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Abstract

This paper documents an externality from the agricultural use of the most widely applied herbicide in human history—glyphosate—on birth outcomes of surrounding populations. We focus on the subclinical effects of water contamination in areas distant from the original locations of application. Our identification relies on: (i) the regulation allowing the introduction of genetically modified seeds in Brazil; (ii) the potential gain in municipality-level productivity from adoption of genetically modified soybean seeds; (iii) the strong complementary between glyphosate and genetically modified soybean seeds; and (iv) the direction of water flow within water basins. We document a deterioration in birth outcomes for populations downstream from locations that exogenously expanded glyphosate use, with no effect for populations upstream from these locations. We provide several pieces of evidence indicating that this effect is related to water contamination from expansions in soybean production and rule out alternative channels other than glyphosate. Despite ongoing controversy, little is known about the externality imposed by pesticides on the health of human populations at large. This externality, nevertheless, is essential for assessing the net benefit from the adoption of new agricultural technologies. We provide a first piece of evidence on this type of externality.

JEL: I18, Q53, Q15, O33.
Keywords: glyphosate, herbicides, birth outcomes, infant mortality, water, externalities.

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1 Introduction

Humans have a long history of use of substances to fight pests and increase agricultural productivity. The emergence of pesticides—substances that kill weeds and pests with limited harm to crops—is in fact intimately linked to the development of agriculture itself. Archaeological evidence identifies the first instance as the use of sulfur in Sumer, dating back to around 2500 B.C. (Taylor et al., 2007). These substances, nevertheless, can also have negative health and environmental effects, leading in modern times to regulatory restrictions and sometimes prohibition. The most emblematic case is DDT, a once widely used insecticide later on banned due to its perceived negative consequences (Carson et al., 1962). The regulation of pesticides is therefore a textbook externality problem: optimal policy should find the delicate balance between the productive benefits of use and the negative external effects. The main challenge to policy, though, is that these externalities are difficult to assess. First, adoption of new agricultural technologies—of which pesticides are a particular example—is not exogenous to local development and socioeconomic conditions (Feder et al., 1985). Second, new technologies increase productivity and, as a result, may affect local socioeconomic outcomes through various channels (Bustos et al., 2016; Bharadwaj et al., 2018; Gollin et al., 2018).

This is particularly true for subclinical toxicity, defined as the effect on populations at large, not subject to direct poisoning but to low level exposure through the ingestion of water or food. Landrigan (2018) notes that "(...) recently, understanding has increased that acute poisoning is only the visible tip of a large iceberg and that pesticides are capable of causing a wide range of asymptomatic effects at levels of exposure too low to produce overt signs and symptoms (p.E.1)".[1] Small concentrations of pesticides are recurrently detected in the bodies of the majority of individuals in Western societies, including those who live in urban areas and have no direct contact with the respective substances. The population potentially affected by subclinical toxicity is therefore much larger than that affected by direct poisoning (Landrigan, 2018). But it is not clear whether such low concentrations indeed have any negative health implications. Small probabilistic effects spread over very large populations limit the potential role of lab experiments due to lack of statistical power, but, at the same time, mean that aggregate welfare losses may be substantial. Understanding the externalities from pesticide use can contribute to a public debate that, up to now, has been dominated by organized economic interest and scientific controversies (Mesnage and Antoniou, 2017; Landrigan and Belpoggi, 2018). Natural experiments, in this setting, can provide uniquely relevant evidence to establish the plausibility of these external effects and to guide policymaking.

In this paper, we focus on the effect of the agricultural use of glyphosate (*N-phosphonomethyl-glycine*) on health outcomes of surrounding populations. Glyphosate is the most heavily used herbicide in human history, accounting in 2017 for 30% of the aggregate value of the international herbicide market (Benbrook, 2016; DataIntelligence, 2020). In the European Union, where it is tightly controlled, it accounts for 34% of the total use of herbicides (2017 weight of active ingredients, from Antier et al., 2020). In the top producers of soybean, whose genetically modified seeds are highly complementary to glyphosate, these numbers are even higher. In the US, which is estimated to have been responsible for 19% of the historical global usage, glyphosate represents over 50% of the total use of herbicides (Benbrook, 2016; Osteen and Fernandez-Cornejo, 2016). In Brazil, which currently alternates with the US as top soybean

[1] According to Landrigan (2018), this understanding "(...) is based on the recognition that there exists a dose-related continuum of toxic effects ranging from clinically obvious poisoning at high exposure levels down to functional alterations at lower exposures (p.E.1)".

producer and is the focus of this paper, it accounts for 62% of total herbicide use, and over 35% of total pesticide use (averages from 2009 to 2016, from Alcantara-de-la Cruz et al., 2020). In 2016, glyphosate's sales in Brazil added up to more metric tons than the aggregate sales of the next seven top-selling pesticides (Vasconcelos, 2018). Worldwide, glyphosate usage increased fifteen-fold since the development of glyphosate-resistant ("Round-up Ready") genetically modified seeds, in particular soybean seeds, in the mid-1990s. Some fear that, with the ongoing development of new varieties, its usage may grow by yet another 800% between 2017 and 2025 (DataIntelligence, 2020).

We take advantage of the natural experiment represented by the introduction of genetically modified soybean seeds in Brazil to assess the impact of glyphosate use in agriculture on birth outcomes of surrounding populations sharing the same water resources. The first generations of genetically modified soybean seeds were specifically engineered to be resistant, and therefore complementary, to the use of glyphosate. This combination was responsible for major gains in agricultural productivity in the developed and developing world, leading to substantial economic changes (Bustos et al., 2016). Their initial introduction in Brazil in the mid-2000s represented a revolution in soybean production, moving the country from a marginal position to a leadership role in international markets. Meanwhile, the use of glyphosate quickly grew, through the expansion of the soybean frontier and the replacement of up to 40 different kinds of herbicides previously used (Gazziero, 2005; Young, 2006; Pignati et al., 2014; USDA, 2016). Total glyphosate applied in Brazilian agriculture tripled from 2000 to 2010, from 39,515 to 127,586 metric tons (IBGE, 2012).

We look at municipalities in the main soybean-producing regions of Brazil and concentrate on the period between 2000 and 2010, when soybean production expanded rapidly following the introduction of genetically modified seeds. We focus on the externality at large—what the toxicological literature calls subclinical toxicity—not on the effect of use for those handling or directly exposed to glyphosate. In doing so, we deal with both empirical challenges typical of the estimation of the impact of pesticide use on human health. First, in order to address the endogeneity of technology adoption, we build an instrument for the introduction of genetically modified soybean seeds based on the natural suitability of different areas and on the timing of the regulatory change that allowed their use in the country (as Bustos et al., 2016). The instrument is also essential to deal with measurement error in our variable for glyphosate use at the municipality level. Second, we focus on the effect of glyphosate use in one area on health outcomes in other areas that share the same water resources, minimizing the potential bias from the effect of increased agricultural productivity on local socioeconomic outcomes. This allows us to use the direction of water flow inside water basins to isolate the effect through water contamination and to validate our empirical strategy. If our strategy indeed works, health outcomes in a given location should be affected only by the use of glyphosate upstream, but not downstream, from it.

Our design isolates specifically the externality from long-distance water contamination, which we advance is due to glyphosate. We present various pieces of evidence to support these two steps in our argument. The interpretation of our instrumental variable is key in this respect. From the perspective of a municipality that shares its water resources with other areas, our instrument should be interpreted as generating exogenous variation in the use of glyphosate in these other areas, not in the municipality itself.

We use data from the Brazilian Ministry of Health on births and mortality, information on the structure of water basins from the Brazilian National Waters Agency, and various auxiliary data sources. Our analyses and robustness exercises concentrate on infant mortality, but we also present results for other birth outcomes. We focus on events surrounding birth because the exposure period can be clearly identified, as opposed to potential long-term effects of continued exposure, which would require longitudinal data with past history of residence. In addition, human embryos during the gestational period are particularly responsive to environmental conditions and laboratory research has shown that glyphosate can affect placental cells, disrupting fetal development, and also that it can cross the placenta directly reaching the fetus *in utero* (Richard et al., 2005; Benachour et al., 2007; Benachour and Séralini, 2009; Poulsen et al., 2009).

Our main results show that locations receiving water from areas that expanded the use of glyphosate experienced significant deteriorations in birth outcomes. We estimate significant increases in infant mortality, in the incidence of pre-term births, and in the frequency of low birth weights. According to our preferred specification, the average increase in glyphosate use in the sample during this period led to an increase in the infant mortality rate of 0.88 per 1,000 births (or 5% of the average). This corresponds to an yearly average of 0.45 death per municipality, adding up to a total of 503 infant deaths per year. Since we are looking at areas distant from locations of use and focusing only on infant mortality, this number is likely to underestimate the overall externality of glyphosate use on human health. This type of long-range externality of pesticides through the contamination of water bodies has not been documented before in the literature, either in the case of glyphosate or any other pesticide.

Looking at causes of death, we show that this mortality response is consistent with what would be expected from exposure to glyphosate during pregnancy. Approximately 75 percent of the overall effect on mortality comes from only two causes of death: perinatal period conditions, accounting for 56 percent of the total effect, and respiratory conditions, accounting for the remaining 19 percent. Glyphosate has been documented to affect human placental cells in a laboratory setting, so it should be expected to affect nutrition and oxygenation *in utero*, possibly disrupting fetal growth (Richard et al., 2005; Benachour et al., 2007; Benachour and Séralini, 2009; Poulsen et al., 2009). Through its endocrine disruptor activity, it might also generate problems of malformation. Issues related to fetal growth, malformation, and placental dysfunction would all end up reflected on mortality due to perinatal period conditions. Respiratory problems among infants—particularly respiratory distress syndrome and chronic lung disease—are the most common complications from prematurity, so they are also likely to be affected by these same factors (Behrman and Butler, 2007). The following two largest estimated effects among causes of death—already not statistically significant—are for congenital anomalies and endocrine conditions, both of which are also likely to be affected by glyphosate. Together with the significant effects on perinatal and respiratory deaths, these add up to 93% of the total estimated impact on infant mortality. We find very small coefficients and no significant impact for other causes of death, including some with high overall incidence (e.g., infectious diseases, external causes, and ill-defined causes).

We conduct a series of additional exercises to provide evidence that the effect that we estimate is indeed associated with the use of glyphosate. There are three main threats to identification that we address in these exercises. First, we show that the documented effect is indeed working through water bodies and that it is associated with something that is carried from surrounding soil into the water. Second, we show that the effect is indeed associated with the expansion of soybean production, and not a result of some spurious spatial correlation or overall expansion in agricultural activity. And third, we show that it is not due to some other form of water contamination brought about by the expansion in soybean production.

On the first point, we present several pieces of direct evidence. We start by showing that mortality effects are only present when there is an increase in glyphosate use upstream from a given municipality, and that the effects are absent when the expansion in glyphosate use is downstream from it. Following, we draw from the scientific literature to characterize the contexts in which the risk of water contamination with glyphosate should be higher. Borggaard and Gimsing (2008) explain that the risk of surface water contamination by glyphosate should be higher when there is sufficient rainfall and where the soil is more erodible. In reduced-form estimates, we show that our estimated effect is only significant when rainfall during the glyphosate application season is above a minimum level and where soil erodibility is sufficiently high. We show as well that rainfall in other times of the year, when glyphosate is not being applied, does not interfere with the estimated effect. Additionally, we show that the estimated effect is higher (though not significantly at usual levels) for municipalities that make use of surface, rather than underground, sources of water, and that the effect becomes smaller as the distance between the source and receiving municipalities increases. By exploring month of birth, we also show that estimated effects are systematically higher for births with a longer *in-utero* exposure to the glyphosate application season. Lastly, we show that there are no significant economic spillovers from upstream areas that could plausibly explain these documented effects.

On the second point, we present two pieces of evidence to show that the estimated effect is particularly related to soybean production. We first estimate the reduced form of our model using an event-studies type of framework and show that estimated effects are close to zero and not statistically significant before the use of genetically modified seeds was officially authorized in Brazil. Second, we estimate our first stage using corn—the second main crop in terms of area planted—instead of soybean and find coefficients that are close to zero and not statistically significant. For technological reasons, the marginal gain in productivity from the introduction of genetically modified corn seeds in the mid 2000's was small (Young, 2006). In addition, the importance of glyphosate in corn and other major crops is orders of magnitude smaller than in soybean. These two points are essential because they indicate that the effect we document is not related to an overall increase in agricultural productivity during this period. It is particularly associated with the technological innovation represented by the introduction of genetically modified soybean seeds and the changes that it brought together.

On the third point, the main concern is that expansion in soybean production upstream from a municipality could have affected the environment and contaminated water bodies in other ways besides the use of glyphosate. This could have been the case through changes in the pattern of land use or through water contamination by other chemicals used in soybean production. We present evidence that, if anything, changes in patterns of land use are likely to have contributed to reduce water contamination. We show that the most important change in land use was a substitution on an almost one-to-one basis of pasture by agricultural area. This is in line with anecdotal and historical accounts of the way the process of soybean expansion took place in Brazil (Brandao et al., 2006; Neto, 2017). We find no significant effect on the coverage of forest area, native non-forest area, or total farming area. If anything, point estimates indicate a small increase in forest coverage and a small reduction in total farming area (of very similar magnitudes), consistent with the "Borlaug hypothesis" of increased intensiveness of agricultural activity, as documented by Gollin et al. (2018) in a cross-country context. Given that the soybean expansion was mostly based on a "no-tillage" technique, the switch from pasture to agricultural areas is likely to have improved natural water filtration, in particular if forest coverage increased.[2] Using the very limited

[2] Tillage is a technique used to prepare the soil before planting. It consists in mechanically agitating the soil and is used to

data available on direct measurements of water pollution, we show that this indeed seems to be the case. There is no significant effect of soybean expansion on common indices of water pollution downstream from the locations of use. And, again, if anything, point estimates suggest that it was associated with a marginal reduction in pollution.

The last threat to identification mentioned in the previous paragraph is that other substances used in soybean production, rather than glyphosate, could account for the documented effect. This does not seem plausible since the introduction of genetically engineered soybean seeds increased the use of glyphosate but greatly reduced the use of other herbicides (Young, 2006; Gazziero, 2005). Estimates suggest that glyphosate typically represents well over 70 percent of the total volume of herbicides used in soybean production (in terms of weight active ingredients).[3] For no other active ingredient there is such a difference in intensity of use across soybean and other major crops (Pignati et al., 2014). All the evidence indicates that, in terms of use of chemicals, the only peculiar aspect of the expansion in genetically modified soybean production was its overreliance on glyphosate. Our results related to cause of death, rainfall and month of birth, discussed in previous paragraphs, further reinforce this point. In particular: (i) mortality effects are concentrated on causes of death that should be affected by glyphosate exposure; (ii) upstream rainfall significantly impacts the estimated effect only during the glyphosate application season, but not during the remainder of the year; and (iii) estimated effects are larger for births with longer *in utero* exposure to the glyphosate application season.

Glyphosate was historically classified as a low toxicity pesticide, meaning that it was considered safe at environmentally realistic concentrations (Borggaard and Gimsing, 2008). Reviews of observational studies in toxicology, for example, claimed that the "... available literature shows no solid evidence linking glyphosate exposure to adverse developmental or reproductive effects at environmentally realistic exposure..." (Williams et al., 2012, p.39). But this view has been recently challenged by lawsuits in the US and the threat of ban in Europe, and by laboratory evidence showing that, even at concentrations below regulatory limits, glyphosate can damage human cells (Benachour et al., 2007; Mesnage et al., 2015; Economist, 2016; Hakim, 2017).[4] The case of glyphosate therefore highlights in an extreme fashion the trade-off between agricultural productivity and health implicit in the regulation of pesticides. We show here that there indeed exists a subclinical externality from glyphosate use affecting populations through water contamination over long distances.

There is a vast array of correlational and case studies on the effect of pesticides in general on human health, focused on small populations directly exposed to pesticides or living in agricultural communities where they are used (e.g., Antle and Pingali, 1994; Antle et al., 1998; Arbuckle et al., 2001; Sathya-

aerate, loosen the top layer, and mix organic matter and nutrients. However, it also has important downsides: it makes the soil lose nutrients and its ability to retain water, reduces organic matter, dries the soil before seeding, and induces erosion.

[3]After an initial overreliance in glyphosate and the appearance of resistance among some pests, subsequent use of glyphosate was enhanced and also combined with other herbicides. By 2012, evidence from case studies indicate that glyphosate represented typically between 66 and 81 percent of the total volume of herbicides' active ingredients used in soybean production. The remainder 19-34 percent were more evenly distributed among between 2 to 5 active ingredients, with none individually being used in more than 18 percent of the volume of glyphosate (Pignati et al., 2014). The number for glyphosate were very likely higher during the first years of adoption, since resistance among pests was lower.

[4]There is some discussion in the toxicology literature as to whether glyphosate itself or its commercial formulations, such as Roundup, are more toxic (see, for example, Benachour et al., 2007 or Watts et al., 2016). Commercial formulations are typically composed of a combination of glyphosate, water, salts and adjuvants. Adjuvants are substances that promote the toxicity of the active principle, increasing its potential as a pesticide (Mesnage et al., 2015). We make no distinction in the text between glyphosate and its commercial formulations. Given our empirical setting, our results refer strictly to the commercial formulations typically used in soybean production.

narayana et al., 2010; de Siqueira et al., 2010). Some of these papers document that increased pesticide use is associated with deteriorations in health, while other papers report inconclusive results. Surprisingly enough, causal evidence of the effect of pesticide use on health outcomes outside of laboratory settings is extremely scarce. Frank (2016) exploits a mortality shock to bats—a predator of some insects that attack crops—to show that increased use of insecticides leads to increases in infant mortality rates. Maertens (2017) uses the expansion of corn production driven by the Renewable Fuel Standard in the US to show that increased use of the pesticide atrazine is associated with increases in fetal malformation and perinatal deaths. Camacho and Mejia (2017) show that the unchecked aerial spraying of coca producing areas in Colombia with glyphosate, during the "Plan Colombia" campaign to eradicate coca production, led to increases in miscarriages and in medical consultations due to dermatological and respiratory conditions. Finally, Taylor (2019) uses cicada cycles in orchard areas of the US to show that insecticide use increases infant mortality and worsens long-term educational outcomes of affected cohorts. These papers focus on the local impacts in areas where pesticides are applied and typically do not account explicitly for the effect of pesticide use on local incomes and socioeconomic conditions. Most importantly, they do not consider externalities imposed on human populations at large.

Our paper also relates to the large literature on the health effects of various other forms of environmental contamination (e.g., Chay and Greenstone, 2003; Currie and Neidel, 2005; Winchester et al., 2009; Brainerd and Menon, 2014; Clay et al., 2016). Specifically, from a methodological perspective, our use of the information on water basins bears similarities to Ebenstein (2012), who looks at the health effects of water pollution in China. The way we leverage the direction of water flow, in turn, is reminiscent of Lipscomb and Mobarak (2017), He et al. (2018), and Rangel and Vogl (2019), who analyze, respectively, the political economy of environmental regulations in Brazil, the economic costs of enforcement in China, and the impact of harvest fires on health at birth also in Brazil.

We have two main contributions to the literature. First, we document a health externality for populations at large, distant from locations of pesticide use, through water contamination. This type of subclinical health effect over long distances has not been documented before, even though it is a recurrent conjecture in the medical literature (see, for example, Landrigan, 2018). This externality partly offsets the local benefits from productivity gains—such as documented by Bustos et al. (2016)—being therefore essential for any economic assessment of the net welfare benefits from the adoption of new agricultural technologies. Second, we focus on glyphosate, the most widely used herbicide in human history, in a context of common agricultural use, where it has been traditionally considered safe (Borggaard and Gimsing, 2008). The presence of subclinical externalities in this setting suggests that current monitoring and regulations on the handling and use of pesticides should go through a profound revision process. This should be a first order concern, above all, to the main soybean producers in the world—Argentina, Brazil, and the US—, but also to other countries where specific types of pesticides are heavily used and where scientific controversies have created substantial regulatory uncertainty.[5]

The remainder of the paper is organized as follows. Section 2 provides the background on glyphosate and its use on soybean production in Brazil, and discusses the expected effects of glyphosate on birth outcomes. Section 3 describes the data used in the paper. Section 4 presents our empirical strategy. Section 5 reports our findings. Finally, Section 6 concludes the paper.

[5]For instance, in 2017 the European Commission extended the authorization for glyphosate use for another 5 years, until 2022, when regulation will once again be reassessed.

2 Background

2.1 Glyphosate

Glyphosate is, nowadays, the most used herbicide in the world. Discovered in 1970 by Monsanto and first commercialized in 1974 under the name Roundup, it is a systemic, post-emergence, non-selective, foliar applied herbicide. This means that it is used after the emergence of weeds, that it is absorbed by the exposed parts of the plant and translocated through the whole plant, and that it affects any kind of plant (Vats, 2015). It is also used as a crop desiccant, meaning that it can be applied before harvest to speed up the maturation process.

Glyphosate was rapidly adopted by farmers, particularly after genetically modified soybean seeds resistant to glyphosate, also developed by Monsanto and commercialized under the name Roundup Ready Soybean, were introduced. Varieties of these seeds adapted to the different climatic conditions found in Brazil were developed with great success (Roessing and Lazzarotto, 2005).

Regarding the use of glyphosate in transgenic soybean, the Roundup Ready leaflet instructs that glyphosate can be applied in a single dose or sequentially, in two doses with an interval of 15-20 days between doses.[6] It also advises that weeds are best controlled when the herbicide is applied from 20 to 30 days after soybean emergence—which, considering Brazilian characteristics, is expected to happen 7-10 days after planting (Mundstock and Thomas, 2005). Hence, in this case, glyphosate should be applied from 27 to 60 days after planting. Since soybean is planted between October and January in Brazil, glyphosate application season typically ranges from October to March.

Glyphosate is applied after mixed with water, by manual or aerial spraying. The minimum recommended interval between last application and harvest is 56 days. There is also an indication of the ideal climatic conditions for application: no more than 28º C, minimum relative humidity of 55 percent and maximum wind velocity of 10km/h (3m/s).

2.2 Genetically Engineered Soybean

Genetically engineered soybean was developed by Monsanto and first commercialized in the US in 1996. In Brazil, its initial adoption history was convoluted. A first authorization to use transgenic soybean was approved in 1998, but the judiciary suspended it immediately afterwards. In early 2003, the government temporarily authorized commercialization of transgenic soybean production, but also established that producers should incinerate the remaining stock in order to prevent the use of genetically engineered seeds in the following year (*Medida Provisória*, or Provisory Measure, MP 113 from March 2003, later transformed in Law 10.688/2003). However, MP 131 from September 2003 (later, Law 10.184/2003) authorized producers who still had genetically engineered seeds from the previous season to cultivate them and MP 223 from October 2004 (later, Law 11.092/2005) renewed the authorization to commercialize the product of transgenic soybean seeds. Finally, in March 2005, the New Bio-Safety Law (law 11.105/2005) permanently authorized the production and commercialization of genetically engineered soybean.[7]

This convoluted history is partly explained by the fact that some smuggling of transgenic seeds from Argentina into Brazil had been taking place even before 2003 (USDA, 2001; Gazziero, 2005). The extent

[6] Available at http://www.monsanto.com/global/br/produtos/documents/roundup-ready-bula.pdf

[7] EMBRAPA (2003), Gazziero (2005), and Meyer and Cederberg (2010) discuss the legal battles surrounding the introduction of genetically modified soybean seeds in Brazil.

of smuggling was limited and, due to its proximity to Argentina, mostly restricted to the southernmost state of Rio Grande do Sul (EMBRAPA, 2003). But pressure from a group of producers using smuggled seeds was enough for the government to issue the Provisory Measures MP 113 and MP 131 in 2003 (Barboza, 2004). Roessing and Lazzarotto (2005), writing before the approval of the New Bio-Safety Law in 2005, argue that MP 131 was taken as a strong signal that the government was willing to accommodate the demands of farmers even before the law was finally approved by congress. With MP 131 holding from the end of 2003 into 2004, and being followed in October by MP 223, Roessing and Lazzarotto (2005) state that there was widespread expectation that the law would eventually be approved and that, in the meantime, the government would extend temporary authorizations through Provisory Measures for as long as necessary. Meyer and Cederberg (2010), similarly, identify the planting season from the end of 2003 to the first months of 2004 as marking the beginning of the widespread introduction of genetically engineered soybean in Brazil. For our purposes, therefore, it seems reasonable to define 2004 as the first year of adoption of transgenic soybean in the country. This is also supported by the data presented in Figure 1, which shows that area planted with soybean per worker increased slowly since the 1990's, but experienced a sharp change in trend after 2004, reflecting the gradual adoption of the new technology..[8]

The use of transgenic soybean is so advantageous because of its resistance to glyphosate-based herbicides, of which the main commercial formulation is Monsanto's Roundup (Young, 2006). Since glyphosate is a non-selective herbicide, being therefore effective against a wide spectrum of different species, it facilitates the control of weeds. Its initial introduction in soybean production in Brazil replaced close to 40 products or combinations of products that were previously used to fight specific weeds (Gazziero, 2005). The resistance of genetically engineered soybean means that glyphosate can be used after emergence without harming the crop, also allowing farmers to use more productive techniques like no-tillage. In contrast, traditional seeds require tillage and do not allow the use of glyphosate-based herbicides after planting and emergence, since it would then harm the crop because of its non-selective nature.

Genetically engineered soybean spread fast in Brazil after 2004, with the adoption rate reaching 93 percent by the 2010's (USDA, 2016). After adoption, Brazilian soybean production increased tremendously, doubling in less than 10 years between the late 1990's and the late 2000's (Meyer and Cederberg, 2010). Figure 1 shows that, concomitantly with the gains in soybean productivity, there was a major increase in the use of glyphosate in the country. Total glyphosate in Brazilian agriculture tripled from 2000 to 2010, from 39,515 to 127,586 metric tons, accounting by the end of the decade for 71 percent of the total weight of the active ingredients of herbicides used in the country (IBGE, 2012). Though we cannot identify precisely how much of this increase in glyphosate use was due to soybean, overall use of herbicides in soybean production, of which glyphosate can account for up to 80 percent, more than tripled during this period. A back of the envelope calculation based on the numbers on crop-specific pesticide use presented by Pignati et al. (2014) suggests that soybean alone accounts for between 61 and 88 percent of the increased use of glyphosate observed during this period, with anecdotal evidence indicating that the actual number is likely to be closer to the upper bound.[9]

[8] More specifically, as detailed in Section 3, area planted with soybean per worker increases sharply starting in 2005, which corresponds to the planting season of 2004-2005, while glyphosate use increases starting in 2003 and 2004. These patterns coincide exactly with the beginning of the widespread introduction of genetically engineered soybean seeds in Brazil.

[9] This back of the envelope calculation assumes that glyphosate accounts for 74 percent of the total weight of the active ingredients of herbicides used in soybean production after the introduction of genetically modified seeds (this is the simple average calculated from the numbers presented in Pignati et al., 2014). The lower and upper bounds are obtained by assuming that, before the introduction of genetically modified seeds, glyphosate accounted for, respectively, 74 and 0 percent of the total weight of the active ingredients of herbicides used in soybean production. These numbers are then just applied to the total

2.3 Glyphosate, Water Contamination, and Birth Outcomes

According to Cox (1998), people can be exposed to glyphosate through direct contact in the workplace, through drift,[10] by eating contaminated food, by coming into contact with contaminated soil, and by contact with contaminated water (by drinking or bathing). Glyphosate nevertheless was historically considered a low-toxicity pesticide due to its good physicochemical properties, particularly its high sorption and degradation rates.[11]

The risk of water contamination specifically was considered limited because of quick sorption onto soil minerals and ensuing microbial degradation. But, at the same time, it has always been recognized that this risk should depend on soil characteristics, surface water run-off, and leaching (Borggaard and Gimsing, 2008). In any case, environmental analyses in Argentina, Brazil, and the US—the top-three world soybean producers—have recurrently detected glyphosate in various types of bodies of water, including rivers, streams, ditches, and drains (Edwards et al., 1980; Frank et al., 1990; Rashin and Graber, 1993; Bortleson and Davis, 1997; Peruzzo et al., 2008; Aparicio et al., 2013; Battaglin et al., 2014; de Souza, 2014; Ronco et al., 2016; Primost et al., 2017). Its persistence in water has been documented to be of up to 60 days (Goldsborough and Beck, 1989; Goldsborough and Brown, 1993).

There has been more systematic measurement of the presence of glyphosate in the water in Argentina than in Brazil. In addition, the Argentinean evidence is useful because the country shares similar climatic, geographic, and productive characteristics with one of the main soybean producing areas in Brazil. Various studies in Argentina have detected glyphosate in bodies of water, sometimes in concentrations well above regulatory limits and other times in sites considerably distant from cultivation areas. These studies also document that concentration is strongly affected by run-off and by the occurrence of rain events, and that, at distant sites, it is much higher in rivers for which tributaries go through agricultural areas (Peruzzo et al., 2008; Aparicio et al., 2013; Ronco et al., 2016; Primost et al., 2017). Mesnage et al. (2015) claim that the presence of glyphosate in surface water in the US is ubiquitous, being detected even in areas without genetically modified crops, which means that there is regular ingestion by humans.[12] In Brazil, though there is less evidence available, de Souza (2014) documents similar patterns in terms of presence of glyphosate in the water and Lima (2017) detects the presence of glyphosate in the breast milk of 64 percent of women living and giving birth in one specific area of agricultural production.

For these reasons, despite the fact that glyphosate has traditionally been marketed as a low-toxicity pesticide, concerns related to its potential effect on human health have increased in recent years. These concerns are reinforced by a body of compelling laboratory evidence establishing pathways through which glyphosate could affect humans, in particular during pregnancy.

weight of the active ingredients of herbicides used in soybean, available from the National Union of Pesticide Industries – SINDAG for 2000 and 2009 (these are, respectively, 32,625 and 105,095 metric tons). Young (2006) explains that glyphosate was not used particularly intensively in soybean production before the introduction of genetically engineered seeds, so soybean did not account for a major share of glyphosate use before 2004 (it was just used for weed control before planting, as it is used in any other crop or in gardening). This is why we argue that the number is likely to be closer to the upper bound, meaning that soybean alone would have accounted for close to 90 percent of the expansion in glyphosate use in Brazil during this period. For the US, Young (2006) shows that glyphosate use in soybean increased by twelvefold in only 6 years after the introduction of genetically modified seeds.

[10] Exposure through drift is the exposure caused by off-target movement after the application of the pesticide.

[11] Sorption is the process by which one substance becomes attached to another. Degradation is the rate at which an active ingredient in chemical substances becomes inactive.

[12] Mesnage et al. (2015) also mention that glyphosate has been regularly found in the urine of individuals not involved in agricultural production, but typically at concentration levels considered safe.

An unborn child can be affected by glyphosate *in utero* through contamination of the mother. Richard et al. (2005) and Benachour et al. (2007) demonstrate that glyphosate has a toxic effect on human placental cells. Benachour et al. (2007) investigate the effects of glyphosate on human embryonic and placental cells and how these effects are amplified with dosage and time, suggesting that exposure to glyphosate may affect fetal development. Benachour and Séralini (2009), in turn, show that, even at low concentrations, glyphosate-based herbicides can induce apoptosis and necrosis—i.e., have toxic effects—on human embryonic, umbilical, and placental cells.[13] Another possibility is that the infant herself is exposed directly to glyphosate, since Poulsen et al. (2009) shows that glyphosate can cross the placenta, reaching the infant *in utero*. This mechanism could affect the balance of estrogen through glyphosate's endocrine disruptor activity, affecting the development of testicular cells and testosterone production (Richard et al., 2005; Émilie Clair et al., 2012; Haverfield et al., 2011).

Based on this information, we can conjecture how infants *in utero* should be affected by glyphosate. Since it damages the placenta, which is responsible for fetal nutrition and oxygenation—and, hence, fetal development—, we expect glyphosate to generally worsen indicators of health outcomes at birth (gestational length and birth weight, for example). Ultimately, these problems can also lead to death. In this case, it is likely that most deaths would be either fetal deaths (if occurring before delivery) or deaths due to perinatal period conditions (if occurring during delivery or soon after birth). Also, because of glyphosate's endocrine disruptor activity, we might expect an increase in deaths due to endocrine conditions. Other malformations might also lead to later mortality from more specific causes of death.

3 Data

3.1 Glyphosate Use at the Municipality Level

We do not observe directly the use of glyphosate at the local level. From the Brazilian Environmental Agency (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis* – IBAMA), we have yearly information on aggregate glyphosate use in Brazil.[14] Figure 1 already presented our aggregate glyphosate series for the period 2000-2010. We observe that glyphosate use increases sharply starting in 2003 and 2004. This pattern coincides exactly with the planting season of 2003-2004 being the one that marks the beginning of the widespread introduction of genetically engineered soybean seeds in Brazil.

We impute glyphosate use at the municipality level in two steps. First, for the period 2000-2003, we distribute the aggregate glyphosate in proportion to the area planted with seasonal row crops. More specifically, our glyphosate variable is constructed in the following way. For the period 2000-2003, we use the equation below:

$$muni\_glyph_{it} = country\_glyph_t \times \frac{seasonal\_area_{it}}{seasonal\_area\_country_t}, t \leq 2003, \tag{1}$$

where $muni\_glyph_{it}$ is the use of glyphosate in municipality i in year t, $country\_glyph_t$ is the total amount

[13] Apoptosis is the process of death of cells that happens normally during an organism's development. Necrosis is the death of a major part of the cells in an organ as a result of some external factor.

[14] The IBAMA series is interrupted in the period 2006-2008. We impute data linearly for these years. Qualitative results are identical, and quantitative results very similar, when we use other imputation methods, using, for example, the ratio between glyphosate and overall herbicide use. In the Appendix, we present our benchmark result using various alternative imputation methods.

of glyphosate used in the country in year t (in metric tons of active ingredient), $seasonal\_area_{it}$ indicates the seasonal row crops planted area in municipality i in year t and $seasonal\_area\_country_t$ is the aggregate seasonal row crops planted area in the country in year t.

Seasonal row crops, as opposed to permanent crops, are planted and cultivated on a seasonal or yearly basis. These cover most of the area planted in Brazil and include soybean, corn, sugarcane, cotton, etc. Therefore, since genetically modified soybean seeds had not yet been introduced, we assume that glyphosate was homogeneously used across all temporary crops up to 2003 (proportionally to planted area), as suggested by Young (2006).

Following, from 2004 onwards, we distribute the aggregate increase in glyphosate usage between 2003 and a given year ($\Delta country\_glyph_{t,2003}$) in proportion to the area planted with soybean in that year. More precisely:

$$muni\_glyph_{it} = muni\_glyph_{i2003} + \Delta country\_glyph_{t,2003} \times \frac{soy\_area_{it}}{soy\_area\_country_t}, t \geq 2004, \tag{2}$$

where soy_area_{it} is the soybean planted area in municipality i in year t and $soy\_area\_country_t$ is the total soybean planted area in the country in t. We therefore assume that the increase in glyphosate use in Brazil from 2004 onwards, after genetically modified soybean seeds were introduced, was due entirely to soybean production (and, in the cross-section, was proportional to soybean planted area).

The glyphosate variable used in our empirical exercises is, in the end, the imputed municipality use of glyphosate normalized by the municipality area:

$$glyph_{it} = \frac{muni\_glyphosate_{it}}{area_i}, \tag{3}$$

where $area_i$ is the total area of municipality i.[15]

To follow the logic of the soybean cycles, where planting happens at the very end of a year and harvesting at the beginning of the next, data on soybean area planted on t corresponds to the planting season from the end of $t-1$ to the first months of t. The data on soybean and temporary crops planted area are from the Municipal Agricultural Production dataset from the Brazilian Census Bureau (*Instituto Brasileiro de Geografia e Estatística* – IBGE). This is an annual survey that collects information on area planted, production, and revenue for various crops at the municipality level for the whole country.

Two potential problems of measurement error arise from our imputation of glyphosate use at the municipality level. First, the expansion in glyphosate use after 2003 was not due exclusively to soybean

[15] We tried various other strategies for imputation of glyphosate to municipalities, with virtually no changes to qualitative or quantitative results. These alternative methods make use of aggregate numbers for total herbicides allocated to soybean (of which glyphosate is a major component), of state level herbicide use, and of combinations of these different pieces of information. In addition, we also tested minor variations around our main imputation method (for example, we assigned glyphosate equal to zero until 2003 and, from 2004 onwards, allocated the marginal glyphosate increase using municipality soybean planted; or we assigned glyphosate equal to zero until 2003 and, from 2004 onwards, allocated total glyphosate according to municipality soybean planted area; or, finally, for the entire period, we simply allocated total glyphosate according to municipality soybean planted area). We believe that our preferred strategy, presented in the main text, is the more careful one and the one that makes the best use of the information available. But, as mentioned in the beginning of this footnote, our results are not sensitive to the choice among a vast array of alternative imputation methods. We believe this is the case because of the key role played by the instrument in our identification strategy.

production and a small part of it was likely allocated to other crops. Second, the intensity of glyphosate use in soybean after the introduction of genetically modified seeds may have been different across areas according to local conditions. Our instrumental variable strategy, discussed in detail in the next section, deals with both these problems. It does so by isolating the variation in increased glyphosate use across areas due to the exogenous component of the productivity gain from adopting genetically modified soybean seeds (explained by local climatic and soil conditions).

3.2 Other Variables and Data Sources

Our birth outcomes variables are constructed from the Brazilian Ministry of Health's Birth and Mortality Database, which provides information on infant mortality and birth outcomes by municipality and year. Mortality rates are defined by year of birth and are computed per 1,000 live births accordingly. The Ministry of Health's system of information (DataSUS) also provides data on various local health inputs used as controls in our regressions: local presence of a hospital, number of hospital beds, and presence of a major primary care program called Family Health Program (*Programa Saúde da Familia*). We use census and municipality estimates of GDP and population from IBGE to construct other socioeconomic controls.

Potential yields under different agricultural technologies, which are essential to construct our instrument, are from the FAO-GAEZ database. These data provide maximum attainable yields in a certain area under different technologies, calculated based on a model that accounts for soil and weather characteristics. Yields under "low" technology are those obtained using traditional seeds, no chemicals and no mechanization, whereas yields under "high" technology are those obtained using improved seeds, fertilizers, herbicides, and mechanization.

Data on precipitation, soil erodibility, and local sources of water, used in some heterogeneity exercises, are taken from, respectively, the Willmott & Matsuura University of Delaware's Global (Land) Precipitation and Temperature database, da Silva et al. (2011), and the Brazilian National Waters Agency (*Agência Nacional de Águas* – ANA). Finally, the land-use data analyzed in some exercises are from MapBiomas version 3.0.

3.3 Water Basins and Exposure to Upstream Use of Glyphosate

In order to explore the structure and direction of flow of water basins, key to our identification strategy, we use hydrological data from ANA. The agency provides georeferenced data on the drainage basins of water courses in Brazil, coded with the method developed by Otto Pfafstetter (and hence called ottobasins). A water course's drainage basin is the area of land (topographically defined) where all precipitation flows to this water course. It includes all the surface water from rain runoff and the tributaries of the water course, as well as groundwater. Drainage basins—in our case, ottobasins—are separated by boundaries called drainage divides; precipitation on different sides of a drainage divide flows into different drainage basins.

ANA provides data at different levels of aggregation, starting from level 1 ottobasins—which are drainage basins at the continental level—and going down to more local basins that are subdivisions of the higher levels. Levels 1 and 2 are excessively large—with some ottobasins covering entire states in Brazil—and level 4 ottobasins are too small—with an excessive number of municipalities containing entire ottobasins. Therefore, we focus our discussion on level 3 ottobasins. We also use information on level 4 ottobasins to identify the direction of ottobasin drainage and the upstream and downstream municipalities inside each level 3 ottobasin.

Using the structure of ottobasins, we define the exposure of municipality i to glyphosate used in municipalities upstream from it as the sum of the estimated use of glyphosate in soybean in all municipalities in the same ottobasin upstream from i, divided by the total area of these municipalities. When a municipality is in more than one ottobasin, its contribution to each ottobasin is multiplied by the proportion of its area in each ottobasin. Similarly, when a municipality is in more than one ottobasin, the contribution of each ottobasin to its exposure is weighted by the proportion of the municipality area in each ottobasin. For the uppermost municipalities in a given ottobasin, which do not have any other municipalities upstream from them, we assign value zero to this variable (in the Appendix, we also present results for robustness exercises excluding municipalities without any other municipality upstream from them, without major quantitative or qualitative change). Similarly, we can define the potential soybean productivity under different technologies for the area upstream from a municipality within a given ottobasin.

3.4 Units of Observation and Sample

Since the number of municipalities in Brazil changes over time, we use Minimum Comparable Areas (in Portuguese, *Áreas Mínimas Comparáveis – AMCs*) as units of observation, so that we are able to compare the same geographic units over time. This is a common methodological procedure in most of the empirical literature using municipality level data from Brazil (Reis et al., 2008). Nevertheless, for expositional purposes, we still refer to the units of observation as municipalities throughout the text.

We match ottobasins to municipalities using the municipal shape file provided by IpeaGEO. In Brazil, there are 345 level 3 ottobasins, each including on average 19.6 municipalities—entirely or partially—and covering an area of 39,532 km^2. The median ottobasin has 4 municipalities and an area of 9165 km^2.

Our analysis focuses on the period between 2000 and 2010, when we observe the main expansion in adoption of genetically modified soybean seeds. Also, we restrict the sample to the main soybean producing regions of Brazil—the Center-West and the South—since they concentrate over 80 percent of the Brazilian soybean production and share more homogeneous socioeconomic and geographic characteristics.[16] In these areas, there is a total of 1,119 municipalities, distributed into 57 different level 3 ottobasins (the main water basins considered in our analysis), and into 570 level 4 sub-basins (used to identify the upstream/downstream position of municipalities). The median level 3 ottobasin in the sample includes 13 municipalities—either partially or entirely—and covers an area of 31,974 km^2. The average ottobasin includes 35 municipalities and covers an area of 51,868 km^2.

4 Empirical Strategy

4.1 Identification

We estimate the externality of glyphosate use in agriculture on birth outcomes. There are two challenges in this direction. First, adoption of a certain agricultural technology—in our setting, genetically modified seeds coupled with glyphosate—is not exogenous. Adoption is usually thought to be a function of local

[16] Figure A.1 illustrates the sample region with respective level-3 ottobasins.

entrepreneurship, availability of infrastructure to distribute production, and capacity of local producers to coordinate, as discussed, for example, in the classic work by Feder et al. (1985). All of these factors are likely to be correlated, through various channels, with socioeconomic outcomes. Second, adoption of new agricultural technologies may affect socioeconomic outcomes directly as a result of increased agricultural productivity, as documented by Bustos et al. (2016), Gollin et al. (2018), and Bharadwaj et al. (2018).

To deal with the endogeneity of adoption, we use an instrument based on the potential yield gains from adoption of genetically modified soybean seeds, calculated from the FAO-GAEZ database (as Bustos et al., 2016). Areas with larger differences between low and high potentials in the FAO-GAEZ database are those that should benefit more from the adoption of new technologies. Given our discussion in Section 2, identifying 2004 as the moment marking the definitive introduction of genetically modified seeds in Brazil, we define our instrument for a given municipality as the yield under the "low" technology up until 2003, and as the yield under the "high" technology from 2004 onwards.

Notice that the time series variation in the instrument isolates the changes due particularly to the introduction of genetically modified seeds, while the cross-section variation isolates the changes due to the adaptability of the new technology to different areas. Therefore, the instrument also deals with the measurement error in our glyphosate variable discussed in the previous section. When instrumented, our glyphosate variable isolates changes in use due to the introduction of the new soybean seeds and to their adaptability to local conditions.

Our focus on subclinical effects through water contamination over long distances, on its turn, immediately deals with the second identification problem. By looking at the effect of increased use in one area on health outcomes in other areas, we minimize impacts of the adoption of new agricultural technologies through improved local socioeconomic outcomes. Our main treatment variable is thus defined as the exposure of a municipality to glyphosate used in municipalities that are in the same water basin but upstream from it. The instrument discussed above is constructed accordingly, using this same logic. The main idea behind the construction of this variable is that use of glyphosate in a given municipality affects not only the municipality itself, but also other municipalities through contamination of bodies of water. This focus minimizes the indirect impact of glyphosate use on health through improved agricultural productivity and changes in socioeconomic outcomes. We provide direct evidence on this point in the results section.

Our strategy is nevertheless unable to isolate the very local impact of glyphosate use. We do present results applying our strategy to the local use of glyphosate, but coefficients are small and non-significant. This could be a result of bias due to the effect of changes in local socioeconomic conditions on health, or evidence that, in terms of contamination through water, local use is relatively less important than use in upstream locations. In any case, it means that our empirical strategy is likely to provide a lower bound to the total effect of glyphosate use on birth outcomes. Irrespectively, we explore an externality of glyphosate use through the contamination of water bodies over long distances that has not been analyzed so far. This is on itself of major importance for the ongoing debate on the optimal regulation of pesticides.

Figure 2 illustrates our identification strategy for one particular level 3 ottobasin. The subdivisions in the map indicate municipalities within the same ottobasin. The municipality marked in red is the reference municipality, or municipality i. The lighter color in the figure represents municipalities that are upstream from i according to the classification of level 4 sub-basins, while the darker color indicates municipalities that are downstream from i. The intermediary color indicates municipalities that are at the same level 4 sub-basin as municipality i and, therefore, cannot be unequivocally considered upstream or downstream from it. Our instrument is constructed considering the use of glyphosate in the lighter area, meaning considering only municipalities unequivocally upstream from i. By excluding municipalities at the same level of i from this calculation, we also minimize concerns related to the correlation in socioeconomic characteristics between municipality i and the immediately surrounding areas.

4.2 Specification

Our first stage equation is the following:

$$glyph\_up_{it} = \tilde{\alpha} + \tilde{\gamma} soy\_potential\_up_{it} + \tilde{\beta} X_{it} + \tilde{\delta}_i + \tilde{\pi}_{st} + \epsilon_{it}, \tag{4}$$

where $soy\_potential\_up_{it}$ is the maximum attainable yield upstream from i with "low" technology for $t < 2004$ and with genetically modified seeds if $t \geq 2004$, $\tilde{\delta}_i$ indicates municipality fixed effects, $\tilde{\pi}_{it}$ state-year fixed effects, X_{it} is a set of municipality level controls, and ϵ_{it} is a random term.

Our second stage equation is given by:

$$outcome_{it} = \alpha + \gamma \widehat{glyph\_up}_{it} + \beta X_{it} + \delta_i + \pi_{st} + \varepsilon_{it}, \tag{5}$$

where $outcome_{it}$ is some birth outcome for municipality i for births that occurred in year t, ε_{it} is a random term, and the other variables are the same as those defined in the first stage. Since, by construction, our instrument is correlated across municipalities within the same water basin, we cluster standard errors at the ottobasin level.[17] Regressions are weighted by the mean number of births over the entire sample period. We also present results of reduced-form estimations regressing birth outcomes directly on our instrument.

Our set of controls include socioeconomic characteristics (GDP per capita and share of GDP from agriculture), health inputs (hospital beds, presence of hospitals, and of the Family Health Program), coverage by *Bolsa Família* (the Brazilian CCT program), and, most importantly, the potential local gain in soybean productivity—the same variable used as instrument, but calculated for municipality i itself (instead of for municipalities upstream from it). Our goal is to control for local socioeconomic conditions and investments in health that may directly affect health outcomes, and also for the local potential for soybean expansion, which may be correlated to changes in the use of glyphosate in municipalities upstream from i (if potential for soybean production is sufficiently correlated across space). The identifying assumption is that, conditional on these local socioeconomic characteristics, the instrumented use of glyphosate upstream from i should not have other indirect impacts on birth outcomes in i.

We conduct a long series of complementary exercises to validate our empirical strategy. Our main goal with these exercises is to show that the effect we document is indeed related to the expansion in soybean production following the adoption of genetically modified seeds, that it operated through water, and that it was not due to other changes brought about by the expansion in soybean production. Each exercise

[17] If a municipality is in more than one ottobasin, we assign it for the purposes of clustering to the ottobasin containing most of its area.

is described in detail as results are presented in the next section. For the sake of conciseness, since we already mentioned them in the introduction, we do not list them again here.

4.3 Descriptive Statistics

The position of municipalities within ottobasins plays a crucial role in our identification strategy. One concern in this respect is that municipalities in different positions within ottobasins could be intrinsically different, maybe due to the economic benefits of being in a specific position within an ottobasin. To address this question and assess whether it indeed should be a concern, we start by listing in Table 1 a series of descriptive statistics for municipalities in different positions within their respective ottobasins in the baseline year 2000. As 2000 was a census year, we can compare a vast array of baseline socioeconomic characteristics. The first column presents the average for each variable in our sample, while the second and third columns present averages for municipalities, respectively, in higher (upstream) and lower (downstream) positions in the ottobasin, defined in relation to position 5. The final column presents the difference between municipalities in high and low positions and indicates whether it is statistically significant.

The first row in the table simply shows that the average municipality in the sample is roughly in position 5, while the municipalities downstream from it are on average in position 7.4, and the municipalities upstream from it are on average in position 2.6 (close to symmetric around the mean). This means an average distance between municipalities in high and low positions of 4.8 sub-basins, which is a substantial difference in terms of position within an ottobasin (there are never more than 9 sub-basin positions within an ottobasin).

Nevertheless, the other rows in the table show that these municipalities are very similar. Most importantly, differences in health outcomes at birth and socioeconomic conditions—including infant mortality, income per capita, poverty, illiteracy, and inequality, among others—-are very small and never statistically significant. The list of variables includes all the socioeconomic characteristics used at some point in the paper. Among the 17 variables considered (excluding position in the ottobasin), only one difference is statistically significant at the 5 percent level and one at the 10 percent level, in line with what one would expect from random variation in the sample. Municipalities in low positions seem to have a slightly higher presence of hospitals, though the difference is quantitatively small, and a larger share of area planted with soybean at the baseline, which is only marginally significant. But the key piece of evidence from Table 1 is that, at the baseline, municipalities in high and low positions within ottobasins are remarkably similar in terms of health and socioeconomic outcomes.

5 Results

5.1 Main Results

Table 2 presents the main results of the paper. It shows results of OLS and IV estimates of the effect of glyphosate use in municipalities upstream from a given municipality on infant mortality in the municipality. It also presents reduced-form estimates of regressions of infant mortality on our instrument (soybean potential upstream from the municipality). For each specification, we present results without controls, controlling for soybean potential in the municipality (defined in the same way as the instrument, but calculated for the municipality itself), and including the full set of controls for health inputs and socioeconomic conditions (listed in the previous section).

The first three columns, which present the OLS results, indicate that glyphosate use upstream from a given municipality is positively correlated with infant mortality, but that the correlation is not particularly strong. The coefficient is statistically significant at the 10% level in column 3, when all controls are included, but it is not significant in columns 1 and 2. The introduction of controls makes little difference in terms of point estimates, just increasing slightly the coefficient. Columns 4 to 6 present the results of the reduced-form estimation. They show that potential gains in soybean productivity after 2004 upstream from a given municipality are significantly correlated with relative increases in infant mortality in the municipality. Again, the introduction of additional controls makes little difference it terms of results.

Finally, columns 7 to 10 present our IV results. In this strategy, we instrument glyphosate use upstream from a given municipality with the potential gain in soybean productivity in the respective area. The IV strategy deals simultaneously with concerns related to the endogeneity of adoption of genetically modified seeds and with the measurement error in our municipal glyphosate variable. Table 3 presents the first stage of our IV strategy. It shows that the instrument is strong (F-statistic above 50 in all specifications) and roughly orthogonal to the socioeconomic characteristics and health inputs used as controls.

The IV results from Table 2 indicate a positive and statistically significant effect of glyphosate use upstream from a municipality on infant mortality in the municipality. As in the previous cases, the introduction of the different sets of controls makes little difference for the results. The IV estimates are roughly 3 times larger than the respective OLS results, consistent with the presence of measurement error in our glyphosate variable discussed in Section 3.

For the IV case, in addition to the specifications presented for the reduced form, we present in column 10 an additional specification where both the use of glyphosate upstream from the municipality and in the municipality itself are instrumented with the respective soybean potentials. The coefficient on the use of glyphosate upstream from the municipality is similar to the previous columns and remains strongly significant, while the coefficient on the use of glyphosate in the municipality itself is positive, much smaller in magnitude, and not statistically significant. We present this last column for the IV specification just for completeness, but stick to column 9 as our benchmark specification, since the instrument becomes weaker when we instrument simultaneously for glyphosate use in the municipality itself and in the area upstream from it.

Our point estimate from column 9 implies that the average increase in glyphosate use after 2004 is associated with an increase of 0.88 in the infant mortality rate (or 5% of the sample mean). Because the affected area is large, this effect adds up to a total of 503 additional infant deaths per year after 2004 (or 0.45 additional death per municipality per year). We are not looking at the local effect of glyphosate use, so this number is arguably a lower bound to the total impact on infant mortality.[18]

It is worth pointing out that the effect of soybean potential in the municipality itself always appears as positive, but is never statistically significant. In the reduced-form results, for example, its magnitude is between one-fourth and one-eighth of the magnitude of the coefficient for upstream soybean potential.

[18] Appendix Table A.1 reproduces the main specification from Table 2 with various alternative glyphosate imputation strategies for the missing interval 2006-2008. Qualitative and quantitative results remain very similar. Table A.2, in turn, presents results changing the way we deal with municipalities with no area upstream from them. In our benchmark specification, we assign value zero to municipalities with no areas upstream from them. In Appendix Table A.2, instead, we drop these municipalities. Results remain again very similar qualitative and quantitatively to those from Table 2.

Similarly, in the IV strategy where we instrument glyphosate use both in the municipality itself and upstream from it, the coefficient on glyphosate use in the municipality is one-tenth of that on upstream glyphosate use. This is in line with what should be expected given the large documented effects of adoption of genetically modified seeds on local productivity (for the case of Brazil, see Bustos et al., 2016). Local effects should lead to socioeconomic changes that would confound the externalities from glyphosate use, biasing the estimated coefficient towards negative values. It may also indicate that, in terms of water contamination, local use of glyphosate is less relevant than whether or not upstream tributaries go through agricultural areas of intensive use (as suggested by Ronco et al., 2016).

In Table 4, we expand the analysis and present the results of our benchmark IV specification (column 9 from 2) for other birth outcomes: Panel A considers mortality by cause of death, fetal mortality, sex-ratio at birth, and gender-specific infant mortality, while Panel B considers measures of health at birth and fertility outcomes.

Panel A shows that 75 percent of the infant mortality effect estimated in Table 2 is due to two causes of death: perinatal period conditions, which account for 56 percent of the total effect, and respiratory conditions, which account for the remaining 19 percent. As discussed in Section 2, glyphosate has been documented to affect human placental cells in ways that should be expected to disrupt fetal growth and formation. These are problems that end up reflected on mortality due to perinatal period conditions. In terms of respiratory conditions, there are various documented cases where direct exposure to glyphosate seems to have caused respiratory problems (as reported, for example, in Mesnage et al., 2015, de Araujo et al., 2016, Watts et al., 2016, and Camacho and Mejia, 2017) and glyphosate also has been detected in the lungs of chickens and piglets (Shehata et al., 2014; Kruger et al., 2014). But, in our case, it seems more likely that it is a direct result of prematurity. Respiratory distress syndrome and chronic lung disease among infants are the most common complications from premature birth (Behrman and Butler, 2007).

The next two largest estimated effects among causes of death—already not statistically significant—are for congenital anomalies and endocrine conditions, both of which are also likely to be affected by glyphosate. Together with the significant effects on perinatal and respiratory deaths, these add up to 93% of the total estimated impact on infant mortality. We find very small coefficients and no significant impact for other causes of death, including some with high overall incidence (e.g., infectious diseases, external causes, and ill-defined causes).

Surprisingly, we also do not find significant effects for fetal deaths. Late fetal deaths and perinatal deaths tend to share some of the same underlying causes, so we would expect a significant effect on the former. But, at the same time, fetal deaths are measured with a lot of error, and births induced due to pregnancy problems may turn potential fetal deaths into perinatal deaths. In addition, early miscarriages due to glyphosate exposure, which have been documented in various observational studies and also in the case of aerial spraying in Colombia (see de Araujo et al., 2016, Watts et al., 2016, and Camacho and Mejia, 2017), could go undetected and further increase the measurement problem in fetal deaths. In order to address this issue, we also look at sex ratio at birth. Previous research has used sex ratio at birth as a proxy for fetal mortality, under the assumption that when fetal mortality is high, the sex ratio at birth tends to be biased towards females (McMillen, 1979). We find a point estimate for male infant mortality that is indeed larger than that for female infant mortality, as should be expected. But, in terms of sex ratio at birth, we find a very small and not statistically significant coefficient.

Panel B, which reports results for other birth outcomes, shows an increased likelihood of pre-term births and also of low birth weights. When we break down gestational length into five different categories, we see that the main effect is coming from a statistically significant increase in the share of births between 28 and 36 weeks, and a reduction in the share of births between 37 and 41 weeks. These results are in line with evidence from observational studies (de Araujo et al., 2016; Watts et al., 2016) and corroborate the interpretation based on fetal development discussed in the beginning of this section. We find no statistically significant effect on APGAR1 and APGAR5 scores, despite negative point estimates.

Finally, the last few lines in the table explore some characteristics of the births under consideration. Unexpectedly, we estimate a positive and statistically significant coefficient for the birth rate (per woman of reproductive age). We show below that this result is a statistical fluke due to a pre-trend in birth rates, and that it is unrelated to the estimated impact on birth outcomes. But, before that, Table 4 also shows that this is unlikely to be a concern, since the unexpected positive sign for the birth rate is not related to any systematic change in the characteristics of mothers giving birth (in terms of education and age). The change in the birth rate could be worrisome if it were associated with some systematic change in the pool of mothers giving birth, therefore confounding the identification of the effect of glyphosate on birth outcomes. The last four rows in Panel B show evidence that this is not the case: there are no significant changes in the educational or age composition of mothers giving birth.

In any case, in order to explicitly rule out this concern, we re-estimate our main specification allowing for non-linear time trends as functions of initial municipality characteristics. We do this by including as independent variables interactions of time dummies with the initial (2000) values of various socioeconomic indicators (share of the population rural, share of the population poor, and inequality) and the birth rate. Table 5 presents the reduced-form and IV results of this exercise, for both infant mortality (Panel A) and birth rate (Panel B) as dependent variables. For each case, we present the results including only the interactions with initial socioeconomic conditions (columns 1 and 3), and then the interactions with both initial socioeconomic conditions and the initial birth rate (columns 2 and 4). The results show that there is very little change in the coefficients when we include the interactions with socioeconomic conditions in the infant mortality regressions, and only a small reduction in point estimates when we add the interaction with the initial birth rate. In both cases, coefficients remain statistically significant. By itself, Panel A implies that unobserved trends correlated with initial characteristics cannot account for the results documented in Table 2. But, most importantly, Panel B in Table 5 shows that, once we control for the interactions between the initial birth rate and time dummies, the coefficients in the birth rate regressions become very small—roughly 4 times smaller—and cease to be statistically significant. Panel B confirms the suspicion that the significant coefficient for the birth rate in Table 4 is spurious, coming from pre-existing dynamics that are not related to the impact estimated on infant mortality. Confirming this observation, the results for infant mortality in Panel A from Table 5 remain significant and of similar magnitude when we include these same additional controls.

Our results indicate that glyphosate use upstream from a given municipality, following the adoption of genetically modified seeds, is robustly associated with worse birth outcomes. In the following subsections, we provide several pieces of direct evidence in support of this interpretation and rule out the main alternative interpretations. We focus the remainder of the paper on infant mortality. We start by showing that the estimated effect is indeed working through water contamination. Following, we show that it is specifically related to genetically modified soybean production and to the use of glyphosate.

5.2 The Water Contamination Mechanism

We start by showing that mortality effects can only be detected when there is an increase in glyphosate use upstream from a given municipality, but that there are no detectable effects when the expansion in glyphosate is downstream from it. Table 6 replicates Table 2, but replaces the measures of glyphosate use upstream from a given municipality, as well as its respective potential gain in soybean productivity, by their downstream counterparts (defined in the same way as in the upstream case). OLS estimates indicate a significant negative correlation between glyphosate use downstream from a municipality and infant mortality in the municipality, contrary to the pattern documented for upstream areas. In any case, this significant correlation disappears in the reduced form and IV specifications. In both cases, point estimates are negative and small in magnitude in comparison to their upstream counterparts from Table 2. The point estimate in column 9, for example, has the opposite sign and almost one-sixth of the absolute value of the respective coefficient in Table 2.

While municipalities in high and low positions within ottobasins are remarkably similar in terms of health and socioeconomic outcomes at the baseline (Table 1), we detect mortality effects only when there is an increase in glyphosate use upstream from a given municipality. This is consistent with the structure and direction of flow of water basins, running from upstream to downstream sites. It is also in line with evidence for Argentina documented by Ronco et al. (2016), who detect glyphosate in water and sediments in the Paraná basin, which is part of our sample (the Paraná basin is shared by Argentina, Brazil, Paraguay, and Uruguay). They detect considerably high concentrations in regions distant from cultivation areas, but with tributaries that go through these areas.[19]

In Table 7, we consider different upstream areas, according to distance from the treated municipalities. In order to focus on a homogeneous sample, we consider upstream areas distant up to 200 kilometers from the municipality and restrict the sample to municipalities that have upstream areas with at least this distance (distances are defined based on municipalities' centroids). For comparison purposes, column 1 repeats the main results for our benchmark reduced-form and IV specifications from Table 2, while column 2 reproduces the benchmark specification in the restricted sample. Point estimates are similar to those obtained before. Columns 3 to 6, in sequence, consider only upstream areas at different radii from the treated municipality: 0-50 km, 50-100 km, 100-150 km, and 150-200 km. The results show that estimated effects become weaker for upstream areas that are further away from the municipality, falling strongly and becoming less significant particularly after 100 km.

As a final exercise to confirm that the effect we estimate is indeed working through water contamination, we test for the presence of socioeconomic spillovers from upstream areas to downstream municipalities. The point estimates from Table 6 suggest that, if anything, these spillovers should be positive, in the sense of improving socioeconomic outcomes. If that is the case, our estimates from Table 2 are likely downward biased. Nevertheless, we test explicitly for the presence of these spillovers in Table 8. As the variables of interest are only available in census years, we follow the strategy of Bustos et al. (2016) and regress the change in outcome variables between 2000 and 2010 on the potential gain in soybean productivity in the municipality, as well as on the potential gain upstream from it. Columns 1, 3, 5, and

[19] Our specification considers average glyphosate use per area. One might expect effects to be stronger if the overall size of the upstream area is larger (for a given average use per area), since this would imply that the total amount of glyphosate exposure in the municipality would also be larger. We show in Appendix Table A.3 that this is indeed the case. There, we run our benchmark reduced-form specification interacting our instrument—upstream soybean potential—with total upstream area. The interaction is positive and strongly significant, indicating that the effect of the instrument is stronger when the upstream area is larger.

7 in Panel A of Table 8 simply replicate as close as possible the results from Bustos et al. (2016), with a few differences: (i) our sample considers only the Southern and Center-Western regions, while they considered the entire country; (ii) our baseline controls are set in 2000, rather than in 1991; and (iii) our standard errors are clustered at the ottobasin level, as in our benchmark specification. In columns 2, 4, 6, and 8, we include the potential gain in soybean productivity upstream from the municipality to test for the presence of socioeconomic spillovers. Ideally, we expect the effect of the gain in soybean productivity in the municipality itself to reproduce the results from Bustos et al. (2016) and the gain upstream from the municipality to display small and non-significant coefficients. In Panel B, we reproduce the same specifications including as additional controls state fixed effects, which are also part of all of our main specifications.

In the first two columns we look at the change in soybean planted area. In column 1 of both panels, we observe a positive and robust association between the potential gains in soybean productivity in a given municipality and the change in the share of its area planted with soybean. In column 2, we observe that the point estimate of the potential gain in soybean productivity in the municipality remains stable, while the coefficient on the upstream effect is very small in magnitude and not statistically significant. This indicates that spillover effects on technology adoption and soybean planted area are not substantial in our context. In the remaining columns, analogously, we test for spillovers on local employment composition (share of the labor force in agriculture and manufacturing) and net migration flows. Regarding the own-municipality effects, the patterns observed in our sample are very similar to the findings of Bustos et al. (2016): the gain in soybean potential in the municipality itself can be interpreted as a labor-saving shock to agriculture, leading to reallocation of employment towards manufacturing and to outflow migration. Still, we do not observe significant spillovers from soybean potential upstream from a municipality on the composition of employment and net migration flows in the municipality.[20] These results reinforce the idea that the effects on infant mortality estimated before are not driven by confounding economic changes brought about by the expansion in soybean production upstream from a municipality. Indeed, the effect seems to work through water.

5.3 The Role of Soybean Production

Our first stage has a difference-in-differences flavor, so one potential concern would be the absence of parallel trends in health outcomes across municipalities with different initial characteristics. This would be the case if municipalities downstream from areas with large gains in soybean productivity were, for potentially unknown reasons, already experiencing a different dynamics of infant mortality even before the introduction of genetically engineered soybean seeds. This would call into question the interpretation that our results are driven by the introduction of soybean genetically modified seeds and their impact on the use of glyphosate starting in the mid-2000s. Table 5 in the previous section already partly dealt with this concern by incorporating non-linear trends as functions of initial municipality characteristics. In this sub-section, we extend this discussion by conducting an event-study exercise using our reduced-form specification. In this exercise, the potential gain in productivity in the area upstream from each municipality is interacted with year fixed effects (with the coefficient in the last year before the introduction of the new technology, 2003, normalized to zero).

[20] The point estimates of some of the coefficients on the upstream soybean potential could indicate some minor spillovers across areas. So we do not want to argue that we rule out entirely the possibility of these external effects. But, if they are present, they are quite small in magnitude and, if anything, bias our main estimates towards zero.

The results from this exercise are presented graphically in Figure 3. The figure shows that municipalities with upstream areas with high potential gains did not experience different dynamics of infant mortality before 2004: coefficients for the period between 2000 and 2002 are small and not statistically significant. Only in 2004 these municipalities start experiencing significant increases in infant mortality, matching precisely the period of introduction of genetically engineered soybean seeds and the expansion in the use of glyphosate in the sample.

A similar but somewhat more specific concern would be that the effects documented in Table 2 are due to gains in agricultural productivity more generally, not related to soybean in particular. This would be a concern if the introduction of genetically engineered seeds impacted productivity in other crops by as much as in soybean, and if the potential gains from the introduction of the new seeds were correlated across crops. That possibility would be problematic because it would imply that the increase in mortality was driven by gains in agricultural productivity in general, weakening the case for glyphosate as the main driving factor (as discussed in Section 2, the use of glyphosate is much more intensive in soybean than in other major crops).

In order to address this concern, Appendix Table A.4 presents the results of a placebo exercise that reproduces our first-stage estimation replacing the glyphosate variable by the area planted with corn. Similarly, we reconstruct our instrument replacing the potential for soybean under different technologies with the potential for corn. Since corn is the second main crop in Brazil in terms of area planted and use of pesticides, behind soybean in both cases (Pignati et al., 2017), one should expect to find an effect similar to that estimated before if the driving force were just an overall expansion in agricultural productivity. As discussed in Section 2, we do not expect this to be the case because the gain in productivity in soybean was particularly strong and represented the main shock brought about by the regulatory change of the 2000's (Young, 2006). Appendix Table A.4 confirms this idea. When we run our first stage with corn instead of soybean, the coefficient on the instrument is basically zero and far from statistically significant (the F-statistic of the excluded instrument is smaller than 1 in all specifications). In other words, the introduction of genetically engineered seeds in 2004 did not lead, by itself, to significant increases in corn productivity. The evidence from this section implies that the results presented in Table 2 are indeed driven by the 2004 regulatory change and, specifically, by the gain in soybean productivity that it generated.

5.4 Heterogeneities

In this subsection, we analyze various dimensions of heterogeneity that confirm the interpretation that the effect on birth outcomes documented in previous sections is due particularly to the use of glyphosate in soybean production.

We start by drawing from the toxicologic literature to characterize the contexts in which the risk of water contamination with glyphosate should be higher. Glyphosate concentration is strongly affected by run-off and precipitation, which flows into drainage basins through surface as well as groundwater. In particular, the risk of surface water contamination by glyphosate should be higher when there is sufficient rainfall and where the soil is more erodible (Borggaard and Gimsing, 2008).

We rely on reduced-form estimates to examine whether the effect of glyphosate is stronger when there is more rainfall during the season of application. We use monthly precipitation data at the municipality level to calculate total precipitation during the glyphosate application season (October through March).

We then look at the interaction between the instrument and this measure of rainfall in the area upstream from a municipality. Column 1 in Table 9 presents the result. It shows that potential gains in soybean yield upstream from a given municipality are significantly correlated with increases in infant mortality in the municipality only when there is sufficient upstream rainfall. In the specification in the table, we break precipitation into quartiles of its distribution across years and municipalities, and omit the first quartile. The estimated effect is only significant if rainfall is above that minimum level, being roughly constant after that. In column 2, we replicate the same exercise, but interacting the instrument with rainfall between April and September, when there is no application of glyphosate in soybean production. In this case, the interaction coefficients are systematically smaller and only one of them is borderline significant, at the 10% level. In other words, precipitation significantly increases the mortality effects estimated in Table 2 only when it occurs during the glyphosate application season.

Following, we document that the reduced-form effect is stronger when the potential for soil erosion is higher in upstream areas. Research conducted by da Silva et al. (2011) provides an index for the Natural Potential for Erosion (NPE) for the Brazilian territory, mapping soil loss rates and areas highly predisposed to erosion at the 1 km^2 pixel level.[21] The NPE indicates the inherent risk of erosion in a given location, irrespective of current land use or vegetation cover, and can be defined as the total number of tonnes of soil that is lost per hectare in a typical year. These authors define highly erodible soils as those with NPE greater than 1,600 tonnes/hectare, and show that these are prevalent in a relevant share of the Brazilian territory (14 percent of the country, widely spread across regions). We build on da Silva et al. (2011) and create a variable measuring the share of pixels with high erodibility in each municipality. The average of this variable for the area upstream from a municipality is then interacted with our instrument to generate the result presented in column 3 from Table 9. We estimate a positive and statistically significant coefficient on the interaction between the instrument and the measure of soil erodibility upstream from a municipality. In addition, the effect of the instrument is positive and statistically significant only for upstream areas with a sufficiently high share of soil with high erodibility rates.

Finally, we also show that mortality effects are relatively larger for municipalities that make use of surface rather than underground sources of water. Groundwater is generally considered more adequate for human consumption as the water percolation into the ground, through rocks, cracks and aquifer pores tends to be accompanied by a series of purifying physicochemical processes (such as ion exchange, radioactive decay, and the removal of suspended solids and pathogenic microorganisms, as discussed by Silva, 2003). Nevertheless, there is a substantial degree of interaction between groundwater and surface water (Winter et al., 1998), so, without a detailed analysis of the structure of this interaction within each ottobasin, this specific result should be seen with caution. We draw on data from *Atlas Brasil*, provided by the Brazilian National Waters Agency (ANA), indicating whether the drinkable water in a given municipality is collected from surface *vs* groundwater sources. We then interact a municipality indicator for surface sources of water with our instrument, again in a reduced-form specification. Column 4 in Table 9 presents the result. We find that the interaction of the instrument with the dummy indicating surface sources of water has a positive coefficient, but with a p-value of 0.17. So, the effect documented before seems to be higher in municipalities making use of surface water, but the result is not statically

[21] Erosion is the natural process that causes breakdown of soil aggregates and accelerates the motion of organic and mineral materials (Gilley, 2005). It occurs when the erosive forces of rainfall or flowing water are greater than the soil's resistance to erosion, typically determined by soil texture and topographical features of the site. Topography, soil type and rainfall can be used to predict the Natural Potential for Erosion (NPE).

significant at usual significance levels.

We conclude this subsection by considering heterogeneity in terms of the timing of births. Because of the season of glyphosate application discussed before, births occurring during certain months of the year may be more subject to glyphosate exposure than others. Considering the month of conception, it is possible to calculate the number of months during the gestation period that fall inside the glyphosate application window (October to March). Appendix Table A.5 addresses this issue in detail and shows that births occurring between March and June should be those with maximum exposure to glyphosate during the gestational period. Births during this interval should have experienced 6 months of exposure to glyphosate during gestation, while births occurring in other months should have experienced between 3 and 5 months of exposure (the average difference in exposure between the two groups would be 2.25 months). So the difference in exposure is not stark, but it may be enough to generate systematic differences in terms of the estimated impact. Table 10 reproduces our benchmark specification considering, separately, births occurring during "higher exposure months" (March to June) and births occurring during "lower exposure" months (July to February). The table shows that estimated effects are systematically higher during higher exposure months. Both the reduced-form and IV estimated coefficients are 44% higher for births between March and June, when compared to births between July and February.[22] For the interested reader, Appendix Figure A.2 reproduces our event study analysis from Figure 3 for higher and lower exposure months separately. The figure makes it clear that the increase in infant mortality in 2004 is much more pronounced for higher exposure months, when compared to lower exposure months. Also, it shows that before 2004, when genetically modified soybean seeds had not been introduced in the country, there was no clear distinction in infant mortality patterns across higher and lower exposure months.

Summing up, the relative increase in infant mortality in municipalities downstream from areas with high potential gains in soybean productivity is particularly large when the upstream areas experience sufficient rainfall during the application season, when they have a higher share of soil with high erodibility rates, in municipalities that use surface sources of water, and for births that have higher *in-utero* exposure to the glyphosate application season.[23] The heterogeneity in birth outcomes occurring in different months of the year, in particular, only appears after the introduction of genetically modified soybean seeds in 2004. These results are in line with the predictions from the toxicologic literature. They indicate that water contamination from something in the soil in upstream soybean-producing areas, particularly during the glyphosate application season, is indeed behind the results reported in Table 2.

5.5 Ruling out Other Potential Effects from Soybean Expansion

We now examine other potential changes brought about by the expansion in soybean production that might have had spillovers through the water used in surrounding areas. Notice that various pieces of evidence presented in the previous subsection, particularly those related to monthly rainfall and births by

[22]Appendix Table A.5 shows that, if there is a lag of up to two months between application of glyphosate in soybean planting areas and population exposure (due to the time it takes for water to travel within water basins), then our results from Table 10 underestimate the differences across higher and lower exposure months (because we would be defining the two groups incorrectly, in a way that minimizes the difference in exposure). Estimates of the time of water travel suggest that it should take days for water from soybean planting areas to reach downstream municipalities over a hundred kilometers away (see, for example, Arntson et al., 2004), so we consider the definition adopted in the Table 10 the most adequate one.

[23]We also tried specifications with multiple interactions (e.g., between rainfall, erodibility, and the instrument), but there does not seem to be enough variation in the data to identify these. In these specifications, the coefficients on multiple interactions were not statistically significant.

month, point particularly to glyphosate. Nevertheless, we discuss these issues explicitly in this section in order to rule out any remaining concern.

One possibility is that expansion in soybean production upstream from a municipality could have altered the environment and contaminated water bodies in other ways besides the use of glyphosate, in particular, through a change in patterns of land use (for example, see discussion in Winter et al., 1998 and Vorosmarty et al., 2010). The environmental literature has shown that natural vegetation can act as a filtration mechanism for water, so that deterioration in natural vegetation may lead to worsening of the quality of downstream water in the same water basin. If soybean production expanded over areas that were previously covered by natural vegetation, this type of effect could violate our exclusion restriction. The main concern with the expansion of agricultural activity is related to the use of tillage techniques, since they affect the infiltration and run-off properties of the soil (Winter et al., 1998). This already minimizes the problem in our setting, since the adoption of genetically modified seeds and glyphosate often come together with the use of no-tillage techniques. In any case, we explicitly analyze this issue by looking at patterns of land use.

We use data from MapBiomas, which collects satellite images on land cover and processes them into a yearly municipality dataset for the entire country. The data describe land use patterns across a range of uses. We rely on a specification similar to our reduced form to analyze how potential gains in soybean productivity are associated with changes in the pattern of land use in a municipality. The dependent variables are different uses of land as shares of the total municipality area. Notice that the main goal of this exercise is to understand whether the expansion in soybean planted area was associated with a reduction in natural vegetation area, so we look at the effect of soybean potential on land use in the municipality itself.

Table 11 presents the results. The most important change in land use associated with the soybean expansion is a substitution on an almost one-to-one basis of pasture by agricultural area. This is in line with accounts of the way the process of agricultural expansion took place in our sample region during the period of expansion in soybean production (Brandao et al., 2006; Neto, 2017). We find no significant effect on the coverage of forest area, natural non-forest area, or total farming area. If anything, point estimates indicate a small increase in forest coverage and a small reduction in total farming area (of very similar magnitudes), consistent with the "Borlaug hypothesis" of increased intensiveness of agricultural activity, and similar to what Gollin et al. (2018) documented in a cross-country context. The transition from pasture to agriculture, if anything, is expected to improve natural water filtration, particularly given the use of no-tillage techniques common in soybean areas. The reduction in total farming area, though not statistically significant, would suggest the same effect.

In order to reinforce this point, we also look directly at the measures of water quality currently available. Unfortunately, these measurements are only available for a very reduced sample during our period of analysis (between 49 and 93 municipalities, depending on the specific measure and period). We consider two measures of water quality: biochemical oxygen demand (BOD) and ammoniacal nitrogen. BOD is a measure of the level of organic pollution in water, and it can be affected, for example, by the introduction of fertilizers or organic matter in water bodies. Ammoniacal nitrogen measures the concentration of ammonia, a toxic substance often found in liquid waste, such as landfill leachate and sewage. These measures capture dimensions of water contamination associated with both other substances used in agriculture, such as fertilizers, and general pollution from industrial activity and human occupation.

We run our benchmark reduced-form specification for both measures of water pollution, therefore analyzing whether potential gains in soybean productivity upstream form a given municipality worsen water quality in the municipality. We consider three alterative samples, corresponding to different criteria to assign BOD and ammoniacal nitrogen measuring stations to municipalities: (1) each station is assigned to the closest municipality center, irrespectively of where it is officially located; (2) each station is assigned to the municipality where it is officially located, with those located on the border between two municipalities being assigned to both; and (3) each station is assigned to the municipality where it is officially located, with those on the border between two municipalities being assigned to the one with the closest municipality center.

The results are presented in Appendix Table A.6. Since there is such a radical change in the samples considered, we also replicate our infant mortality regressions for each different sample. In the BOD samples, the results for infant mortality remain positive and statistically significant, but the point estimates become at least three times larger than those from Table 2. In the ammoniacal nitrogen samples, which are substantially smaller, point estimates for infant mortality remain positive—similar or larger than those from Table 2—but are not statistically significant. In any case, in all samples considered, the basic correlation between upstream soybean potential and infant mortality remains positive, as before. Yet, in all cases considered, the estimated coefficient for the two measures of water quality are negative (with one exception, which has a very small coefficient), indicating that, if anything, upstream gains in soybean productivity are associated with local improvements in water quality. Despite the limitations in terms of sample size, this set of results reinforces the evidence from land use discussed before. In terms of overall water quality, the evidence available suggests that soybean expansion most likely represented a modest reduction in general water pollution in surrounding areas.

Given all that is known about pesticide use in genetically modified soybean production, the results from Tables 2 and 11 should not be surprising. The introduction of genetically engineered soybean seeds increased the use of glyphosate but greatly reduced the use of other herbicides (Young, 2006). In Brazil, with the introduction of genetically modified soybean seeds, glyphosate was expected to replace up to 40 different herbicide varieties that were previously used (Gazziero, 2005). As mentioned before, the evidence indicates that, in 2012, glyphosate represented up to 81 percent of the total volume of herbicides' active ingredients used in soybean production (Pignati et al., 2014). No other substance displays a remotely similar difference in intensity of use across soybean and other major crops. In addition, patterns of land use and management improved after the introduction of genetically modified soybean seeds, moving, at the margin, from pasture to no-tillage agriculture. These are generally seen as positive developments from an environmental perspective.

Overall, our exercises show that the effect we document is indeed related to the expansion in soybean production following the adoption of genetically modified seeds, that it operated through water bodies, that it was particularly intense during the season of application of glyphosate, and that it is was not due to other potential changes brought about by the expansion in soybean production.

6 Conclusion

This paper assesses the effect of glyphosate use on health outcomes of surrounding populations using data from Brazilian soybean producing areas between 2000 and 2010. We look at municipality data and find a positive impact of upstream use of glyphosate on infant mortality. Our estimates are likely to give a lower bound to the effect of glyphosate use on infant health, since we do not look at areas of use and do not consider other potential morbidity effects. Our main specification points to an average increase in the infant mortality rate due to the increased use of glyphosate of 0.88 per 1,000 births.

All of the different pieces of evidence presented in the paper support our interpretation. Areas downstream from regions that experienced high productivity gains in soybean after the introduction of the technological package GMO-glyphosate observe relative increases in infant mortality. The timing of the increase in mortality and its pattern across characteristics of soil, rainfall, source of local drinking water, and cause of death agree with what would be expected from contamination of water supplies by glyphosate applied in soybean production. Similarly, its seasonal profile, both in terms of timing of births and the role of rainfall, matches the glyphosate application period.

Recently there has been a reexamination by scientists, specially by biochemists, of claims that glyphosate is a safe pesticide with little to no effect on human health. These have typically used controlled laboratory experiments. Our work adds to this literature by providing evidence that glyphosate can affect human populations at large in a real world setting, at the levels of use typically observed in agriculture.

Combining our results with the most recent estimates for the value of a statistical life in Brazil points to an externality associated with the use of glyphosate in soybean production of the order of US$ 583 million per year.[24] Brazilian exports of soybean-related products alone, ignoring domestic consumption, have amounted to over US$ 30 billion per year in the recent past (data from EMBRAPA, the Brazilian Agricultural Research Institute). In few cases the trade-off between agricultural productivity and external effects of pesticides manifests itself so clearly as in the case of soybean production in Brazil, where welfare losses spread over a very large population put in perspective the local benefits from technology adoption (as documented by Bustos et al., 2016). Since the type of externality documented here was unknown when current regulations were originally set in place, a new discussion must be initiated on the optimal regulatory mark for the future use and handling of glyphosate-based herbicides.

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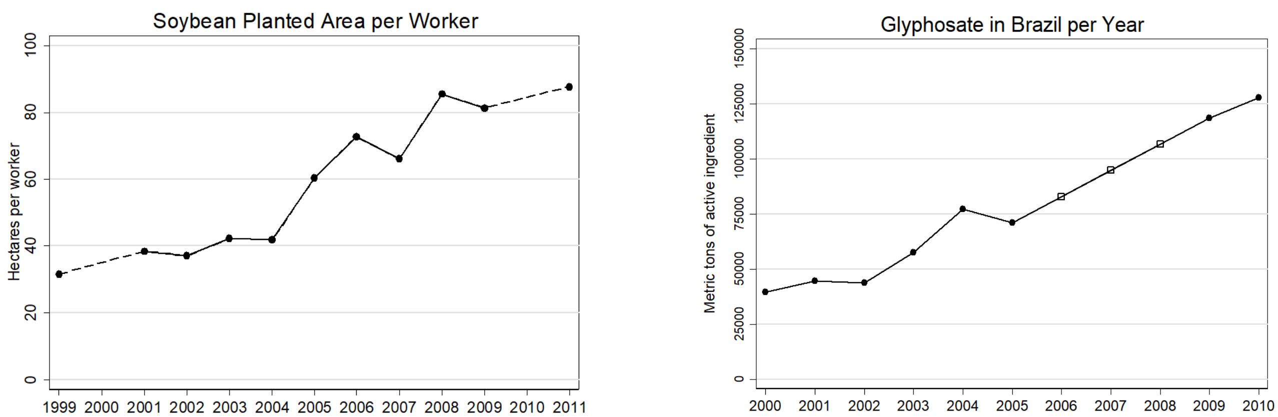
Main Figures and Tables

Figure 1: Soybean and Glyphosate in Brazil, 2000-2010

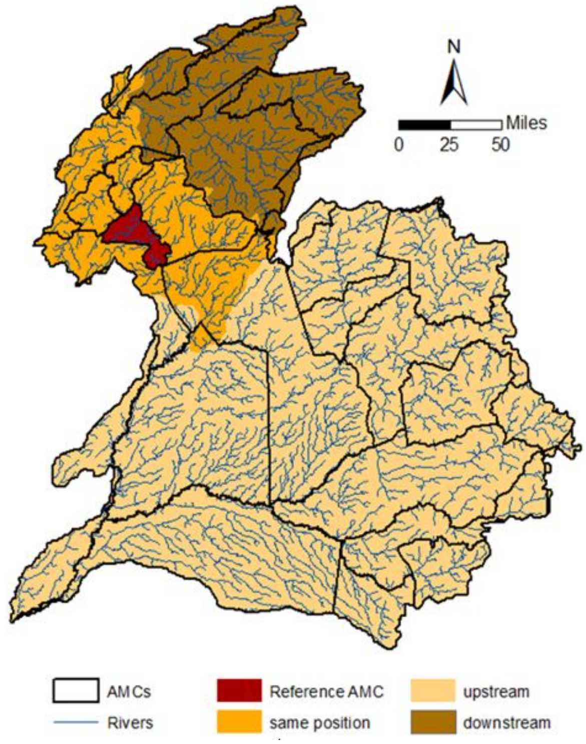
(a) Changes in Hectare per Worker in Brazilian Soybean Production, 1999-2011

(b) Glyphosate commercialized in Brazil, 2000-2010 (imputed for 2006-2008)



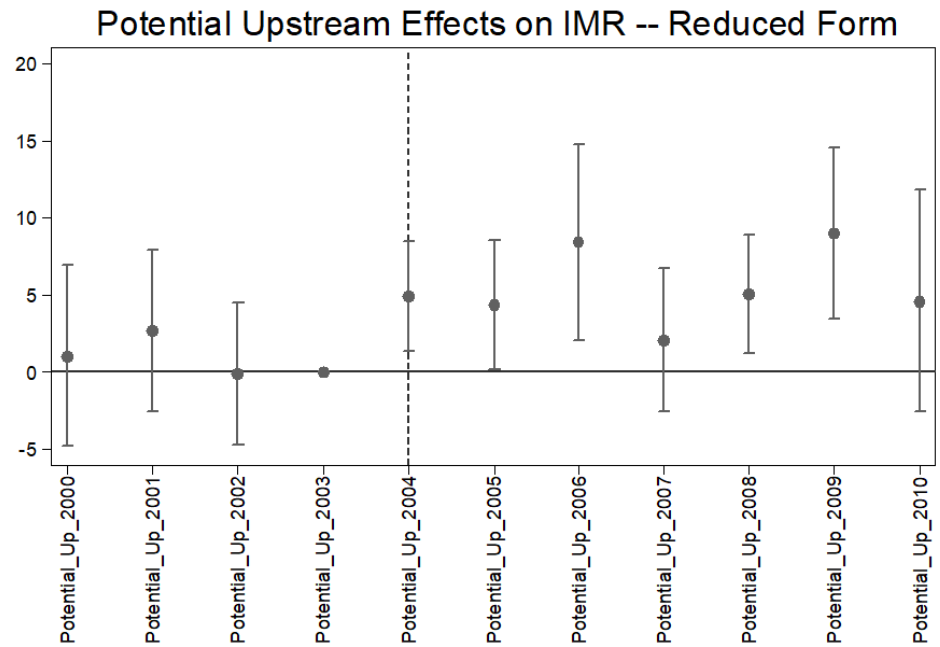
Notes: Authors' own elaboration. Data on glyphosate comes from the Brazilian Environmental Agency (IBAMA), soybean planted area comes from IBGE's Municipal Agricultural Production dataset, and data on workers employed in soybean production is from IBGE's PNAD – the National Household Sample Survey. PNAD was not carried out in census years, 2000 and 2010, so we include 1999 and 2011 to allow for a linear interpolation for those years. Also, in six states (Acre, Amapá, Amazonas, Pará, Rondônia, and Roraima) only urban areas were covered by PNAD until 2004, so those states are discarded in the first figure. In the second figure, we do not have data for 2006, 2007, and 2008, so those are imputed by linear interpolation.

Figure 2: Illustration of the Identification Strategy for a Level-3 Ottobasin



Notes: Authors' own elaboration based on geocoded data from the Brazilian National Waters Agency (*Agência Nacional de Águas* – ANA).

Figure 3: Reduced-Form Event-Study Results – Municipalities in the Brazilian Center-West and South Regions, 2000-2010



Notes: This plot displays the result of a reduced-form specification in which IMR is regressed on the potential gain in productivity in the area upstream from each municipality interacted with year fixed-effects (with the coefficient in the last year before the introduction of the new technology, 2003, normalized to zero). Standard errors are clustered at the ottobasin level, and confidence intervals are computed at the 95% level. The regression also includes municipality fixed-effects and state-year fixed effects, socioeconomic controls (municipality GDP per capita (in log) and the share of GDP from agriculture), health inputs (hospital beds, presence of hospitals, and of the Family Health Program), population coverage by *Bolsa Família*, and Soybean Potential in the Municipality. The regression is weighted by the mean number of births over the entire sample period.

Table 1: Descriptive Statistics, 2000 Brazilian Census, Municipalities in Center-West and South Regions

	Baseline year (2000, excluding position = 5)			
	Mean	High Position (>5)	Low Position (<5)	Diff
Position in Basin	5.169	7.411	2.560	-4.851***
Infant Mortality Rate - IMR	18.273	17.632	19.019	1.387
% Low Apgar 1	0.189	0.184	0.195	0.011
% Low Apgar 5	0.031	0.032	0.030	-0.001
% Preterm Birth (<37 weeks)	0.071	0.073	0.069	-0.003
% Low Birth Weight	0.066	0.066	0.066	-0.000
Pop Coverage of Family Health Program (PSF)	0.184	0.172	0.197	0.024
Hospital Presence	0.869	0.850	0.890	0.040**
Hospital Beds per Capita*1000	3.500	3.621	3.359	-0.262
% Rural Pop	0.355	0.381	0.324	-0.057
% Illiterate (15yo+)	0.130	0.125	0.137	0.012
Theil Index	0.520	0.519	0.520	0.001
Income Per Capita	231.708	235.861	226.874	-8.986
Share GDP Agro	0.273	0.274	0.272	-0.002
Poverty Rate	0.300	0.294	0.306	0.012
% Agric Employment	0.376	0.388	0.362	-0.026
% Manuf Employment	0.126	0.119	0.134	0.015
% Soybean Area	0.092	0.073	0.114	0.040*

Notes: All tabulations refer to the baseline year (2000), authors' own elaboration from different sources of data: Datasus (SIM and SINASC for IMR and other birth outcomes), Census/IBGE (socioeconomic indicators), Ministry of Health (PSF and hospital beds) and PAM/IBGE (soybean area). Significance in the last column: *** p<0.01, ** p<0.05, * p<0.1.

Table 2: Main Results (OLS, Reduced Form, IV) – Effects of Glyphosate Upstream on Infant Mortality Rate – Municipalities in Brazilian Center-West and South Regions, 2000-2010

	OLS			Reduced Form			IV			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Glyphosate Upstream	10.491	10.528	11.598				36.553	36.756	39.012	37.210
	(7.948)	(8.008)	(6.408)*				(13.190)***	(13.466)***	(14.814)***	(8.720)***
Soybean Potential Upstream				4.331	4.356	4.587				
				(1.459)***	(1.482)***	(1.548)***				
Soybean Potential in Municip		0.864	0.396		1.009	0.567		0.956	0.511	
		(3.737)	(3.122)		(3.420)	(2.759)		(3.200)	(2.557)	
Glyphosate in Municip										3.812
										(18.652)
Socioeconomic Controls	No	No	Yes	No	No	Yes	No	No	Yes	Yes
Observations	12,309	12,309	12,309	12,309	12,309	12,309	12,309	12,309	12,309	12,309
R-squared	0.100	0.100	0.103	0.100	0.100	0.103				
Number of Municip	1,119	1,119	1,119	1,119	1,119	1,119	1,119	1,119	1,119	1,119
1st Stage F-stat							52.88	52.45	51.37	5.168

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. In all regressions the dependent variable is infant mortality rate. All regressions include municipality fixed-effects and state-year fixed effects. Socioeconomic controls include municipality GDP per capita (in log) and the share of GDP from agriculture, health inputs (hospital beds, presence of hospitals, and of the Family Health Program) and population coverage by *Bolsa Família*. In columns 7-10, Glyphosate Upstream is instrumented by Soybean Potential Upstream. In column 10, Glyphosate in Municipality is analogously instrumented by Soybean Potential in Municipality. Regressions are weighted by the mean number of births over the entire sample period.

Table 3: First Stage - Municipalities in Brazilian Center-West and South Regions, 2000-2010

	Dep Var: Glyphosate Upstream		
	(1)	(2)	(3)
Soybean Potential Upstream	0.118	0.119	0.118
	(0.016)***	(0.016)***	(0.016)***
Soybean Potential in Municipality		0.001	0.001
		(0.011)	(0.011)
Socioeconomic Controls	No	No	Yes
Observations	12,309	12,309	12,309
R-squared	0.763	0.763	0.765
Number of Municipalities	1,119	1,119	1,119
Partial-F	52.88	52.44	51.36

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. In all regressions the dependent variable is Glyphosate Upstream. All regressions include municipality fixed-effects and state-year fixed effects. Socioeconomic controls include municipality GDP per capita (in log) and the share of GDP from agriculture, health inputs (hospital beds, presence of hospitals, and of the Family Health Program) and population coverage by *Bolsa Família*. Regressions are weighted by the mean number of births over the entire sample period.

Table 4: IV Results for Other Outcomes – Municipalities in Brazilian Center-West and South Regions, 2000-2010

	Effects of Glyph Upstream	S.E.
	Panel A - IV Results: Mortality Outcomes	
Infectious	1.814	(2.318)
Respiratory	7.586	(2.383)***
Perinatal	21.776	(9.450)**
Congenital	4.975	(4.464)
External Causes	0.920	(2.653)
Endocrine-Nutritional	1.895	(1.195)
Genito-Urinary	0.146	(0.317)
Ill-defined	-1.271	(2.653)
Fetal Mortality Rate	1.490	(4.649)
Sex Ratio at Birth	0.001	(0.103)
IMR Males	40.788	(18.720)**
IMR Females	37.477	(17.663)*
	Panel B - IV Results: Other Birth Outcomes	
Low Birth Weight	0.080	(0.039)**
Preterm Birth (<37 weeks)	0.299	(0.133)**
Gestational Length:		
<22 weeks	-0.001	(0.002)
22-27 weeks	0.008	(0.004)*
28-36 weeks	0.291	(0.133)**
37-41 weeks	-0.372	(0.190)*
>41 weeks	0.090	(0.056)
Low APGAR 1	-0.185	(0.220)
Low APGAR 5	-0.016	(0.027)
Birth Rate	0.074	(0.020)***
Mother Education : 0-3 years	-0.003	(0.158)
Mother Education: 4-7 years	0.103	(0.212)
Mother Education: 8+ years	-0.100	(0.152)
Mean Age of Mother	-0.773	(0.694)

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. Dependent variables are displayed in the first column, while the second and third columns present coefficients and standard errors for each regression, respectively. All regressions include municipality fixed-effects and state-year fixed effects, socioeconomic controls (GDP per capita (in log) and the share of GDP from agriculture), health inputs (hospital beds, presence of hospitals, and of the Family Health Program), population coverage by *Bolsa Família*, and Soybean Potential in the Municipality. Regressions are weighted by the mean number of births over the entire sample period.

Table 5: Reduced Form and IV Controlling for Differential Trends – Municipalities in Brazilian Center-West and South Regions, 2000-2010

	Reduced Form		IV	
	(1)	(2)	(3)	(4)
		PANEL A: IMR		
Glyph Upstream			37.473	31.402
			(16.777)**	(15.374)**
Soybean Potential Upstream	4.315	3.635		
	(1.711)**	(1.592)**		
Initial Socioecon. × Time Dummies	X	X	X	X
Initial Birth Rate × Time Dummies		X		X
Observations	12,309	12,309	12,309	12,309
R-squared	0.111	0.112		
Number of Municip	1,119	1,119	1,119	1,119
1st Stage F-stat			45.42	44.92
		PANEL B: Birth Rate		
Glyph Upstream			0.066	0.017
			(0.021)***	(0.012)
Soybean Potential Upstream	0.008	0.002		
	(0.003)***	(0.002)		
Initial Socioecon. × Time Dummies	X	X	X	X
Initial Birth Rate × Time Dummies		X		X
Observations	12,309	12,309	12,309	12,309
R-squared	0.628	0.684		
Number of Municip	1,119	1,119	1,119	1,119
1st Stage F-stat			45.42	44.92

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. In all regressions the dependent variable is infant mortality rate. All regressions include municipality fixed-effects and state-year fixed effects, socioeconomic controls (municipality GDP per capita (in log) and the share of GDP from agriculture, health inputs (hospital beds, presence of hospitals and of the Family Health Program), population coverage by *Bolsa Família*) and Soybean Potential in Municipality. Columns 1 and 3 include year dummies interacted with municipal socioeconomic indicators at the baseline year, 2000 (share of the population rural, share of the population poor, Theil Index, and per capita income). Columns 2 and 4 include year dummies interacted with IMR at the baseline year, 2000. Regressions are weighted by the mean number of births over the entire sample period.

Table 6: Placebo Exercises (OLS, Reduced Form, IV) with Downstream Area – Municipalities in Brazilian Center-West and South Regions, 2000-2010

	OLS			Reduced Form			IV		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Glyphosate Downstream	-22.044	-22.148	-20.117				-10.057	-9.982	-6.659
	(3.964)***	(3.884)***	(4.064)***				(9.464)	(9.465)	(11.289)
Soybean Potential Downstream				-1.684	-1.674	-1.095			
				(1.806)	(1.798)	(1.985)			
Soybean Potential in Municip		1.175	0.790		0.790	0.333		0.984	0.494
		(3.957)	(3.477)		(3.932)	(3.388)		(3.943)	(3.451)
Socioeconomic Controls	No	No	Yes	No	No	Yes	No	No	Yes
Observations	12,309	12,309	12,309	12,309	12,309	12,309	12,309	12,309	12,309
R-squared	0.102	0.102	0.104	0.100	0.100	0.102			
Number of Municip	1,119	1,119	1,119	1,119	1,119	1,119	1,119	1,119	1,119
1st Stage F-stat							15.03	14.87	16.67

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. In all regressions the dependent variable is infant mortality rate. All regressions include municipality fixed-effects and state-year fixed effects. Socioeconomic controls include municipality GDP per capita (in log) and the share of GDP from agriculture, health inputs (hospital beds, presence of hospitals, and of the Family Health Program) and population coverage by *Bolsa Família*. In columns 7-9, Glyphosate Upstream is instrumented by Soybean Potential Upstream in both panels. In panel B, columns 7-9, Glyphosate Difference Upstream-Downstream is instrumented by Soybean Potential Difference Upstream-Downstream. Regressions are weighted by the mean number of births over the entire sample period.

Table 7: Effect by Distance Results - Municipalities in Brazilian Center-West and South Regions, 2000-2010

	Full Sample	Restricted Sample	Restricted Sample	Restricted Sample	Restricted Sample	Restricted Sample
	(1)	(2)	(3)	(4)	(5)	(6)
	PANEL A: Reduced Form					
Potential Upstream	4.587	3.928				
	(1.548)***	(2.061)**				
Potential Upstream: 0-50km			3.858			
			(1.757)**			
Potential Upstream: 50-100km				4.222		
				(1.927)**		
Potential Upstream: 100-150km					2.864	
					(1.924)	
Potential Upstream: 150-200km						2.615
						(1.600)
Observations	12,309	8,415	8,415	8,415	8,415	8,415
R-Squared	0.103	0.123	0.123	0.123	0.122	0.122
	PANEL B: IV					
Glyphosate Upstream	39.012	34.532				
	(14.814)***	(18.089)*				
Glyphosate Upstream: 0-50km			32.813			
			(14.184)**			
Glyphosate Upstream: 50-100km				32.051		
				(13.358)**		
Glyphosate Upstream: 100-150km					20.710	
					(12.509)*	
Glyphosate Upstream: 150-200km						19.563
						(11.777)*
Observations	12,309	8,415	8,415	8,415	8,415	8,415
1st Stage F-stat	51.37	35.44	20.77	54.53	51.42	56.78

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. In all regressions the dependent variable is infant mortality rate. All regressions include municipality fixed-effects and state-year fixed effects, socioeconomic controls (GDP per capita (in log) and the share of GDP from agriculture), health inputs (hospital beds, presence of hospitals, and of the Family Health Program), population coverage by *Bolsa Família*, and Soybean Potential in the Municipality. Regressions are weighted by the mean number of births over the entire sample period. Columns 2-6 restrict the sample to municipalities with positive area upstream in all the distance ranges considered.

Table 8: Reproducing Bustos et al. (2016) and Testing for Economic Spillovers from Upstream Expansion of Soybean Production - Effect of Soybean Potential on Economic Outcomes - Municipalities in Brazilian Center-West and South Regions, Long Differences 2000-2010

	Change in Soybean Area		Change in Agr. Empl.		Change in Manuf. Empl.		Net Migration Pop. 16-55	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
PANEL A: Bustos et al. (2016) Specification								
Change in Soybean Potential in Municip	0.020	0.019	-0.009	-0.008	0.013	0.011	-0.015	-0.017
	(0.006)***	(0.004)***	(0.007)	(0.006)	(0.006)**	(0.005)**	(0.008)*	(0.007)**
Change in Soybean Potential Upstream		0.004		-0.002		0.005		0.006
		(0.004)		(0.005)		(0.004)		(0.008)
Observations	1,119	1,119	1,119	1,119	1,119	1,119	1,119	1,119
R-squared	0.066	0.069	0.140	0.141	0.086	0.092	0.187	0.189
PANEL B: Bustos et al. (2016) Specification + Our Controls								
Change in Soybean Potential in Municip	0.010	0.011	-0.012	-0.012	0.016	0.015	-0.008	-0.009
	(0.004)***	(0.003)***	(0.004)***	(0.005)**	(0.003)***	(0.003)***	(0.005)*	(0.004)**
Change in Soybean Potential Upstream		-0.004		0.002		0.002		0.006
		(0.004)		(0.004)		(0.004)		(0.010)
Observations	1,119	1,119	1,119	1,119	1,119	1,119	1,119	1,119
R-squared	0.186	0.188	0.206	0.207	0.198	0.198	0.269	0.270

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. Dependent variables are displayed above the respective numbered columns and are computed as long changes between Census years 2000-2010. Specifications in Panel A include socioeconomic variables at the baseline year, 2000: share of the population rural, share of the population illiterate, income per capita and population density. Specifications of Panel B add state fixed-effects.

Table 9: Reduced-Form Heterogeneity Results – Municipalities in Brazilian Center-West and South Regions, 2000-2010

	Rainfall Oct-Mar	Rainfall Apr-Sep	Erodibility	Source of Drinking Water
	(1)	(2)	(3)	(4)
Soybean Potential Upstream	-2.274	1.171	-0.768	4.133
	(2.536)	(2.909)	(2.157)	(1.597)**
Rain Quartile 2 × Soybean Pot. Up.	6.873	4.723		
	(2.159)**	(2.539)		
Rain Quartile 3 × Soybean Pot. Up.	8.717	2.044		
	(2.540)***	(2.769)		
Rain Quartile 4 × Soybean Pot. Up.	6.142	4.003		
	(2.857)**	(3.058)		
% High Erod. × Soybean Pot. Up.			42.635	
			(15.872)***	
Superficial Source × Soybean Pot. Up.				2.051
				(1.506)
Observations	12,309	12,309	12,309	12,265
R-squared	0.105	0.104	0.104	0.104
Number of Municip	1,119	1,119	1,119	1,115

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. In all regressions the dependent variable is infant mortality rate. All regressions include municipality fixed-effects and state-year fixed effects, socioeconomic controls (GDP per capita (in log) and the share of GDP from agriculture), health inputs (hospital beds, presence of hospitals, and of the Family Health Program), population coverage by *Bolsa Família*, and Soybean Potential in the Municipality. Column 1 includes independent rainfall terms, with variation across time and municipalities. Regressions are weighted by the mean number of births over the entire sample period.

Table 10: Main Results (OLS, RF, IV) - Results by Exposure Months, 2000-2010

	OLS		Reduced Form		IV	
	Higher Exposure Months	Lower Exposure Months	Higher Exposure Months	Lower Exposure Months	Higher Exposure Months	Lower Exposure Months
	(1)	(2)	(3)	(4)	(5)	(6)
Glyphosate Upstream	11.659	11.750			47.684	33.080
	(6.216)*	(7.431)			(14.769)***	(16.570)**
Soybean Potential Upstream			5.607	3.890		
			(1.539)***	(1.823)**		
Soybean Potential in Municip	1.045	-0.085	1.264	0.052	1.196	0.004
	(3.140)	(3.473)	(2.566)	(3.277)	(2.409)	(3.080)
Socioeconomic Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12,306	12,309	12,306	12,309	12,306	12,309
R-Squared	0.047	0.061	0.048	0.061		
Number of Municip	1,119	1,119	1,119	1,119	1,119	1,119
1st Stage F-stat					51.36	51.37

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. The exposure of a given month is taken as the number of months an infant born on that same month was exposed to glyhposate, where the glyphosate period of application is from October to March. We then consider higher exposure months as those with six months of exposure, namely March to June. All the other months are considered lower exposure months. There were no births reported during higher exposure months in three municipality-year observations and, thus, we lose three observations for higher exposure months.

Table 11: Effect of Soybean Potential on Local Land Use - Municipalities in Brazilian Center-West and South Regions, 2000-2010

	Farming Area	Agriculture Area	Pasture Area	Forest Area	Natural Non-Forest Area
	(1)	(2)	(3)	(4)	(5)
Soybean Potential in Municip	-0.026	0.113	-0.118	0.025	-0.002
	(0.018)	(0.049)**	(0.055)**	(0.018)	(0.008)
Observations	12,309	12,309	12,309	12,309	12,309
R-squared	0.185	0.451	0.439	0.226	0.075
Number of Municip	1,119	1,119	1,119	1,119	1,119

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. Dependent variables are displayed above the respective numbered columns and are computed from MapBiomas data as the share of municipal area (in %). All regressions include municipality fixed-effects and state-year fixed effects, GDP per capita (in log), health inputs (hospital beds, presence of hospitals, and of the Family Health Program) and population coverage by *Bolsa Família*. Share of GDP from agriculture is omitted to avoid creating an endogeneity problem. Regressions here are not weighted.

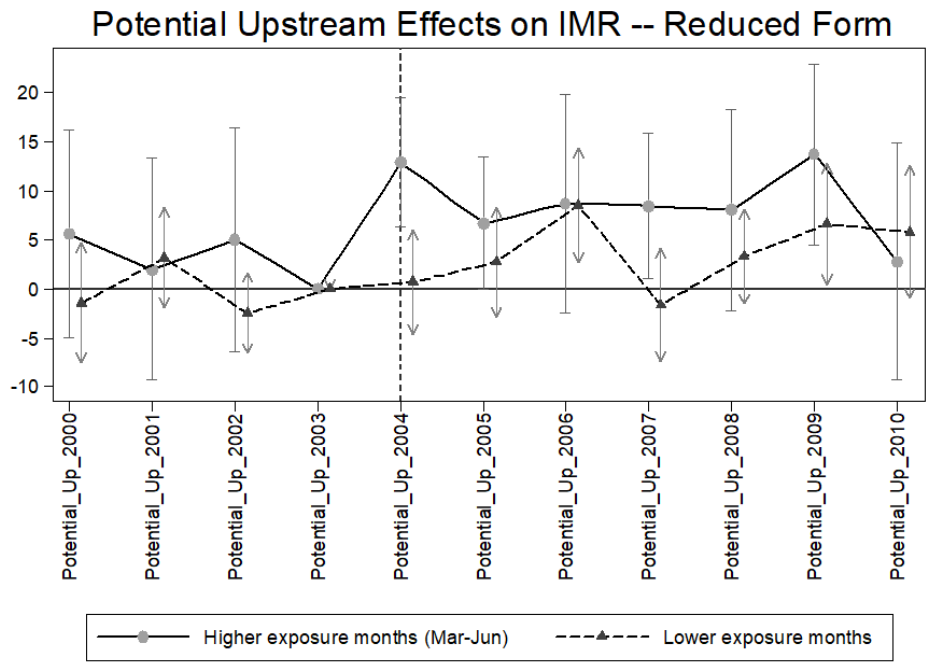
Appendix Section

A Appendix Figures

Figure A.1: Sample Area in the Brazilian Territory with Respective Level-3 Ottobasins

Notes: Authors' own elaboration based on geocoded data from the Brazilian National Waters Agency (*Agência Nacional de Águas* – ANA).

Figure A.2: Reduced-Form Event-Study by Exposure Months - Municipalities in the Brazilian Center-West and South Regions, 2000-2010



Notes: This plot displays the result of two reduced-form specifications, one for months with higher exposure to glyphosate and other for months with lower exposure. The exposure of a given month is taken as the number of months an infant born on that same month was exposed to glyhposate, where the glyphosate period of application is from October to March. We then consider higher exposure months as those with six months of exposure, namely March to June. All the other months are considered lower exposure months. Standard errors are clustered at the ottobasin level, and confidence intervals are computed at the 95% level. The regression also includes municipality fixed-effects and state-year fixed effects, socioeconomic controls (municipality GDP per capita (in log) and the share of GDP from agriculture), health inputs (hospital beds, presence of hospitals, and of the Family Health Program), population coverage by *Bolsa Família*, and Soybean Potential in the Municipality. The regression is weighted by the mean number of births over the entire sample period.

B Appendix Tables

Table A.1: Main Results (IV) - Alternate Glyphosate Measures, 2000-2010

	IV				
	(1)	(2)	(3)	(4)	(5)
Glyphosate Upstream	39.012	37.455	48.691	39.117	19.634
	(14.814)***	(14.244)***	(18.820)***	(15.399)**	(7.602)***
Soybean Potential in Municip	0.511	0.509	0.525	0.530	0.489
	(2.557)	(2.554)	(2.578)	(2.553)	(2.541)
Implied Effect: $\delta(glyph_{post} - glyph_{pre})$	0.881	0.880	0.864	0.540	0.860
Socioeconomic Controls	Yes	Yes	Yes	Yes	Yes
Observations	12,309	12,309	12,309	12,309	12,309
Number of Municip	1,119	1,119	1,119	1,119	1,119
1st Stage F-stat	51.37	50.96	45.93	44.23	44.93

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. Specification 1 uses our main glyphosate measure. Specification 2 uses a different imputation method for 2006-2008, using herbicides commercialized in the country. Specification 3 uses glyphosate equal to zero until 2003 and, for 2004 onwards, it allocates the marginal glyphosate with respect to 2003 (for 200X, difference between glyhposate in 200X and glyphosate in 2003) using soybean planted area each year. Specification 4 allocates the total glyphosate used each year using the soybean planted area for each year. Specification 5 uses glyphosate equal to zero until 2003 and, from 2004 onwards, allocates the total glyphosate used each year using the soybean planted area for each year. Implied effect is calculated using the difference between average glyphosate use post-2004 (inclusive) and pre-2004.

Table A.2: Main Results from Table 2 and Main Placebo from Table 5 with Different Treatment for Municipalities with No Upstream Area - Municipalities in Brazilian Center-West and South Regions, 2000-2010

	Main Results					
	Reduced Form			IV		
	(1)	(2)	(3)	(4)	(5)	(6)
Glyph Upstream				35.543	35.892	39.396
				(16.668)**	(16.238)**	(16.137)**
Soybean Potential Upstream	4.217	4.260	4.629			
	(1.945)**	(1.878)**	(1.779)**			
Soybean Potential in Municip		1.886	1.410		1.795	1.315
		(4.026)	(3.263)		(3.796)	(3.034)
Socioeconomic Controls			X			X
Observations	11,319	11,319	11,319	11,319	11,319	11,319
R-squared	0.103	0.104	0.106			
Number of Municip	1,029	1,029	1,029	1,029	1,029	1,029
1st Stage F-stat				48.39	47.86	47.38

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1.

Table A.3: Results Including Interaction with Area - Municipalities in Brazilian Center-West and South Regions, 2000-2010

	Reduced Form		
	(1)	(2)	(3)
Soybean Potential Upstream	0.452	0.385	0.877
	(1.632)	(1.952)	(1.868)
Potential Upstream * Area Upstream	0.532	0.539	0.504
	(0.144)***	(0.162)***	(0.120)***
Soybean Potential in Municip		-0.452	-0.696
		(3.225)	(2.532)
Area Upstream: Mean ($km^2/10000$)	4.684	4.684	4.684
Coefficient Upstream with Area = Mean	2.943	2.911	3.236
p-value	0.0466	0.0716	0.0541
Socioeconomic Controls			X
Observations	12,309	12,309	12,309
R-squared	0.102	0.102	0.104
Number of Municip	1,119	1,119	1,119

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. In all regressions the dependent variable is infant mortality rate. All regressions include municipality fixed-effects and state-year fixed effects. Socioeconomic controls include municipality GDP per capita (in log) and the share of GDP from agriculture, health inputs (hospital beds, presence of hospitals, and of the Family Health Program) and population coverage by *Bolsa Família*. Regressions are weighted by the mean number of births over the entire sample period.

Table A.4: First Stage with Corn Potential - Municipalities in Brazilian Center-West and South Regions, 2000-2010

	Dep Var: Corn Area Upstream		
	(1)	(2)	(3)
Corn Potential Upstream	-0.005	-0.005	-0.005
	(0.007)	(0.006)	(0.005)
Corn Potential in Municipality		-0.002	-0.003
		(0.004)	(0.004)
Socioeconomic Controls	No	No	Yes
Observations	12,309	12,309	12,309
R-squared	0.119	0.139	0.129
Number of Municipalities	1,119	1,119	1,119
Partial-F	0.500	0.673	0.778

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. All regressions include municipality fixed-effects and state-year fixed effects. Socioeconomic controls include GDP per capita (in log) and the share of GDP from agriculture, health inputs (hospital beds, presence of hospitals and of the Family Health Program), and population coverage by *Bolsa Família*. Regressions are weighted by the mean number of births over the entire sample period.

Table A.5: Expected Exposure to Glyphosate Application Season, According to Month of Birth and Under Different Scenarios

Birth Conception	Oct Jan	Nov Feb	Dec Mar	Jan Apr	Feb May	Mar Jun	Apr Jul	May Aug	Jun Sep	Jul Oct	Aug Nov	Sep Dec
Months in Utero during Oct-Mar	3	3	3	4	5	6	6	6	6	5	4	3
Pregnancy Trimester in Oct-Mar	1 & 3	1 & 3	3	2 & 3	2 & 3	2 & 3	1 & 2 & 3	1 & 2 & 3	1 & 2	1 & 2	1 & 2	1
Exposure due to Current Harvest	33%	67%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Exposure with lag to water contamination of surrounding areas												
If one month	3	3	3	3	4	5	6	6	6	6	5	4
Pregnancy Trimester in Nov-Apr	1	1 & 3	1 & 3	3	2 & 3	2 & 3	2 & 3	1 & 2 & 3	1 & 2 & 3	1 & 2	1 & 2	1 & 2
Exposure due to Current Harvest	0	33%	67%	100%	100%	100%	100%	100%	100%	100%	100%	100%
If two months	3	3	3	3	3	4	5	6	6	6	6	5
Pregnancy Trimester in Dec-May	1 & 2	1	1 & 3	1 & 3	3	2 & 3	2 & 3	2 & 3	1 & 2 & 3	1 & 2 & 3	1 & 2	1 & 2
Exposure due to Current Harvest	0	0	33%	67%	100%	100%	100%	100%	100%	100%	100%	100%

Table A.6: Water Quality Results (Reduced Form) - Municipalities in Brazilian Center-West and South Regions, 2000-2010

	Water Quality Measure			IMR		
	(1)	(2)	(3)	(4)	(5)	(6)
	PANEL A: BOD					
Soybean Potential Upstream	-45.376	-29.620	-29.625	16.378	17.673	17.404
	(22.878)*	(25.082)	(26.120)	(9.011)*	(8.082)**	(8.136)*
Soybean Potential in Municip	52.050	42.003	46.784	4.696	3.564	3.407
	(32.785)	(23.509)*	(26.439)*	(10.790)	(12.513)	(12.510)
Sample	1	2	3	1	2	3
Socioeconomic Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	739	628	595	1,023	847	814
R-squared	0.438	0.569	0.583	0.313	0.342	0.345
Number of Municip	93	77	74	93	77	74
1st Stage F-stat						
	PANEL B: Ammoniacal Nitrogen					
Soybean Potential Upstream	-1.258	-0.464	-0.151	6.562	10.794	8.936
	(3.423)	(1.480)	(1.636)	(21.442)	(19.693)	(21.080)
Soybean Potential in Municip	-1.602	0.008	-0.115	5.932	9.005	9.290
	(2.816)	(1.690)	(1.806)	(17.450)	(21.089)	(21.142)
Sample	1	2	3	1	2	3
Socioeconomic Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	558	480	451	671	572	539
R-squared	0.551	0.472	0.474	0.343	0.383	0.389
Number of Municip	61	52	49	61	52	49
1st Stage F-stat						

Notes: Standard errors clustered at the ottobasin level: *** p<0.01, ** p<0.05, * p<0.1. All regressions include municipality fixed-effects and state-year fixed effects. Socioeconomic controls include GDP per capita (in log) and the share of GDP from agriculture, health inputs (hospital beds, presence of hospitals and of the Family Health Program), and population coverage by *Bolsa Família*. Regressions are weighted by the mean number of births over the entire sample period. Due to the high number of missing observations for both water quality measures, all regressions only consider municipalities with nonmissing water quality measures in 2003. Columns 1, 2, and 3 show the results for the water quality measure and columns 4, 5, and 6 show the results for our baseline specification using the same sample. The water stations assignment differ in the way we assign water stations and its measures to municipalities, since many stations are in water courses that define borders. In sample 1, we assign each water station to the closest municipal capital. Sample 2 assigns water stations in the borders to both relevant municipalities. Sample 3 assigns each station not in a border to the municipality assigned by the water agency (ANA) and assigns municipalities in borders to the closest capital.