control. Pre-emergence application rates were lower than post-emergence application rates, confirming that, on average, weed pressure tends to be more problematic at the post-emergence stage. Finally, and having controlled for price differentials, generic products were applied at statistically significantly higher rates when compared to non-generics (i.e., Monsanto products). Although the difference is small in magnitude, it suggests that some farmers are either unaware of existing studies on the efficacy of generic versus non-generic products, or do not believe the results of such studies. This finding complements some previous work that has shown consumers to purchase non-generic medications at a significant price premium (Handel and Schwartzstein, 2018).

The concentration coefficients are statistically significant and large in magnitude. The linear specification implies that a 1 lb/gal increase in the concentration level increased the application rate by over 0.14 lb/acre, or about 19% of the standard rate of 0.75 lb/acre. The dummy variable specification produces coefficient effects that are nearly the same as those implied by the linear specification. For example, the coefficient for dummy variable D_4 implies that, relative to the baseline 3 lb/gal formulation, adding 1 lb/gal of glyphosate increases the average application rate by 0.145 lb/acre, while the coefficient for the dummy variable D_5 implies that adding 2 lb/gal of glyphosate increases the average application rate by 0.276 lb/acre. Overall, these magnitudes explain a significant share of the overall increase in application rates over time.

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[10] We also estimated all specifications with nominal prices and CPI-deflated prices. In both cases, the results are largely unchanged.

Table 6

Summary statistics of farmer characteristics by concentration level.

	Glyphosate concentration level (lb/gal)					
	3	3.7	4	4.17	4.5	5
Acres grown range[a]						
<100	0.17	0.14	0.12	0.11	0.13	0.13
100–249	0.24	0.24	0.21	0.19	0.21	0.26
250–499	0.23	0.22	0.24	0.24	0.22	0.22
500–999	0.21	0.23	0.23	0.25	0.23	0.24
≥1000	0.16	0.17	0.20	0.21	0.20	0.16
Corn yield[b]	136.82	138.18	148.21	149.22	145.61	135.77
Soybean yield[b]	40.25	40.54	44.04	44.00	42.65	40.40
Central corn belt[c]	0.33	0.34	0.46	0.52	0.45	0.29
Observations	99,053	18,468	11,198	6231	48,882	950

[a] The variables for "Acres grown range" (e.g., <100, 100-249, etc.) are indicator variables equal to one if the specified number of acres were planted for a particular crop. For each concentration level, the values indicate the percentage of observations that pertain to each range. Note that for each concentration the shares sum to one.

[b] County-level yield, bu/acre (source: USDA-NASS).

[c] The central corn belt (CCB) includes IL, IN, IA, and the southern CRDs in WI and MN.

Multiple robustness checks were conducted to ascertain the sensitivity of the baseline regression results. These robustness checks consist of the following: adding different sets of fixed effects, removing potentially endogenous controls, estimating separate models for generic and non-generic products, and removing outliers. Overall, the estimation results from these alternative specifications demonstrate the same patterns as those presented in Table 5. For further details and description, see *Robustness Checks* in the Appendix, as well as Tables A6 and A7.

4.1. Factors associated with the "Usual" 32 ounce rate and the standard 0.75 lb/acre rate

As noted, one limitation of the baseline regression approach is that we cannot control for unobservable factors that are individual and time specific. However, *even if* farmers deliberately use more concentrated products when applying glyphosate at higher rates, the previously demonstrated clustering at 32 ounces indicates that farmers likely use a "rule of thumb" in choosing their rates. The characteristics that are correlated with these choices are therefore of interest in their own right. Unfortunately, our dataset limits the set of characteristics we can investigate: we do not directly observe variables of possible interest such as farm size, education, or age. But we do observe how many acres a farmer planted to each crop, the county where a farmer is located, whether a farmer was an early adopter of a new glyphosate product, and the length (in years) of experience a farmer had with a particular concentration. In this section, we estimate linear probability models that relate each of these characteristics to two types of application rate choices with more concentrated products: (i) the pre-patent-expiration product-specific rate of 32 oz/acre and (ii) the standard field rate of 0.75 lb/acre.

Previous research has generally found that factors such as larger farm size, education, and experience are associated with early adoption of new technologies and information acquisition (see, e.g., Feder and Slade, 1984; Diederen et al., 2003). These findings suggest that certain types of farmers will be more likely to choose the historical usual rate of 32 oz/acre. Specifically, if we view the choice of 32 oz/acre with more concentrated products as the habitual choice, then existing research suggests that larger operations, early adopters of new products, and more experienced users will be less likely to choose this rate. Conversely, choosing an application rate of 0.75 lb/acre with more concentrated products requires greater acquisition of information, which suggests that larger operations, early adopters, and experienced users will be *more* likely to use 0.75 lb/acre.

Table 6 contains summary statistics for several characteristics of interest. The first five rows illustrate the distribution of observations pertaining to each product concentration by acres planted. The remaining rows contain average corn and soybean yields, as measured by NASS county average data, as well as the frequency of use in the central corn belt (CCB) by product concentration.[11] Two patterns are apparent in Table 6. First, larger operations are more likely to use more concentrated products. For example, 17% of 3 lb/gal product users planted less than 100 acres versus 13% of 4.5 lb/gal product users. Conversely, relatively more users of 4.17 and 4.5 lb/gal products were larger operations. Second, regions with higher yield per acre tend to use more concentrated products. The exception to these regularities is for 5 lb/gal products, which seem to be an outlier among the more concentrated products. This concentration level was introduced later in the sample and was used by very few farmers. Additional details and statistics on the factors associated with chosen concentration levels are provided in the Appendix (see Table A8).

To estimate the linear probability models, the distribution by farm size presented in Table 6 is converted into indicator variables that take a value equal to one whenever a farmer planted within the given acre range. For example, the indicator

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[11] The CCB includes IA, IL, IN, and the southern agricultural CRDs in MN and WI.

Table 7
Linear probability model results for 32 oz/acre and 0.75 lb/acre Choices.

	Applied product at 32 oz/acre[†]			Applied product at 0.75 lb/acre[§]		
	(1)	(2)[d]	(3)[e]	(4)	(5)[d]	(6)[e]
Acres grown[a]						
100–249	−0.0387***	−0.0566**	−0.0538**	0.0322***	0.0473***	0.0437***
	(0.0120)	(0.0233)	(0.0231)	(0.0092)	(0.0175)	(0.0147)
250–499	−0.0789***	−0.0706***	−0.1000***	0.0741***	0.0694***	0.0930***
	(0.0133)	(0.0254)	(0.0253)	(0.0115)	(0.0197)	(0.0163)
500–999	−0.1172***	−0.0956***	−0.0879***	0.0943***	0.0970***	0.0969***
	(0.0136)	(0.0254)	(0.0305)	(0.0104)	(0.0182)	(0.0187)
≥1000	−0.1376***	−0.1483***	−0.1549***	0.1314***	0.1162***	0.1524***
	(0.0139)	(0.0239)	(0.0289)	(0.0134)	(0.0253)	(0.0222)
Experience[b]	−0.0097**	−0.0070	−0.0085	0.0155***	0.0145***	0.0044
	(0.0041)	(0.0061)	(0.0060)	(0.0026)	(0.0042)	(0.0040)
Trend	0.0081***	0.0113***	0.0107***	−0.0069***	−0.0036	−0.0015
	(0.0014)	(0.0034)	(0.0028)	(0.0017)	(0.0025)	(0.0027)
CCB[c]	−0.0237*	−0.0395**	−0.0277	−0.0155	0.0196	−0.0100
	(0.0128)	(0.0181)	(0.0184)	(0.0136)	(0.0207)	(0.0184)
Early adopter		−0.0550***	−0.1080***		0.0814***	0.1190***
		(0.0204)	(0.0180)		(0.0135)	(0.0153)
Constant	0.3224***	0.3325***	0.3469***	0.2615***	0.1755***	0.1643***
	(0.0161)	(0.0338)	(0.0293)	(0.0168)	(0.0232)	(0.0228)
N	36,847	10,935	11,174	85,729	20,098	24,719
R^2	0.014	0.026	0.027	0.014	0.021	0.032

Standard errors, in parentheses, are clustered at the CRD level. The coefficients were estimated using ordinary least squares.

[†] Dependent variable: indicator variable equal to one if farmer applied glyphosate product at the historical usage rate of 32 oz/acre. Sample includes 3.7, 4, 4.17, and 5 lb/gal. products.

[§] Dependent variable: indicator variable equal to one if farmer applied glyphosate product at 0.75 lb/acre. Sample includes 3.7, 4, 4.17, 4.5, and 5 lb/gal. products.

[a] The reference category is (<100 acres).

[b] Equal to the number of years since a farmer first adopted a particular concentration.

[c] The Central Corn Belt (CCB) includes IL, IN, IA, and the southern CRDs in WI and MN.

[d] Restricted to farms originally sampled in 2001. Early adopters are farms that used Roundup UltraMax in 2001.

[e] Restricted to farms originally sampled in 2003. Early adopters are farms that used Roundup WeatherMAX in 2003.

* $p < 0.10$.

** $p < 0.05$.

*** $p < 0.01$.

variable (<100) takes a value of one if a farmer planted less than 100 acres in soybeans (or corn). The two types of application rate variables are created as follows. First, we create an indicator variable equal to one for each observation in which the application rate was 32 fluid ounces per acre, or what may be thought of as the pre-patent-expiration "usual" rate. For these observations, we restrict the analysis to 3.7, 4, 4.17, and 5 lb/gal products. We (conservatively) omit 4.5 lb/gal products because 32 ounces is the suggested rate for the 1.5x dose for this product, and thus a reasonable focal point adjustment for farmers who sought a more potent dose. We create a second indicator variable that takes the value of one whenever the standard application rate of 0.75 lb/acre is used. In this case, the analysis is restricted to all concentrations exceeding 3 lb/gal. Summary statistics and additional description for each of these dummy variables are provided in the Appendix (see *Summary Statistics for 32 oz/acre and 0.75 lb/acre Application Choices* and Tables A9 and A10). About 30% of applications were 32 oz/acre and about 30% were also 0.75 lb/acre.

Because the panel is not balanced, in order to estimate models with an early adoption variable, the analysis was restricted to subsamples of farmers from specific years.[12] We estimate models for two such subsamples. In one case we look at surveyed farmers from 2001, with early adopters being coded as those who used Roundup UltraMax (3.7 lb/gal). In a second case, we estimate a model using the 2003 subsample of farmers, with early adopters being coded as those who used Roundup WeatherMAX (4.5 lb/gal).[13] Table 7 reports results for these regressions. The first three columns contain results for the 32 oz/acre rate regressions and the last three columns report results for the standard 0.75 lb/acre regressions. Overall, a strong pattern emerges: larger operations are significantly less likely to use the usual 32 oz. rate. For example, a farmer that planted more than 1000 acres in corn or soybeans was anywhere from just under 14% to over 15% less likely than a farmer with less than 100 acres to use the 32 oz. rate. Columns 2 and 3 indicate that early adopters were also significantly less likely to apply glyphosate at 32 oz/acre. Early adopters from 2001 were over 5% less likely to use the usual rate (compared to their 2001 cohort), and 2003 early adopters were nearly 11% less likely to use the usual rate (compared to their 2003

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[12] The main issue is that many individuals were not surveyed in the years that a new product was released.

[13] We considered other products as well, but for these other products the number of early adopters was very small.

cohort). There is also limited evidence of experience reducing the likelihood of the 32 oz. rate: the experience coefficient is negative and significant in the first column but insignificant in the second and third columns. Farmers in the CCB were also less likely to use a 32 oz. rate in two of three specifications.

The estimation results for the "standard" rate dummy variable models (columns 4–6) mirror the "usual" rate results of columns 1–3: larger operations and early adopters are significantly *more* likely to use the standard rate. In two cases, experience with a product increases the likelihood of using the standard rate. CCB farmers are not significantly different from non-CCB farmers.

Overall, these results suggest that using a "rule of thumb" is significantly more likely among small farms and late adopters, whereas using the standard rate, which requires the acquisition and implementation of label information (either acquired from the label itself or from someone familiar with the label), is significantly more likely among large operations and early adopters.

4.2. Was rational behavior or label confusion behind the concentration effect?

An important question remains: why do U.S. corn and soybean farmers apply more concentrated products at significantly higher rates? More specifically, is the positive association between concentration and the application rate the result of error and/or label confusion, or rather the result of farmers deliberately choosing to use more concentrated products at higher rates (e.g., for cost reduction reasons)? The evidence so far suggests that both mechanisms may play a role. The fact that 32 oz/acre appears so often in the data, and the fact that application rates increased substantially well before significant price declines, and before the emergence of glyphosate weed resistance, suggests that behavioral and/or inattentive elements played a role. A behavioral element is also indirectly implicated by the results from the analysis of factors related to what type of rate is chosen (the "usual" rate or the "standard" rate). On the other hand, the positive correlation between planted acres and concentration levels leaves open the possibility of cost savings. To answer this question satisfactorily would require more information about farmers' knowledge of each product, as well as further details about their decision processes concerning both why they chose a particular concentration and why they chose a particular rate. We can nonetheless use the panel aspect of the data to gain insights into this issue. Specifically, we conduct an exercise that uncovers differences in usage tendencies between a population of farmers that are likely informed about proper rates and a population of farmers that likely includes some individuals that are uninformed or inattentive. The exercise is as follows.

First, we identify a subset of farmers we term "rationally *attentive*." These are farmers who, early on, applied new glyphosate products at the (recommended) standard rate. Specifically, we identify the subset of farmers that applied Roundup UltraMax®, which contains 3.7 lb/gal of glyphosate, at the standard acre rate of 0.75 lb/acre in the years 2000–2002. We then compare the behavior of this subset of farmers to all other farmers during the period 2003–2011.[14] In particular, we estimate the dummy variable version of Eq. (1), but allow for all coefficients to differ for each sub-group during the 2003–2011 interval.[15] In total, we observe 9119 applications across 909 rationally attentive individuals, and 132,065 applications across 22,004 other individuals.

We select farmers that used Roundup UltraMax® at the standard rate for two reasons. First, a standard dose for Roundup UltraMax® is 26 fl oz/acre. Because this dose rarely occurred with 3 lb/gal products, there is little possibility that a farmer's choice of this rate was the result of a mistake or habit. By choosing this application rate an individual clearly demonstrates knowledge of the appropriate rate and a willingness to adjust their behavior. The second reason is more practical – Roundup UltraMax® is the first major product with a different concentration rate. Thus, by using it as an identifier for rationally attentive behavior, we still have nine years left in our sample to compare the behavior of rationally attentive individuals with the rest of the population.[16]

In allowing for different coefficients for each population, we aim to learn two things. First, if the concentration coefficients for rationally attentive farmers are still positive and significant then this would suggest that there are genuine reasons (cost reduction, perhaps) for using more concentrated products at higher rates.[17] Second, if label confusion existed for some farmers, then we would expect the estimated concentration coefficients for rationally attentive farmers to be smaller than the same coefficients for the general population. The basic idea is that the general population will consist partly of rationally attentive farmers and partly of non-rationally-attentive farmers, by which we mean those farmers that are other than rationally attentive, i.e., everyone else. The regression estimates will therefore consist of a mixture of the concentration effects for these two subgroups and thus exceed the estimates for rationally attentive farmers if there is label confusion among non-rationally attentive farmers.

Table 8 presents summary statistics for each of the two groups (see Figure A2 for the geographical distribution of rationally attentive farmers). Overall, the means are similar in magnitude but differ statistically in most cases. Rationally attentive

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[14] We use the 2003–2011 sub-period because if we used the entire period then the coefficients for the rationally attentive individuals would have downward bias by construction. Put differently, rationally attentive individuals are precisely those individuals for whom we do not observe a concentration effect in the 2000–2002 interval.

[15] Specifically, we estimate a pooled regression but allow for the variable coefficients to differ by sub-group.

[16] As an alternative, we use Roundup WeatherMAX® in 2003 and 2004 for identifying rationally attentive behavior. Results for this procedure are provided in Table A11 of the Appendix. In short, we find similar results.

[17] The caveat to this is that rationally attentive farmers may still err later in the sample with other products. Our underlying assumption is that this is going to be a relatively rare occurrence.

Table 8

Summary statistics for "Rationally Attentive" individuals and "Everyone Else", 2003–2011.

	"Rationally Attentive"	"Everyone Else"	Difference[†]
Application rate	0.818	0.843	−0.025***
	(0.232)	(0.284)	
D_3	0.391	0.464	0.074***
	(0.488)	(0.499)	
$D_{3.7}$	0.0673	0.0667	−0.001
	(0.251)	(0.250)	
D_4	0.0708	0.0771	0.006**
	(0.257)	(0.267)	
$D_{4.17}$	0.0229	0.0456	0.023***
	(0.150)	(0.209)	
$D_{4.5}$	0.443	0.340	−0.104***
	(0.497)	(0.474)	
D_5	0.0052	0.0068	0.002*
	(0.072)	(0.082)	
Price	10.55	9.507	−1.045***
	(5.390)	(5.006)	
Corn	0.424	0.470	0.046***
	(0.494)	(0.499)	
Pre-plant	0.222	0.247	0.0248***
	(0.416)	(0.431)	
Generic	0.427	0.527	0.100***
	(0.495)	(0.499)	
No-Till	0.447	0.465	0.019***
	(0.497)	(0.499)	
Acres grown range			
<100	0.096	0.152	0.056***
	(0.295)	(0.359)	
100–249	0.191	0.233	0.042***
	(0.393)	(0.423)	
250–499	0.249	0.221	−0.028***
	(0.433)	(0.415)	
500–999	0.251	0.216	−0.036***
	(0.434)	(0.411)	
≥1000	0.212	0.179	−0.034***
	(0.409)	(0.383)	
Observations	9119	132,065	

Note: summary statistics include means and standard deviations (in parentheses) for key variables.

* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.
[†] Statistical significance of t-test for difference between means.

individuals purchase fewer products with 3 lb/gal, instead opting more frequently for 4.5 lb/gal products. They are also less likely to purchase generics and they tend to purchase products with slightly higher prices. Rationally attentive farmers also tend to have larger operations: only 9.6% of operations are less than 100 acres, compared to 15% for everyone else. Conversely, more than 46% of their operations were greater than 500 acres, compared to just under 40% for everyone else.

Table 9 reports the coefficients (and standard errors) for each of the two sub-groups, as well as their differences, estimated with a pooled regression model. Overall, the coefficients are tightly estimated. For variables other than concentration levels, the coefficients are similar (the difference between the two groups is not statistically significant).

For the concentration parameters, two findings emerge. First, even rationally attentive individuals apply glyphosate at higher rates with more concentrated products. The effect is relatively stable across products, with the exception of 4.5 lb/gal products, for which the concentration effect is 0.17 lb/acre. One potential explanation for this is that the 1.5x standard dose for 4.5 lb/gal is 32 fl oz/acre, the historical "usual" rate for 3 lb/gal products. Thus, farmers wanting to use a higher rate, but still use 32 fl oz/acre, may have jumped to a 4.5 lb/gal product.

The second finding is that the concentration effect for rationally attentive individuals is considerably lower than the effect for all other individuals, and these differences are statistically significant.[18] In most cases the coefficient is about 30% lower. For 5 lb/gal products, the effect is nearly 66% lower. Overall, we interpret these differences as evidence that part of the concentration effect was due to label confusion, error, habit, or some combination of these mechanisms. A possible alternative explanation is that these differences are due to differences in the structure of cost savings between the two

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[18] The F-statistic associated with the test that the concentration parameters for rationally attentive individuals are jointly zero is 12.65, which corresponds to a p-value < 0.0001.

Table 9
Regression results of "Rationally Attentive" growers and "Everyone Else".

	"Rationally Attentive"[a]	"Everyone Else"	Difference
$D_{3.7}$	0.0719***	0.1232***	−0.0513*
	(0.0279)	(0.0083)	(0.0288)
D_4	0.1088***	0.1525***	−0.0437**
	(0.0179)	(0.0074)	(0.0188)
$D_{4.17}$	0.0905***	0.1392***	−0.0487*
	(0.0277)	(0.0092)	(0.0283)
$D_{4.5}$	0.1701***	0.2490***	−0.0789***
	(0.0210)	(0.0073)	(0.0234)
D_5	0.0986***	0.2976***	−0.1990***
	(0.0236)	(0.0214)	(0.0303)
Price	−0.0033**	−0.0037***	0.0004
	(0.0014)	(0.0005)	(0.0015)
Corn	−0.0208***	−0.0099***	−0.0109
	(0.0061)	(0.0026)	(0.0066)
Pre-Plant	−0.0369***	−0.0239***	−0.0129
	(0.0112)	(0.0042)	(0.0101)
Generic	0.0435**	0.0345***	0.0090
	(0.0215)	(0.0061)	(0.0232)
No-till	−0.0079	0.0037	−0.0117
	(0.0077)	(0.0026)	(0.0083)

$N = 141,184$. $R^2 = 0.5224$. Dependent Variable: Application Rate (lb/acre/treatment). There are 9119 rationally attentive observations and 132,065 observations for everyone else. Standard errors, in parentheses, are clustered at the CRD level. All regressions include farmer-specific and time fixed effects. The coefficients were estimated using the Stata *reghdfe* package, based on the fixed effects estimator in Correia (2016).
  [a] The results in this column were obtained by summing the "Everyone Else" and Difference column coefficients, which were obtained using a pooled regression. Standard errors computed using the delta method.
  * $p < 0.10$.
  ** $p < 0.05$.
  *** $p < 0.01$.

populations. One possibility we considered is that the same pattern would emerge if we estimated the concentration models separately for each acres planted range, the idea being that cost savings would differ by the size of operation. We found, however, that concentration coefficients, while slightly different, did not differ significantly by size of operation, and are nowhere near the extent of the differences presented in Table 9. Overall, this suggests that the differences are likely due to a greater frequency of label confusion, error, or habit in the general population.

5. Some implications

Using our estimates from Table 9, we simulate two counterfactual scenarios: one in which all growers behave as "rationally attentive" individuals, and one in which the concentration level does not impact the application rate. The latter scenario is simulated to give an upper bound on the concentration effect. As previously discussed, part of the concentration effect may be due to a complementarity effect: using more concentrated products at higher rates may offer costs savings. Thus, the "No Concentration Effect" simulation may be viewed as informing on the scenario in which both behavioral and complementarity effects are absent.

We simulate two variables of interest: total annual glyphosate use and total annual glyphosate expenditures by farmers. In running these simulations, we are implicitly assuming that agrochemical firms would not have adjusted their product lines or prices in a world where farmers' glyphosate demand is adjusted as per the scenarios considered. The fact that the glyphosate market became largely competitive with the expiration of Monsanto' patent suggests that this assumption of unchanged prices is plausible.

5.1. Counterfactual use and costs

For each observation, we compute predicted glyphosate use under three scenarios, denoted by $h = 1, 2, 3$. Predicted glyphosate use for application i, by farmer f, in year t, and for scenario h, is written as

$$q_{ift}^h = a_{ift}\hat{y}_{ift}^h \tag{2}$$

where $\hat{y}_{ift}^h$ is the predicted application rate using the estimated parameters under scenario h and a_{ift} is the observed number of treated acres during application i. Total annual glyphosate use is obtained by summing over applications and individuals:

Table 10
Predicted glyphosate quantity and expenditures in U.S. corn and soybeans for three different scenarios, 2003–2011.

Year	Total quantity (millions of lbs)			Total cost ($ million)		
	Status Quo	All rationally attentive	No concentration effect	Status Quo	All rationally attentive	No concentration effect
2003	90	87	79	1539	1474	1331
2004	100	97	89	1387	1327	1196
2005	107	103	94	1173	1122	1,014
2006	110	106	97	1064	1018	921
2007	131	126	115	1076	1030	929
2008	163	155	138	1726	1639	1450
2009	164	157	142	1862	1776	1582
2010	176	169	153	1096	1046	932
2011	181	172	151	858	812	709
Mean	136	130	117	1309	1250	1118

$Q_t^h = \sum_f \sum_i q_{ift}^h$. Predicted revenues are generated by multiplying predicted quantities by price and summing over applications and individuals: $C_t^h = \sum_f \sum_i p_{ijt} q_{ift}^h$, where p_{ift} is the actual price paid for glyphosate by farmer f ($/lb of ae). Table 10 presents simulated glyphosate quantities and farmers' expenditures. The predicted values for scenario $h = 1$, what we term the "Status Quo" scenario, contains the predicted annual values using the estimated parameters from Table 9. Specifically, for rationally attentive farmers, q_{ift}^1 is generated using the estimated parameters from the "Rationally Attentive" column in Table 9, and for all other farmers q_{ift}^1 is computing using the estimated parameters from the "Everyone Else" column. For scenario $h = 2$, termed the "All Rationally Attentive" scenario, we alter the predictions for non-rationally attentive farmers by replacing their estimated concentration coefficients ($D_{3.7}$ to D_5) with the estimated concentration coefficients from the "Rationally Attentive" column in Table 9. Finally, scenario $h = 3$, or the "No Concentration Effect" scenario, predicts quantities and expenditures by setting the concentration parameters to zero (i.e., we set the coefficients on $D_{3.7}$ to D_5 in Table 9 to zero). Because we estimate the parameters during the 2003–2011 period, we restrict our predictions to this time frame.

Had all farmers behaved in the same way as rationally attentive individuals, the reduction in glyphosate use would have ranged from 3.5 million pounds (3.8%) in 2003 to a high of 10 million pounds (5.1%) in 2011. In the absence of any product concentration effect, the reduction would have ranged from approximately 11 million pounds (13.6%) to over 30 million pounds (17%).

Perhaps the most interesting results are for total glyphosate expenditures. The average increase due to higher concentration products, based on the "All Rationally Attentive" scenario, was about $59 million per year (4.5%), with a high of $86.5 million (5%) in 2008 and 2009. In the "No Concentration Effect" scenario, the average increase was $191 million per year (14.6%), with a high of $280 million (15%) in 2009. From the perspective of the farmer, the average value of $59 million per year may be viewed as the cost of learning and adapting to the exact acre rate. Alternatively, the increase in farmers' expenditures translates into additional revenues for glyphosate sellers. Hence, the effects we have uncovered constitute a sizeable transfer of rents from agricultural producers to agrochemical firms.

Using product information, the surplus can be disaggregated by glyphosate firm. In particular, each predicted value for q_{ift}^h corresponds to a particular product (e.g., Roundup UltraMax) and in turn a particular company (e.g., Monsanto). Thus, under each scenario we can obtain firm-specific predicted revenues by summing over $p_{ift} q_{ift}^h$ by company. Letting R_d^h denote total revenue for company d under scenario h, the fraction of surplus due to inattentive behavior for firm d is given by: $(R_d^1 - R_d^2)/(R^1 - R^2)$, where R^h is total predicted revenue under scenario h. Of the total surplus, Monsanto received 89%, Syngenta 6%, and Dow AgroSciences 4%, with all remaining companies receiving less than 1%. Monsanto received such a large share because they sold, by far, the largest quantity of high concentration glyphosate products (see Table A12).[19] Whether Monsanto's leading market position in high concentration products was part of a pre-conceived strategy is difficult to ascertain. The fact that Monsanto introduced new types of products upon the expiration of their patent suggests a deliberate attempt to differentiate their products from generics. Because some of the modifications in these new products were patent protected or required regulatory approval (Green and Beestman, 2007), Monsanto was apparently able to dominate the higher concentration product market for several years. This type of strategy has been observed in other markets such as pharmaceuticals (Grabowski and Vernon, 1992). That farmers used newer, more concentrated products at higher rates, however, may have simply been a byproduct of Monsanto's goal to further differentiate their products.

6. Conclusion

This paper explores the impact of changing glyphosate products' concentration levels on U.S. farmers' glyphosate usage behavior. We find that farmers apply more concentrated glyphosate products at significantly higher application rates,

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[19] For context, during the period 2007–2011, Monsanto's net income ranged from a low of $993 million to a high of $2.2 billion (Source: Monsanto Archived Annual Reports). Given that corn and soybeans are not the only source of glyphosate revenues, an additional $59 million per year constituted a nontrivial addition to Monsanto's bottom line.

even after controlling for prices, unobserved heterogeneity, time effects, and several other controls. We further explore the behavioral sources of this effect, and attribute part of it to rational behavior and part of it to label confusion and/or habit.

In recent years, the preponderant view among economists about the ways that economic decisions are made has shifted from that of rational and consistent choice to a broader perspective where ostensibly non-rational and inconsistent choices can persist. These types of choices have been increasingly recognized as emanating from situations where information is incomplete, resources are limited, and complexity is high (Simon, 1955; Handel and Schwartzstein, 2018). As such, the best coping strategy – what may be viewed as individually rational under this broader viewpoint – may often involve heuristics that carry biases (Kahneman, 2003).

Modern crop farming is a technologically intensive business where producers must manage production, storage, distribution, and marketing, while also dealing with finance, weather, pests, regulations, and other hazards. Successful farming in the face of such complexity leaves latitude for apparent inefficiencies in some activities. For example, it was recently observed that farmers likely do not take out subsidized insurance at levels that would both increase farm profit and provide greater financial protection (Du et al., 2017). Prior to 2000, the U.S. glyphosate market was simple both in form (essentially a monopoly) and in product formulation (just one concentration level). With emerging competition came alternative formulations, creating a more complex decision environment for farmers.

Our work suggests that the choices of some individuals were driven by behavior that is heuristic in nature. This is important for several reasons. First, it implies an opportunity to reduce the use of glyphosate without losses in efficiency. In addition to increasing profitability, policy approaches to reduce input use will mitigate any adverse effects that the chemical has on ecological and human health. More generally our work points to the need to investigate possible behavioral effects for other household products, medications and inputs where negative externalities are a major concern (e.g., antibiotic use in animal agriculture or acetaminophen products). Among recent trends in the global agrichemical industry have been the growth of firms producing off-patent herbicides and insecticides, the quest for novel uses of these pesticides, and efforts to penetrate markets in low-income countries where farmers cannot afford branded and patented products (Weiss and Burger, 2017). All else equal, label rate complexity is likely to have greater impacts in lightly regulated countries, where farm operators have lower educational attainment, and where herbicide application is commonly done by hand.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jebo.2018.12.027.

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