Product Formulation and Glyphosate Application Rates: Confusion or Rational Behavior?

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Abstract. The effects of portion size and various other product modifications on consumption behavior have been widely studied, but there is little work on these issues in production contexts. In this paper, we study the effect of changing glyphosate concentration levels on U.S. farmers' application rates. In 2000, Monsanto's glyphosate patent expired and in the following years new products with higher concentration levels entered the market, providing a unique opportunity to observe how farmers adjust their behavior. Using detailed farm-level pesticide use data in corn and soybeans, we find that a doubling of the concentration level of glyphosate increases the application rate by more than 60%. We then use an empirical strategy that allows us to ascertain the behavioral drivers of this effect. We find that a significant portion of the concentration effect can be attributed to rationally inattentive and/or mindless behavior. A counterfactual simulation predicts that this behavior was responsible for an additional $60 million per year in glyphosate revenues, the vast majority of which went to Monsanto.

Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2017 AAEA Annual Meeting, Chicago, IL, July 30-August 1, 2017.

This version: 24 May 2017.

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Introduction

Seemingly innocuous and subtle changes to the formulation and packaging of products can often lead to significant changes in consumption behavior (Wansink, 2004; Wansink, Just, and Payne, 2009). Simply doubling the package size of a food product, for example, can increase consumption by as much 45% (Wansink, 1996), and this effect extends to less palatable foods (Wansink and Kim, 2005). Although these issues have been explored widely for consumption goods, they have been less studied in production contexts. Several reasons probably underlie this fact. One is that we typically view firms as profit maximizers, and as such, less susceptible to the behavioral effects observed for consumption goods. Another reason is that inputs tend to be more standardized and uniform, leaving less scope for the kinds of variations that influence usage. A final reason is that the choice and use of inputs occurs along a supply chain, and thus the consequences of behavioral effects are often not as palpable as in consumption good markets (e.g., obesity). Nonetheless, the presence of such effects can have significant implications for efficiency, the distribution of producer surplus, and, in some cases, the environment.

In this paper, we study how increases in the concentration rate of glyphosate products impact U.S. corn and soybean farmers' application rates. Glyphosate, known by many as Roundup®, is the most used herbicide in the world, largely due to the widespread adoption of genetically engineered glyphosate tolerant crops. 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 an isopropalymine salt. The standard recommended dose for a single application of glyphosate was 0.75 lb/acre. Thus, to achieve this rate, the classic 3 lb/gal product needed to be applied at the rate of 32 fl oz/acre, and indeed this is the rate that the vast majority of farmers used.

In 2000, Monsanto's long-held glyphosate patent expired and, in subsequent years, a large number of new products gradually entered 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 of these new products had higher concentration levels (e.g., 3.7, 4, and 4.5 lb/gal). As such, the dose required to achieve the standard field rate of 0.75 lb/acre was lower, and the instructions on these products reflected this. However, as agricultural producers applied the higher concentration products, a strong pattern emerged: many were applying them at the old rate of 32 fl oz/acre. The extent of this tendency was such that, from

2000-2011, the mean application rate for glyphosate, which had been flat for several years, rose from 0.72 lb/acre to 0.89 lb/acre, a more than 20% increase.

In many ways, the expiration of Monsanto's patent and the subsequent introduction of new and different products comprises a natural experiment (Harrison and List, 2004). This presents the opportunity to observe how individuals actually respond to glyphosate product modifications in the real world. However, the fact that this occurred in an environment where many other variables were changing, and where individuals were able to choose which products to buy, means that a multitude of factors, some unobserved, could be responsible for famers' increasing application rates. Consider, for example, that glyphosate prices, an important driver of application rates, fell by more than 60% from 1998-2011. Thus, our ability to distinguish between the various causes of farmers' changing usage behavior depends critically on controlling for important factors, as well as various identifying assumptions. Given this, in this paper we explore the relationship of glyphosate concentration levels to application rates more systematically in two steps.

First, we estimate whether the concentration level of glyphosate impacts the application rate, controlling for prices and several other potentially confounding variables. To do so, we exploit a rich farm-level dataset on pesticide use during the 1998-2011 period. Importantly, we observe multiple time periods for many of the sampled farmers, permitting us to control for time-invariant farm-level unobserved heterogeneity. We find that there is a robust and large positive effect of glyphosate concentration levels on the application rate. Our estimates indicate that a doubling of the concentration level increases the application rate by nearly 60%, even after controlling for prices.

The initial estimate we obtain for the concentration effect leaves open several different behavioral explanations. Part of the effect could be explained by farmers' complete unawareness that the newer products they were applying had more glyphosate. Alternatively, individuals may have been *aware* that these new products differed but consciously chose not to learn the new rate and instead rely on habit, the latter having been identified as an important driver of consumption behavior (Wood and Neal, 2009). A recent and expanding literature has termed this type of thinking "rationally inattentive" (Sims, 2003; Matejka, F. and McKay, A., 2014). It applies to situations in which an individual has imperfect information about the payoffs associated with different actions. Given this, they must decide whether to allocate scarce (and thus valuable) attention to acquire more information about the payoffs. In many cases it will be rational to conserve their attention and instead resort to heuristics, habit, or rules of thumb (Simon, 1959). The rapid changes in products and formulations that shortly followed the glyphosate patent expiration certainly led to the sort of confusion and uncertainty that could generate this behavior. A simple search on Google about glyphosate application rates, for example, reveals a high level of confusion about how to apply new products. Indeed, numerous extension webpages have been written to address the differences in concentrations, surfactants, salts, and conversion rates (Nordby and Hager, 2004; Sprague, 2006; Armstrong and Lancaster). Finally, it is also possible that the positive effect of concentration on application rates could be the result of fully informed, rational behavior. There may be real benefits to using products that are more concentrated when one plans to apply glyphosate at higher rates. For example, for a given application rate it is cheaper to store and transport more concentrated products and this benefit increases at higher application rates.

To further explore and disentangle fully informed, rational behavior from rationally inattentive or mindless behavior, we exploit the panel nature of our data. In particular, we identify a subset of farmers that we term "rationally *attentive*". These are agricultural producers whom 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 compare the behavior of this subset of farmers to the behavior of all other farmers by re-estimating the relationship between application rates and concentration levels for each of the two subgroups.

We find that even "rationally attentive" individuals use more concentrated products at higher rates. Thus, part of the positive concentration effect we initially estimate can be attributed to fully informed, 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. We interpret this as strong evidence that rational inattention and/or unawareness were significant factors underlying the concentration effect. Using the model estimates for the rationally attentive individuals, we simulate a counterfactual in which all individuals are rationally attentive. The simulation predicts rational inattention and/or unawareness raised glyphosate revenues by $60 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, application rates, and their relationship to concentration rates. We then present the basic econometric framework, followed by a description of the data and initial regression results. We follow this with a development of our strategy to decompose the concentration effect.

Results for rationally attentive and all other individuals are then presented, followed by a counterfactual simulation of glyphosate use and revenues. Finally, we provide concluding comments.

Background

A Brief History of 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). As such, it quickly gained commercial success among agricultural producers. However, its use was limited by its non-selective properties. Growers primarily used it prior to planting or in circumstances where the crop could be avoided (Duke and Powles, 2008). These limitations were lifted when, in 1996, the first genetically engineered glyphosate tolerant (GT) crops were introduced. Farmers could now apply glyphosate to GT varieties post-emergence without causing injury to the crop. As GT crops became more widely adopted, the use of glyphosate expanded commensurately, leading to its ascension as the most used herbicide in the world. In the United States, where the adoption of GT crops now exceeds 90% of acres in corn, soybeans, and cotton, total agricultural glyphosate use exceeded 284 million pounds in 2014, a more than twenty-fold increase from 1992 (USGS, 2017). Glyphosate use in corn and soybeans alone accounted for about 73% of the 284 million pounds.

In 2000, Monsanto's patent on glyphosate expired. In the years that followed, significant changes took place (Table 1). The number of companies producing glyphosate expanded from 1 to 30, the number products rose from 6 to more than 70, and the number of concentrations rose from 4 to 6 (at one point, there were as many as 9). The increased competition in turn led to a precipitous fall in 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%.

--Table 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 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 concentrations will perform essentially the same. Differences in the salt and proprietary components – inert ingredients like surfactants and defoamers – do not generate significant differences in effectiveness (Mueller et al., 2006; Mahoney, Shropshire, and Sikkema, 2014).[1]

Prior to the year 2000 there was essentially one glyphosate formulation: Monsanto's Roundup Ultra®, which contained 3 lb ae/gal of glyphosate. Shortly after the 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 came to dominate 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).

Application Rates

The product label for each of the different 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. A label may thus be quite lengthy, sometimes exceeding 50 pages. The general standard recommended rate – the rate recommended for most situations – has historically been 0.75 lb/acre. The *product-specific rate* – the rate in fl oz/acre – required to achieve this rate is given by

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

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. 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.

--Table 2--

[1] Nonetheless, the proprietary components are an important source of product differentiation.

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 would adjust their application rates in accordance with label recommendations. However, this has not been the case. One indication of this is the overall trend in application rates. As the market became increasingly saturated with higher concentration products, application rates rose significantly. From 1998-2011, the mean application rate rose from 0.73 lb/acre to 0.89 lb/acre, a more than 20% increase. During the same time, the quantity share for products with 3 lb/gal fell from 99% to about 26%.

--Figure 1--

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 purchased concentrations in our sample. Three stylized facts emerge from these numbers. First, more concentrated products are applied at significantly higher rates and this difference is fairly stable over time. Second, and relatedly, the prices of the different formulations cannot explain these differences. In other words, for most of the sample, more concentrated products are priced higher. Finally, there is also an upward trend in application rates 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 rising output prices and/or glyphosate weed resistance.

--Table 3--

The most revealing piece of evidence lies in the distribution of application rates across the different concentrations. Figure 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 0.75-0.78 lb/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 implied acre rate at 32 fl oz/acre, the historical use rate for 3 lb/gal products. This clustering occurs for all products in Figure 2, and we found it to occur for virtually every product not shown here. The clustering is also fairly stable over time.

--Figure 2--

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 oz/gal formulations, the implied acre rate at 32 fl oz/acre has no historical precedent other than that it's what farmers had always used. Whether pure error was involved is also 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, e.g., 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 square 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. Unobserved heterogeneity, prices, and other time effects are some of the factors that need to be more systematically controlled for. Ultimately, an econometric framework is required to more precisely estimate the concentration effect.

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 the amount of glyphosate per acre applied by farmer f in year t during application i. We estimate regressions of the following form:

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

where y_{ift} is the application rate of glyphosate (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), and dummy variables for whether or not the product is generic, the type of crop, and whether glyphosate is applied in pre- or post-emergence.

The main component of interest is the function of the concentration level, $g(z_{ift})$. We consider two different specifications of this function: $g(z_{ift}) = \alpha z_{ift}$ and $g(z_{ift}) = \gamma_j$, $j \in \{3.7, 4, 4.17, 4.5, 5\}$. The former imposes a linear relationship between the concentration level and the application rate. Concentration levels do not impact the application rate if α is not statistically different from zero. In the second function, the concentration level is simply a concentration-specific intercept shifter (relative to the base concentration level of 3 lb ae/gal). More specifically, this second specification consists of estimating a separate intercept for each of the different concentration levels, which amounts to including a dummy variable for each concentration. As such, it is more flexible 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 coefficients.

The model also includes time and farm 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 weed resistance. Both potentially increase the application rate and, because they increased later in the sample, are positively correlated with concentration levels.[2] Farm fixed effects control for time-invariant unobserved heterogeneity at the farm-level. They control for the possibility that growers who apply glyphosate at higher field rates prefer using more concentrated products.

Identification

The impact of concentration levels on the application rate is identified by variation within farmers' application rates across the different products. It is important to be clear about what we are not identifying. Unobserved factors that are individual or field specific that vary over time are not controlled for. Thus, it may be the case that when a producer plans to spray at higher rates he deliberately uses higher concentration products. Why might this be? One possible reason is that more concentrated products require less storage for a given application rate. Another potential reason is

[2] Both variables may also vary spatially, particularly weed resistance. Thus, as part of robustness checks we estimated specifications with year-state-specific fixed effects. These effects capture statewide effects that vary over time. Overall, the results are unchanged when these effects are included.

that the equipment used is calibrated to certain product application rates. If true, these unobserved elements will be conflated with the estimated coefficients on the concentration variable(s). Here, in the first stage of our initial analysis, our main goal is to establish whether these patterns can be explained by prices, the type of products, or the other controllable factors. In the second stage of our empirical analysis we explore further whether the estimated effect on the concentration variables represent deliberate choices or heuristic behavior.

Results

The econometric analysis relies on a large sample of farm-level data on applications of glyphosate, in 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.[3] Each year GfK conducts surveys 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 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, with what crops, and the prices paid.

While producers report all of the pesticides they used, here we only use observations in which glyphosate was used. This results in 191,789 observations across an annual average of 5,228 farmers. We further reduce this dataset in two ways. First, a small share of glyphosate products are pre-mixes. These are 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 seldomly observed (595 observations).[4] Overall, our final dataset consists of 184,782 observations across 31,417 farmers. Importantly, for many individuals we observe multiple time 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.

[3] These data were used in Perry, Moschini, and Hennessy (2016) and Perry et al. (2016).

[4] Nonetheless, we have run our analysis including these products and they do not affect our results.

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 lbs./acre as the standard rate. The mean concentration level was 3.5 lb/gal, with a max 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 we have deflated by the crop index (source: USDA-NASS), was $12.61/lb, 41% of applications were on corn, 27% were pre-plant, 47% were on no-till fields, and 42% of products were generic (i.e., non-Monsanto products).

--Table 4--

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 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 1998-2011, the mean real price of glyphosate fell by about $24/lb. Thus, the fall in prices can explain about 50% of the 0.16 lb/acre observed increase in mean application rates. Applications on corn were slightly lower than on soybeans. This can possibly be explained by corn having better alternative herbicide options (e.g., atrazine) than soybeans. Pre-plant application rates were lower than post-plant application rates, which is consistent with the fact that post-plant applications are typically more re-active and thus weed height tends to be higher. Finally, generic products were applied at slightly higher rates compared to non-generics (i.e., Monsanto products).

--Table 5--

The concentration coefficients are tightly estimated and large in magnitude. The linear specification implies that a 1 lb/gal increase in the concentration level increased the application rate by nearly 0.15 lb/acre, or about 20% 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. Indeed, there is almost no difference in fit between the two. Relative to products with 3 lb/gal, a product with 4 lb/gal is applied, on average, at 0.143 lb/acre higher, and a product with 5 lb/gal is applied at 0.276 lb/acre higher. Overall, these magnitudes explain a significant share of the overall increase in application rates over time.

Breaking down the Concentration Effect

We now turn to the question of what is driving the large positive concentration effect. Our primary goal is to identify whether the effect is the result of fully-informed, rational behavior, or the result of rational inattention and/or complete unawareness. To do so, we identify a subset of farmers that we deem "rationally *attentive*". These are farmers whom, early on, applied new glyphosate products at the 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.[5] In particular, we re-estimate the dummy variable version of equation (1) for each sub-group during the 2003-2011 interval and compare the coefficient estimates. In total, we observe 9,119 applications across 909 rationally attentive indivduals, and 132,065 observations 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, and 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 rest of the population.

Table 6 presents summary statistics for each of the two groups. Overall, the means are quite similar, differing primarily in the types of products chosen. Rationally attentive individuals purchase fewer products with 3 lb/gal, instead opting for 4.5 lb/gal products. Relatedly, they are less likely to purchases generics and they tend to purchase products with slightly higher prices. In work not reported here, we found that the two groups have similar geographic distributions, ameliorating any concern that these differences are due to unaccounted for regional effects.

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[5] We use the 2003-2011 sub-period because if we used the entire period the coefficients for the rationally attentive individuals would be biased downward by construction.,i.e., they are precisely those individuals for whom we do not observe a concentration effect in the 2000-2002 interval.

--Table 6--

Table 7 reports the coefficients for each of the two sub-groups. Overall, the coefficients are tightly estimated. For the non-concentration variables, the coefficients are similar. The price coefficients are almost the same and the generic coefficients are not statistically different. Rationally attentive individuals apply slightly less pre-plant and slightly less on corn.

--Table 7--

For the concentration parameters, two findings emerge. First, even rationally attentive individuals apply glyphosate at higher rates with more concentration 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 1.5 standard dose for 4.5 lb/gal is 32 fl oz/acre, the historically standard rate for 3 lb/gal products. The second finding is that the concentration effect for rationally attentive individuals is statistically significantly lower than the effect for all other individuals. In most cases, about 30% lower, the exception being at 5 lb/gal, where the effect is nearly 66% lower. Overall, we interpret this as strong evidence that part of what is driving the concentration effect is rational inattention.

Implications

Using our estimates from Table 7, we simulate two counterfactuals: 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 is simulated to give an upper bound on the concentration effect. We simulate two variables of interest: total annual glyphosate use and total annual glyphosate revenue. In running this simulation, we are implicitly assuming that firms would not have adjusted their product lines or prices in a world with slightly different demand patterns. While this is probably not exactly true, the fact that the glyphosate market is highly competitive means that the assumption of unchanged prices is not far from the truth.

Counterfactual Use and Costs

Table 8 presents the simulated quantities and revenues in millions of U.S. dollars. The "*Status Quo*" column contains the predicted values using the estimated parameters for each subset of individuals from Table 6. The "All Informed" column sets the concentration parameters to the estimated values from the "Rationally Attentive" column in Table 6. Finally, the "No Concentration Effect" predicts values with the concentration parameters all set to zero. We obtain individual predictions of glyphosate use by multiplying an individual's predicted application rate with the observed quantity of area they treated with glyphosate. Predicted revenues are then generated by multiplying by prices. Because we estimate the parameters during the 2003-2011 period we restrict our predictions to this time frame.

--Table 8--

If all individuals had 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 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 the revenues. The average annual increase in revenue from higher concentration products, based on the "All Informed" scenario, was about $59 million (4.5%), with a high of $86.5 million (5%) in 2008 and 2009. Relative to the no effect scenario, the average increase was $191 million (14.6%), with a high of $280 million (15%). There are a couple of ways to interpret these values. One is 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 increased revenues constitute a transfer of rents from agricultural producers to glyphosate firms. The greater revenue received by glyphosate sellers is a source of pure profits. Interestingly, we can break down the surplus among glyphosate firms. 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 produces. 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. Given that corn and soybeans are not the only source of glyphosate revenues, these values contributed a nontrivial amount to Monsanto's bottom line.

Conclusion

This paper explores the impact of changing glyphosate concentration levels on U.S. farmers' application rates. We find that farmers apply higher concentration glyphosate products at significantly higher application rates, 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 inattention and/or mindless behavior.

In recent years, the preponderant view among economists of the ways that economic decisions are made has shifted from that of rational and consistent choice to a broader viewpoint 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). 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 proprietors 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 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. 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. This would not only increase profitability but ameliorate concerns about any adverse impacts the chemical may have on ecological and human health. More generally, our work points to the need to investigate these issues for other, possibly more concerning, pesticides. 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 with low school attendance rates and where application is commonly by hand.

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Figures and Tables

Figure 1. Glyphosate Concentration Shares and Application Rates in U.S. Corn and Soybeans

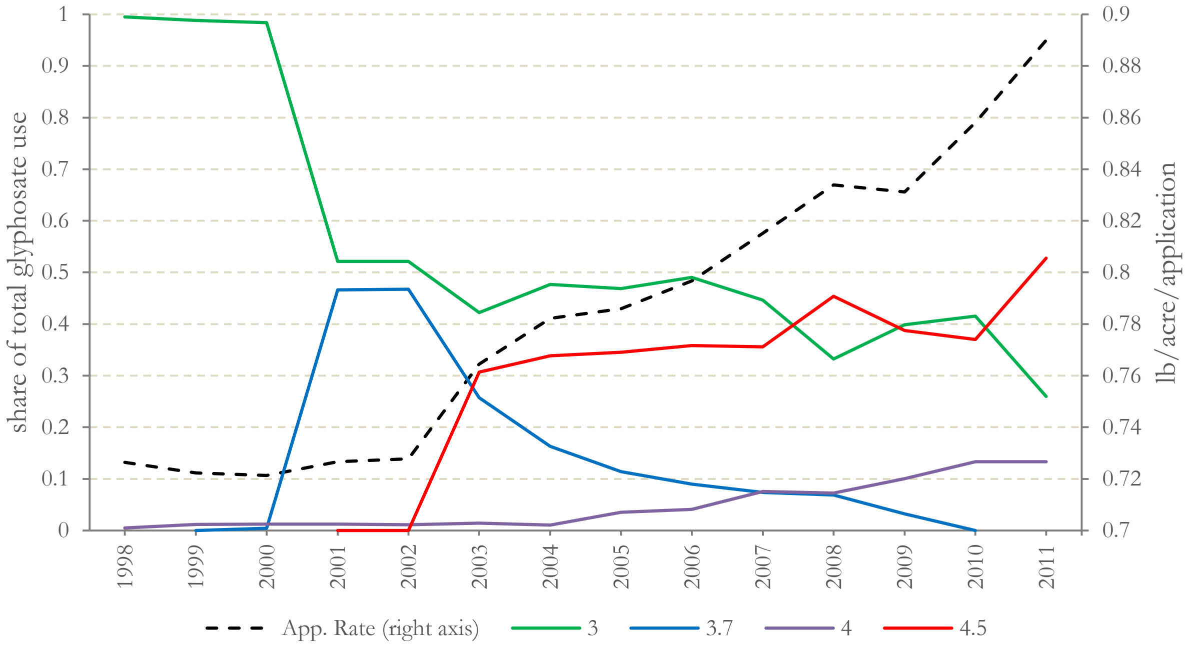

Figure 2. Selected Top Product Histograms

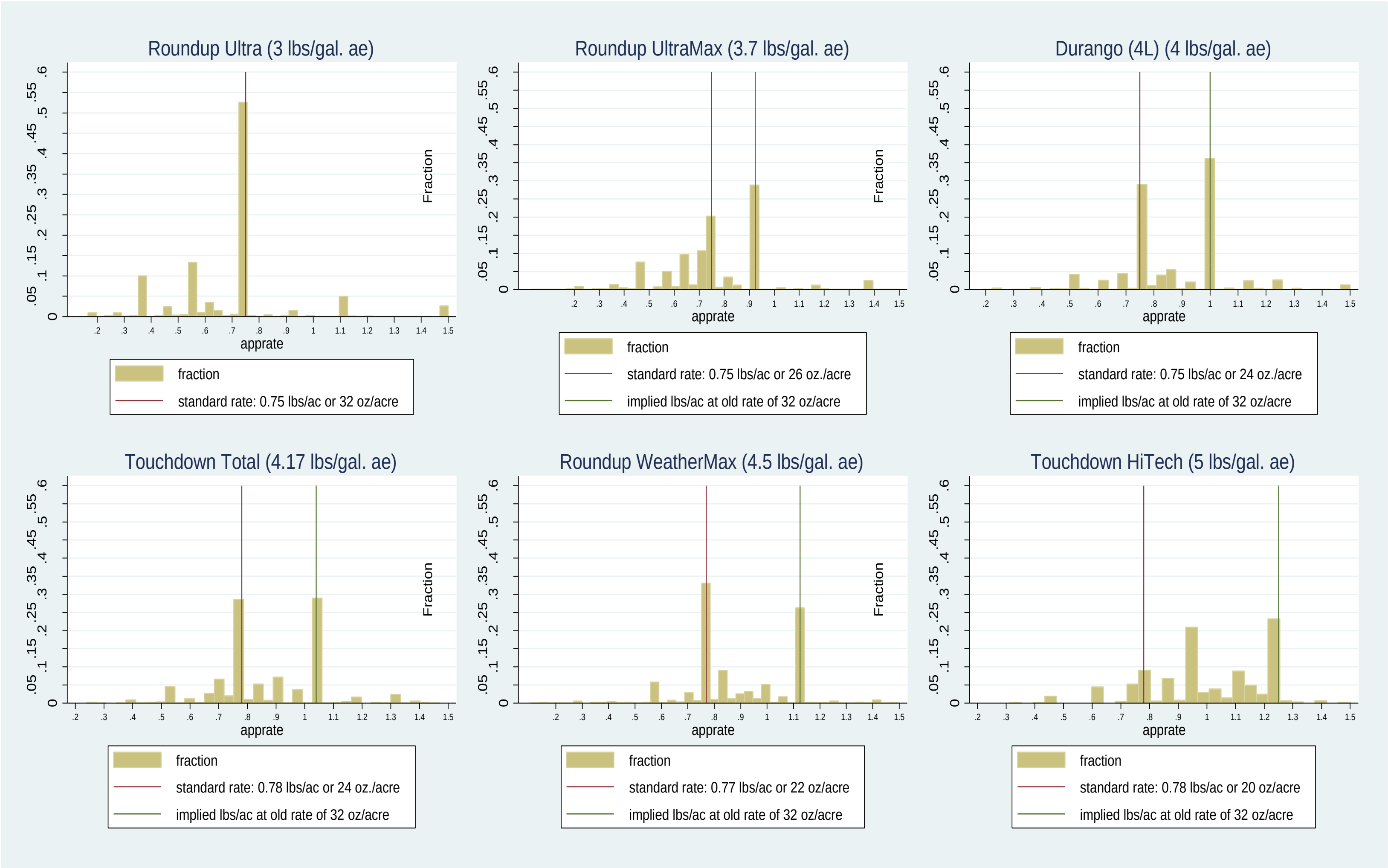

Table 1. Trends in the U.S. Glyphosate Market

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

[a]lb/acre of glyphosate *conditional* on using glyphosate.

Table 2. Comparison of Application Rates for common glyphosate formulations

	----Glyphosate Formulation----		0.75 lb ae/acre standard 1x dose	1.13 lb ae/acre 1.5x dose
Salt	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

Table 3. Prices and Application Rates for the top three glyphosate concentrations

Year	Overall Rate lbs ae/acre	Rate (lb/acre) by Concentration			Price ($/lb ae) by Concentration		
		3 lb/gal	3.7 lb/gal	4.5 lb/gal.	3 lbs/gal.	3.7 lbs/gal	4.5 lbs/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

Table 4. Summary Statistics

Variable	Mean	S.D.	Min	0.25	Mdn	0.75	Max
Application Rate	0.82	0.29	0.01	0.75	0.75	0.92	4.69
Concentration	3.58	0.66	3	3	3	4.5	5
3	0.54	0.5	0	0	1	1	1
3.7	0.1	0.3	0	0	0	0	1
4	0.06	0.24	0	0	0	0	1
4.17	0.03	0.18	0	0	0	0	1
4.5	0.26	0.44	0	0	0	1	1
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 deflated by the USDA crop sector index for price .

Table 5. Basic Regression Results

	(1)	(2)
Concentration	0.1431***	
	(0.0017)	
3.7		0.1065***
		(0.0031)
4		0.1450***
		(0.0035)
4.17		0.1313***
		(0.0045)
4.5		0.2253***
		(0.0031)
5		0.2763***
		(0.0106)
Price	-0.0035***	-0.0034***
	(0.0002)	(0.0002)
Corn	-0.0089***	-0.0087***
	(0.0014)	(0.0014)
Pre-plant	-0.0252***	-0.0252***
	(0.0015)	(0.0015)
Generic	0.0189***	0.0293***
	(0.0025)	(0.0030)
No-till	0.0019	0.0018
	(0.0017)	(0.0017)
N	184,782	184,782
R^2	0.086	0.087

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All regressions include farmer-specific and time fixed effects.

Table 6. Summary Statistics for "Rationally Attentive" Individuals and "Everyone Else", 2003-2011

	"Everyone Else"	"Rationally Attentive"
Application Rate	0.843	0.818
	(0.284)	(0.232)
3	0.464	0.391
	(0.499)	(0.488)
3.7	0.0667	0.0673
	(0.250)	(0.251)
4	0.0771	0.0708
	(0.267)	(0.257)
4.17	0.0456	0.0229
	(0.209)	(0.150)
4.5	0.340	0.443
	(0.474)	(0.497)
5	0.0068	0.0052
	(0.082)	(0.072)
Price	9.507	10.55
	(5.006)	(5.390)
Corn	0.470	0.424
	(0.499)	(0.494)
Pre-plant	0.247	0.222
	(0.431)	(0.416)
Generic	0.527	0.427
	(0.499)	(0.495)
No-Till	0.465	0.447
	(0.499)	(0.497)
Observations	132,065	9,119

Table 7. Regression Results of "Rationally Attentive" Growers and "Everyone Else"

	"Everyone Else"	"Rationally Attentive"
3.7	0.1232***	0.0719***
	(0.0046)	(0.0135)
4	0.1525***	0.1088***
	(0.0037)	(0.0116)
4.17	0.1392***	0.0905***
	(0.0046)	(0.0192)
4.5	0.2490***	0.1701***
	(0.0037)	(0.0106)
5	0.2976***	0.0986***
	(0.0109)	(0.0356)
Price	-0.0037***	-0.0033***
	(0.0003)	(0.0008)
Corn	-0.0099***	-0.0208***
	(0.0015)	(0.0049)
Pre-Plant	-0.0239***	-0.0369***
	(0.0017)	(0.0056)
Generic	0.0345***	0.0435***
	(0.0037)	(0.0112)
No-till	0.0037*	-0.0079
	(0.0020)	(0.0063)
N	132,065	9,119
R^2	0.101	0.081

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All regressions include farmer-specific and time fixed effects.

Table 8. Predicted Glyphosate Quantity and Revenue in U.S. Corn and Soybeans, 2003-2011

	---Total Quantity (millions of lbs.)---			---Total Cost ($ in millions)---		
Year	Status Quo	All "Informed"	No Concentration Effect	Status Quo	All "Informed"	No Concentration Effect
2003	90	87	79	1,539	1,474	1,331
2004	100	97	89	1,387	1,327	1,196
2005	107	103	94	1,173	1,122	1,014
2006	110	106	97	1,064	1,018	921
2007	131	126	115	1,076	1,030	929
2008	163	155	138	1,726	1,639	1,450
2009	164	157	142	1,862	1,776	1,582
2010	176	169	153	1,096	1,046	932
2011	181	172	151	858	812	709
Mean	136	130	117	1,309	1,250	1,118