Title

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Permalink
https://escholarship.org/uc/item/36b648n8

Journal
Environmental Health Perspectives, 131(12)

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Publication Date
2023-12-01

DOI
10.1289/EHP12768

Peer reviewed

A Section 508–conformant HTML version of this article
is available at https://doi.org/10.1289/EHP12768.

# The Effect of Pesticide Spray Season and Residential Proximity to Agriculture on Glyphosate Exposure among Pregnant People in Southern Idaho, 2021

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**Background:** Glyphosate is one of the most heavily used pesticides in the world, but little is known about sources of glyphosate exposure in pregnant people living in agricultural regions.

**Objective:** Our objective was to evaluate glyphosate exposure during pregnancy in relation to residential proximity to agriculture as well as agricultural spray season.

**Methods:** We quantified glyphosate concentrations in 453 urine samples collected biweekly from a cohort of 40 pregnant people in southern Idaho from February through December 2021. We estimated each participant's glyphosate exposure as the geometric mean (GM) of glyphosate concentrations measured in all samples (average $n = 11$ samples/participant), as well as the GM of samples collected during the pesticide "spray season" (defined as those collected 1 May–15 August; average $n = 5$ samples/participant) and the "nonspray season" (defined as those collected before 1 May or after 15 August; average $n = 6$ samples/participant). We defined participants who resided <0.5 km from an actively cultivated agriculture field to live "near fields" and those residing ≥0.5 km from an agricultural field to live "far from fields" ($n = 22$ and 18, respectively).

**Results:** Among participants living near fields, urinary glyphosate was detected more frequently and at significantly increased GM concentrations during the spray season in comparison with the nonspray season (81% vs. 55%; 0.228 μg/L vs. 0.150 μg/L, $p < 0.001$). In contrast, among participants who lived far from fields, neither glyphosate detection frequency nor GMs differed in the spray vs nonspray season (66% vs. 64%; 0.154 μg/L vs. 0.165 μg/L, $p = 0.45$). Concentrations did not differ by residential proximity to fields during the nonspray season (0.154 μg/L vs. 0.165 μg/L, for near vs. far, $p = 0.53$).

**Discussion:** Pregnant people living near agriculture fields had significantly increased urinary glyphosate concentrations during the agricultural spray season than during the nonspray season. They also had significantly higher urinary glyphosate concentrations during the spray season than those who lived far from agricultural fields at any time of year, but concentrations did not differ during the nonspray season. These findings suggest that agricultural glyphosate spray is a source of exposure for people living near fields. https://doi.org/10.1289/EHP12768

## Introduction

In 2019, Gillezeau et al.[1] published a review of the strikingly sparse scientific evidence documenting human exposure to glyphosate. Glyphosate, which entered the agrochemical market over 50 y ago, is the most commonly and intensively used herbicide in the world due to both the introduction of glyphosate-tolerant genetically modified crops starting in 1996 and its more recent adoption as a desiccant prior to harvest of crops such as cereals and pulses.[2] Yet by 2019, only 19 studies of glyphosate concentrations in humans had been published. Moreover, these studies usually included small numbers of participants, evaluated glyphosate concentrations in different tissues with varying detection limits, and provided little information on temporal trends or potential sources of exposure.

Important advances have been made in our understanding of glyphosate exposure in the 3 y since Gillezeau et al. published their review. In 2023, the U.S. Centers for Disease Control and Prevention (CDC) reported, for the first time, urinary glyphosate concentrations using samples from the 2013–2014 and 2015–2016 National Health and Nutrition Examination Survey (NHANES).[3] The population-representative 2013–2014 NHANES data showed that an estimated 81% of the U.S. population ≥6 y of age had recent exposure to glyphosate.[4] In a population-based survey in France, glyphosate was detected in 99% of urine samples collected from nearly 7,000 participants recruited between 2018 and 2020.[5] Several other studies published in the past year alone have measured glyphosate concentrations in both occupationally and nonoccupationally exposed populations, with most reporting glyphosate concentrations in a single spot urine sample.[6–12]

Human studies have reported adverse reproductive effects of glyphosate exposure at environmentally relevant levels. Four recent investigations found that gestational glyphosate exposure was associated with shortened gestational length,[13] preterm birth,[14,15] and reduced fetal growth.[16] If the developing fetus is especially vulnerable to glyphosate, it is critical to understand the magnitude and sources of exposure during this critical developmental period. Still, few studies have examined glyphosate exposure during pregnancy. Beyond the four studies of glyphosate exposure and reproductive outcomes, we are aware of only two other studies of glyphosate exposure during pregnancy, neither of which occurred within the past decade.[17,18] Given the increasing use of glyphosate and glyphosate-based herbicides (GBH; e.g., Roundup), the results of earlier studies may not be indicative of current exposures.

Another important data gap relates to sources of glyphosate exposure. Diet is one potentially important source[19,20]; agricultural use may be another. More than 250 million pounds of glyphosate are applied each year to cropland in the United States alone,[2] and exposure to many types of pesticides is higher among individuals living near agricultural fields.[21,22] Pesticide exposure among

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Supplemental Material is available online (https://doi.org/10.1289/EHP12768).

The authors declare they have no actual or potential conflicts of interest.

Received 18 January 2023; Revised 20 September 2023; Accepted 17 October 2023; Published 6 December 2023.

residents of agricultural regions can occur through inhalation or dermal absorption via spray drift from active applications or through ingestion of pesticide residues in soil or water.[23] A few studies have evaluated the effect of residential location on glyphosate exposure and found higher exposure among those in rural/agricultural locations than those living in urban regions.[13,18,24] The purpose of this study was to evaluate glyphosate exposure in pregnant women in relation to residential proximity to agriculture as well as agricultural spray season.

## Methods

### *Study Setting and Design*

In 2021, we recruited 40 participants living in southern Idaho during the first trimester of pregnancy and collected weekly urine samples from enrollment through delivery. Participants lived either close to ($<0.5$ km) or far from ($\geq 0.5$ km) actively cultivated agricultural fields. We recruited participants from Women, Infants and Children (WIC) clinics in three health districts of Idaho: Southwest District Health (serving the towns of Nampa and Caldwell), South Central District Health (serving Twin Falls, Shoshone, Gooding, Jerome, and Heyburn), and Central District Health (serving Boise, Meridian, and Garden City). Administered through local agencies, WIC is a federal program that provides nutritional support to low-income pregnant, postpartum, and breastfeeding women and low-income infants and children up to 5 y of age.

We calculated a sample size to provide a power of 0.80 at a 0.05 significance level in a two-sided test of the difference in exposure between participants living near and far from agricultural fields, based on the geometric mean (GM) glyphosate concentrations measured in urine samples collected from mothers in farm and nonfarm households[25] and an assumed standard deviation (SD) of 0.5 $\mu g/L$. We estimated this SD from the ratio of mean to variance in organophosphate pesticide (OP) concentrations from a repeated measures study,[26] which we used because no comparable glyphosate data exist and half-lives are similar ($<12$–16 h).[27,28]

We began our study prior to the annual initiation of agricultural pesticide applications and continued sample collection throughout the year, thus capturing exposure before, during, and after the agricultural pesticide spray season. We defined the agricultural pesticide spray season *a priori* as 1 May through 15 August, based on conversations with local agricultural experts, including land grant extension specialists and educators regarding weather and conditions for 2021.

### *Participant Recruitment and Eligibility*

Because of the COVID-19 pandemic, we developed contactless approaches to communicate with and engage our community partners. Specifically, we developed a video (https://www.youtube.com/watch?v=pFH3MIELXNU), which we shared with WIC clinic staff in lieu of visiting the clinics for in-person presentations. We worked remotely with clinic directors to identify on-site "project champions" at each Health District who connected with us regularly and directly, advocated for our research project, and helped answer any of their colleagues' questions. In addition to the videos we prepared for WIC clinic staff, our research team created brief videos to advertise the study to potential participants (https://www.youtube.com/watch?v=sOG0lppKzUw and https://www.youtube.com/watch?v=p75mIj0hwrc); all materials intended for participants were prepared in both English and Spanish. We asked the WIC staff to share these videos with any clients they thought might be interested in participating in this study. We also created electronic versions of full-page recruitment flyers and shorter index card–sized recruitment flyers that could be emailed to potential participants.

When a WIC staff member spoke with a potential participant who wanted to learn more about the study, the staff member asked them for permission to share their contact information with our research team. Our research staff then contacted interested individuals to assess eligibility. Eligible participants were in their first trimester of pregnancy; over the age of 18 y; had not been told by a medical professional that their pregnancy was high risk; did not work with pesticides or have a household member who worked with pesticides; did not regularly eat organic food; had access to a smartphone, tablet, or computer that could connect to the Internet; and spoke either English or Spanish. We scheduled initial meetings with interested and eligible participants for the end of the participant's first trimester at 13–14 wk of pregnancy. The Boise State University institutional review board reviewed and approved this study.

### *Informed Consent, Demographic Questionnaire, and Pesticide Exposure Interview*

All contact with participants occurred in English or Spanish, as preferred by the participant, and all were conducted in a contactless manner. For the initial meetings, research staff traveled to each participant's home and phoned the participant on arrival. Staff then placed paper consent forms outside the participant's home, returned to their vehicles, and texted the participant the link to a study-specific video that provided a detailed explanation of all components of the informed consent process. They then asked the participant to either call the research staff member with any questions or to sign the consent form and leave it outside. Each participant was assigned a unique Study ID.

Following the consent process, research staff phoned the participant and verbally administered a basic demographic questionnaire to collect self-reported information on age, household income, education, race/ethnicity (African American or Black; Asian; Caucasian or White; Hispanic or Latino; Native Hawaiian or other Pacific Islander; American Indian or Alaskan Native), occupation, household size, and whether or not they were a current smoker or vape user. Research staff also verbally administered a pesticide exposure interview about residential use of pesticides to control for indoor and outdoor insects, weeds, fleas, or ticks on domestic pets or for other pests, including snails, slugs, birds, rabbits, squirrels, rats, mice, gophers, raccoons, or deer (see Table S1). Participants were asked about both their personal use of residential pesticides, use by any other member of their household, and use by a pest control company. For any pesticides used by a participant or a member of their household, participants were asked whether they knew what product was used and/or had the containers available. For any containers they had available, participants were asked to locate and photograph those products and to text the pictures to our research staff.

### *Urine Sample Collection*

During the initial meeting, participants were asked to provide a spot urine sample. Following completion of the surveys, research staff texted the participant with a link to a study-specific video that described how to collect that sample. Research staff then placed a 4-oz polypropylene specimen cup with a unique barcoded label in a resealable plastic bag outside the participant's door. The participant then collected and returned the sample. Research staff then left the participant with a USD $10 gift card, a small plastic cooler and reusable ice pack, and a prelabeled specimen cup for the next week's sample.

We established a regular day of the week for urine sample collection, and for each subsequent week, we asked participants to collect their first urine of the day [first morning void (FMV)], to write the time and date of collection on the specimen cup, and to leave it outside their home in the study cooler with ice packs for collection by research staff that same day. We provided participants with posters to hang in their bathrooms as reminders and sent text messages the night before each participant's scheduled sample collection to remind them to collect their sample the next morning. Research staff then traveled to each participant's home on the preestablished day to collect that week's sample and to leave another $10 gift card and a labeled specimen cup for the following week.

We collected weekly urine samples from enrollment through delivery except for a 2-wk period from 14 June to 30 June, during which the cohort took part in a randomized crossover trial of an organic diet. During the crossover trial, participants provided daily urine samples; the details of the dietary intervention are described elsewhere.[29] None of the results from daily samples collected during this dietary intervention are included in this analysis.

We collected an average of 22 weekly urine samples from each of the 40 participants and grouped these samples by calendar week. Because of funding limitations, we selected for analysis all samples collected during every other week.

### *Urine Sample Processing and Laboratory Analysis*

Research staff completed a chain-of-custody form to record the date and time of each urine collection and make any notes about the collection process or sample condition. Samples were transported on ice to our laboratory at Boise State University, where they were refrigerated for no more than 24 h before processing. All samples were analyzed for color, clarity, and specific gravity (Atago Urine Specific Gravity Refractometer, PAL 10-S) at 5°C. Research staff aliquoted four identical 4-mL subsamples into 5-mL cryovials for storage at −80°C.

In addition to participant samples selected for glyphosate quantification, for quality assurance, we also randomly selected a set of duplicates from 10% of the sample set sent for analysis, which were submitted without identifying characteristics. We shipped samples and duplicates to the CDC overnight on dry ice in January 2022 for analysis.

Details of the analytical method have been described previously.[30] Briefly, the method employs ion chromatography-isotope dilution–tandem mass spectrometry using a Dionex ICS-5000 + ion chromatography system (using polyether ether ketone materials to prevent carryover and interaction with metal surfaces) and an AB Sciex 5500 triple quadrupole mass spectrometer. The limit of detection (LOD) was 0.1 $\mu g/L$. Method accuracy was established by spiking two different urine samples at zero, low, mid, and high glyphosate concentrations. Samples were prepared in triplicates and the results averaged. Recovery of the spiked analytes was calculated as $[(\text{final concentration} - \text{initial concentration})/\text{spiked concentration}]$, and the mean relative recovery for this method was 99% (97%–103%). Along with study samples and analytical standards, each analytical batch included high- and low-concentration quality control materials (QCs) and reagent blanks to assure the accuracy and reproducibility of the data. The concentrations of the QCs were evaluated using standard statistical probability rules.[31]

As described above, we also submitted 55 duplicate samples collected during the weekly urine sample processing. The relative percent difference (RPD) between these paired sets was 5.3%, indicating excellent reproducibility and precision. The analysis of de-identified specimens at the CDC laboratory was determined not to constitute human subject research.

### *Assessment of Residential Proximity to Agriculture*

We collected participants' residential addresses at baseline and recorded whether they moved or lived in additional locations during the study. We geocoded all addresses and physically verified the existence and location of all actively cultivated agricultural fields within a 0.5-km radius of each address during the growing season concurrent with sample collection (August 2021); if no potential fields were present within this radius, we expanded to a 1-km buffer. As we described in detail elsewhere,[32] we entered each address into Google Earth and identified any area within the 0.5-km buffer that could potentially be an agricultural field (defined as areas of green or brown that did not contain homes or other structures). We drove to each of the locations and visually inspected it to identify whether it was an agricultural field in current cultivation. If the location was not accessible (e.g., if it was surrounded by private property), we used a combination of National Land Cover Database (NLCD) and Landsat imagery paired with Normalized Difference Vegetative Index (NDVI) thresholds to determine whether it was an agricultural field likely to be in current cultivation, using the method described by Hyland et al.[32] We then created polygons identifying each actively cultivated agricultural field in ArcGIS and calculated the distance from each residence to the nearest such field (up to 1 km). We also calculated total agricultural acreage within a 0.5-km buffer.

### *Data Analysis*

We imputed glyphosate concentrations below the LOD as the $\mathrm{LOD}/\sqrt{2}$.[33] We corrected glyphosate concentrations for hydration by adjusting for specific gravity according to: $C_{SG} = C \times \frac{1.016 - 1}{SG - 1}$, where $C_{SG}$ is the adjusted result ($\mu g/L$), $C$ is the reported glyphosate concentration ($\mu g/L$), 1.016 is the mean specific gravity measured within the study population, and $SG$ is the specific gravity of the individual sample.[34] All results presented in this manuscript represent these SG-corrected concentrations.

We evaluated the normality of the data set with the Kolmogorov-Smirnov test and found that the glyphosate concentrations were not normally distributed but were right-skewed with long tails both within and between participants. Therefore, for each participant, we estimated the central tendency of her individual exposure as the GM of all her samples ("overall exposure"; average per participant = 11 samples), and the GMs of samples collected during the pesticide spray season ("spray season exposure"; average per participant = 5 samples) and the nonspray season ("nonspray season exposure"; average per participant = 6 samples). These individual GMs represent the central tendencies of the within-participant distributions of glyphosate concentrations; thus, we consider them to be estimates of each participant's glyphosate exposure.

These overall exposure estimates were also not normally distributed ($n = 40$, $p = 0.012$). Therefore, to characterize the distribution of estimated glyphosate exposures in the cohort (i.e., the between-participant distribution), we used these exposure estimates to calculate the cohort GM and percentiles. These were also calculated stratified by spray season and residential proximity to agriculture. We evaluated the effect of spray season on glyphosate exposure with Wilcoxon signed rank tests for paired data; we evaluated the effect of residential proximity using Wilcoxon rank sum tests for independent data. As a sensitivity analysis, we evaluated the potential for confounding by age, income, education, race/ethnicity, occupation, and household size. These variables were selected because they are commonly collected demographics and because we hypothesized that they could be indicators of, or associated with, socioeconomic status or community identification, which could influence location of residence. First, we ran independent $t$-tests to evaluate the association between residential proximity and each of these variables. We also conducted a multivariable regression analysis to evaluate the relationship between glyphosate concentration during the spray season and residential proximity to agriculture adjusting for these variables. Finally, we evaluated the relationship

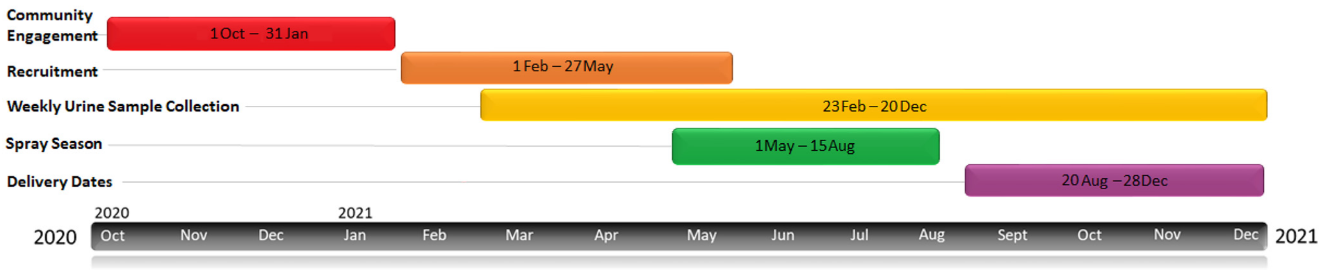

**Figure 1.** Timeline of the study, including community engagement, recruitment, weekly urine sample collection, and dates of delivery. The spray season is also indicated.

between glyphosate concentration and spray season among the near field participants and adjusted for these variables using generalized estimating equations (GEE) to account for the repeated measures within individuals. We conducted all analyses in SPSS Statistics [version 28.0.0.0; IBM].

## Results

### *Study Participants*

We enrolled our first participant on 23 February 2021 and completed enrollment on 3 June 2021. Weekly urine sample collection continued for each participant until she delivered her baby, with delivery dates occurring from 20 August through 28 December 2021. We collected the last weekly sample on 20 December (see Figure 1).

Table 1 shows the demographic characteristics of the study participants collectively and separately for those who live near and far from fields. Participants ranged in age from 18 to 37 y, with approximately half of the cohort ($n = 21$) age 18–27 y. Gestational length at enrollment averaged 14.4 wk (SD = 2.2 wk). One participant identified as Asian and one as American Indian or Alaskan native; the rest of the cohort identified as either White (52.5%, $n = 21$) or Hispanic/Latina (47.5%, $n = 19$), with two participants identifying as both White and Hispanic/Latina. We ran these analyses categorizing these two participants first in one

**Table 1.** Demographic characteristics of 40 pregnant people participating in a study of the association between residential proximity to agricultural and glyphosate concentrations. Twenty-two (22) participants lived <0.5 km of an agricultural field ("near field"), and 18 participants lived ≥0.5 km of an agricultural field ("far from field") in southern Idaho, 2021.

| | Full sample ($n = 40$) mean ± SD or $n$ (%) | Near field participants ($n = 22$) mean ± SD or $n$ (%) | Far field participants ($n = 18$) mean ± SD or $n$ (%) |
|---|---|---|---|
| Age (y) | | | |
| 18–22 | 11 (28%) | 5 (23%) | 6 (34%) |
| 23–27 | 10 (25%) | 7 (32%) | 3 (17%) |
| 28–32 | 14 (35%) | 7 (32%) | 7 (39%) |
| 33–37 | 5 (13%) | 3 (14%) | 2 (11%) |
| Gestational age at enrollment (wk) | 14.4 (2.3) | 14.2 (2.2) | 14.6 (2.4) |
| Race and ethnicity[a] | | | |
| Caucasian or White | 21 (53%) | 11 (50%) | 10 (56%) |
| Hispanic or Latina | 19 (48%) | 11 (50%) | 8 (45%) |
| Asian | 1 (2.5%) | 1 (4.5%) | 0 (0%) |
| American Indian or Alaskan Native | 1 (2.5%) | 1 (4.5%) | 0 (0%) |
| African American or Black | 0 (0%) | 0 (0%) | 0 (0%) |
| Highest level of education | | | |
| Less than high school | 5 (13%) | 3 (14%) | 2 (11%) |
| Graduated high school or earned GED | 14 (35%) | 9 (41%) | 5 (28%) |
| Some college | 19 (48%) | 9 (41%) | 10 (56%) |
| Bachelor's degree | 1 (2.5%) | 0 (0%) | 1 (5.5%) |
| Graduate degree or other advanced degree | 1 (2.5%) | 1 (4.5%) | 0 (0%) |
| Income [last year, household (USD)] | | | |
| <\$10,000–\$19,999 | 9 (24%) | 4 (20%) | 5 (28%) |
| \$20,000–\$29,999 | 10 (26%) | 6 (30%) | 4 (22%) |
| \$30,000–\$39,999 | 8 (21%) | 3 (15%) | 5 (28%) |
| \$40,000–\$59,999 | 6 (16%) | 3 (15%) | 3 (17%) |
| ≥\$60,000 | 5 (13%) | 4 (20%) | 1 (5.5%) |
| Missing or declined to answer | 2 | 2 | 0 |
| Employment | | | |
| "Stay-at-home mom" | 16 (40%) | 10 (46%) | 6 (34%) |
| Working outside the home | 21 (53%) | 11 (50%) | 10 (56%) |
| Unemployed | 3 (7.5%) | 1 (4.5%) | 2 (11%) |
| Number living in household | | | |
| 1–3 | 15 (38%) | 9 (41%) | 6 (34%) |
| 4–6 | 23 (58%) | 11 (50%) | 12 (67%) |
| 7–9 | 2 (5%) | 2 (9%) | 0 (0%) |
| Current tobacco smoker or vape user | | | |
| Yes | 2 (5%) | 2 (9%) | 0 (0%) |
| No | 38 (95%) | 20 (91%) | 18 (100%) |

Note: GED, general equivalency diploma; SD, standard deviation; USD, U.S. dollars.

[a] Participants could choose more than one option.

category and then in the other; findings were unchanged. For the results presented here, we included them in the Hispanic/Latina category. Most study participants reported graduating high school or earning their general equivalency diploma (35%, $n = 14$) or completing some college (47.5%, $n = 19$) as their highest level of education. Two-thirds of the participants had a combined household income of USD \$39,999 or less. Approximately half the cohort (52.5%, $n = 21$) reported working outside the home, 16 (40%) described themselves as "stay-at-home moms," and 3 (7.5%) were unemployed. We did not observe any differences between the near and far from field participants in any of these variables (independent samples $t$-test: age, $p = 0.83$; income, $p = 0.35$; education, $p = 0.59$; race/ethnicity, $p = 0.10$; occupation, $p = 0.57$; household size, $p = 0.78$). No participants reported applying herbicides during their pregnancies (Table S1).

### Residential Proximity to Agriculture

Thirty-one participants (78%) had only one residence throughout the study period. No participant lived in more than two locations during the study. For seven of the nine participants who had two residences during the study, both locations were either near fields or far from fields. The other two participants were assigned to the location where they spent most of their time (one near field and one far from field). As shown in Table 2, 22 (55%) of the study participants lived near fields, whereas 18 (45%) lived far from fields. Of the 22 participants who lived near fields, 3 lived within 100 m of a field, 9 lived 100 to <300 m from a field, and 10 lived 300 to <500 m from the nearest field. Of the 18 participants who lived far from fields, 4 lived 500–1,000 m from a field and 14 lived more than 1,000 m from the nearest field. By definition, none of the participants who lived far from a field had any cultivated acreage within a 0.5-km radius of their homes. Of the participants who lived near fields, approximately one-third had more than 25 acres, 10–25 acres, and <10 acres each within a 0.5-km radius of their homes. Alfalfa was the most common crop nearest to participants' homes (35%), followed by corn (15%).

**Table 2.** This table describes residential proximity to agriculture for the 40 participants in this study, including the number living "near" vs. "far from" fields (dichotomized at 0.5 km) in southern Idaho, 2021.

| | $n$ | % |
|---|---|---|
| Cultivated field <0.5 km | | |
| Yes ("Near field") | 22 | 55% |
| No ("Far from field") | 18 | 45% |
| Distance from nearest field | | |
| <100 m | 3 | 8% |
| 100 to <300 m | 9 | 23% |
| 300 to <500 m | 10 | 25% |
| 500 to <1,000 m | 4 | 10% |
| ≥1,000 m | 14 | 35% |
| Total cultivated acreage <0.5 km from residence | | |
| 25 + acres | 7 | 18% |
| 10 to <25 acres | 8 | 20% |
| >1 to <10 acres | 7 | 18% |
| 0 acres | 18 | 45% |
| Crop type closest to residence | | |
| Alfalfa | 14 | 35% |
| Corn | 6 | 15% |
| Dry beans | 2 | 5% |
| Wheat | 1 | 3% |
| Mint | 1 | 3% |
| Onions | 1 | 3% |
| Sugar beet | 1 | 3% |
| None | 14 | 35% |

### Sample Collection

We collected a total of 864 weekly urine samples, averaging 21.6 samples per participant and representing 98% of our study goal. Thirty-eight (95%) of the study participants were enrolled in the study until they delivered their babies. Of the remaining two, one participant developed pregnancy complications and relocated out of state, where she remained until she delivered her baby, and one participant experienced housing instability and was unable to continue in the study; both were lost to follow-up in mid-July. Samples collected from these participants were included in data analysis. As described in the "Methods" section, we submitted biweekly samples from each participant for analysis; this process ultimately resulted in the selection of 453 samples (52% of all collected). Figure 2 illustrates the timing and density of sample collections, indicates when samples were missed, and shows which samples were analyzed for glyphosate concentrations.

### Glyphosate Concentrations, Residential Proximity to Agriculture, and Spray Season

Two-thirds (66%) of all individual samples contained detectable concentrations ($\geq 0.1\ \mu g/L$) of glyphosate (Table 3). The detection frequency across all samples was similar among participants living near and far from fields (67% and 65%). Estimated individual-level glyphosate exposure, calculated as the GM glyphosate concentrations for each participant, ranged from <LOD to $0.44\ \mu g/L$, with a GM of $0.17\ \mu g/L$, median of $0.18\ \mu g/L$, and a 90th percentile of $0.27\ \mu g/L$. Although estimated glyphosate exposures were slightly higher among participants living near fields in comparison with those living far from fields across the entire study period, this difference was not significant ($0.19$ vs. $0.16\ \mu g/L$, $p = 0.19$).

Figure 3 shows each participant's estimated glyphosate exposure (calculated as the GM of glyphosate concentrations measured in all her relevant samples) during the spray season vs. the nonspray season. Filled black circles indicate participants who live near fields, and hollow circles indicate participants living far from fields. Although participants living far from fields are distributed uniformly around the 1:1 line, most participants living near fields were above this line, indicating increased exposure during the agricultural spray season.

Figure 4 shows the overall distributions of the cohort's estimated glyphosate exposure during the spray and nonspray seasons, stratified by residential proximity to agriculture. As shown in Table 3, among participants living near fields, urinary glyphosate was detected more frequently and at significantly increased GM concentrations during the spray season in comparison with the nonspray season (81% vs. 55%; $0.228\ \mu g/L$ vs. $0.150\ \mu g/L$, $p < 0.001$, $z$-score $= -3.528$). In contrast, among participants who lived far from fields, neither glyphosate detection frequency nor GMs differed in the spray vs. nonspray season (66% vs. 64%; $0.154\ \mu g/L$ vs. $0.165\ \mu g/L$, $p = 0.45$). Further, we found no difference in estimated glyphosate exposures between participants living near and far from fields during the nonspray season ($0.150$ vs. $0.165\ \mu g/L$, $p = 0.53$), but near-field participants had significantly higher estimated exposures than those living far from fields during the spray season ($0.228$ vs. $0.154\ \mu g/L$, $p = 0.01$). These findings were robust to adjustment for age, income, education, race/ethnicity, occupation, and household size in a multivariate regression analysis ($p = 0.008$). When we evaluated the relationship between glyphosate concentration and spray season among the near-field participants adjusted for these covariates using GEE to account for repeated measures, spray season remained significantly associated with glyphosate concentrations ($p < 0.001$ for the full model with all variables and in models including each factor individually.) Finally, we noted the presence of one outlier among the

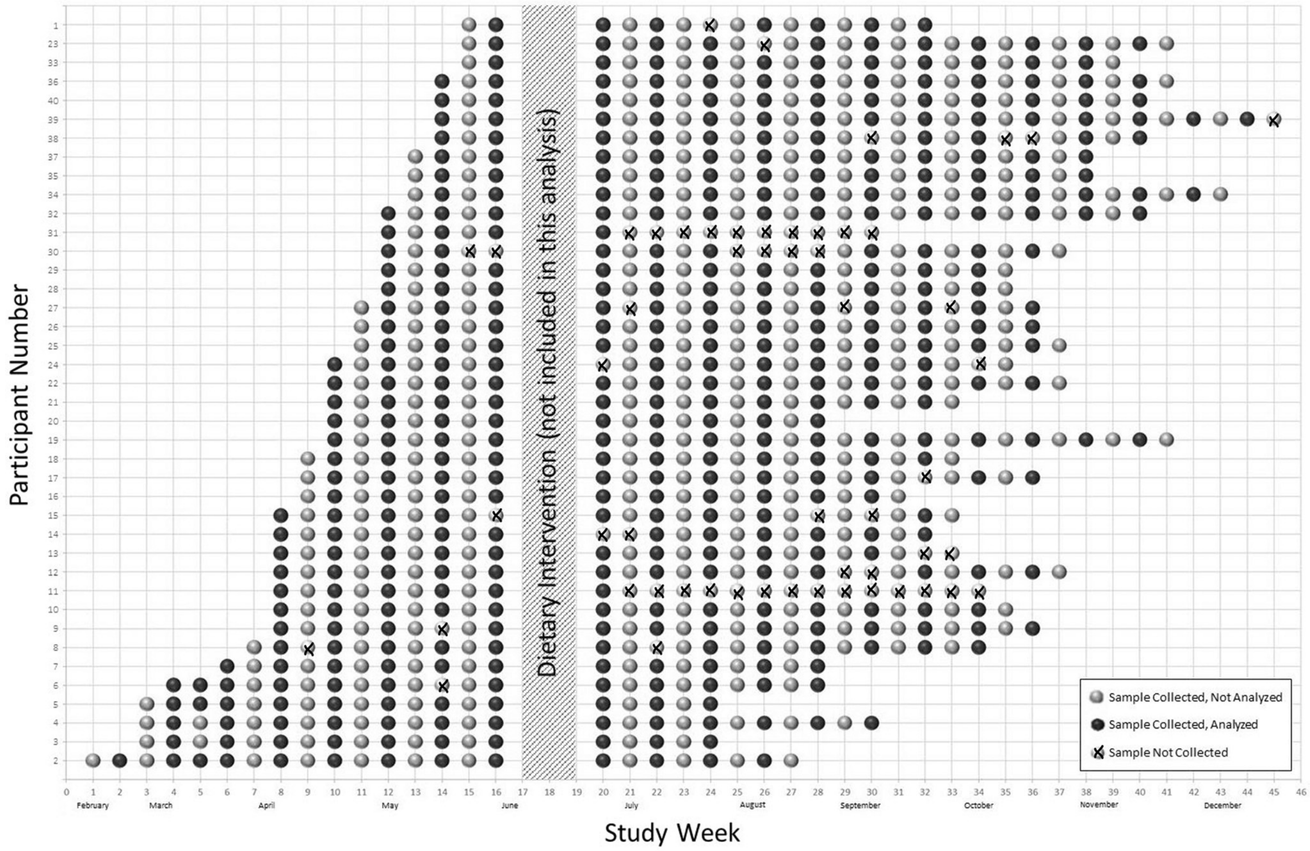

**Figure 2.** Weekly urine sample collections by participant among 40 pregnant people in southern Idaho. Darker circles indicate that a sample was collected and analyzed for glyphosate concentration; lighter circles indicate a sample that was collected but not analyzed; and circles containing an "x" indicate a missed sample. The *y*-axis shows Participant IDs, ordered chronologically by date of first sample. For the most part, these IDs were assigned in numerical order, but some were assigned out of order because of logistical or scheduling issues.

participants living near fields, apparent in the top left corner of Figure 3. In an ad hoc sensitivity analysis, we reran our calculations and found that excluding this outlier did not change our findings. For example, when comparing GM concentrations during the spray vs. nonspray season, the results were very similar with this outlier excluded (0.217 vs. 0.150 $\mu g/L$, $p < 0.001$, $z$-score $= -3.397$); when comparing GM concentrations between participants living near and far from fields during the spray season, the results were also unchanged (0.217 vs. 0.154 $\mu g/L$, $p = 0.02$).

## Discussion

In this study, we estimated glyphosate exposure based on concentrations measured in 453 biweekly urine samples collected from 40 pregnant people throughout pregnancy. We found that those who lived <0.5 km of an actively cultivated agricultural field had significantly increased glyphosate exposure during the pesticide spray season in comparison with the nonspray season. We found no change in glyphosate exposure by season for participants who lived far from fields and no difference between nonspray season exposure for

**Table 3.** Samples sizes, detection frequencies, and central tendency and distributional characteristics of glyphosate concentrations ($\mu g/L$) among 40 pregnant people living near (<0.5 km) and far from (≥0.5 km) agricultural fields in southern Idaho. All glyphosate concentrations are corrected for specific gravity ($\mu g/L$). The LOD was 0.1 $\mu g/L$.

| | | | | | | Percentiles[a] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Participant (*n*) | Sample (*n*) | Detection frequency [*n* (%)] | Average number samples per participant | Overall geometric mean[a] | 10th | 25th | 50th | 75th | 90th |
| All participants | 40 | 453 | 299 (66%) | 11 | 0.175 | 0.11 | 0.14 | 0.18 | 0.22 | 0.27 |
| Near field | 22 | 257 | 172 (67%) | 12 | 0.190 | 0.14 | 0.15 | 0.19 | 0.23 | 0.29 |
| Far from field | 18 | 196 | 127 (65%) | 11 | 0.157 | <LOD | 0.14 | 0.16 | 0.20 | 0.22 |
| Near field | | | | | | | | | | |
| Spray season | 22 | 119 | 96 (81%) | 5 | 0.228[b] | 0.15 | 0.18 | 0.21 | 0.34 | 0.39 |
| Nonspray season | 22 | 138 | 76 (55%) | 6 | 0.150 | 0.11 | 0.12 | 0.15 | 0.19 | 0.21 |
| Far from field | | | | | | | | | | |
| Spray season | 18 | 96 | 66 (66%) | 5 | 0.154 | <LOD | 0.11 | 0.17 | 0.20 | 0.24 |
| Nonspray season | 18 | 100 | 61 (64%) | 6 | 0.165 | 0.11 | 0.14 | 0.16 | 0.21 | 0.25 |

Note: LOD, limit of detection.

[a] The central tendency of each participant's glyphosate concentrations was calculated as the geometric mean of her relevant individual samples. The geometric mean and percentiles presented in this table describe the central tendency and distribution across those individual geometric means.

[b] Glyphosate concentrations were significantly higher among near field participants during the spray season in comparison with the nonspray season ($p < 0.001$) or in comparison with participants living far from fields during either season ($p < 0.01$).

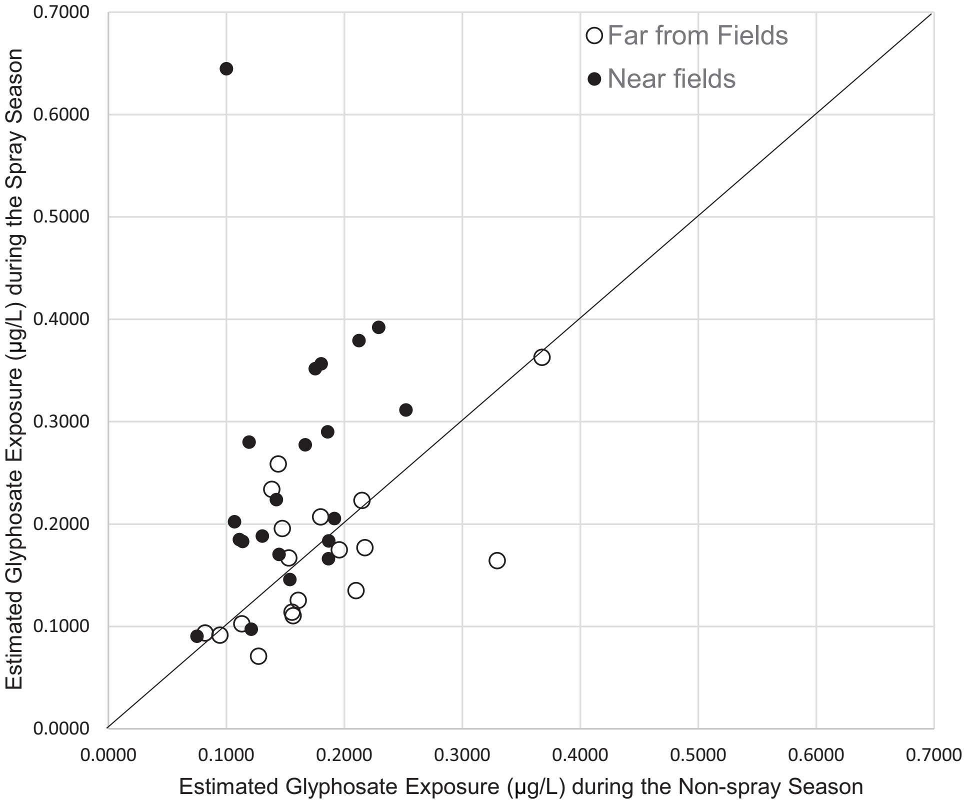

**Figure 3.** Each participant's estimated glyphosate exposure (defined as the GM of glyphosate concentrations measured in all of her relevant samples, µg/L) during the 2021 spray season (1 May–15 August, *y*-axis) vs. the nonspray season (*x*-axis) in southern Idaho. Filled black circles indicate participants who live near fields (<0.5 km, $n = 22$), and hollow circles indicate participants living far from fields (≥0.5 km, $n = 18$). A uniform distribution indicates equal exposure during both seasons, whereas distribution to one side of the line indicates a higher exposure during that period. Glyphosate concentrations were specific gravity–adjusted prior to calculating individual-level GMs. Numeric data can be found in Excel Table S1. Note: GM, geometric mean.

participants living near fields and participants living far from fields at any time of year. These results suggest that agricultural glyphosate spray is a source of exposure for people living near fields.

To our knowledge, this is the first study of the effect of residential proximity to agriculture on biomarkers of glyphosate exposure with sufficient temporal resolution to investigate the effect of spray season. Previous studies have found that people who live in rural and agricultural regions have higher glyphosate exposure than those in urban and suburban regions. In a study of 71 pregnant women in Indiana, Parvez et al.[13] reported that the 14 women who lived in rural areas had significantly higher urinary glyphosate concentrations than the 57 women who lived in urban or suburban areas. These results are consistent with our findings, but proximity to agricultural fields was not measured nor was the impact of agricultural spray season. In two other studies of glyphosate concentrations in umbilical cord serum from 82 pregnant women in 2011[18] and urine from 41 Portuguese children in 2018–2019,[24] investigators reported positive associations between residential proximity to agriculture and glyphosate detection frequency and concentration. However, in both studies, researchers had samples from a single time point and did not evaluate the effect of agricultural spray season. Similarly, in a Flemish study among 424 adolescents, De Troeyer et al.[35] observed a significant relationship between higher proportions of agricultural land around residences and increased urinary concentrations of the primary degradation product of glyphosate, aminomethylphosphonic acid (AMPA). Again, however, the researchers relied on a single sample per participant to estimate exposure.

We know of no previous research regarding agricultural spray season and glyphosate exposure, but a larger body of literature has investigated residential proximity to agriculture, agricultural spray season, and exposure to different classes and types of pesticides. Most of these studies reported a positive relationship between pesticide concentrations and residential proximity to agriculture,[21,22] but the relationship with agricultural spray season has been mixed. For example, in a repeated measures assessment, urinary diakylphosphate metabolites of OPs were found to be higher during the agricultural spray season in comparison with the nonspray season.[36] However, the urinary biomarkers of the chloroacetanilide and triazine herbicides did not differ by season in the PELAGIE mother–child cohort study.[37] These inconsistencies may reflect the differences in chemical properties across various pesticide classes (e.g., volatility), physical differences in application methods (e.g., crop dusting vs. backpack spraying), and different formulation characteristics (e.g., the inclusion of amino groups to create herbicide-amine salts[38]).

Our finding that agricultural spray season was associated with increased glyphosate exposure among near field participants suggests that agricultural spray as a source of glyphosate exposure warrants additional investigation. Exposure may occur directly from drift of glyphosate leading to uptake via dermal and inhalation routes or glyphosate may adhere to soil and dust particles that infiltrate nearby residences.[39] Glyphosate is considered not volatile (vapor pressure ∼0.01–0.02 mPa at 25°C[40]) and therefore is unlikely to aerosolize but could be transported as residues attached to windblown particles. House dust can serve as a reservoir for some pesticides, leading to exposures that may or may not vary with time and spray season. Indeed, a recent study of factors associated with levels of OPs in agricultural communities found that pesticide levels in dust were

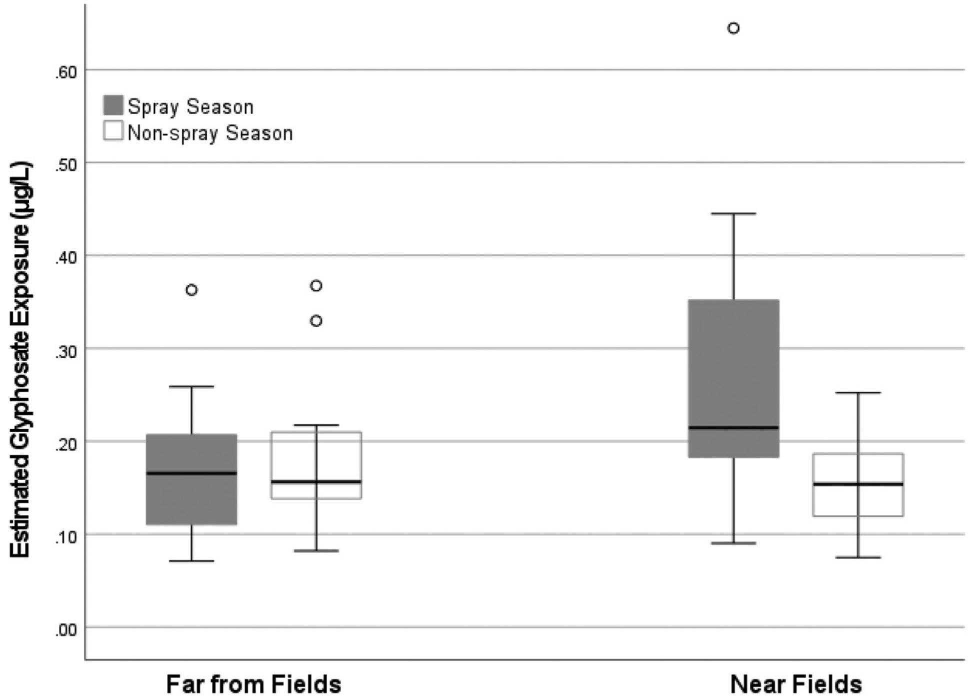

**Figure 4.** Estimated glyphosate exposure among pregnant participants living far from ($\geq 0.5$ km, $n = 18$) and near to ($< 0.5$ km, $n = 22$) fields during the 2021 spray (1 May–15 August) and nonspray seasons in southern Idaho. Each individual's glyphosate exposure is estimated as the GM of all of her relevant samples, which were specific gravity–adjusted prior to calculating the individual-level GMs. The box-and-whisker plots represent the overall distribution of these estimated exposures, with the black line indicating the median, the bottom and top lines of the boxes indicating the 25th and 75th percentiles, and the whiskers indicate the minimum and maximum values excepting outliers, which are represented by circles. Numeric data can be found in Excel Table S1. Note: GM, geometric mean.

affected by household cooling strategies, occupational exposures, and geographic location but not agricultural spray season.[41] However, the half-lives of pesticides in dust likely differ by pesticide type, and although new evidence is emerging about glyphosate in roadway dust,[42] little data exist about the half-life of glyphosate in household dust.

Identifying specific sources of exposure is crucial for developing effective interventions. If airborne drift from active agricultural applications is a primary exposure source for participants living near agricultural fields, appropriate interventions may include windbreaks or notification of spray timing and window closing[43]; if the source is contaminated soil blowing or tracking into homes, reducing track-in and cleaning may be more effective.[44]

We found lower glyphosate concentrations among participants in this study than other populations. In the recently released 2013–2014 NHANES data, the GM glyphosate concentration in the total population was 0.411 µg/L,[3] in comparison with concentrations to this study, where the overall GM glyphosate concentration was 0.17 µg/L. Glyphosate concentrations among pregnant women in a Puerto Rican cohort study were similar to those measured in NHANES (GM = 0.41–0.44 µg/L),[4,14] although concentrations measured in the multicenter The Infant Development and Environment Study (TIDES) cohort (median = 0.23 µg/L)[15] were more similar to those we observed. In contrast, urinary glyphosate concentrations in pregnant women in the Indiana Pregnancy Environmental Exposures Study (PEES)[16] and a prospective birth cohort also in Indiana, reported in Parvez et al.,[13,16] were found to be an order of magnitude greater than the urinary concentrations found in NHANES and other pregnancy cohorts (mean = 3.33–3.40 µg/L).

The reason for these differences in glyphosate concentrations are unclear and could be related to study design (e.g., FMV vs. spot urine sampling strategies), analytical methods (both the PEES study and Parvez et al. used the same laboratory), or the populations studied. It is also possible that the differences reflect higher glyphosate use in the midwestern United States, where intensive production of glyphosate-tolerant genetically modified Roundup-Ready corn and soybean crops leads to high glyphosate application volumes.[45] The cohorts in both the PEES study and Parvez et al. were recruited from Indiana, and none of the other studies were restricted to this region.

These and other exposure studies reveal a high prevalence of exposure to glyphosate but at levels that are considered low in comparison with most risk benchmarks. However, it is unclear whether these benchmarks are based on the most sensitive and appropriate end points.[46–49] Much of this discussion centers on possible carcinogenic effects, especially non-Hodgkin's lymphoma,[50–52] but, given the recent research on birth outcomes, reproductive effects may also be indicated. In addition to the epidemiological studies described previously, strong evidence from laboratory animal studies suggests that gestational exposure to glyphosate and GBHs can lead to adverse outcomes including birth defects,[53,54] defects in spermatogenesis,[55] gut microbiome dysbiosis,[56] and transgenerational impairment of female reproductive outcomes[57] likely mediated by epigenetic changes (DNA methylation status).[58] Collectively, these animal studies underscore the importance of investigations including pregnant people.

Our study has important strengths and limitations. Although the small sample size limits generalizability, we were able to observe meaningful differences in glyphosate exposures across the study factors we investigated. In addition, we collected and analyzed an extensive number of samples per participant. This sampling approach is a critical strength, not just because it permitted assessment of temporal concentration trends, but also because of the short half-life of glyphosate. The human biological half-life of glyphosate is estimated to be 5.5–10 h,[59] meaning that an individual spot urine sample essentially reflects exposure during, at most, the previous day. Data from the NHANES have shown a significant relationship between fasting time and urinary glyphosate concentrations; individuals who report eating in the 8 h prior to sample collection had higher urinary glyphosate levels than those who had fasted for 8 or more hours, further supporting the idea of rapid excretion following dietary intake.[4] Thus, studies that rely on single spot urine samples are likely insufficient to accurately characterize glyphosate exposure throughout pregnancy. Because of the relatively large number of samples per participant, we were able to assess exposures during both spray and nonspray seasons using longer-term averages that reduced intra-individual variability.

This study also occurred in a relatively small geographic region that is not as heavily treated with glyphosate as some other parts of the United States. Participants in this study lived along the Snake River Valley of Idaho, across an approximately 200-mi range from the western part of the state at the Oregon border to the south-central part of the state just east of Twin Falls. Although this is an agricultural region, it is not dominated by corn and soy crops. Instead, the most common crop near to participants' homes in this study was alfalfa, which is often the Roundup Ready type, but is treated with glyphosate only once or twice per season. Nevertheless, we observed differences in glyphosate exposure by residential location and season, even with this lower density of application than is used on other crops grown more commonly in the midwestern United States. A related strength of this study was the careful characterization of active agricultural fields. By ground-truthing the location and crop type of all fields within 0.5-km buffers around each participant's home, we are confident in the accuracy of our near and far from field characterizations.

In this study, we did not measure glyphosate's primary degradation product, AMPA, which is primarily formed by soil microbes.[60,61] AMPA is a nonspecific metabolite of glyphosate and can be formed from other sources; thus, it may not represent direct exposure to glyphosate.[62] Similarly, we did not evaluate exposure to coformulants, which form part of commercial glyphosate-based herbicide formulations and which possess their own innate toxicity[63] and may increase the toxicity of glyphosate.[64]

Future studies should increase the understanding of specific pathways through which glyphosate exposure occurs during the spray season (e.g., through suspended airborne particles from active drift and/or through tracked-in or windblown soil to which glyphosate has adhered). In such future studies, it would be valuable to characterize behaviors potentially associated with exposure, such as frequency of cleaning homes, amount of time spent at home outdoors during the spray season, and typical practices around wearing shoes inside the home. It would also be valuable to explore the relationship between residential proximity to agriculture during the agriculture spray season and glyphosate exposure in other populations, including individuals living in Midwestern states where glyphosate application rates are even higher than in our study region.

## Acknowledgments

The authors gratefully acknowledge the study participants and the Women Infants and Children (WIC) clinics who helped us recruit participants. The authors also acknowledge P. Morales-Agudelo and M. Vidal for technical assistance in measuring glyphosate. The authors thank A. Hernandez, B. Ellison, A. O'Brien, A. Balentine, C. Schvaneveldt, and E. Watkins for their efforts in conducting the fieldwork, including collection of daily urine samples.

To protect the confidentiality of our study participants, data from this study are not available.

This study was funded by National Institute of Environmental Health Sciences grant K01ES028745.

The findings and conclusions of this report are those of the authors and do not necessarily represent the official position of the CDC. Use of trade names is for identification only and does not imply endorsement by the CDC, the Public Health Service, or the U.S. Department of Health and Human Services.

## References

1. Gillezeau C, van Gerwen M, Shaffer RM, Rana I, Zhang L, Sheppard L, et al. 2019. The evidence of human exposure to glyphosate: a review. Environ Health 18(1):2, PMID: 30612564, https://doi.org/10.1186/s12940-018-0435-5.
2. Benbrook CM. 2016. Trends in glyphosate herbicide use in the United States and globally. Environ Sci Eur 28(1):3, PMID: 27752438, https://doi.org/10.1186/s12302-016-0070-0.
3. CDC (U.S. Centers for Disease Control and Prevention). 2023. Urinary Glyphosate (N-Phosphonomethyl)glycine) Data Tables. National Report on Human Exposure to Environmental Chemicals. https://www.cdc.gov/exposurereport/index.html [accessed 1 November 2023].
4. Ospina M, Schütze A, Morales-Agudelo P, Vidal M, Wong LY, Calafat AM. 2022. Exposure to glyphosate in the United States: data from the 2013–2014 national Health and Nutrition Examination Survey. Environ Int 170:107620, PMID: 36368224, https://doi.org/10.1016/j.envint.2022.107620.
5. Grau D, Grau N, Gascuel Q, Paroissin C, Stratonovitch C, Lairon D, et al. 2022. Quantifiable urine glyphosate levels detected in 99% of the French population, with higher values in men, in younger people, and in farmers. Environ Sci Pollut Res Int 29(22):32882–32893, PMID: 35018595, https://doi.org/10.1007/s11356-021-18110-0.
6. Cosemans C, Van Larebeke N, Janssen BG, Martens DS, Baeyens W, Bruckers L, et al. 2022. Glyphosate and AMPA exposure in relation to markers of biological aging in an adult population-based study. Int J Hyg Environ Health 240:113895, PMID: 34883335, https://doi.org/10.1016/j.ijheh.2021.113895.
7. Lucia RM, Huang W-L, Pathak KV, McGilvrey M, David-Dirgo V, Alvarez A, et al. 2022. Association of glyphosate exposure with blood DNA methylation in a cross-sectional study of postmenopausal women. Environ Health Perspect 130(4):47001, PMID: 35377194, https://doi.org/10.1289/EHP10174.
8. Poh C, McPherson JD, Tuscano J, Li Q, Parikh-Patel A, Vogel CFA, et al. 2022. Environmental pesticide exposure and non-Hodgkin lymphoma survival: a population-based study. BMC Med 20(1):165, PMID: 35468782, https://doi.org/10.1186/s12916-022-02348-7.
9. Lemke N, Murawski A, Schmied-Tobies MIH, Rucic E, Hoppe H-W, Conrad A, et al. 2021. Glyphosate and aminomethylphosphonic acid (AMPA) in urine of children and adolescents in Germany – human biomonitoring results of the German Environmental Survey 2014–2017 (GerES V). Environ Int 156:106769, PMID: 34274860, https://doi.org/10.1016/j.envint.2021.106769.
10. Campbell G, Mannetje A, Keer S, Eaglesham G, Wang X, Lin C-Y, et al. 2022. Characterization of glyphosate and AMPA concentrations in the urine of Australian and New Zealand populations. Sci Total Environ 847:157585, PMID: 35882334, https://doi.org/10.1016/j.scitotenv.2022.157585.
11. Buekers J, Remy S, Bessems J, Govarts E, Rambaud L, Riou M, et al. 2022. Glyphosate and AMPA in human urine of HBM4EU aligned studies: Part A Children. Toxics 10(8), PMID: 36006149, https://doi.org/10.3390/toxics10080470.
12. Makris KC, Efthymiou N, Konstantinou C, Anastasi E, Schoeters G, Kolossa-Gehring M, et al. 2022. Oxidative stress of glyphosate, AMPA and metabolites of pyrethroids and chlorpyrifos pesticides among primary school children in Cyprus. Environ Res 212(pt B):113316, PMID: 35439459, https://doi.org/10.1016/j.envres.2022.113316.
13. Parvez S, Gerona RR, Proctor C, Friesen M, Ashby JL, Reiter JL, et al. 2018. Glyphosate exposure in pregnancy and shortened gestational length: a prospective Indiana birth cohort study. Environ Health 17(1):23, PMID: 29519238, https://doi.org/10.1186/s12940-018-0367-0.
14. Lesseur C, Pathak KV, Pirrotte P, Martinez MN, Ferguson KK, Barrett ES, et al. 2022. Urinary glyphosate concentration in pregnant women in relation to length of gestation. Environ Res 203:111811, PMID: 34339697, https://doi.org/10.1016/j.envres.2021.111811.
15. Silver MK, Fernandez J, Tang J, McDade A, Sabino J, Rosario Z, et al. 2021. Prenatal exposure to glyphosate and its environmental degradate, aminomethylphosphonic acid (AMPA), and preterm birth: a nested case-control study in the PROTECT cohort (Puerto Rico). Environ Health Perspect 129(5):57011, PMID: 34009015, https://doi.org/10.1289/EHP7295.
16. Gerona RR, Reiter JL, Zakharevich I, Proctor C, Ying J, Mesnage R, et al. 2022. Glyphosate exposure in early pregnancy and reduced fetal growth: a prospective observational study of high-risk pregnancies. Environ Health 21(1):95, PMID: 36221133, https://doi.org/10.1186/s12940-022-00906-3.
17. Aris A, Leblanc S. 2011. Maternal and fetal exposure to pesticides associated to genetically modified foods in Eastern Townships of Quebec, Canada. Reprod Toxicol 31(4):528–533, PMID: 21338670, https://doi.org/10.1016/j.reprotox.2011.02.004.
18. Kongtip P, Nankongnab N, Phupancharoensuk R, Palarach C, Sujirarat D, Sangprasert S, et al. 2017. Glyphosate and paraquat in maternal and fetal serums in Thai women. J Agromedicine 22(3):282–289, PMID: 28422580, https://doi.org/10.1080/1059924X.2017.1319315.

19. Fagan J, Bohlen L, Patton S, Klein K. 2020. Organic diet intervention significantly reduces urinary glyphosate levels in U.S. children and adults. Environ Res 189:109898, PMID: 32797996, https://doi.org/10.1016/j.envres.2020.109898.
20. Rempelos L, Wang J, Barański M, Watson A, Volakakis N, Hoppe H-W, et al. 2022. Diet and food type affect urinary pesticide residue excretion profiles in healthy individuals: results of a randomized controlled dietary intervention trial. Am J Clin Nutr 115(2):364–377, PMID: 34718382, https://doi.org/10.1093/ajcn/nqab308.
21. Dereumeaux C, Fillol C, Quenel P, Denys S. 2020. Pesticide exposures for residents living close to agricultural lands: a review. Environ Int 134:105210, PMID: 31739132, https://doi.org/10.1016/j.envint.2019.105210.
22. Teysseire R, Manangama G, Baldi I, Carles C, Brochard P, Bedos C, et al. 2021. Determinants of non-dietary exposure to agricultural pesticides in populations living close to fields: a systematic review. Sci Total Environ 761:143294, PMID: 33280875, https://doi.org/10.1016/j.scitotenv.2020.143294.
23. Figueiredo DM, Krop EJM, Duyzer J, Gerritsen-Ebben RM, Gooijer YM, Holterman HJ, et al. 2021. Pesticide exposure of residents living close to agricultural fields in The Netherlands: protocol for an observational study. JMIR Res Protoc 10(4):e27883, PMID: 33908892, https://doi.org/10.2196/27883.
24. Ferreira C, Duarte SC, Costa E, Pereira AMPT, Silva LJG, Almeida A, et al. 2021. Urine biomonitoring of glyphosate in children: exposure and risk assessment. Environ Res 198:111294, PMID: 33971124, https://doi.org/10.1016/j.envres.2021.111294.
25. Curwin BD, Hein MJ, Sanderson WT, Striley C, Heederik D, Kromhout H, et al. 2007. Urinary pesticide concentrations among children, mothers and fathers living in farm and non-farm households in Iowa. Ann Occup Hyg 51(1):53–65, PMID: 16984946, https://doi.org/10.1093/annhyg/mel062.
26. Griffith W, Curl CL, Fenske RA, Lu CA, Vigoren EM, Faustman EM. 2011. Organophosphate pesticide metabolite levels in pre-school children in an agricultural community: within- and between-child variability in a longitudinal study. Environ Res 111(6):751–756, PMID: 21636082, https://doi.org/10.1016/j.envres.2011.05.008.
27. Anadón A, Martínez-Larrañaga MR, Martínez MA, Castellano VJ, Martínez M, Martin MT, et al. 2009. Toxicokinetics of glyphosate and its metabolite aminomethyl phosphonic acid in rats. Toxicol Lett 190(1):91–95, PMID: 19607892, https://doi.org/10.1016/j.toxlet.2009.07.008.
28. Spaan S, Pronk A, Koch HM, Jusko TA, Jaddoe VWV, Shaw PA, et al. 2015. Reliability of concentrations of organophosphate pesticide metabolites in serial urine specimens from pregnancy in the Generation R Study. J Expo Sci Environ Epidemiol 25(3):286–294, PMID: 25515376, https://doi.org/10.1038/jes.2014.81.
29. Hyland C, Spivak M, Sheppard L, Lanphear BP, Antoniou M, Ospina M, et al. 2023. Urinary glyphosate concentrations among pregnant participants in a randomized, crossover trial of organic and conventional diets. Environ Health Perspect 131(7):77005, PMID: 37493357, https://doi.org/10.1289/EHP12155.
30. Schütze A, Morales-Agudelo P, Vidal M, Calafat AM, Ospina M. 2021. Quantification of glyphosate and other organophosphorus compounds in human urine via ion chromatography isotope dilution tandem mass spectrometry. Chemosphere 274:129427, PMID: 33529959, https://doi.org/10.1016/j.chemosphere.2020.129427.
31. Caudill SP, Schleicher RL, Pirkle JL. 2008. Multi-rule quality control for the age-related eye disease study. Stat Med 27(20):4094–4106, PMID: 18344178, https://doi.org/10.1002/sim.3222.
32. Hyland C, McConnell K, DeYoung E, Curl CL. 2022. Evaluating the accuracy of satellite-based methods to estimate residential proximity to agricultural crops. J Expo Sci Environ Epidemiol, https://doi.org/10.1038/s41370-022-00467-0.
33. Hornung RW, Reed LD. 1990. Estimation of average concentration in the presence of nondetectable values. Appl Occup Environ Hyg 5(1):46–51, https://doi.org/10.1080/1047322X.1990.10389587.
34. Duty SM, Calafat AM, Silva MJ, Ryan L, Hauser R. 2005. Phthalate exposure and reproductive hormones in adult men. Hum Reprod 20(3):604–610, PMID: 15591081, https://doi.org/10.1093/humrep/deh656.
35. De Troeyer K, Casas L, Bijnens EM, Bruckers L, Covaci A, De Henauw S, et al. 2022. Higher proportion of agricultural land use around the residence is associated with higher urinary concentrations of AMPA, a glyphosate metabolite. Int J Hyg Environ Health 246:114039, PMID: 36279788, https://doi.org/10.1016/j.ijheh.2022.114039.
36. Koch D, Lu C, Fisker-Andersen J, Jolley L, Fenske RA. 2002. Temporal association of children's pesticide exposure and agricultural spraying: report of a longitudinal biological monitoring study. Environ Health Perspect 110(8):829–833, PMID: 12153767, https://doi.org/10.1289/ehp.02110829.
37. Chevrier C, Serrano T, Lecerf R, Limon G, Petit C, Monfort C, et al. 2014. Environmental determinants of the urinary concentrations of herbicides during pregnancy: the PELAGIE mother–child cohort (France). Environ Int 63:11–18, PMID: 24246238, https://doi.org/10.1016/j.envint.2013.10.010.
38. Sharkey SM, Hartig AM, Dang AJ, Chatterjee A, Williams BJ, Parker KM. 2022. Amine volatilization from herbicide salts: implications for herbicide formulations and atmospheric chemistry. Environ Sci Technol 56(19):13644–13653, PMID: 36150089, https://doi.org/10.1021/acs.est.2c03740.
39. Tudi M, Li H, Li H, Wang L, Lyu J, Yang L, et al. 2022. Exposure routes and health risks associated with pesticide application. Toxics 10(6), PMID: 35736943, https://doi.org/10.3390/toxics10060335.
40. Henderson A, Gervais J, Luukinen B, Buhl K, Stone D, Strid A, et al. 2010. Glyphosate Technical Fact Sheet. Corvallis, OR: National Pesticide Information Center Oregon State University Extension Services.
41. Kuiper G, Young BN, WeMott S, Erlandson G, Martinez N, Mendoza J, et al. 2022. Factors associated with levels of organophosphate pesticides in household dust in agricultural communities. Int J Environ Res Public Health 19(2), PMID: 35055689, https://doi.org/10.3390/ijerph19020862.
42. Ramirez Haberkon NB, Aparicio VC, Mendez MJ. 2021. First evidence of glyphosate and aminomethylphosphonic acid (AMPA) in the respirable dust (PM10) emitted from unpaved rural roads of Argentina. Sci Total Environ 773:145055, PMID: 33592477, https://doi.org/10.1016/j.scitotenv.2021.145055.
43. Fishel FM, Ferrell JA. 2010. *Managing Pesticide Drift*. Gainesville, FL: University of Florida IFAS Extension.
44. Roberts JW, Wallace LA, Camann DE, Dickey P, Gilbert SG, Lewis RG, et al. 2009. Monitoring and reducing exposure of infants to pollutants in house dust. Rev Environ Contam Toxicol 201:1–39, PMID: 19484587, https://doi.org/10.1007/978-1-4419-0032-6_1.
45. Dempsey P. 2019. Breaking down the use of glyphosate in the U.S. Investigate Midwest. https://investigatemidwest.org/2019/05/26/breaking-down-the-use-of-glyphosate-in-the-u-s/ [accessed 20 September 2023].
46. Soares D, Silva L, Duarte S, Pena A, Pereira A. 2021. Glyphosate use, toxicity and occurrence in food. Foods 10(11), PMID: 34829065, https://doi.org/10.3390/foods10112785.
47. Peillex C, Pelletier M. 2020. The impact and toxicity of glyphosate and glyphosate-based herbicides on health and immunity. J Immunotoxicol 17(1):163–174, PMID: 32897110, https://doi.org/10.1080/1547691X.2020.1804492.
48. Davoren MJ, Schiestl RH. 2018. Glyphosate-based herbicides and cancer risk: a post-IARC decision review of potential mechanisms, policy and avenues of research. Carcinogenesis 39(10):1207–1215, PMID: 30060078, https://doi.org/10.1093/carcin/bgy105.
49. Myers JP, Antoniou MN, Blumberg B, Carroll L, Colborn T, Everett LG, et al. 2016. Concerns over use of glyphosate-based herbicides and risks associated with exposures: a consensus statement. Environ Health 15:19, PMID: 26883814, https://doi.org/10.1186/s12940-016-0117-0.
50. Boffetta P, Ciocan C, Zunarelli C, Pira E. 2021. Exposure to glyphosate and risk of non-Hodgkin lymphoma: an updated meta-analysis. Med Lav 112(3):194–199, PMID: 34142676, https://doi.org/10.23749/mdl.v112i3.11123.
51. Donato F, Pira E, Ciocan C, Boffetta P. 2020. Exposure to glyphosate and risk of non-Hodgkin lymphoma and multiple myeloma: an updated meta-analysis. Med Lav 111(1):63–73, PMID: 32096774, https://doi.org/10.23749/mdl.v111i1.8967.
52. Zhang L, Rana I, Shaffer RM, Taioli E, Sheppard L. 2019. Exposure to glyphosate-based herbicides and risk for non-Hodgkin lymphoma: a meta-analysis and supporting evidence. Mutat Res Rev Mutat Res 781:186–206, PMID: 31342895, https://doi.org/10.1016/j.mrrev.2019.02.001.
53. Antoniou M, Habib M, Howard C, Jennings R, Leifert C, Nodari R, et al. 2012. Teratogenic effects of glyphosate-based herbicides: divergence of regulatory decisions from scientific evidence. J Environ Anal Toxicol S4. https://doi.org/10.4172/2161-0525.S4-006.
54. Paganelli A, Gnazzo V, Acosta H, López SL, Carrasco AE. 2010. Glyphosate-based herbicides produce teratogenic effects on vertebrates by impairing retinoic acid signaling. Chem Res Toxicol 23(10):1586–1595, PMID: 20695457, https://doi.org/10.1021/tx1001749.
55. Pham TH, Derian L, Kervarrec C, Kernanec P-Y, Jégou B, Smagulova F, et al. 2019. Perinatal exposure to glyphosate and a glyphosate-based herbicide affect spermatogenesis in mice. Toxicol Sci 169(1):260–271, PMID: 30785197, https://doi.org/10.1093/toxsci/kfz039.
56. Mesnage R, Panzacchi S, Bourne E, Mein CA, Perry MJ, Hu J, et al. 2022. Glyphosate and its formulations Roundup Bioflow and RangerPro alter bacterial and fungal community composition in the rat caecum microbiome. Front Microbiol 13:888853, PMID: 36274693, https://doi.org/10.3389/fmicb.2022.888853.
57. Milesi MM, Lorenz V, Pacini G, Repetti MR, Demonte LD, Varayoud J, et al. 2018. Perinatal exposure to a glyphosate-based herbicide impairs female reproductive outcomes and induces second-generation adverse effects in Wistar rats. Arch Toxicol 92(8):2629–2643, PMID: 29947892, https://doi.org/10.1007/s00204-018-2236-6.
58. Kubsad D, Nilsson EE, King SE, Sadler-Riggleman I, Beck D, Skinner MK. 2019. Assessment of glyphosate induced epigenetic transgenerational inheritance of pathologies and sperm epimutations: generational toxicology. Sci Rep 9(1):6372, PMID: 31011160, https://doi.org/10.1038/s41598-019-42860-0.
59. Connolly A, Jones K, Basinas I, Galea KS, Kenny L, McGowan P, et al. 2019. Exploring the half-life of glyphosate in human urine samples. Int J Hyg Environ Health 222(2):205–210, PMID: 30293930, https://doi.org/10.1016/j.ijheh.2018.09.004.
60. Grandcoin A, Piel S, Baurès E. 2017. AminoMethylPhosphonic acid (AMPA) in natural waters: its sources, behavior and environmental fate. Water Res 117:187–197, PMID: 28391123, https://doi.org/10.1016/j.watres.2017.03.055.

61. Kanissery RG, Welsh A, Sims GK. 2015. Effect of soil aeration and phosphate addition on the microbial bioavailability of carbon-14-glyphosate. J Environ Qual 44(1):137–144, PMID: 25602328, https://doi.org/10.2134/jeq2014.08.0331.
62. Connolly A, Coggins MA, Koch HM. 2020. Human biomonitoring of glyphosate exposures: state-of-the-art and future research challenges. Toxics 8(3), PMID: 32824707, https://doi.org/10.3390/toxics8030060.
63. Mesnage R, Antoniou MN. 2017. Ignoring adjuvant toxicity falsifies the safety profile of commercial pesticides. Front Public Health 5:361, PMID: 29404314, https://doi.org/10.3389/fpubh.2017.00361.
64. Mesnage R, Benbrook C, Antoniou MN. 2019. Insight into the confusion over surfactant co-formulants in glyphosate-based herbicides. Food Chem Toxicol 128:137–145, PMID: 30951798, https://doi.org/10.1016/j.fct.2019.03.053.