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Glyphosate Use in Agriculture and Birth Outcomes of Surrounding Populations[*]

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Abstract

This paper assesses the impact of glyphosate use in agriculture on birth outcomes of human populations in surrounding areas. Glyphosate is the most widely used herbicide in the world. Still, despite ongoing controversy, little is known about its effects on human populations at large. Our empirical strategy relies on the fact that glyphosate is strongly complementary to the use of genetically modified seeds in soybean production. We use an instrument based on the gains in productivity from adoption of genetically modified soybeans and look at externalities across municipalities sharing the same water resources. We detect negative and statistically significant effects of glyphosate use on birth outcomes. Our results indicate externality effects of glyphosate use on populations distant from the original locations of use, but receiving water from these locations.

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 documented 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 effects on human health, 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 environmental and health consequences (Carson et al., 1962). The optimal regulation of pesticides, therefore, must find the difficult balance between the productive benefits of use and the negative health externalities. This is not an easy task because these externalities are very hard to measure. First, adoption of new agricultural technologies – of which pesticides are a particular example – is not exogenous to local economic conditions. Second, increased agricultural productivity may affect health directly, through changes in socioeconomic outcomes.

Nowadays glyphosate (N-phosphonomethyl-glycine), the most widely used herbicide in the world, is the pesticide under the spotlight. Its use has risen dramatically in the last few decades after the introduction of new genetically modified seeds. Some genetically modified seeds – soybean seeds in particular – are specifically engineered to be resistant, and therefore complementary, to the use of glyphosate. This combination has been responsible for major gains in agricultural productivity in the developed and developing world, leading to substantial economic changes and, in some cases, helping trigger a process of structural transformation (Bustos et al., 2016).

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 laboratory evidence showing that, even at concentrations below regulatory limits, glyphosate can have damaging effects on human cells, and by law suits in the US and the threat of ban in Europe (Benachour et al., 2007; Mesnage et al., 2015; Economist, 2016; Hakim, 2017).[1] The case of glyphosate therefore highlights in an extreme fashion the trade-off between agricultural productivity and health implicit in the regulation of pesticides. Still, despite the ongoing public controversy, little is known about its subclinical effects on human populations at large (those not directly involved in its handling and use and not in close proximity to application areas). The latter is true not only in relation to glyphosate, but to most pesticides currently used, even though some measurable level of pesticides is found in the bodies of the vast majority of people in Western countries (Landrigan, 2018). Landrigan (2018) argues that, in fact, the population affected

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[1] 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.

by the subclinical toxicity of pesticides is likely to be much larger than that directly affected by acute poisoning.

This paper assesses the impact of glyphosate use in agriculture on birth outcomes of surrounding populations. We look at the main soybean-producing areas of Brazil and concentrate on the period between 2000 and 2010, when soybean production expanded rapidly following the introduction of genetically modified seeds. The key advantage of genetically modified soybean seeds is their strong complementarity to glyphosate and the use of this pesticide in Brazil increased concomitantly with the expansion in soybean production (Pignati et al., 2014; Young, 2006; USDA, 2016). We focus on the externality at large, not on the effect of use for those directly handling it. 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 glyphosate use based on the natural suitability of each area to genetically modified soybean seeds and on the timing of the regulatory change that allowed their introduction in the country, following Bustos et al. (2016). The instrument also deals with measurement error in our variable for use of glyphosate at the municipality level. Second, we analyze the effect of glyphosate use in one area on health outcomes in other areas that share the same water resources. This minimizes the indirect impact of glyphosate use on health through increased agricultural productivity, therefore coming closer to isolating its health externalities. In addition, it allows us to use the direction of river flow to validate the empirical strategy, since health outcomes in a given location should be affected by the use of glyphosate upstream, but not downstream, from it (similarly to Lipscomb and Mobarak, 2017).

We use data from the Brazilian Ministry of Health on infant mortality (including cause of death), birth weight, and gestational length, among others. Most of our analyses and robustness exercises concentrate on infant mortality, but we also present results for these 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 in the 2000's experienced significant deteriorations in birth outcomes, in particular 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 0.93 per 1,000 births. This corresponds to an yearly average of 0.5 death per municipality, adding up to a total of 557 infant deaths per year. Since we are looking at areas distant from the location of use and focusing only on infant mortality, this number is likely to underestimate the overall impact of glyphosate use on human health. This type of long-range externality of glyphosate use in agriculture through the contamination of water bodies has not been documented before in the literature.

We conduct a series of additional exercises to provide evidence that the effect that we estimate is indeed associated with the use of glyphosate in soybean production. There are three main points that we want to convey when performing these exercises. First, 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 bodies. Second, that it 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, 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 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. 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 if rainfall is above a minimum level and for municipalities with a sufficiently high percentage of soil with high erodibility rates. We also show that the effect is higher for municipalities that make use of superficial, rather than underground, sources of water.

On the second point, we present two pieces of evidence. 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 in Brazil was officially authorized. Second, we apply our same empirical strategy to corn instead of soybean and find a very weak first stage. For technological reasons, the marginal gain in productivity from the introduction of genetically modified corn seeds was small, and not even close to that observed for soybean (Young, 2006). In addition, the importance of glyphosate in corn production is much 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 production during this period. It is particularly associated with the technological innovation represented by the introduction of genetically modified soybean seeds and with 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, be it through a change in patterns of land use or the use of other chemicals. In this respect, we present evidence that changes in patterns of land use are unlikely to account for the worsening of health outcomes. We show that 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 anecdotal and historical accounts of the way the process of agricultural expansion took place in our sample region (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, and as documented by Gollin et al. (2018) in a cross-country context. Another possibility would be that other substances used in soybean production, not glyphosate, account for the documented effect. This is unlikely to be the case, since the introduction of genetically engineered soybean seeds increased the use of glyphosate but greatly reduced the use of other herbicides (Young, 2006). The initial introduction of genetically modified soybean seeds in Brazil, for example, was expected to lead glyphosate to replace up to 40 different kinds of previously used herbicides (Gazziero, 2005).[2] In addition, for no other active ingredient the difference in intensity of use between soybean and other major crops is close to that observed for glyphosate (Pignati et al., 2014). Coupled with the absence of significant results for corn mentioned in the previous paragraph, the evidence indicates that glyphosate is the key factor.

Finally, we also show that the response of mortality by cause of death is consistent with what would be expected from the effect of exposure to glyphosate during pregnancy. The results indicate that 81 percent of the overall effect on mortality comes from only two causes of death: perinatal period conditions, accounting for 63 percent of the total effect, and respiratory conditions, accounting for the remaining 18 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, in turn, have been reported for adults in various observational studies of direct poisoning (e.g., Mesnage et al., 2015) and in the single study that analyzed, in a very specific setting, the causal impact of exposure to glyphosate on health outcomes (Camacho and Mejia, 2017; we discuss this paper in further detail below). But, most importantly in our setting, respiratory problems among infants – particularly respiratory distress syndrome and chronic lung disease – are among the most common complications from prematurity (Behrman and Butler, 2007). We also detect a borderline significant effect (at the 10 percent level) for mortality due to endocrine conditions. Though the coefficient is very small, this is remarkable because the incidence of endocrine conditions among cases of infant death is also small and, at the same time, endocrine conditions constitute a specific cause of death that should be affected by glyphosate's endocrine disruptor activity. We find no significant effect for other causes of death, including some with much higher incidence (e.g., infectious diseases and ill-defined causes).

There is a vast array of correlational 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; Sathyanarayana et al., 2010; de Siqueira et al., 2010). Most of these papers report significant correlations between increased pesticide use and deteriorations in birth outcomes, including gestation length, birth weight, and miscarriages, though some papers also report inconclusive results.

Surprisingly enough, we know of only three papers that provide causal evidence of the effect of pesticide use on health outcomes. Two of these look at the effect of pesticides other than glyphosate. Frank (2016) exploits a mortality shock to bats – a predator of some insects that attack crops – caused by the white-nose syndrome. He shows that the increase in insecticide use following the increased mortality

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[2] 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).

of bats in areas affected by the disease led to an increase in infant mortality rates. Maertens (2017) analyzes the expansion in corn production driven by the enactment of the Renewable Fuel Standard in 2005 in the US to analyze the impact of atrazine, an important pesticide used in corn production, on fetal malformation and infant mortality. He uses an identification strategy also inspired by Bustos et al. (2016) and documents an increase in fetal malformations and perinatal deaths as a results of the increased use of pesticides. The only paper exploring the causal effect of glyphosate on human health in a natural experiment setting is Camacho and Mejia (2017). They show that the unchecked aerial spraying of coca producing areas in Colombia with glyphosate, during the "Plan Colombia" campaign,[3] led to increases in medical consultations due to dermatological and respiratory conditions, and also to increases in miscarriages.[4]

Our work adds to this literature in two directions. First, we focus on glyphosate, the most widely used herbicide in the world, in a context of common agricultural use and therefore environmentally realistic concentration levels. Second, we document an externality of glyphosate use through the contamination of water across distant locations. The existence of these neglected externalities suggests that current regulations on the handling and use of glyphosate should go through a profound revision process.

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.

2 Background

2.1 Glyphosate

Glyphosate is, nowadays, the most used herbicide in the world. Discovered as an herbicide 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, it is absorbed by the exposed parts of the plant and translocated through the whole plant, and 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

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[3] "Plan Colombia" was a joint initiative of the Colombian and American governments to eradicate coca production in Colombia.

[4] More broadly, our paper also relates to the large literature on pollution and health outcomes. This literature has analyzed extensively the effects of both water and air pollution on birth outcomes (e.g., Chay and Greenstone, 2003; Currie and Neidel, 2005; Winchester et al., 2009; Ebenstein, 2012; Brainerd and Menon, 2014; Clay et al., 2016).

can be applied in a single dose or sequentially, in two doses with an interval of 15-20 days between doses.[5] 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 spraying it on the desired area either manually, using sprayers adequate to herbicide application, or by plane. 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.[6]

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 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 a 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

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

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

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 discussion and evidence presented by Bustos et al. (2016), who show that area planted per worker in soybean increased slowly since the 1990's, but that there was a sharp change in trend in 2004, reflecting the adoption of the new technology (see Figure 1).

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.[7] 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 and bringing together a major increase in the use of glyphosate (Meyer and Cederberg, 2010). Total glyphosate used in Brazilian agriculture tripled from 2000 to 2010, from 39,515 tons to 127,586, 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 precisely identify 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.[8]

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

[8] 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 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 tons and 105,095 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 bar, meaning that soy 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.

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,[9] 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.[10]

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.[11] 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.

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 placen-

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

[10] 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. Glyphosate, therefore, attaches to minerals in the soil and becomes chemically inactive relatively quickly.

[11] 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.

tal 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.[12] 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. We impute glyphosate use at the municipality level by distributing this aggregate number in proportion to the area planted with soybean and normalize it by the municipality area. The data on soybean area planted is 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. So our glyphosate variable is constructed in the following way:

$$glyph_{it} = glyph\_country_t \times \frac{soy\_area_{it}}{soy\_area\_country_t} \times \frac{1}{area_i}, \tag{1}$$

where $glyph_{it}$ is the use of glyphosate per squared kilometers in municipality i in year t, the term $glyph\_country_t$ is the aggregate amount of glyphosate used in the country in year t (in tons of active ingredient), soy_area_{it} is the soybean planted area in municipality i in year t, $soy\_area\_country_t$ is the aggregate soybean planted area in the country in year t, and $area_i$ is the area of municipality i.

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[12] 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.

Two potential problems of measurement error arise from this imputation. First, glyphosate is not used exclusively in soybean production. Nevertheless, if the proportion of glyphosate used in soybean were constant over time, this would be only a scaling issue and would not interfere with the qualitative results. The real problem exists if the share of glyphosate used in soybean changes over time, which is likely to be the case due to the introduction of genetically modified seeds. Second, the intensity of glyphosate use in soybean may vary across areas as a function of local conditions. Our instrumental variable strategy, discussed in detail in the next section, deals with both these problems. As it will be clear, it does so by isolating the variation in glyphosate use that is due to the exogenous component – explained by local climatic and soil conditions – of the productivity gain from the introduction of genetically modified seeds.

We also tried other imputation strategies with very similar qualitative and quantitative results. These 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. We choose the strategy described in the text because it is more straightforward and its potential limitations, as well as the way our instrumental variable deals with them, are more transparent.

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. The Ministry of Health's system of information (DataSUS) also provides data on various local health inputs used as controls in our specifications: local presence of a hospital, number of hospital beds, and presence of a major program of basic attention 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.[13] 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 39,532km^2. The median ottobasin has 4 municipalities in it and an area of 9165km^2.

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[13] In the Appendix, we also present results from robustness exercises excluding municipalities without any other municipality upstream from them from the sample.

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.[14] 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 31,974km^2. The average ottobasin includes 35 municipalities and covers an area of 51,868km^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 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.[15]

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 will isolate changes in use due to the introduction of the new soybean seeds and to their adaptability to local conditions.

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

[15] We aggregate this information to the Minimum Comparable Areas level by calculating a weighted average of the original municipalities contained in an Minimum Comparable Areas, where weights are given by the areas of the original municipalities.

To deal with the fact that adoption of a new agricultural technology may affect health through improved socioeconomic outcomes, we choose to focus on the effect of use in one area on health outcomes in other areas. In order to achieve this goal, we use the variable measuring the exposure of a municipality to glyphosate used in municipalities that are in the same water basin but upstream from it, defined in the previous section. 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 these points in the results section.

The downside of this strategy is that it is unable to isolate the local impact of glyphosate use. We do present results applying our strategy to the local use of glyphosate, but coefficients are smaller 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 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 glyphosate and other 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:

$$glyph\_up_{it} = \tilde{\alpha} + \tilde{\gamma} soy\_potential\_up_{it} + \tilde{\beta} X_{it} + \tilde{\delta}_i + \tilde{\pi}_{st} + \epsilon_{it}, \tag{2}$$

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:

$$outcome_{it} = \alpha + \gamma \widehat{glyph\_up}_{it} + \beta X_{it} + \delta_i + \pi_{st} + \varepsilon_{it}, \tag{3}$$

where $outcome_{it}$ is some birth outcome for municipality i 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.[16] 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 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. First, in order to show that the effect was due to the introduction of genetically modified soybean seeds, we test for parallel trends in birth outcomes by allowing for non-linear trends as a function of initial characteristics (time dummies interacted with initial infant mortality, share of the population rural, share of the population poor, and inequality) and by estimating an "event-study" reduced-form tracing out the timing of the estimated impact. We complement this evidence by presenting in the Appendix the results from a "placebo" exercise that applies our empirical strategy using area planted with corn instead of soybean. Following, in order to show that the estimated effect is indeed operating through water, we reverse the logic of our identification and try to falsify our empirical strategy by estimating the "placebo" effect of use of glyphosate downstream from municipality i. We then use again reduced-form estimates to show that the heterogeneity of the estimated impact is in line with the predictions from the scientific literature on water contamination along three margins: incidence of rainfall, erodibility of soil, and local source of drinkable water. Finally, we analyze the effect of soybean adoption on land use to rule out some potential alternative mechanisms linking soybean expansion to a deterioration in birth outcomes.

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[16] 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.

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 seems to 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. 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, reduced-form, and IV estimates of the effect of glyphosate use in municipalities upstream from a given municipality on infant mortality in 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 statistically significant. The addition of controls makes little difference to the point estimate, just increasing slightly its precision in column 3. Columns 4 to 6 present the results of the reduced-form estimation. It shows that potential gains in soybean productivity after 2004 upstream from a given municipality are significantly correlated with increases in infant mortality in the municipality. Again, the introduction of additional controls makes little difference for the 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 after the introduction of genetically modified seeds in 2004. 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 40) 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 a little more than 4 times larger than the respective OLS results, consistent with the presence of measurement error in our glyphosate variable discussed in Section 3. Remember that we do not observe the use of glyphosate at the municipality level and impute it from aggregate numbers using the relative size of soybean planted area.

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 0.93 in the infant mortality rate (per 1,000 births). Since the affected area is large, this effect adds up to a total of 557 additional infant deaths per year after 2004 (or 0.5 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.[17]

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[17] For the interested reader, Appendix Table A.1 reproduces the main specification from Table 2 changing the way we deal with municipalities with no area upstream from it. In our benchmark specification, we assign value zero to municipalities with no areas upstream from them. In Appendix Table A.1, instead, we drop these municipalities. Results remain very similar qualitative and quantitatively to those from Table 2.

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 around one-fourth of the magnitude of the coefficient for upstream soybean potential. 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-sixth 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. 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).

5.2 Testing for Parallel Trends and Other Concurrent Changes

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. We deal with this concern in two ways.

First, we conduct 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). 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 2003 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.

Second, we re-estimate our main specification allowing explicitly 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 infant mortality. Table 4 presents the reduced-form and IV results of this exercise. For each case, we present the results including only the interactions with initial socioeconomic conditions (columns 1 and 4), then only the interaction with initial infant mortality (columns 2 and 5), and then the interactions with both (columns 3 and 6). The results show that there is very little change in the coefficients when we include the interactions with socioeconomic conditions in columns 1 and 4. Coefficients are reduced but remain strongly significant in the specifications including interactions with initial infant mortality. Overall, the table shows that unobserved municipality-specific trends cannot account for the results documented in Table 2. Together with Figure 3, this suggests that lack of parallel trends is not a threat to our identification strategy.

A similar but somewhat more specific concern would be that the effects documented in Table 2 are due to expansions of agricultural production more generally, not of soybean in particular. This would be a concern if the introduction of genetically engineered seeds impacted the 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 expansions in agricultural activity in general, seriously 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.2 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.2 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 to any significant expansion in the area planted with corn. 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 expansion in soybean production that it unleashed.

5.3 The Water Mechanism

Our estimates indicate that glyphosate use upstream from a given municipality, following the adoption of genetically modified seeds, is robustly associated with infant mortality. We now present several pieces of direct evidence in support of this interpretation. These additional results confirm that the estimated effect is indeed working through water and that it is driven by something that is carried from upstream soybean-producing areas into water bodies.

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 5 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 absolute value) in comparison to their upstream counterparts from Table 2 (the point estimate in column 9, for example, has the opposite sign and less than one-third of the magnitude 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.

Following, we draw from the scientific 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 6 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.

Next, 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 pre-disposed to erosion at the 1 km^2 pixel level.[18] 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 2 from Table 6. 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

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[18] 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).

municipalities 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 superficial rather than underground sources of water. Groundwater is generally considered more adequate to 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 care. 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 superficial *vs* groundwater sources. We then interact a municipality indicator for superficial sources of water with our instrument, again in a reduced-form specification. Column 3 in Table 6 presents the result. We find that the interaction of the instrument with the dummy indicating superficial sources of water has a positive and statistically significant coefficient (at the 10 percent level), indicating that the effect documented before is substantially higher in municipalities making use of surface water.

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, when they have a higher share of soil with high erodibility rates, and in municipalities that use surface sources of water.[19] These results are in line with the predictions from the scientific literature and indicate that water contamination from something in the soil in upstream soy-producing areas is indeed behind the results reported in Table 2.

5.4 Other Potential Spillovers from Soybean Expansion

We now examine other potential changes brought about by the expansion in soybean production, which might have had spillovers onto surrounding areas and, through those, might have affected infant mortality in downstream municipalities. We conduct two exercises to address this concern and reassure that the exclusion restriction of our IV strategy is valid.

First, we test for the presence of spillovers from potential gains in soybean productivity upstream from a municipality on socioeconomic outcomes in the municipality. As some of the variables considered 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. Table 7 presents the results. Columns 1, 3, 5, and 7 in Panel A simply replicate as close as possible the results from Bustos et al. (2016) in our sample, 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,

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[19] 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.

4, 6, and 8, we include the potential gain in soybean productivity upstream from the municipality to test for the presence of economic 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 gains 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 observed 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. These results reassure that the effects on mortality estimated before are not driven by confounding economic changes brought about by the expansion in soybean production upstream from a municipality.

We also test explicitly for the other potential threat to the exclusion restriction of our IV strategy. Another important concern 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 water downstream 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 comes together with the use of no-tillage techniques. Nevertheless, 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 8 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 entire 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.

Finally, one might wonder whether it is not other substances used in soybean production, possibly in a way that is highly correlated with the use of glyphosate, that generate the effect on infant mortality. Given all that is known about pesticide use in genetically modified soybean production, this possibility seems implausible. 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). For no other herbicide, the difference in intensity of use between soybean and other major crops, such as corn, is close to that observed for glyphosate (Pignati et al., 2014).[20]

This section provides evidence that other spillovers across areas cannot account for the increases in infant mortality in municipalities downstream from soybean-producing areas. 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 (Section 5.2), that it operated through water bodies (Section 5.3), and that it is was not due to other potential changes brought about by the expansion in soybean production (Section 5.4).

5.5 Other Birth Outcomes

Our last set of results, presented in Table 9, expands the analysis to other birth outcomes besides just infant mortality. We present the results of estimations using our benchmark IV specification for various different 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 81 percent of the infant mortality effect estimated in Table 2 is due to two causes of death: perinatal period conditions, which account for 63 percent of the total effect, and respiratory conditions, which account for the remaining 18 percent. As discussed in Section 2, glyphosate has been

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[20] Remember, nevertheless, that our results refer to the commercial formulations typically used in soybean production. So, as mentioned before, it is possible that results are affected by the set of adjuvants used in these commercial formulations, which are designed to increase glyphosate's toxicity and its effectiveness as a herbicide (Mesnage et al., 2015).

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 serious 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 among the most common complications from premature birth (Behrman and Butler, 2007). The only other cause of death that appears as statistically significant (at the 10 percent level) in Panel A is endocrine conditions. Though the coefficient is quantitatively small, this is somewhat remarkable because the incidence of endocrine conditions among cases of infant death is small, but, at the same time, it is a specific cause of death that should be affected by glyphosate's endocrine disruptor activity. We find no significant effect for other causes of death, including some with much higher incidence, such as infectious diseases and ill-defined causes.

Surprisingly, we also find no effect on 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 positive coefficient for the sex ratio at birth, but it is not statistically significant. Finally, Panel A shows that the point estimate for male infant mortality is indeed slightly higher than that for female infant mortality, which should be expected given the idea that male infants are more fragile than female infants.

Panel B, which reports results for other birth outcomes, shows an increased likelihood of pre-term births and also of low birth weights, though the latter is statistically significant only at the 10 percent level. 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 effects on APGAR1 and APGAR5, despite negative point estimates.

Finally, we 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). Though we cannot rationalize this result and, based on the other evidence presented in the paper, think that it is just a statistical fluke, we asses whether it could be a concern. 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. We show in the last four rows in Panel B that this is not the case. The unexpected positive sign for the birth rate is not related to any systematic change in the characteristics of mothers giving birth. [21]

Appendix Table A.3 confirms the suspicion that the significant coefficient for the birth rate is spurious by showing that it comes from pre-existing dynamics. Once we replicate specifications analogous to those from Table 4 using the birth rate as the dependent variable, the significant result disappears. Interactions of the initial birth rate with time dummies account for the magnitude and significance of the coefficient estimated in Table 9. Similarly, an event-study analysis analogous to that from Figure 3 detects significant pre-trends in the birth rate, meaning that the dynamic pattern of responses for birth rates cannot possibly account for the pattern observed for infant mortality. Confirming this observation, the results for infant mortality in Table 4 remain significant and of similar magnitude when we include additional interactions of the initial birth rate with time dummies (results not shown here, but available upon request).

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 0.93 per 1,000 births, adding up to a total of 557 infant deaths per year in the sample.

Though we do not observe directly the use of glyphosate in different locations, and therefore have to use an imputed variable (corrected by an instrumental variable strategy), 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.

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$ 646

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[21] A back of the envelope calculation shows that the infant mortality rate among these extra births would have to be roughly 160 percent higher than the average mortality rate in the pre-intervention period in order for selection to be able to account for the results. Remember that these births are coming from mothers with similar characteristics, so this scenario is implausible.

million per year.[22] Brazilian exports of soybean-related products alone, ignoring domestic consumption, have amounted to over US$ 30 billion per year in recent years (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. 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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[22] The most recent estimate of the value of a statistical life in Brazil is of the order of US$ 1.16 million (estimates from Lavetti and Schmutte, 2018, adjusted for 2010 US$).

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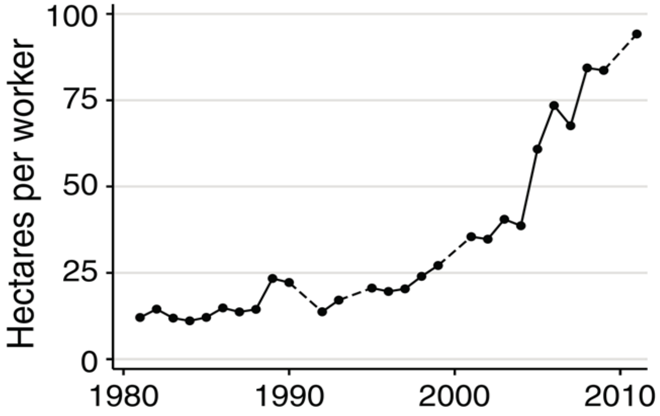
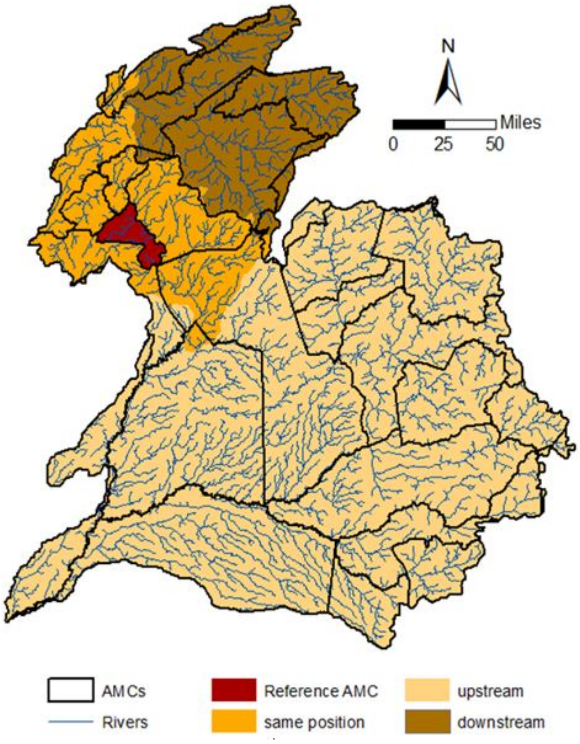
Main Figures and Tables

Figure 1: Changes in Hectare per Worker in Brazilian Soybean Production, 1980-2011



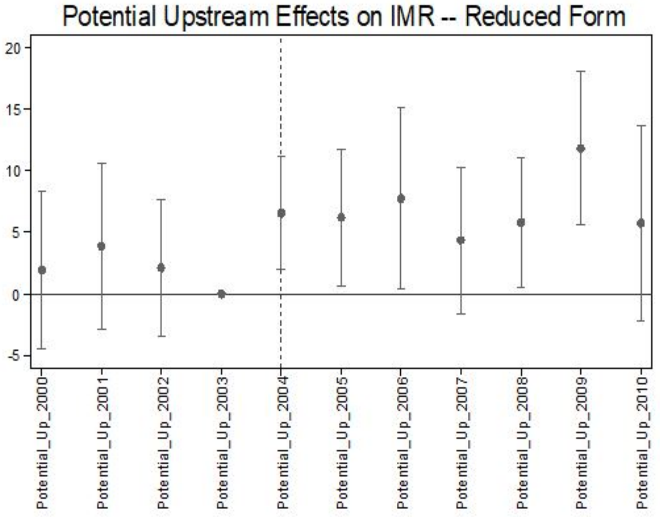
Source: Bustos et al. (2016).

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 Soy 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	18.648	18.364	18.979	0.615
% Low Apgar 1	0.189	0.184	0.195	0.011
% Low Apgar 5	0.031	0.032	0.030	-0.001
% >37 Weeks Pregnancy	0.929	0.927	0.931	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
% Soy Area	0.084	0.067	0.103	0.036*

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 (soy 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	9.075 (9.914)	9.161 (10.039)	9.911 (7.895)				43.391 (16.578)***	43.797 (16.929)***	45.538 (17.678)***	42.651 (10.733)***
Soy Potential Upstream				4.714 (1.676)***	4.759 (1.699)***	4.917 (1.666)***				
Soy Potential in Municip		1.144 (3.588)	0.504 (3.010)		1.326 (3.214)	0.708 (2.588)		1.302 (3.015)	0.707 (2.445)	
Glyphosate in Municip										6,808 (22.958)
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	0.101	0.101	0.103	0.101	0.102	0.104				
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							44.45	44.13	43.53	5.265

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 Soy Potential Upstream. In column 10, Glyphosate in Municipality is analogously instrumented by Soy 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)
Soy Potential Upstream	0.109	0.109	0.108
	(0.016)***	(0.016)***	(0.016)***
Soy Potential in Municipality		0.001	0.000
		(0.011)	(0.011)
Socioeconomic Controls	No	No	Yes
Observations	12,309	12,309	12,309
R-squared	0.769	0.769	0.770
Number of Municipalities	1,119	1,119	1,119
Partial-F	44.45	44.12	43.52

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: 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)	(5)	(6)
Glyph Upstream				42.419 (19.452)**	29.261 (13.096)**	28.046 (13.766)**
Soy Potential Upstream	4.502 (1.823)**	3.161 (1.219)**	2.974 (1.278)**			
Initial Socioecon. × Time Dummies	X		X	X		X
Initial IMR × Time Dummies		X	X		X	X
Observations	12,309	12,309	12,309	12,309	12,309	12,309
R-squared	0,112	0.177	0.189			
Number of Municip	1,119	1,119	1,119	1,119	1,119	1,119
1st Stage F-stat				41.25	42.75	40.74

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 Soy Potential in Municipality. Columns 1, 3, 4 and 6 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, 3, 5 and 6 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 5: 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	-28.605	-28.763	-26.310				-17.938	-17.775	-13.855
	(5.228)***	(5.117)***	(5.493)***				(13.182)	(13.170)	(15.709)
Soy Potential Downstream				-2.434	-2.417	-1.852			
				(2.072)	(2.058)	(2.285)			
Soy Potential in Municip		1.458	0.914		1.045	0.416		1.322	0.693
		(3.744)	(3.288)		(3.731)	(3.208)		(3.736)	(3.284)
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	0.103	0.103	0.105	0.101	0.101	0.103			
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							14.91	14.74	16.64

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 Soy Potential Upstream. Regressions are weighted by the mean number of births over the entire sample period.

Table 6: Reduced-Form Heterogeneity Results – Municipalities in Brazilian Center-West and South Regions, 2000-2010

	Rainfall in Application Season (Oct-Mar)	Erodibility	Source of Drinking Water
	(1)	(2)	(3)
Soy Potential Upstream	-2.579	-2.234	4.213
	(3.073)	(2.359)	(1.782)**
Rain Quartile 2 × Soy Pot. Up.	7.734		
	(2.513)***		
Rain Quartile 3 × Soy Pot. Up.	9.199		
	(2.953)***		
Rain Quartile 4 × Soy Pot. Up.	7.085		
	(3.454)**		
% High Erod. × Soy Pot. Up.		56.555	
		(16.954)***	
Superficial Source × Soy Pot. Up.			2.941
			(1.611)*
Observations	12,309	12,309	12,265
R-squared	0.105	0.105	0.105
Number of Municipalities	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 Soy 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 7: Reproducing Bustos et al. (2016) and Testing for Economic Spillovers from Upstream Expansion of Soy Production - Effect of Soy Potential on Economic Outcomes - Municipalities in Brazilian Center-West and South Regions, Long Differences 2000-2010

	Change in Soy 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 Soy Potential in Municip	0.016 (0.006)***	0.014 (0.005)***	-0.008 (0.007)	-0.008 (0.006)	0.012 (0.006)**	0.011 (0.005)**	-0.014 (0.008)*	-0.016 (0.007)**
Change in Soy Potential Upstream		0.006 (0.004)		-0.001 (0.006)		0.005 (0.005)		0.007 (0.009)
Observations	1,119	1,119	1,119	1,119	1,119	1,119	1,119	1,119
R-squared	0.054	0.060	0.148	0.148	0.098	0.104	0.188	0.190
	Panel B: Bustos et al. (2016) Specification + State Fixed-Effects							
Change in Soy Potential in Municip	0.008 (0.003)**	0.008 (0.003)***	-0.009 (0.004)**	-0.010 (0.005)**	0.014 (0.003)***	0.014 (0.003)***	-0.010 (0.005)**	-0.011 (0.004)***
Change in Soy Potential Upstream		-0.001 (0.003)		0.002 (0.004)		0.002 (0.004)		0.007 (0.011)
Observations	1,119	1,119	1,119	1,119	1,119	1,119	1,119	1,119
R-squared	0.178	0.179	0.240	0.240	0.219	0.219	0.278	0.279

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 8: Effect of Soy 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)
Soy Potential in Municip	-0.025	0.114	-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.

Table 9: IV Results for Other Outcomes – Municipalities in Brazilian Center-West and South Regions, 2000-2010

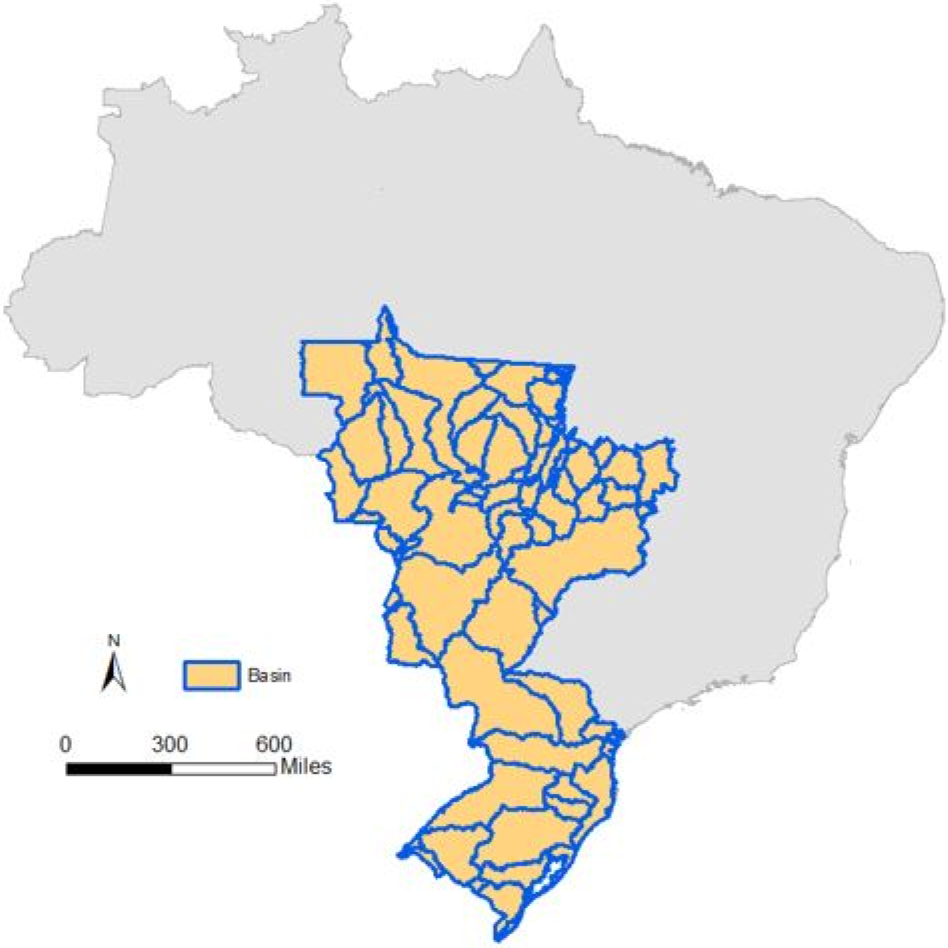
	Effects of Glyph Upstream	S.E.
	Panel A - IV Results: Mortality Outcomes	
Infectious	3.602	(2.937)
Respiratory	8.522	(2.916)***
Perinatal	28.211	(11.205)**
Congenital	3.778	(4.984)
External Causes	2.783	(2.636)
Endocrine-Nutritional	2.321	(1.236)*
Genito-Urinary	0.285	(0.396)
Ill-defined	-0.168	(2.605)
Fetal Mortality Rate	-5.563	(7.469)
Sex Ratio at Birth	0.021	(0.124)
IMR Males	47.362	(21.895)**
IMR Females	44.361	(22.385)**
	Panel B - IV Results: Other Birth Outcomes	
Low Birth Weight	0.091	(0.046)*
Preterm Birth (<37 weeks)	0.357	(0.159)**
Gestational Length:		
<22 weeks	-0.001	(0.002)
22-27 weeks	0.010	(0.005)*
28-36 weeks	0.348	(0.159)**
37-41 weeks	-0.436	(0.226)*
>41 weeks	0.098	(0.063)
Low APGAR 1	-0.198	(0.251)
Low APGAR 5	-0.021	(0.032)
Birth Rate	0.088	(0.025)***
Mother Education : 0-3 years	0.012	(0.190)
Mother Education: 4-7 years	0.117	(0.252)
Mother Education: 8+ years	-0.129	(0.187)
Mean Age of Mother	-0.917	(0.854)

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 Soy Potential in the Municipality. Regressions are weighted by the mean number of births over the entire sample period.

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).

B Appendix Tables

Table A.1: 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						Downstream Placebos					
	Reduced Form			IV			Reduced Form			IV		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Glyph Upstream				45.562	46.196	49.111						
				(21.841)**	(21.466)**	(20.427)**						
Soy Potential Upstream	4.969	5.041	5.315									
	(2.305)**	(2.234)**	(2.003)**									
Glyph Downstream										-20.239	-20.075	-13.929
										(12.959)	(12.801)	(15.380)
Soy Potential Downstream							-2.627	-2.613	-1.759			
							(2.048)	(2.020)	(2.166)			
Soy Potential in Municip		2.131	1.442		2.063	1.404		0.573	-0.016		0.873	0.253
		(3.750)	(3.023)		(3.526)	(2.845)		(3.857)	(3.390)		(3.826)	(3.395)
Socioeconomic Controls			X			X			X			X
Observations	11,319	11,319	11,319	11,319	11,319	11,319	11,528	11,528	11,528	11,528	11,528	11,528
R-squared	0.105	0.105	0.107				0.103	0.103	0.106			
Number of Municip	1,029	1,029	1,029	1,029	1,029	1,029	1,048	1,048	1,048	1,048	1,048	1,048
1st Stage F-stat				38.48	38.06	37.93				10.94	10.80	11.94

Notes: The first 1-6 columns reproduce specifications of Table 2, and columns 7-12 replicate those from Table 5. In our benchmark specifications (in Tables 2 and 5), we assign value zero to municipalities with no areas upstream from them. In all specifications from column 1 through 12 instead, we drop these municipalities.

Table A.2: Results for Placebo Exercise Using Corn - Municipalities in Brazilian Center-West and South Regions, 2000-2010

	Dep Var: Area Maize Upstream		
	(1)	(2)	(3)
Potential Corn Upstream	-0.004	-0.004	-0.004
	(0.006)	(0.005)	(0.005)
Potential Corn Municip		-0.002	-0.003
		(0.003)	(0.003)
Socioeconomic Controls			X
Observations	12,309	12,309	12,309
R-squared	0.352	0.353	0.365
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. 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*.

Table A.3: Effects on Birth Rates: 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)	(5)	(6)
Instrument: Upstream	0.008	0.002	0.002			
	(0.003)***	(0.002)	(0.002)			
Glyph Upstream				0.077	0.014	0.020
				(0.026)***	(0.017)	(0.015)
Initial Socioecon. × Time Dummies	X		X	X		X
Initial Birth Rate × Time Dummies		X	X		X	X
Observations	12,309	12,309	12,309	12,309	12,309	12,309
R-squared	0.628	0.649	0.685			
Number of AMC	1,119	1,119	1,119	1,119	1,119	1,119
AMC FE	Yes	Yes	Yes	Yes	Yes	Yes
UF-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
F-stat				41.25	41.64	41.01

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 Soy Potential in Municipality. Columns 1, 3, 4 and 6 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, 3, 5 and 6 include year dummies interacted with birth rate at the baseline year, 2000. Regressions are weighted by the mean number of births over the entire sample period.