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A mixed-methods approach to determine how conservation management programs and techniques have affected herbicide use and distribution in the environment over time

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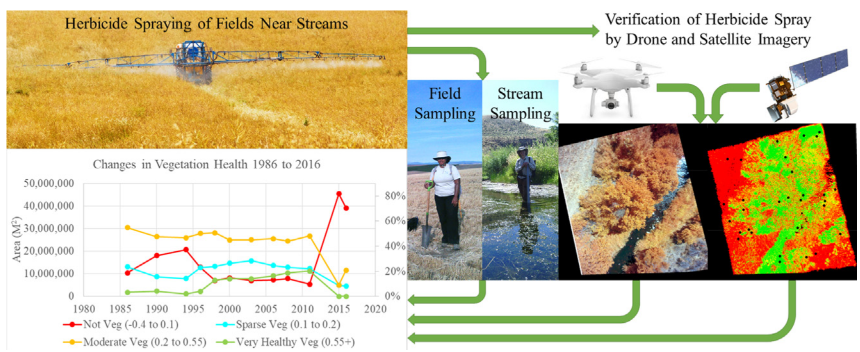
HIGHLIGHTS

- Quantifying herbicide use over time in the environment is difficult.
- Herbicides were analyzed by remote sensing and soil, sediment, and water samples.
- Glyphosate and its metabolite AMPA were found in the majority of samples.
- Herbicide reaches streams despite improvement in conservation agriculture practices.

GRAPHICAL ABSTRACT



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ABSTRACT

No-till agriculture has the ability to reduce fuel consumption, increase soil moisture, reduce soil erosion and increase organic matter. However, it remains unclear whether it increases herbicide use overall in the long term for communities that use no-till as their primary source of conservation agriculture. The preponderance of literature suggests that no-till has increased herbicide use, but it is difficult to quantify how much herbicide has increased in a given location and to directly correlate changes in herbicide use to changes in soil and water quality. This paper provides several methods to determine how herbicide use has changed over time in an agricultural community in Oregon that switched over to no-till in the late 1990s and early 2000s. These methods include: spatial analysis of remote sensing satellite imagery of vegetation health along streams; use of a drone fitted with an agricultural camera to detect vegetation health; and soil, sediment, and water sampling for the most commonly used herbicides in the study area. By using these methods, this study shows where stream vegetation health continues to be an issue in the agricultural community, and where concentrations of a commonly used herbicide in the community may be impacting human and ecological health. This study has important implications for impacts to soil and water quality over time in agricultural communities, as many researchers have noted the need to determine the long term effects of conversion to no-till and other forms of conservation agriculture. By providing these methods, communities heavily engaged in multiple forms of conservation agriculture may be able to track herbicide use changes in real time and on shorter decadal time spans in places where conservation agriculture is practiced.

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1. Introduction

Since the late 1990s and early 2000s, wheat farmers in Wasco County, Oregon have gradually converted from conventional tilling practices to no-till and direct seeding agricultural practices. No-till and direct seed, while technically different, are used interchangeably among farmers in the study area and much of the Pacific Northwest. Both no-till and direct seed are forms of conservation agriculture that refer to the practice of minimal tillage or no-tillage that cause between 15 and 30% of soil disturbance within a row width (NRCS, 2006), which generally is achieved by the use of farm equipment that minimizes the area of disturbance during planting and harvesting activities (Friedrich and Kassam, 2012). Both practices minimize soil erosion by leaving crop stubble and residue on the ground after harvest, increase soil moisture and organic material, and generally reduce fuel consumption for farmers (Williams et al., 2014). While many of the economic and environmental improvements of these conservation management techniques have been significant, interviews with farmers and herbicide distributors in the county, as well as a review of the National Agricultural Statistics Service (NASS) database (USDA, 2012), Oregon Department of Agriculture Pesticide Use database records, and collection of herbicide use records from farmers in the county, all indicate that herbicide use in the study area has increased since the onset of no-till and direct seed agriculture (hereafter referred to as no-till). The increased use of herbicides in soils may be resulting in increased herbicide runoff to streams that is harmful to human and ecological health. However, no studies have been conducted to determine herbicide concentrations in streams or to assess the overall effectiveness of no-till since the majority of the county converted.

1.1. Herbicide use trends in conservation agriculture

Although there are numerous comparative studies focused on differences between conventional tillage and no-till, no clear consensus has been established regarding the effect of conservation tillage on herbicide use (Fernandez-Cornejo and Hallan, 2013; Friedrich and Kassam, 2012). Location, climate, and soil type all affect how long herbicides persist in the soil when used with reduced tillage systems (Hager and Nordby, 2008). Interviews and discussions with farmers and herbicide distributors in Wasco County reveal glyphosate, commonly known as Roundup, is the most commonly used herbicide in the county among wheat farmers and has been used in increasing amounts since the onset of conservation management techniques. This increase mimics a nationwide increase of glyphosate use in the U.S., which is primarily due to the spread of herbicide resistant weeds that have been coproduced with genetically modified crops (Benbrook, 2016; Culpepper, 2006; Givens et al., 2009; Koger et al., 2004 Powles, 2008; Shrestha et al., 2007). Since 1974 when glyphosate was released to the market, over 1.6 billion kg of glyphosate active ingredient have been applied in the U.S. alone, and of that, two-thirds of the total volume of glyphosate applied in the U.S. from 1974 to 2014 has been sprayed in just the last 10 years (Benbrook, 2016). In 2014, the amount of glyphosate that farmers sprayed was enough to apply ~1.0 kg/ha (0.8 lb/acre) on every hectare of U.S.-cultivated cropland and nearly 0.53 kg/ha (0.47 lb/acre) on all cropland worldwide (Benbrook, 2016). Between 1996 and 2011, 527 million lb of herbicides were used in herbicide resistant crops in the U.S. in excess of what would have been needed in non-resistant crops (Benbrook, 2012). Although much of the increase in glyphosate is due to the rise of "Roundup Ready" crops that are resistant to glyphosate damage, the increase in glyphosate is also due to the rise of conservation tillage practices, such as no-till (Service, 2007).

Farmers in the study area use a variety of glyphosate-based mixtures to control weeds prior to and after harvest, as well as to control weeds in fallow fields throughout the year. Because glyphosate is a broad spectrum (e.g. non-selective) systemic herbicide that kills most herbaceous plants and cannot be used for live crops (Kremer and Means, 2009), other herbicides (mostly chlorinated herbicides such as 2,4-D and Dicamba) are applied less frequently to actively growing crops. Glyphosate and chlorinated herbicides are applied in a number of ways in the study area. Most farmers currently use their own boom sprayers or other spray devices to deploy herbicides before harvest and throughout the year to keep weeds under control. Though most farmers use glyphosate on their fields, there are areas where spraying is avoided, such as on land that is enrolled in conservation programs like the Conservation Reserve Program (CRP) or the Conservation Reserve Enhancement Program (CREP) along streams. Generally, farmers try to avoid spray to these areas, both as a matter of compliance with their program specifications, and as a cost saving measure.

1.2. Concerns about glyphosate

The concomitant increase in herbicide use, particularly glyphosate, in Wasco County and the U.S. is concerning for several reasons. Glyphosate was once widely believed to be safe, but an increasing amount of literature is showing that glyphosate is not safe for human or ecological health (e.g. Battaglin et al., 2009; Grandjean and Landrigan, 2014; Porter, 2010; Mesnage et al., 2015; Myers et al., 2016; Relyea, 2005; Schinasi and Leon, 2014). The EPA acknowledges that glyphosate has the potential to contaminate surface water because it does not readily break down in water or sunlight (EPA, 1993a) but has still maintained glyphosate's 1991 EPA classification as a Group E carcinogen (evidence of non-carcinogenicity for humans) (EPA, 1993b). While the EPA has not classified glyphosate as a probable carcinogen (and even increased levels of acceptable use in 2013), the World Health Organization has classified it as such as of 2015 (IARC, 2015).

Despite generalizations that glyphosate degrades quickly and is strongly adsorbed to soil (Mamy and Barriuso, 2005), numerous studies show that glyphosate is available to soil and rhizosphere microbial communities as a substrate for direct metabolism leading to increased microbial biomass and activity (Haney et al., 2000; Wardle and Parkinson, 1990). Further, Simonsen et al. (2008) demonstrated that agricultural soils amended with phosphorus fertilizers show elevated levels of unbound glyphosate as a result of soil sorption sites being occupied by competing phosphate ions which left glyphosate available for potential uptake by plant roots, microbial metabolism, and/or leaching into groundwater.

The half-life of glyphosate in soil ranges from 2 to 215 days, and from 2 to 91 days in aquatic systems (Giesy et al., 2000; Grunewald et al., 2001; NPIC, 2008; Vera et al., 2010). Microbial processes primarily drive the degradation of glyphosate into another compound called aminomethylphosphonic acid (AMPA) (Battaglin et al., 2014; Kremer and Means, 2009). Glyphosate and AMPA are very water soluble, but AMPA degrades more slowly than glyphosate (Grunewald et al., 2001). AMPA has a soil half-life that ranges from 60 to 240 days and an aquatic half-life that is comparable to that of glyphosate (Giesy et al., 2000; Bergström et al., 2011). Substantial increases to total phosphorous in aquatic systems (Vera et al., 2010) can occur as a result of AMPA's ultimate degradation to inorganic phosphate, ammonium, and CO_2 (Borggaard and Gimsing, 2008). The main degradation product AMPA is frequently detected in soils subjected to frequent glyphosate applications (Fomsgaard et al., 2003).

1.3. Objectives

While farmers have used a variety of conservation management practices since the mid-1980s, none have been as impactful to the environmental quality of the study area as the switch to no-till, whereby 95% of farm land has been enrolled in no-till practices to date (NRCS, 2016). No-till was implemented in the county in an effort to conserve soil and therefore reduce the amount of soil and sediment introduced to streams that created water quality issues in the area. However, land managers did not thoroughly consider the implications and effects of how increased herbicide use associated with no-till would affect environmentally sensitive areas. Therefore, this research attempts to examine areas in the study area that are environmentally sensitive to herbicide increases such as riparian areas along streams both inside and outside of CRP and CREP conservation easements.

The three main objectives of this study were to 1) determine if there have been changes in vegetation health in environmentally sensitive areas along streams running through agricultural property over the past several decades as a result of increased herbicide use in the study area 2) determine if there are locations where vegetation health does not improve and 3) determine what concentrations of herbicides are in soils, sediments, and surface water in streams in the study area and how they compare to soil and water quality standards, and human and ecological health studies on herbicides.

2. Materials and methods

This study was conducted in the Fifteenmile and Eightmile Watersheds of Wasco County, Oregon (Fig. 1). We used a mixed-methods approach including: herbicide analysis of water, sediment and soils; a vegetation health analysis by Landsat remote sensing imagery; and an analysis of herbicide stressed imagery using a drone fitted with an agricultural camera. Additional technical details about methodology that are not included in the sections below are included in Appendix A.

2.1. Herbicide sampling

Fields in the study area are sprayed with herbicide at least twice a year, and most are sprayed between two and four times a year. Approximately 72% of the watershed's land base is used for agriculture, primarily dryland wheat croplands consisting of spring wheat and winter wheat (NRCS, 2015). The recommended glyphosate application rates for crop types in the Fifteenmile Watershed are included in Appendix B (Barroso and Morshita, 2015). The most common time for herbicide applications are in spring (May) before summer harvest, in the summer on fallow fields (July and August), and again in the fall right before, or as farmers are planting, their seed (September). Glyphosate may be applied during all of the aforementioned months in fallow fields.

Sampling criteria for herbicide sample collection depended on access, topography, CRP/CREP boundaries, and general spatial coverage. We aimed to collect between eight to ten co-located sediment and water samples during each sampling event, but farming access issues, budgetary constraints, and stream flow conditions hindered sampling attempts in several locations. For soil samples, we chose hillsides with apparent drainage patterns towards streams so that we could sample locations where glyphosate likely leached into the water and sediment in streams. Agricultural fields that were adjacent to, or sloped downwards towards streams, were therefore ideal locations from which to collect soil samples. We also attempted to have an even distribution between stream corridors within CRP/CREP in order to ascertain if there was any difference between vegetation health in the unprotected and protected stream corridors. Finally, we attempted to collect an even spatial distribution of samples throughout the watershed so that at least several samples were present in all four cardinal directions of the watersheds.

Herbicide samples were collected during three sampling events in October 2015, May 2016, and July and August 2016 (Table 1). Glyphosate

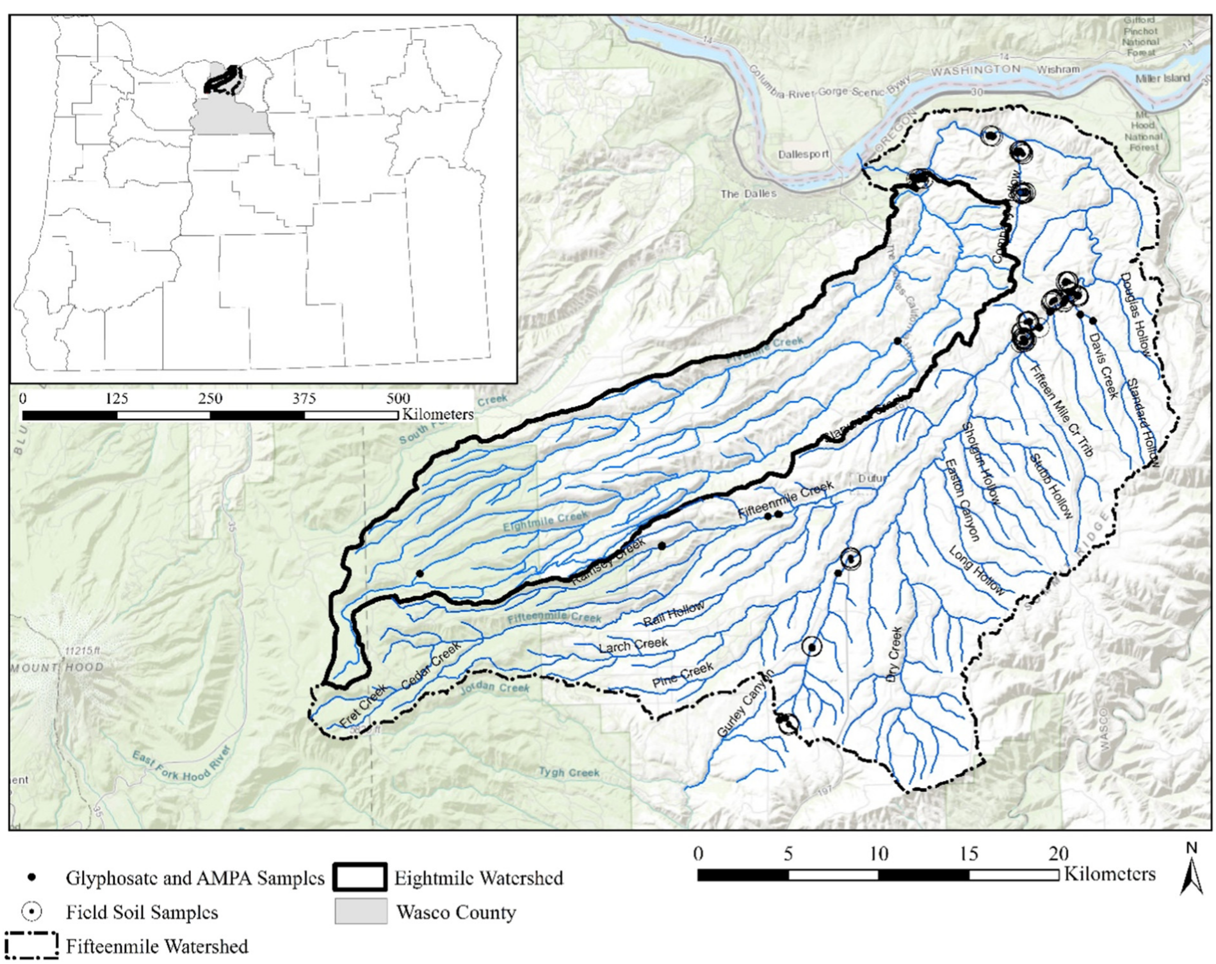

Fig. 1. Study area showing locations of soil, sediment, and surface water samples in the Fifteen and Eightmile Watersheds of Wasco County. Samples were collected and analyzed for glyphosate, AMPA, and chlorinated herbicides during the years 2015 and 2016.

and AMPA sample collection occurred during all sampling events, but sampling for chlorinated herbicides that farmers frequently use, such as 2,4-D and Dicamba, only occurred during one sampling event in July 2016. The collection of chlorinated herbicide samples was limited to surface water in streams and in soil or sediment near streams (Appendix C). Sample locations for all months are shown in Fig. 1 and in Appendix D.

At each stream location, sediment and water samples were co-located when possible. Water samples were collected by placing a laboratory approved certified clean bottle into the stream and allowing it to fill with water. They were collected prior to disturbing the sediment in the stream on the upstream side of the person collecting the sample. After the water sample had been collected, the sediment from the streambed was collected by either a 2 inch diameter PVC tube that was decontaminated prior to use with Alconox and deionized (DI) water or a shovel that was decontaminated in the same way. The selection of the method to use depended on flow conditions in the stream and depth that could be obtained by each instrument. The soil/sediment samples taken from 0 to 30 cm below ground surface were loosened with the sampling instrument and placed in lab assigned, certified clean sampling jars. Each sampling location was recorded with a Trimble Juno GPS unit.

Transects representing the top, middle, and toeslope positions of the hillslope were used for composite sampling of agricultural fields (Appendix D). Along each hillslope transect, between four and five discrete soil samples, depending on the size of the hillslope, were collected from a depth of 0 to 30 cm and composited into one sample representing its respective transect. This depth was chosen because it represents the portion of the soil that is most likely to move with overland flow (Zapata, 2003). A separate transect representing the in-stream sediment that drained the depositional area of the hillslope (i.e. the area that would capture runoff from the hillslope above) was also sampled on each property. Samples collected along transects in in-stream sediment were discrete and not composited. In total, four transects (representing top, middle, toe, and in-stream channel) were devised for each property. A portion of each soil and sediment sample from 2015 and 2016 were analyzed for physical and chemical soil quality indicators including pH, total exchange capacity, organic matter, soluble salts (salinity), phosphorous content, and also for soil texture to determine if any soil properties had an influence on herbicide concentrations or if any correlative patterns could be deduced.

2.2. Spatial analysis-NDVI remote sensing analysis

The Normalized Difference Vegetation Index (NDVI) was used to determine if herbicide drift and runoff to stream corridors with riparian vegetation varied with practices in conservation management techniques and programs practiced in the study area. In the study area and much of the Pacific Northwest, the late growing season in the study area is July and early August (Small et al., 1990). Therefore, imagery from the last two weeks of July from Landsat 5TM satellites and the Landsat 7TM+ satellite was downloaded and analyzed in ArcMap software for vegetation health representing the past 30 years.

Table 1
Samples collected and analyzed for glyphosate and AMPA for the years 2015 to 2016.

Sample type	Number of samples collected	Month and year collected	Location type	Analysis
Sediment	5	October 2015	Stream	Glyphosate/AMPA
Water	8		Stream	
Sediment	8	May 2016	Stream	
Water	9		Stream	
Soil	15	July and August 2016	Agricultural hillslope	
Sediment	11		Stream	
Water	10		Stream	

To determine if vegetation health in riparian areas had been affected by conservation practices, 30 meter buffers of vegetation along riparian stream corridors were extracted from Landsat images from years when conservation practices and no-till/direct seed were likely to affect stream vegetation: 1986, 1990, 1994, 1996, 1998, 2000, 2003, 2006, 2008, and 2011, 2015 to 2016. These years were chosen because changes in conservation and no-till practices occurred during these years. Further, a two to four year interval between years allowed us to determine if any other trends not related to these practices (such as weather or other environmental phenomena) were occurring over a 30 year time span. The width of 30 m was chosen because it is the average buffer width of CREP land in the state or Oregon (DEQ, 2010; U.S. Fish and Wildlife Service, 2009). Appendix E shows a variety of conservation programs that have been practiced in the study area that were driven by farm bills passed since 1985. The year 1986 was chosen as the start date for analysis of imagery because it occurred after the first year that sweeping conservation efforts were made in 1985 to most of the study area.

After vegetation in the 30 m buffered areas near streams were extracted from the Landsat multispectral imagery, the Image Analysis toolbar in ArcMap was used to convert the imagery into NDVI images. The NDVI vegetation categories of not vegetation (all values below 0.1), sparse vegetation (0.1 to 0.2), moderate vegetation health (0.2 to 0.55), and very healthy vegetation (0.55 to 1.0) were assigned to each image (Weier and Herring, 2000). These NDVI values represent the typical range of healthy vegetation in many environments around the world (Weier and Herring, 2000) and were consistent with the health of vegetation in the study area. Inspection of one-meter resolution National Agriculture Imagery Program (NAIP) aerial imagery verified that values in each NDVI category typically matched the vegetation health assigned in the satellite imagery. After the satellite images were classified into the vegetation health categories, change detection statistics were performed in the software program ENVI. Change detection statistics were used to calculate the changes that occurred between each progressive year and also to determine the initial and final stages of vegetation health from year to year.

2.3. Drone sample site selection and field verification

Landsat imagery provided historical analysis of vegetation health that may have been impacted by herbicide drift and runoff. The use of an Unmanned Aerial Vehicle (UAV), commonly referred to as a drone, in the field also provided a finer scale resolution of vegetation stress caused by herbicide drift and runoff than could be provided with satellite imagery alone. The drone was also useful for determination of vegetation health at the time of sample collection, and drone use to monitor crop health and crop spraying of various agrochemical inputs has been increasing in recent years (Estrin, 2015; Hunt et al., 2010). For this study, a DJI Phantom 4 drone fitted with a NDVI-7 optical grade glass narrow multi-band filter camera lens was used to capture images of possibly stressed vegetation during May and July 2016 when crops had recently been sprayed. After drone flights were completed, the imagery obtained from the drone was processed in ArcMap software to ground-truth vegetation values.

To determine how similar NDVI values collected by drone were to those collected by satellite, NDVI pixel values from vegetation (e.g. trees, low lying grasses, and shrubs near streams) were randomly selected using the ArcMap Data Management Tool "Create Random Points" within ten image locations near streams (Fig. 2). Thirty random points were generated within the 30 meter boundary of riparian vegetation for each location where drone imagery had been collected and where samples were taken. The average vegetation values for the cells in the random point locations in drone imagery were compared to the values of the vegetation in the cells of the satellite imagery to determine how closely the values in each type of imagery resembled one another.

While images were taken in May and July of 2016, only drone images collected during the month of July were compared for NDVI values of satellite images because of the phenological growth stage of vegetation in July. Since late July and early August are the months for peak biomass growth in vegetation in the study area (Small et al., 1990), images from this time period were likely the most useful for vegetation health analysis. The use of the drone during May assisted in identifying sample locations in areas where vegetation stress from herbicide spray could not be seen with the naked eye.

3. Results and discussion

3.1. NDVI analysis of satellite imagery 1986 to 2016

Fig. 3 shows the trend in vegetation health from 1986 to 2016 in both the Fifteenmile and Eightmile Watersheds. In general, the trend for very healthy vegetation (0.55 or higher on the NDVI scale), remained steady between 1986 and 1996 and then rose from 1996 to 2011. Moderately healthy vegetation (0.2 to 0.55 on the NDVI scale) fluctuated between approximately 44% and 55% of total vegetation, but retained the same general health over the whole period from 1986 to 2011. Unhealthy or sparse vegetation health (0.2 to 0.55) decreased from 1986 to 1996, increased between 1996 and 2003, and then decreased to levels near the previous 1986 level in 2011. These patterns are displayed in Figs. 3 and 4 and Appendix F. Post 2011, a sharp decline in all vegetation health categories (except the not vegetation category) occurred due to severe droughts in Oregon in the years 2014 and 2015. In this year, the areas classified as not vegetation increased from below 20% of vegetation to over 80%. PRISM precipitation data and temperature data (PRISM Climate Group, 2017) (Appendix G) show that precipitation was lower during the year 2015 and it was also the hottest year on record in 30 years.

Figs. 3 and 4 (and Appendix F) demonstrate that streams that were formerly in lower vegetation health categories initially increased in the 1980s and early 1990s, particularly from 1986 to 1990 and 1990 to 1994, showing that stream health was in general decline during these years when conservation programs were in the early stages of introduction in the study area. The 1998 to 2000 period (Fig. 5) shows a dramatic improvement in vegetation near streams that were formerly in the not vegetation category in 1994. This improvement can likely be attributed to the large number of streams that were enrolled in CREP due to the 1996 farm bill. Conversations with farmers and a list of streams and dates from the local Soil and Water Conservation District (SWCD) showed that the majority of streams in the study area were enrolled into CREP in the late 1990s (e.g. 1996/1997) and also in the early 2000s from 2001 to 2003.

A large portion of the vegetation near streams was classified in the not vegetation category during 2011 to 2015 and 2015 to 2016 in the satellite imagery, which is somewhat misleading. An inspection of the NAIP imagery and experience from field work during these years revealed that the pixels in the satellite imagery were assigned to the majority value of the NDVI pixels in the imagery, which cover a cell of 30 × 30 m. While the vegetation in riparian areas was stressed during the drought year, to say that no vegetation was present is not accurate. Vegetation in riparian areas during the year 2015 was present, but was not as dense as in previous years and more dead vegetation was present. More bare rock and soil (e.g. the not vegetation category) was exposed within the riparian area during this year and the majority value

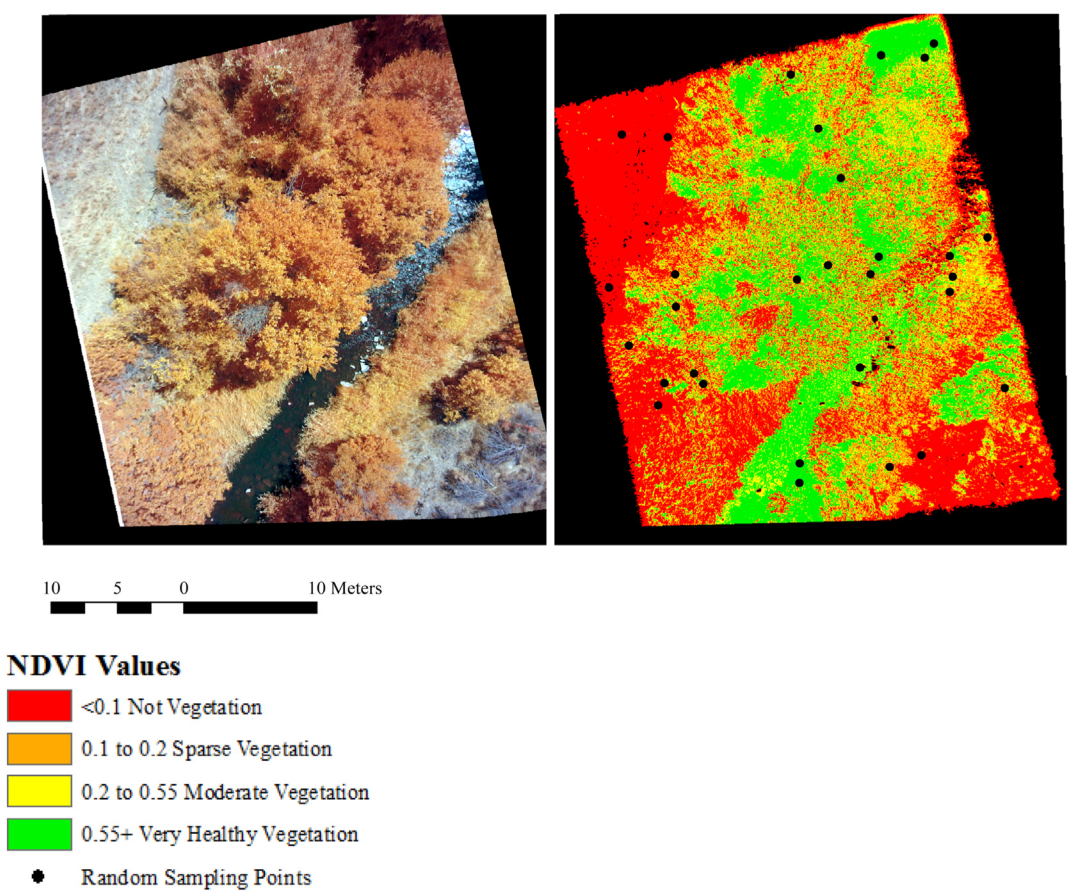

Fig. 2. An example of drone imagery used to verify NDVI values. The image on the left shows a picture of a riparian area that was collected by the NDVI-7 camera on the drone. With the raw NDVI image, green healthy vegetation appears in yellow/orange/gold while other surrounding surfaces and dead or stressed vegetation appears in grey or brown. The raw NDVI image must be post-processed to obtain the actual NDVI values, which the image on the right shows. Some aquatic plants in the stream display as green (very healthy vegetation) in the post-processed image. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

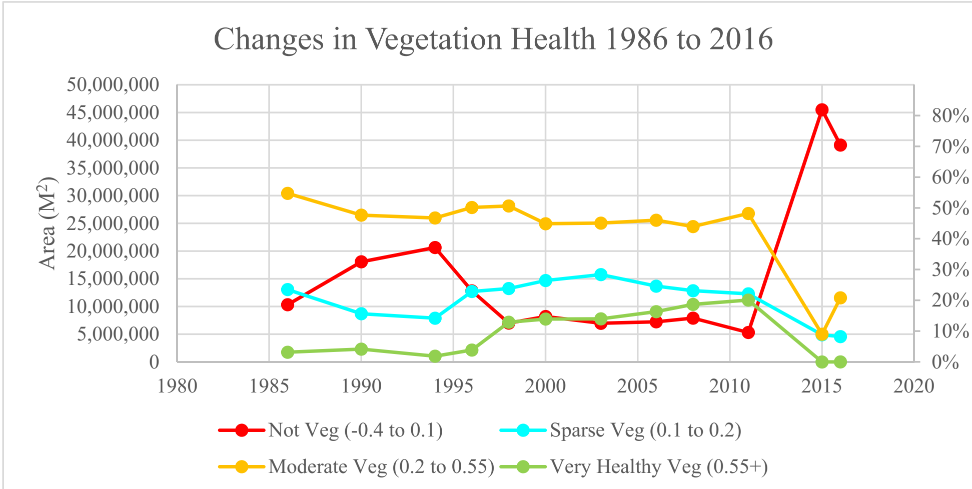

Fig. 3. Changes in vegetation health from 1986 to 2016. The trend lines in the graph show how vegetation has changed during the years when farmers were most active in conservation programs in the study area. Over time, vegetation health has generally improved especially in comparison to vegetation health prior to no-till agriculture.

of NDVI values for those bare surfaces were assigned to the cells representing the riparian areas in the watershed. Therefore, the drastic change between 2011 and 2015 and 2016, is more representative of a large amount of dead and stressed vegetation exposing bare rocks and soil, rather than the absence of vegetation.

In some locations, stream health never improved between 1986 and 2011, regardless of temperature and precipitation changes (Fig. 6). Vegetation that fell into the always unhealthy not vegetation category accounted for approximately 732,000 m^2 of vegetation, which is approximately 1.3% of the 55,566,000 m^2 of vegetation in the Fifteenmile and Eightmile Watersheds in the 30 meter buffer area surrounding streams. These locations were mostly located in the eastern portion of unnamed tributary streams of the Fifteenmile Watershed.

It is unlikely that vegetation that remains in the unhealthy vegetation categories remains as such because of drought conditions or vegetation variety. If weather patterns were affecting the areas that consistently had unhealthy vegetation, they would likely improve during at least some of the years when other vegetation improved as well. Further, many of the persistently unhealthy locations are comprised of vegetation varieties that are similar to other locations throughout the watershed with similar corridor widths and healthy vegetation.

Based on ground-truth images collected with the drone, persistent off target movement of herbicide from overspray, drift, or runoff which is different from persistent residual herbicides in soils or water, is likely the cause of persistent unhealthy vegetation. The drone was flown in locations that showed signs of recent herbicide spray in many locations throughout the watershed and in areas of the consistently unhealthy vegetation category. Many of the ground-truthing flights took place in the areas between riparian vegetation and the field, where farmers usually spray to keep weeds from creeping into crop areas. NDVI vegetation values for vegetation that was intentionally sprayed with herbicide and those in or near the stream (that should not have been sprayed) were within 5% of each other. The similarity in values between sprayed vegetation and riparian areas within proximity to the spray would indicate that either some herbicide drift had occurred, or that runoff to the stream had occurred and had affected vegetation health.

Here, we should also clarify the difference between locations that experience persistent herbicide overspray and drift and the persistence of glyphosate and AMPA in soil, sediment, and water. The concentration of glyphosate in the sample media collected does not necessarily correlate with vegetation health shown in the imagery. Glyphosate is a post-emergence, non-selective, foliar herbicide (Okada et al., 2017) and is primarily applied by spray to plant leaves. Glyphosate can accumulate in the soil (Okada et al., 2017) and uptake through the root system can contribute to plant mortality (Shushkova et al., 2010). However, it is unlikely that persistent residual levels of glyphosate in the soil would contribute to plant mortality more than the spray events that took place during the time periods that the imagery was analyzed for vegetation health. For example, Simonsen et al. (2008) found that six months after glyphosate application, residues of glyphosate and AMPA were still available for uptake by plants. However, the concentration of residues in plant materials did not seem to pose a risk to the plant yields of the crops that were studied. Further, we collected samples in stream beds in locations where nearby riparian vegetation in CRP and CREP was affected by herbicide drift, and we used vegetation health only as an indicator that herbicide was likely reaching sediment and water in the stream. However, we did not assume that there was a direct correlation between vegetation health and long term persistence of glyphosate and AMPA in soils, sediment, and water, which is the result of many sprays throughout the year. The satellite imagery and drone imagery showed that all of our sampling locations were either in the unhealthy and sparse vegetation categories, and no samples were collected in healthy vegetation categories. The satellite imagery and drone are capturing more of the immediate effects of overspray/drift because of the time period we sampled in, which are the months when farmers spray the most. The effects of persistent glyphosate in soil and sediment may be having an effect on vegetation, but what is detected in the imagery is from the most recent spray that is occurring during months of spray and during times of sample collection. Areas that are intensely sprayed also may be locations where more runoff of herbicide occurs and could be affecting vegetation health in the short term during times of spray as well.

3.2. NDVI analysis with drone 2016

The drone was able to detect varying ranges of vegetation health that were not visible to the naked eye and aided in choosing sites for sampling of herbicides in May and June of 1016. An overlay of sample locations with NDVI post processed imagery typically revealed vegetation in the sparse vegetation health category range of 0.1 to 0.2.

The NDVI values from 2016 Landsat 7TM imagery were compared with NDVI values in images collected by drone in order to act as a ground-truth to see how closely NDVI values matched. The images were mosaicked into areas representing the vicinity of the satellite imagery cells in the Landsat imagery and randomly sampled as described in the Methods section of this paper. After random sampling was performed and the average of the drone imagery was calculated and compared to satellite imagery of the same spatial extent, we found that the

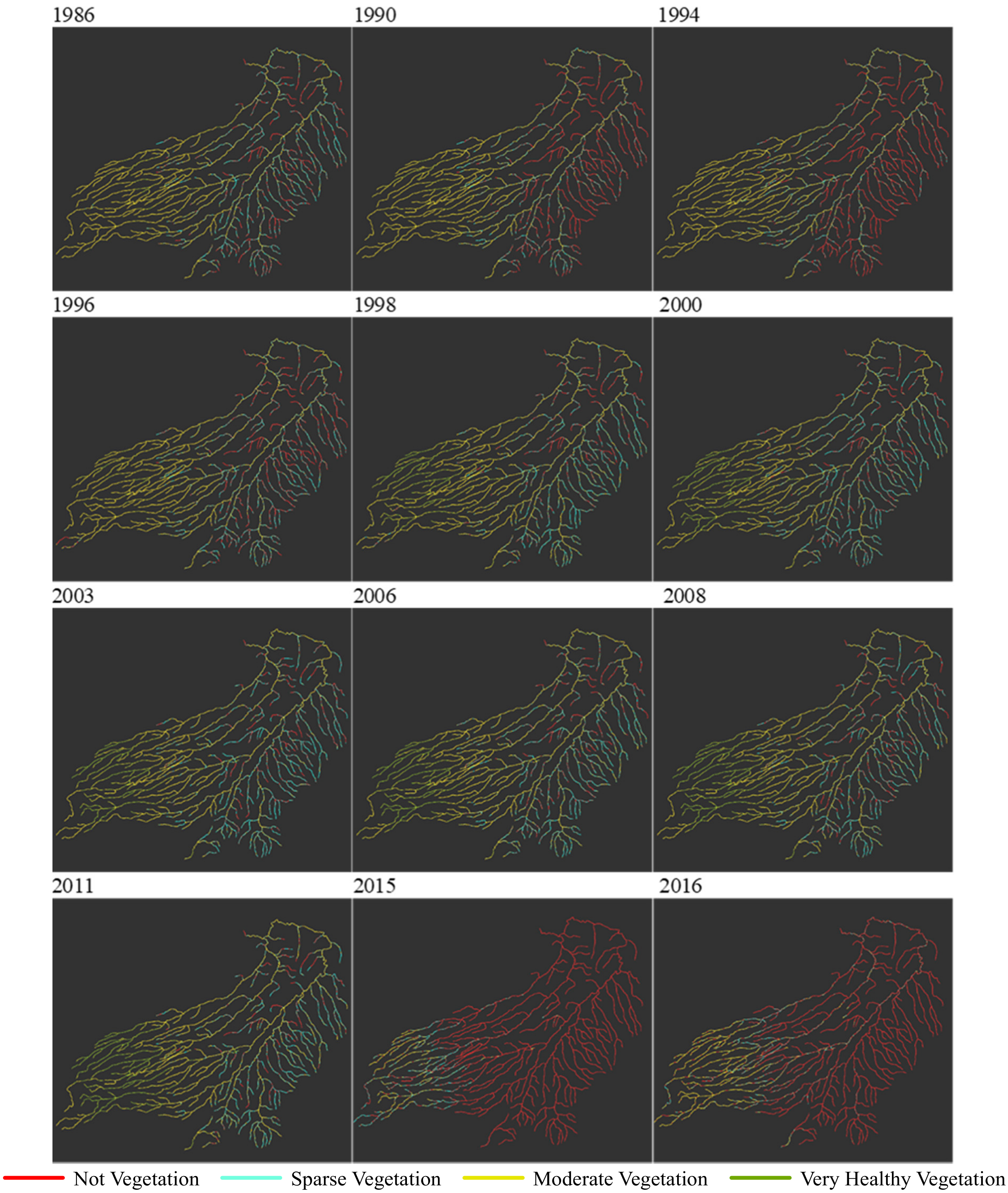

Fig. 4. The changes in vegetation health within a 30 meter buffer area from 1986 to 2016.

NDVI values between the two types of imagery only varied between 1 and 5%, indicating that vegetation health was accurately assessed by the satellite imagery. The NDVI imagery and classification products of Landsat satellites 5TM and 7TM are very similar, and data from the two sensors can be used interchangeably to measure and monitor the same landscape phenomena (Vogelmann, et al., 2001).

3.3. Herbicide concentrations and analysis

We chose to sample glyphosate/AMPA sediment and soil samples from a depth of 0 to 30 cm, but we acknowledge that concentrations of glyphosate can vary with depth. Soils collected in this study were intentionally collected in the upper 30 cm of the soil profile, both because this portion of the soil is likely to move with overland flow (Zapata, 2003), but also because glyphosate has been shown to have vertical mobility that is related mainly to preferential flow and particle-facilitated transport in well-structured soil (Kjær et al., 2011). Studies in field settings, like those conducted by Lupi et al. (2015) and Silva et al. (2018), have shown that while the concentration of glyphosate may be highest in the upper 2 to 5 cm of surface soils, glyphosate concentrations can reach depths of 20 to 30 cm, respectively. Besides depth, we considered the effects that tillage may have on glyphosate concentrations. Studies

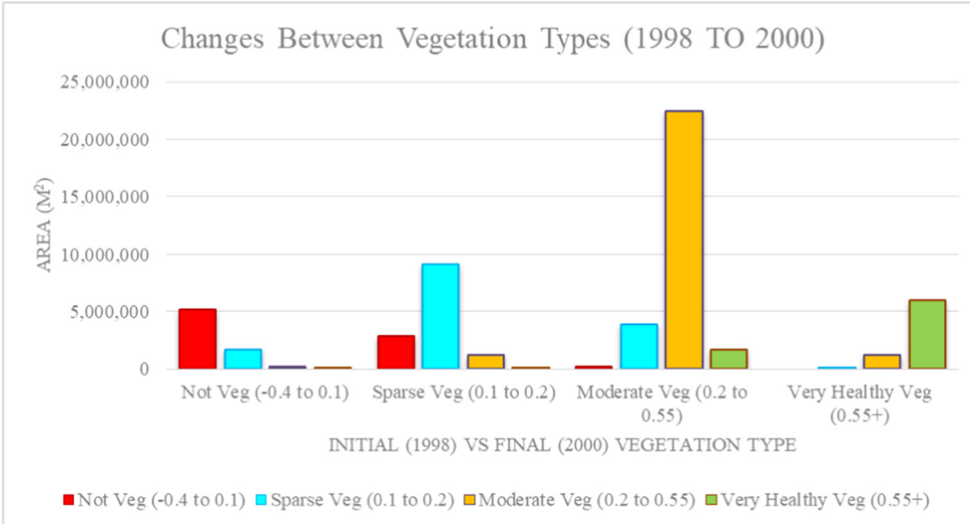

Fig. 5. Changes between vegetation types (1998 to 2000).

that examine the effect of no-tillage and conventional tillage on glyphosate distribution in the field (e.g. Okada et al., 2017 and Zablotowicz et al., 2009) indicate that the type of tillage system used does not have a significant effect on distribution of glyphosate in the environment.

Glyphosate and/or AMPA was detected in the majority of samples collected in all media (Table 2). Simple linear regressions and box plots (Appendix H) were used to determine if there were any significant differences between concentrations within CRP/CREP boundaries versus those outside of conservation corridors and none were found. In water, glyphosate was detected in 15 of the 27 samples collected and concentrations ranged from 0.02 to 0.11 μg/L (Table 2). In sediment, glyphosate was detected in 14 of 24 samples collected with detections that ranged from 0.024 μg/kg to 240 μg/kg. In samples collected from soils on fields, glyphosate was detected in 8 of the 15 samples collected

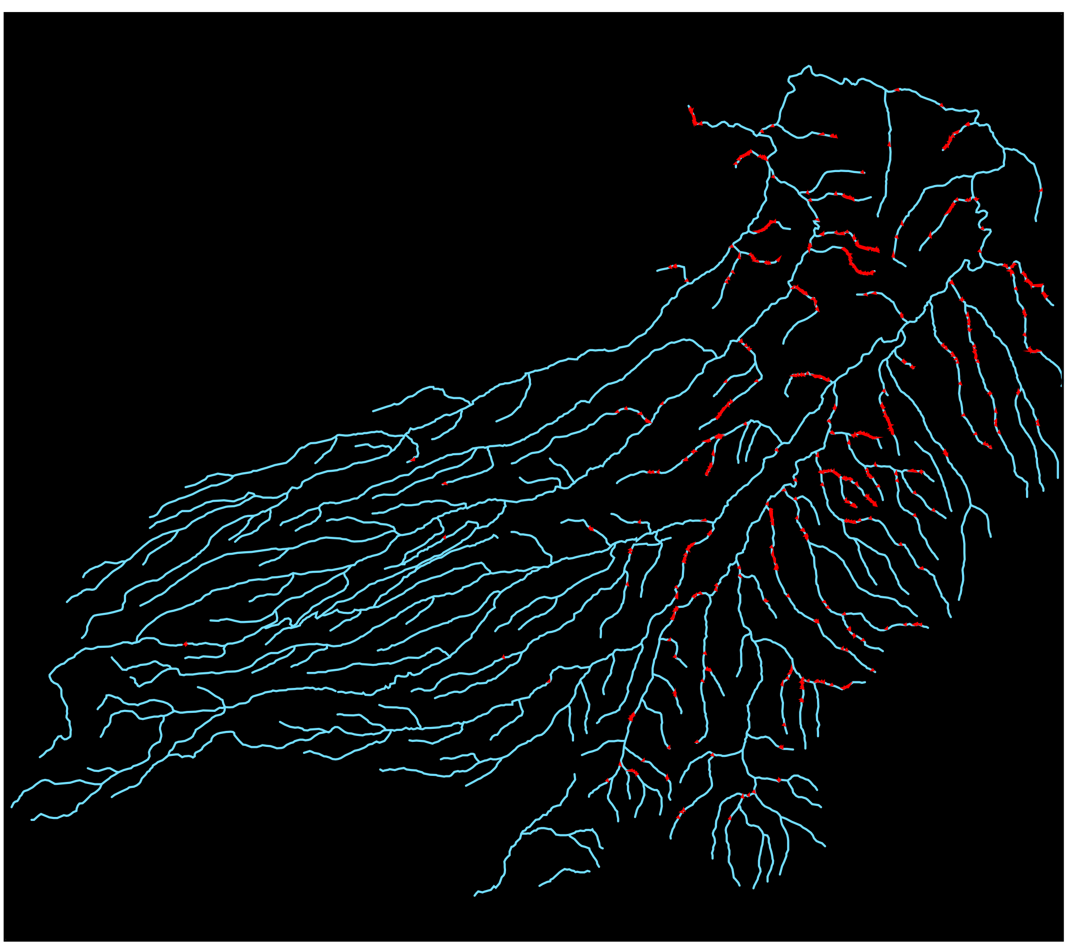

Fig. 6. Areas that remained unhealthy between 1986 and 2016. The areas shown in red never improved in stream health and account for 1.3% of the vegetation in riparian areas within 30 m of streams. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Detections of glyphosate and AMPA in field soils. Detections above the MDL are indicated in bold. Soil samples collected in agricultural fields are denoted with an "S", sediment samples are denoted with "SD", and water samples are denoted with a "W". Soil and sediment samples are measured in units of μg/kg and water samples are measured in units of μg/L. Both units represent parts per billion (ppb).

Location	October 2015			May 2016			July 2016			August 2016		
	Sample name	Glyphosate (ppb)	AMPA (ppb)	Sample name	Glyphosate (ppb)	AMPA (ppb)	Sample name	Glyphosate (ppb)	AMPA (ppb)	Sample name	Glyphosate (ppb)	AMPA (ppb)
1	W2	**0.03**	**0.02**				W23	<0.02	<0.02			
							SD-14	<0.02	<0.02			
2	W5	**0.07**	**0.02**	W16	<0.02	**0.02**	W20	**0.095**	**0.034**			
							SD-23	**0.024**	<0.02			
3	W8	**0.03**	**0.02**				W21	<0.02	**0.04**	W27	<0.02	<0.02
							SD-24	<0.02	<0.02			
4	W4	**0.04**	**0.2**				SD-19	**0.032**	<0.02			
	SD-4	**25**	**28**				S1	<0.02	<0.02			
							S2	<0.02	<0.02			
							S3	**0.024**	<0.02			
5				W15	**0.05**	**0.09**	SD-20	<0.02	**0.036**			
				SD-12	**170**	**160**	S7	<0.02	**0.04**			
							S8	**0.02**	**0.043**			
							S9	<0.02	**0.038**			
6	W1	**0.11**	**0.03**				S4	**0.042**	**0.076**			
	SD-2	**11**	**64**				S5	<0.02	**0.034**			
							S6	**0.031**	**0.042**			
7	W3	<0.02	<0.02									
	SD-3	<1.0	<1.0									
8	W6	**0.04**	**0.03**									
	SD-5	**240**	**290**									
9	W7	**0.03**	**0.02**									
	SD-1	**1.9**	**13**									
10				W9	<0.02	**0.02**						
				SD-6	<1.0	**4.7**						
11				W10	**0.08**	**0.05**						
				SD-7	**3.5**	**4.6**						
12				W11	**0.02**	<0.02						
				SD-8	<1.0	**2.2**						
13				W12	**0.02**	<0.02						
				SD-9	**16**	**18**						
14				W13	**0.04**	**0.05**						
				SD-10	**19**	**25**						
15				W14	<0.02	**0.02**						
				SD-11	**13**	**22**						
16				W17	**0.02**	<0.02						
				SD-13	**9.1**	<1.0						
17							W18	**0.021**	**0.027**			
							SD-21	<0.02	<0.02			
18							W19	<0.02	**0.047**			
							SD-22	**0.034**	<0.02			
19							W22	<0.02	<0.02			
20							W24	<0.02	**0.021**			
							SD-15	**0.036**	**0.079**			
21							W25	<0.02	<0.02	S13	**0.022**	**0.031**
							SD-16	<0.02	**0.023**	S14	**0.021**	<0.02
										S15	**0.026**	**0.022**
22							W26	<0.02	**0.025**			
							SD-17	<0.02	**0.025**			
23							SD-18	<0.02	<0.02			
24										S10	<0.02	**0.033**
										S11	**0.038**	<0.02
										S12	<0.02	**0.034**

and detections ranged from 0.02 to 0.042 μg/kg. Glyphosate's derivative product AMPA was detected in 19 of the 27 samples collected for water and concentrations ranged from 0.02 to 0.2 μg/L. In sediment, AMPA was detected in 15 of the 24 samples collected with detections that ranged from 0.023 to 290 μg/kg. Finally, AMPA was detected in 10 of the 15 samples collected in field soils with concentrations that ranged from 0.022 to 0.076 μg/kg. All details pertaining to sample names, sampling locations, and sample concentration levels are included in Table 2.

The highest concentrations of glyphosate and AMPA were found in sediment samples taken during the months of October 2015 and May 2016. These samples, SD-5 and SD-12, contained concentrations of glyphosate at 240 μg/kg and 170 μg/kg and AMPA concentrations of 290 μg/kg and 160 μg/kg, which were orders of magnitude above the rest of the other samples collected. In general, sediment samples collected during these months had higher concentrations of both glyphosate and AMPA and may be somewhat explained by timing of the year when the samples were collected. While farmers spray during several months of the year to suppress weeds in fallow fields, spraying is particularly prevalent during the month of May when weeds become abundant in the spring and in late September right before farmers plant their seed in the ground. It is likely that spray concentrations during these collection months were high because of the proximity in time to which these spray events occurred.

There is abundant literature on how herbicide persistence and concentration varies by soil type and properties. However, simple linear regressions showed that there were no correlations between glyphosate, AMPA, and any of the soil chemical and physical properties that were tested in the lab in this study (Appendix I) and there was no correlation between glyphosate concentration and media type (Appendix J).

Chlorinated herbicide samples were collected only during July 2016 due to budgetary restrictions for sample collection. In all sample locations, chlorinated herbicides were not detected above the MDL of 0.1 micrograms per liter in water (μg/L) or above the MDL for soil and sediment which ranged between 0.0194 and 0.0198 mg/kg, therefore, the data for the chlorinated herbicide samples is not shown or further discussed.

3.4. Regulatory and toxicological values of concern

The EPA glyphosate regulatory limit for drinking water, maximum contaminant level (MCL) is 700 μg/L, which is the same level as EPA's maximum contaminant level goal (MCLG), and is the level of a contaminant in drinking water below which there is no known or expected risk to health (EPA, 2016). A number of countries have also established a range of “acceptable” daily intake levels of glyphosate-herbicide exposures for humans, generally referred to in the U.S. as the chronic Reference Dose (cRfD), or in the E.U. as the Acceptable Daily Intake (ADI). An EPA cRfD of 1.75 mg of glyphosate per kilogram body weight per day (mg/kg/day) has been established in the U.S. (NPIC, 2015). In the E.U., the current ADI was originally adopted in 2002 and is significantly lower at 0.3 mg/kg/day. The data upon which these exposure thresholds are based were supplied by manufacturers during the registration process, are considered proprietary, and are typically not available for independent review (Myers et al., 2016; Mesnage et al., 2015).

There is growing concern about the increase of glyphosate in the environment and concerns about the levels which are currently allowed and considered acceptable in regulatory literature (Battaglin et al., 2014; Benbrook, 2012; Benbrook, 2016; Grandjean and Landrigan, 2014; Porter, 2010; Kremer and Means, 2009; Mesnage et al., 2015, Myers et al., 2016 Relyea, 2005). Although the concentration values of glyphosate and AMPA detected in this study are below the 700 μg/L or the 1.75 mg/kg/day cRfD established by the EPA, detected concentration levels of both have been found to be harmful to human and ecological health in numerous studies. For example, Mesnage et al. (2015) identified numerous peer-reviewed studies where the toxicological effects of glyphosate-based herbicides and adjuvants (chemicals mixed with glyphosate to make it more effective) were found to have toxicological effects well below regulatory screening levels. In this study on the Fifteenmile Watershed, the concentration values of glyphosate found in surface water (0.02 to 0.11 μg/L) have been found to have endocrine disrupting and chronic effects according to the findings of Mesnage et al. (2015).

In the Fifteenmile Watershed, farmers would likely be most vulnerable to exposure through ingestion of surface water and ground water used for private domestic wells, irrigation, and water contact recreation. The designated beneficial uses listed for the waters in the watershed are: public and private domestic water supply, industrial water supply, irrigation, livestock watering, anadromous fish passage, salmonid fish rearing, salmonid fish spawning, water contact recreation, aesthetic quality, and hydro power (Clark, 2003). Farmers in the watershed and county use surface water and groundwater extensively for irrigation and private water supply (Nelson, 2000; Clark, 2003; WCPD, 2017). Glyphosate based herbicides could contaminate drinking water via rainwater, surface runoff and leaching into groundwater, thereby adding drinking water, bathing, and washing water as possible routine exposure pathways (Battaglin et al., 2014; Majewski et al., 2014; Coupe et al., 2012). Multiple studies have determined that groundwater wells are susceptible to glyphosate leaching from soils (Battaglin et al., 2014; Jayasumana et al., 2015; Myers et al., 2016). Further, this study has shown that surface water (which can be a source for groundwater supplies in much of the watershed) is already impacted by glyphosate at levels that have been found to have endocrine disruption and chronic effects.

Numerous studies (De Roos et al., 2005; Garry et al., 2002; Harrison, 2008; Jayasumana et al., 2015; Mesnage et al., 2015; Mesnage et al., 2012; Rull et al., 2009; Schinasi and Leon, 2014) have also shown that farmers are exposed to herbicides, including glyphosate, through other exposure routes including pesticide drift and exposure to glyphosate during application of herbicides. Farmers in the Fifteenmile Watershed are likely exposed to glyphosate and other herbicides through both of these exposure routes. The contact between continental and maritime air masses produces strong wind patterns in Wasco County and the watersheds, and the area receives high winds over 50% of the time (WCPD, 2017). Residents in the watershed have reported incidents of herbicide drift more frequently as new orchards and vineyards that border wheat land farms are increasingly planted (personal communication with extension agents, NRCS conservation district manager, and SWCD). This drift can cause inhalation or ingestion of herbicide when herbicides are volatilized or carried on soil particles in the wind (ODA, 2017). Concentrations of glyphosate found in soil in this study (0.02 to 0.042 μg/kg) have been found to have endocrine disrupting and chronic effects (Mesnage et al., 2015) and soil particles that have adsorbed glyphosate could be carried on the wind during application times, but even during times when application is not occurring.

Glyphosate and AMPA concentrations present in sediment (0.024 to 290 μg/kg) and water (0.02 to 0.2 μg/L) pose ecological health risks as well. Several rare, endangered, or threatened species are listed in the Fifteenmile Watershed's streams and tributaries (Clark, 2003) that are already impacted by sediment and temperature (ODEQ, 2008). Glyphosate-based formulations have been shown to modify the community assemblage and quality of freshwater periphyton communities (Vera et al., 2010) which could indirectly affect fish. Species that are listed include native runs of winter steelhead (*Oncorhynchus mykiss gairdneri*), which has been listed as a threatened species by the National Marine Fisheries Service. Rainbow trout (the same species as steelhead in the Fifteenmile Watershed) had altered olfaction mediated behavior when exposed to 100 ppb active ingredient Roundup (Tierney et al., 2007) an important sensory function for predator avoidance and homing for salmonid species (Scholz et al., 2000). In general, laboratory glyphosate toxicity studies with species found in Fifteenmile Creek including rainbow trout and Coho salmon (Wan et al., 1989) are as sensitive as other freshwater species (EPA, 2017).

In addition, stream temperatures in the Fifteenmile Watershed are warmer than optimal for salmonids and could be an additional stressor as well as increase the toxicity of glyphosate to these fish species. Studies found that the toxicity of glyphosate doubled in bluegill (*Lepomis macrochirus*) and in rainbow trout (*Oncorhynchus mykiss*) when the temperature of the water was increased from 45 to 63 °F (Folmar et al., 1979 and Austin et al., 1991). Much of the Fifteenmile Watershed reaches temperatures of over 70 °F (Clark, 2003). Although the concentrations causing effects in Armiliato et al., 2014, Cuhra et al., 2013, and Folmar et al., 1979 were orders of magnitude higher than those detected in Fifteenmile Creek, glyphosate levels from runoff events or drift could be episodic and the grab samples collected could underestimate these concentrations.

Further, glyphosate based herbicide product formulations, many of which are used in the study area, pose greater toxicity risks to a large number of non-target organisms than glyphosate alone (Mesnage et al., 2015; Battaglin et al., 2014). These organisms include mammals (Mesnage et al., 2012; Tsui and Chu, 2004), aquatic insects, and fish (Folmar et al., 1979). Risk assessments of glyphosate based herbicides that are based on studies quantifying the impacts of glyphosate alone underestimate both toxicity and exposure, and thus risk (Myers et al., 2016). This approach has led regulators to set thresholds (cRfDs, ADIs) at levels that would not be protective of exposure to glyphosate formulations (Mesnage et al., 2015; Myers et al., 2016).

3.5. Implications for the widespread presence of glyphosate in the environment

This study had a low number of sample campaigns due to budgetary restrictions and access to farms for sampling. However, the data collected during these sampling campaigns demonstrates the widespread presence of glyphosate in soil, sediment, and water, and provides another example of the increasingly ubiquitous presence of glyphosate in the environment that others have also shown (e.g. Battaglin et al., 2014; Benbrook, 2016; Myers et al., 2016). The widespread presence of glyphosate, particularly in agricultural watersheds that use conservation tillage systems like no-till, is increasing. Its use is exacerbated by problems associated with herbicide resistance that encourages farmers to use more herbicide to kill weeds that are increasingly difficult to eliminate (Service, 2007; Benbrook, 2012); the widespread reduction of labor workers in conservation program farms (Lehrer, 2010) to remove weeds from farms; and the relatively cheap cost of glyphosate compared to other herbicides due to its loss of patent in 2000 (Benbrook, 2012). All of these circumstances are currently affecting the farmers in the watersheds of this study, and are representative of the challenges that many U.S. farmers using conservation practices face.

Given that glyphosate is moderately persistent and mobile, levels in the environment will likely rise in step with use, and this will increase the diversity of potential routes of animal and human exposure (Benbrook, 2012). We recommend the following measures to address some the implications of the widespread glyphosate use.

First, the presence of glyphosate and AMPA in agricultural soils may not only form a risk for soil health but also a potential risk of further spreading of these compounds across land, water, and air (Silva et al., 2018). Glyphosate exposure has been documented to occur through dermal contact or ingestion of contaminated surface and groundwater (Jayasumana et al., 2015; Mesnage et al., 2015; Myers et al., 2016), wind and water erosion (Silva et al., 2018), and atmosphere (Battaglin et al., 2014). A more exhaustive effort to quantify the extent and amounts of glyphosate contamination in agricultural watersheds should be attempted by researchers worldwide, coupled with risk assessments for humans and the environment. This effort would require more intensive monitoring of the occurrence and spatial distribution of glyphosate and AMPA across various media in the environment (e.g. vegetation, soils, water, sediment, and atmosphere).

Second, we recommend less cost prohibitive options for the analysis of glyphosate samples at laboratories that are able to obtain low detection levels (e.g. MDLs of <1 parts per billion (ppb)). The ability to achieve low detection levels for samples is important, as the concentration levels of glyphosate and AMPA in the environment persist at low levels that have toxicological effects, and these effects are often below established regulatory levels (Mesnage et al., 2015). While many herbicides cost closer to $100 per sample, the cost of glyphosate is typically closer to $350 to $400 per sample at the detection levels needed for many studies involving toxicological risk. The cost of analysis limits the number of samples that can be collected, and impedes analysis of how much glyphosate and AMPA occurs throughout the spatial environment of a study area. In this study, we noted that even other governmental agencies in the watersheds were not able to adequately sample for glyphosate as frequently as needed, or as in many locations as needed, due to budgetary restrictions. Access to sampling laboratories with low level detection capacities and reduced costs for glyphosate and AMPA analysis would be useful for a more complete monitoring of glyphosate in the environment, especially where conservation programs are implemented.

Third, and related to the need for lower costs of monitoring and greater spatial coverage, we recommend the increased use of technologies that are normally associated with precision agriculture (such as the drone used for this study) to monitor off target movement of herbicide into waterbodies and other protected locations. Precision agriculture has been used to reduce the amount of spray that farmers use in fields primarily as a cost savings benefit (Estrin, 2015), but we also advocate its use as a tool to protect environmentally sensitive areas in agricultural watersheds. During this study, various individuals expressed a common misconception that protected riparian areas were installed with the intent of capturing herbicide from going into streams. While riparian areas may be mitigating some herbicide drift and runoff, this study makes it clear that it is still present in the majority of water and sediment within streams, and increased monitoring of drift locations would help to minimize this phenomenon. Drone technology is becoming more accessible to the public because of decreases in cost and because advances in drone technology have made drones easier to operate by the average user without specialized training in drone operations. Drones fitted with NDVI cameras, such as the DJI Phantom 4 used for this study, are now less than $1500. While that price could be cost prohibitive for some studies, the purchase of one drone is often less expensive than collecting many herbicide samples to determine where herbicide drift has occurred. We do not suggest drone surveillance of herbicide drift as a replacement for sampling, but rather as a complement to sampling of environmental media in agricultural watersheds where increasing herbicide use may be occurring, and where budgets may be limited for sampling campaign efforts.

4. Conclusions

This study provides several methods to evaluate how herbicide occurrence in the environment has been affected by the widespread adoption of no-till and conservation programs intended to protect stream health. While NDVI values of Landsat satellite imagery over the years of 1986 to 2016 showed that vegetation health in streams appears to have improved overall with the increase in conservation management programs and techniques, concentrations of glyphosate and AMPA were found in the majority of surface water, sediment, and soils in the watersheds of the study area, regardless of whether or not the samples were collected inside or outside of CRP/CREP riparian buffer areas. The detections of glyphosate and AMPA in streams, especially during times when spraying was prevalent (October and May) indicates that the herbicide is still reaching streams even with improvements in conservation agricultural practices. Further, certain locations within the watershed appear to be affected by persistent herbicide runoff or drift. The NDVI imagery captures time periods of increased herbicide spray and shows the immediate effects of the spray that is impacting vegetation health in locations that should be protected from the spray. Some locations that show persistently unhealthy vegetation appear to be affected by this type of drift or runoff more than other locations, and increased sampling and imagery surveillance may be useful in these locations to mitigate the entrance of herbicides into protected stream corridors where water and sediment are continually impacted.

Concentrations of glyphosate in water, sediment, and soil samples collected for this study are within range of those that have been found to have human or ecological health impacts. Glyphosate and AMPA in all media types is likely the result of not only increased amounts of glyphosate use, but also the number of months glyphosate is used to keep weeds in fallow fields under control. The presence of glyphosate and/or AMPA in the majority of samples during all months that were sampled is indicative of the persistence of glyphosate and AMPA in the environment and should be addressed for potential effects to human and ecological health. These findings demonstrate that multiple media and endpoints should be considered holistically for the design and implementation of conservation practices.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.12.266.

References

Armiliato, N., Ammar, D., Nezzi, L., Straliotto, M., Muller, Y.M.R., Nazari, E.M., 2014. Changes in ultrastructure and expression of steroidogenic factor-1 in ovaries of zebrafish *Danio rerio* exposed to glyphosate. J. Toxicol. Environ. Health A 77, 405–414. https://doi.org/10.1080/15287394.2014.880393.

Austin, A.P., Harris, G.E., Lucey, W.P., 1991. Impact of an organophosphate herbicide (Glyphosate) on periphyton communities developed in experimental streams. Bull. Environ. Contam. Toxicol. 47, 29–35.

Barroso, J., Morshita, D., 2015. Spring wheat. Pacific Northwest Pest Management Handbooks URL. https://pnwhandbooks.org/weed/agronomic/cereal-grain/spring-wheat, Accessed date: 11 November 2018 (WWW Document).

Battaglin, W.A., Rice, K.C., Focazio, M.J., Salmons, S., Barry, R.X., 2009. The occurrence of glyphosate, atrazine, and other pesticides in vernal pools and adjacent streams in Washington, DC, Maryland, Iowa, and Wyoming, 2005-2006. Environ. Monit. Assess. 155, 281–307. https://doi.org/10.1007/s10661-008-0435-y.

Battaglin, W.A., Meyer, M.T., Kuivila, K.M., Dietze, J.E., 2014. Glyphosate and its degradation product AMPA occur frequently and widely in U.S. soils, surface water, groundwater, and precipitation. J. Am. Water Resour. Assoc. 50, 275–290. https://doi.org/10.1111/jawr.12159.

Benbrook, C.M., 2012. Impacts of genetically engineered crops on pesticide use in the U.S. — the first sixteen years. Environ. Sci. Eur. 24, 24. https://doi.org/10.1186/2190-4715-24-24.

Benbrook, C.M., 2016. Trends in glyphosate herbicide use in the United States and globally. Environ. Sci. Eur. 28, 3. https://doi.org/10.1186/s12302-016-0070-0.

Bergström, L., Börjesson, E., Stenström, J., 2011. Laboratory and lysimeter studies of glyphosate and aminomethylphosphonic acid in a sand and a clay soil. J. Environ. Qual. 40, 98–108.

Borggaard, O.K., Gimsing, A.L., 2008. Fate of glyphosate in soil and the possibility of leaching to ground and surface waters: a review. Pest Manag. Sci. 64, 441–456. https://doi.org/10.1002/ps.1512.

Clark, Jennifer, 2003. Fifteenmile Watershed Council and Wasco County Soil and Water Conservation District. URL. http://www.wasco.oacd.org/15mile%20Watershed%20Assessment.pdf, Accessed date: 22 December 2016 (WWW Document).

Coupe, R.H., Kalkhoff, S.J., Capel, P.D., Gregoire, C., 2012. Fate and transport of glyphosate and aminomethylphosphonic acid in surface waters of agricultural basins. Pest Manag. Sci. 68, 16–30. https://doi.org/10.1002/ps.2212.

Cuhra, M., Traavik, T., Bøhn, T., 2013. Clone- and age-dependent toxicity of a glyphosate commercial formulation and its active ingredient in *Daphnia magna*. Ecotoxicology 22, 251–262. https://doi.org/10.1007/s10646-012-1021-1.

Culpepper, A.S., 2006. Glyphosate-induced weed shifts. Weed Technol. 20, 277–281. https://doi.org/10.1614/WT-04-155R.1.

De Roos, A.J., Blair, A., Rusiecki, J.A., Hoppin, J.A., Svec, M., Dosemeci, M., Sandler, D.P., Alavanja, M.C., 2005. Cancer incidence among glyphosate-exposed pesticide applicators in the Agricultural Health Study. Environ. Health Perspect. 113, 49–54.

DEQ, 2010. Cost estimate to restore riparian forest buffers and improve stream habitat in the Willamette Basin, Oregon. URL. http://www.deq.state.or.us/wq/tmdls/docs/WillametteRipCost030310.pdf (WWW Document).

EPA, 1993a. Reregistration Eligibility Decision (RED): Glyphosate; EPA-738-R-93-014. U.S. EPA, Office of Prevention, Pesticides, and Toxic Substances, Office of Pesticide Programs, U.S. Government Printing Office, Washington, DC (1993).

EPA, 1993b. Reregistration Eligibility Decision (RED) facts. US EPA URL. http://www.epa.gov/oppsrrd1/reregistration/REDs/factsheets/0178fact.pdf (WWW Document).

EPA, 2016. Table of regulated drinking water contaminants. URL. US EPAhttps://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations, Accessed date: 15 August 2018 (WWW Document).

EPA, 2017. Registration review - preliminary ecological risk assessment for glyphosate and its salts. Regulations.gov - supporting & related material document. URL. https://www.regulations.gov/document?D=EPA-HQ-OPP-2009-0361-0077, Accessed date: 11 November 2018 (WWW Document, n.d.).

Estrin, S., 2015. Drones and Their Positive Impact on Precision Agriculture. Drone Universities.

Fernandez-Cornejo, J., Hallan, C., 2013. Conservation tillage, herbicide use, and genetically engineered crops in the United States: the case of soybeans. URL. http://www.agbioforum.org/v15n3/v15n3a01-fernandez-cornejo.htm, Accessed date: 8 May 2015 (WWW Document).

Folmar, L.C., Sanders, H.O., Julin, A.M., 1979. Toxicity of the herbicide glyphosate and several of its formulations to fish and aquatic invertebrates. Arch. Environ. Contam. Toxicol. 8, 269–278. https://doi.org/10.1007/BF01056243.

Fomsgaard, I.S., Spliid, N.H., Felding, G., 2003. Leaching of pesticides through normal-tillage and low-tillage soil—a lysimeter study. II. Glyphosate. J. Environ. Sci. Health B 38, 19–35. https://doi.org/10.1081/PFC-120016603.

Friedrich, T., Kassam, A., 2012. No-till farming and the environment: do no-till systems require more chemicals? Outlooks Pest Manag. 23, 153–157. https://doi.org/10.1564/23aug02.

Garry, V.F., Harkins, M.E., Erickson, L.L., Long-Simpson, L.K., Holland, S.E., Burroughs, B.L., 2002. Birth defects, season of conception, and sex of children born to pesticide applicators living in the Red River Valley of Minnesota, USA. Environ. Health Perspect. Suppl. 110, 441.

Giesy, J.P., Dobson, S., Solomon, K.R., 2000. Ecotoxicological risk assessment for Roundup ® herbicide. Reviews of Environmental Contamination and Toxicology. Springer, New York, NY, pp. 35–120 https://doi.org/10.1007/978-1-4612-1156-3_2.

Givens, W.A., Shaw, D.R., Johnson, W.G., Weller, S.C., Young, B.G., Wilson, R.G., Owen, M.D.K., Jordan, D., 2009. A grower survey of herbicide use patterns in glyphosate-resistant cropping systems. Weed Technol. 23, 156–161.

Grandjean, P., Landrigan, P.J., 2014. Neurobehavioural effects of developmental toxicity. Lancet Neurol. 13, 330–338. https://doi.org/10.1016/S1474-4422(13)70278-3.

Grunewald, K., Schmidt, W., Unger, C., Hanschmann, G., 2001. Behavior of glyphosate and aminomethylphosphonic acid (AMPA) in soils and water of reservoir Radeburg II catchment (Saxony/Germany). Z. Pflanzenernähr. Bodenkd. 164, 65–70. https://doi.org/10.1002/1522-2624(200102)164:1<65::AID-JPLN65>3.0.CO;2-G.

Hager, A.G., Nordby, D., 2008. Herbicide persistence and how to test for residues in soils. Illinois Agricultural Pest Management Handbook. University of Illinois at Urbana-Champagne, Cooperative Extension Service, pp. 279–286.

Haney, R.L., Senseman, S.A., Hons, F.M., Zuberer, D.A., 2000. Effect of glyphosate on soil microbial activity and biomass. Weed Sci. 48, 89–93.

Harrison, J., 2008. Abandoned bodies and spaces of sacrifice: Pesticide drift activism and the contestation of neoliberal environmental politics in California. Geoforum 39, 1197–1214. https://doi.org/10.1016/j.geoforum.2007.02.012.

Hunt, E.R., Hively, W.D., Fujikawa, S.J., Linden, D.S., Daughtry, C.S.T., McCarty, G.W., 2010. Acquisition of NIR-green-blue digital photographs from unmanned aircraft for crop monitoring. Remote Sens. 2, 290–305. https://doi.org/10.3390/rs2010290.

IARC, 2015. IARC Monographs Volume 112: evaluation of five organophosphate insecticides and herbicides. URL. International Agency for Research on Cancer, World Health Organizationhttps://www.iarc.fr/en/media-centre/iarcnews/pdf/MonographVolume112.pdf, Accessed date: 17 June 2016 (WWW Document).

Jayasumana, C., Fonseka, S., Fernando, A., Jayalath, K., Amarasinghe, M., Siribaddana, S., Gunatilake, S., Paranagama, P., 2015. Phosphate fertilizer is a main source of arsenic in areas affected with chronic kidney disease of unknown etiology in Sri Lanka. Springerplus 4, 90. https://doi.org/10.1186/s40064-015-0868-z.

Kjær, J., Ernstsen, V., Jacobsen, O.H., Hansen, N., de Jonge, L.W., Olsen, P., 2011. Transport modes and pathways of the strongly sorbing pesticides glyphosate and pendimethalin through structured drained soils. Chemosphere 84, 471–479. https://doi.org/10.1016/j.chemosphere.2011.03.029.

Koger, C.H., Poston, D.H., Hayes, R.M., Montgomery, R.F., 2004. Glyphosate-resistant horseweed (*Conyza canadensis*) in Mississippi. Weed Technol. 18, 820–825.

Kremer, R.J., Means, N.E., 2009. Glyphosate and glyphosate-resistant crop interactions with rhizosphere microorganisms. Eur. J. Agron. 31, 153–161. https://doi.org/10.1016/j.eja.2009.06.004.

Lehrer, N., 2010. U.S. Farm Bills and Policy Reforms: ideological conflicts over world trade, renewable energy, and sustainable agriculture in politics, institutions, and public policy (ISBN 9781604977011).

Lupi, L., Miglioranza, K.S.B., Aparicio, V.C., Marino, D., Bedmar, F., Wunderlin, D.A., 2015. Occurrence of glyphosate and AMPA in an agricultural watershed from the

southeastern region of Argentina. Sci. Total Environ. 536, 687–694. https://doi.org/10.1016/j.scitotenv.2015.07.090.
Majewski, M.S., Coupe, R.H., Foreman, W.T., Capel, P.D., 2014. Pesticides in Mississippi air and rain: a comparison between 1995 and 2007. Environ. Toxicol. Chem. 33, 1283–1293. https://doi.org/10.1002/etc.2550.
Mamy, L., Barriuso, E., 2005. Glyphosate adsorption in soils compared to herbicides replaced with the introduction of glyphosate resistant crops. Chemosphere 61, 844–855. https://doi.org/10.1016/j.chemosphere.2005.04.051.
Mesnage, R., Moesch, C., Grand, R.L.G., Lauthier, G., Vendomois, J.S.de, Gress, S., Seralini, G.-E., 2012. Glyphosate exposure in a farmers' family. J. Environ. Prot. 03, 1001. https://doi.org/10.4236/jep.2012.39115.
Mesnage, R., Defarge, N., Spiroux de Vendômois, J., Séralini, G.E., 2015. Potential toxic effects of glyphosate and its commercial formulations below regulatory limits. Food Chem. Toxicol. 84, 133–153. https://doi.org/10.1016/j.fct.2015.08.012.
Myers, J.P., Antoniou, M.N., Blumberg, B., Carroll, L., Colborn, T., Everett, L.G., Hansen, M., Landrigan, P.J., Lanphear, B.P., Mesnage, R., Vandenberg, L.N., vom Saal, F.S., Welshons, W.V., Benbrook, C.M., 2016. Concerns over use of glyphosate-based herbicides and risks associated with exposures: a consensus statement. Environ. Health 15, 19. https://doi.org/10.1186/s12940-016-0117-0.
Nelson, L., 2000. Fifteenmile Creek Subbasin Summary (including Oregon Tributaries between Hood River and The Dalles Dam). http://docs.streamnetlibrary.org/Subbasin_Plans/Columbia_Gorge/Fifteenmilesumm2000.pdf, Accessed date: 22 December 2016 (WWW Document).
NPIC, 2008. Glyphosate Technical Fact Sheet. Oregon State University, National Pesticide Information Center, Corvallis, Oregon.
NPIC, 2015. Glyphosate technical fact sheet. URL. http://npic.orst.edu/factsheets/archive/glyphotech.html#toxbox, Accessed date: 23 January 2017 (2017, WWW Document).
NRCS, 2006. Tillage practice guide. A guide to USDA-NRCS Practice Standards329 No Till/Strip Till/Direct Seed and 345 Mulch Till. URL. U.S. Department of Agriculturehttps://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_022062.pdf, Accessed date: 27 December 2016 (WWW Document).
NRCS, 2015. Fifteenmile Creek: A Whole Watershed Restoration Approach, p. 4 URL. https://www.oregon.gov/oweb/Documents/CEP-15Mile.pdf, Accessed date: 18 October 2018 (WWW Document).
NRCS, 2016. Seeing is believing: how no-till farming transformed the landscape. NRCS Oregon URL. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/or/newsroom/stories/?cid=nrcseprd1303806, Accessed date: 23 January 2017 (WWW Document, 2017).
ODA, 2017. Pesticide Drift. https://www.oregon.gov/ODA/programs/Pesticides/RegulatoryIssues/Pages/PesticideDrift.aspx, Accessed date: 3 January 2017 (WWW Document).
ODEQ, 2008. Middle Columbia-Hood (Miles Creeks) Subbasin TMDL. URL. https://www.oregon.gov/deq/FilterDocs/MilesCreeksTMDLFinal.pdf, Accessed date: 12 June 2016 (WWW Document).
Okada, E., Costa, J.L., Bedmar, F., 2017. Glyphosate dissipation in different soils under no-till and conventional tillage. Pedosphere https://doi.org/10.1016/S1002-0160(17)60430-2.
Porter, W., 2010. Literature review on biological effects of Roundup herbicide and evaluation of materials safety data sheet and use instructions for Aquamaster. URL. https://www.healthandenvironment.org/uploads-old/Dr.%20Porter%20literature%20review.pdf (WWW Document).
Powles, S.B., 2008. Evolved glyphosate-resistant weeds around the world: lessons to be learnt. Pest Manag. Sci. 64, 360–365. https://doi.org/10.1002/ps.1525.
PRISM Climate Group, 2017. Oregon State U. URL. http://prism.oregonstate.edu/, Accessed date: 3 January 2017 (WWW Document).
R.F. Service, 2007. Glyphosate—the conservationist's friend? Science 316, 1116–1117. https://doi.org/10.1126/science.316.5828.1116.
Relyea, R.A., 2005. The lethal impact of Roundup on aquatic and terrestrial amphibians. Ecol. Appl. 15, 1118–1124. https://doi.org/10.1890/04-1291.
Rull, R.P., Gunier, R., Von Behren, J., Hertz, A., Crouse, V., Buffler, P.A., Reynolds, P., 2009. Residential proximity to agricultural pesticide applications and childhood acute lymphoblastic leukemia. Environ. Res. 109, 891–899. https://doi.org/10.1016/j.envres.2009.07.014.
Schinasi, L., Leon, M.E., 2014. Non-Hodgkin lymphoma and occupational exposure to agricultural pesticide chemical groups and active ingredients: a systematic review and meta-analysis. Int. J. Environ. Res. Public Health 11, 4449–4527. https://doi.org/10.3390/ijerph110404449.
Scholz, N.L., Truelove, N.K., French, B.L., Berejikian, B.A., Quin, T.P., Casillas, E., Collier, T.K., 2000. Diazinon disrupts antipredator and homing behaviors in chinook salmon (*Oncorhynchus tshawytscha*). Can. J. Fish. Aquat. Sci. 57, 1911–1918. https://doi.org/10.1139/f00-147.
Shrestha, A., Hembree, K., Va, N., 2007. Growth stage influences level of resistance in glyphosate-resistant horseweed. Calif. Agric. 61 (2), 67–70. https://doi.org/10.3733/ca.v061n02p67.
Shushkova, T., Ermakova, I., Leontievsky, A., 2010. Glyphosate bioavailability in soil. Biodegradation 21, 403–410. https://doi.org/10.1007/s10532-009-9310-y.
Silva, V., Montanarella, L., Jones, A., Fernandez-Ugalde, O., Mol, H.G.J., Ritsema, C.J., Geissen, V., 2018. Distribution of glyphosate and aminomethylphosphonic acid (AMPA) in agricultural topsoils of the European Union. Sci. Total Environ. 621, 1352–1359. https://doi.org/10.1016/j.scitotenv.2017.10.093.
Simonsen, L., Fomsgaard, I.S., Svensmark, B., Spliid, N.H., 2008. Fate and availability of glyphosate and AMPA in agricultural soil. J. Environ. Sci. Health B 43, 365–375. https://doi.org/10.1080/03601230802062000.
Small, L.F., McIntire, C.D., MacDonald, K.B., Lara-Lara, J.R., Frey, B.E., Amspoker, M.C., Winfield, T., 1990. Primary production, plant and detrital biomass, and particle transport in the Columbia River Estuary. Prog. Oceanogr. 25, 175–210. https://doi.org/10.1016/0079-6611(90)90007-O.
Tierney, K.B., Singh, C.R., Ross, P.S., Kennedy, C.J., 2007. Relating olfactory neurotoxicity to altered olfactory-mediated behaviors in rainbow trout exposed to three currently-used pesticides. Aquat. Toxicol. 81, 55–64. https://doi.org/10.1016/j.aquatox.2006.11.006.
Tsui, M.T.K., Chu, L.M., 2004. Comparative toxicity of glyphosate-based herbicides: aqueous and sediment porewater exposures. Arch. Environ. Contam. Toxicol. 46, 316–323. https://doi.org/10.1007/s00244-003-2307-3.
U.S. Fish and Wildlife Service, 2009. CREP BO 2009_final.doc TS Number: 09-314 TAILS: 13420-2009-F-0047. URL. https://www.fsa.usda.gov/Internet/FSA_File/crepbo2009final.pdf, Accessed date: 28 February 2017 (WWW Document).
USDA, 2012. 2012 Agricultural Wheat Use Survey. URL. http://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/ChemUseHighlights-Wheat-2012.pdf, Accessed date: 28 February 2017 (2012, WWW Document).
Vera, M.S., Lagomarsino, L., Sylvester, M., Pérez, G.L., Rodríguez, P., Mugni, H., Sinistro, R., Ferraro, M., Bonetto, C., Zagarese, H., Pizarro, H., 2010. New evidences of Roundup (glyphosate formulation) impact on the periphyton community and the water quality of freshwater ecosystems. Ecotoxicology 19, 710–721. https://doi.org/10.1007/s10646-009-0446-7.
Vogelmann, J.E., Helder, D., Morfitt, R., Choate, M.J., Merchant, J.W., Bulley, H., 2001. Effects of Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper Plus radiometric and geometric calibrations and corrections on landscape characterization. Remote Sens. Environ. Landsat 7 78, 55–70. https://doi.org/10.1016/S0034-4257(01)00249-8.
Wan, M.T., Watts, R.G., Moul, D.J., 1989. Effects of different dilution water types on the acute toxicity to juvenile pacific salmonids and rainbow trout of glyphosate and its formulated products. Bull. Environ. Contam. Toxicol. 43, 378–385. https://doi.org/10.1007/BF01701872.
Wardle, D.A., Parkinson, D., 1990. Effects of three herbicides on soil microbial biomass and activity. Plant Soil 122, 21–28. https://doi.org/10.1007/BF02851906.
Wasco County Planning Department (WCPD), 2017. Comprehensive Plan, Chapter 2. URL. http://www.co.wasco.or.us/Planning/Comp_Plan/02Physical_Characterist.pdf, Accessed date: 28 February 2017 (WWW Document).
Weier, J., Herring, D., 2000. Measuring vegetation (NDVI & EVI): feature articles. URL. http://earthobservatory.nasa.gov/Features/MeasuringVegetation/, Accessed date: 18 January 2017 (WWW Document).
Williams, J.D., Wuest, S.B., Long, D.S., 2014. Soil and water conservation in the Pacific Northwest through no-tillage and intensified crop rotations. J. Soil Water Conserv. 69, 495–504. https://doi.org/10.2489/jswc.69.6.495.
Zablotowicz, R.M., Accinelli, C., Krutz, L.J., Reddy, K.N., 2009. Soil depth and tillage effects on glyphosate degradation. J. Agric. Food Chem. 57, 4867–4871. https://doi.org/10.1021/jf900272w.
Zapata, F. (Ed.), 2003. Handbook for the Assessment of Soil Erosion and Sedimentation Using Environmental Radionuclides. Kluwer Academic Publishers, Dordrecht.