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Do awareness-focussed approaches to mitigating diffuse pollution work? A case study using behavioural and water quality evidence

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ABSTRACT

Efforts to tackle diffuse water pollution from agriculture are increasingly focussing on improving farmers' awareness under the expectation that this would contribute to adoption of best management practices (BMPs) and, in turn, result in water quality improvements. To date, however, no study has explored the full awareness-behaviour-water quality pathway; with previous studies having mostly addressed the awareness-behaviour link relying on disciplinary approaches. Using an interdisciplinary approach, we investigate whether awareness-focussed approaches to mitigating diffuse water pollution from agriculture indeed result in water quality improvement, addressing the pathway in full. We worked with Dŵr Cymru Welsh Water (a water and waste utility company in the UK) on a pesticide pollution intervention programme, referred to as "weed wiper trial". The main goal of the trial was to raise farmers' awareness regarding pesticide management practices and to promote uptake of BMPs to tackle the rising concentrations of the pesticide MCPA (2-methyl-4-chlorophenoxyacetic acid) in raw water in three catchments in Wales. Using factorial analysis of variance, we analysed MCPA concentrations from 2006 to 2019 in the three targeted catchments and in three control catchments. This was followed by semi-structured in-depth interviews with institutional stakeholders and farmers with varying degrees of exposure to the weed wiper trial. Results show that MCPA concentration for both targeted and control catchments had reduced after the implementation of the weed wiper trial. However, the decline was significantly larger ($F(1) = 6.551$, $p<0.05$, $n= 3077$, Partial eta-squared (ηp^2) = 0.002) for the targeted catchments (mean = 45.2%) compared to the control catchments (mean = 10.9%). Results from the stakeholder interviews indicate that improved awareness contributed to changes in farmers' behaviour and that these can be related to the water quality improvements reflected by the decline in MCPA concentration. Alongside awareness, other psychosocial, economic, agronomic factors, catchment and weather conditions also influenced farmer's ability to implement BMPs and thus overall water quality improvements.

Keywords: Best Management Practices; Diffuse Pollution; Glyphosate; MCPA (2-methyl-4-chlorophenoxyacetic acid); Pesticides; Wales

1. INTRODUCTION

Diffuse water pollution from agriculture is one of today's major environmental problems, with great social impacts such as cost of water treatment and reduced recreational potential of water resources (Damania et al., 2019; United Nations, 2016; OECD, 2012, OECD, 2017). Policy interventions are increasingly focusing on improving farmers' awareness on these problems under the expectation that this can lead to adoption of best management practices (BMPs), i.e. practical measures to reduce the amount of fertilisers, pesticides and other pollutants entering watercourses. Examples of these policies include, for example, the Water Quality Scheme and the Environmental Quality Incentive Programme in the United States (NRCS, 2018, 2019), the Monitor Farms Programme in New Zealand (Ministry for the Environment, 2014), the Reef 2050 Water Quality Improvement Plan in Australia (Queensland Government, 2018), the Catchment Sensitive Farming Delivery Initiative in England (Environment Agency, 2011, Environment Agency, 2014) and the Diffuse Pollution Management Strategy in Scotland (DPMAG, 2015). Improving farmers' awareness is expected to deepen their understanding of the link between land management practices and diffuse water pollution from agriculture, motivating a change in behaviour that increases uptake of BMPs and that, in turn, reduces risks of diffuse water pollution from agriculture, ultimately contributing to improving water quality (Okumah et al., 2019a, 2019b; DPMAG, 2015; Gibbons et al., 2014; Martin-Ortega and Holstead, 2013; Blackstock et al., 2010; Kay et al., 2009). This expectation is based on the assumption of a relatively straightforward relationship between awareness, behaviour and water quality, herein referred to as the awareness-behaviour-water quality pathway.

However, there is lack of evidence on how this pathway works. Previous studies have often addressed partial aspects of the pathway from disciplinary perspectives. For instance, some studies have focussed on farmers' behavioural intentions, but not on actual adoption of BMPs (e.g., Daxini et al., 2018, Daxini et al., 2019a, Daxini et al., 2019b, Zeweld et al., 2017, Floress et al., 2017). While these studies provide insights into factors influencing uptake of BMPs, they fail to provide a full account of the determinants of behavioural change. This is because farmers' intentions might not always translate into behavioural changes due to the influence of contextual factors such as cost, time, available (or lack of) institutional support and farm tenure (Baumgart-Getz et al., 2012; Barnes et al., 2009; Macgregor and Warren, 2006). Other studies have focussed on the link between awareness and actual adoption of BMPs (e.g., Okumah et al., 2018; Vrain and Lovett, 2016; Macgregor and Warren, 2006), but have not considered the impact of the uptake of BMPs on water quality. Other studies that have investigated the impact of BMPs on water quality did not include information on factors driving adoption of BMPs by farmers (e.g., Collins et al., 2016; Kay et al., 2012).

There is therefore an urgent need to overcome this partial and mono-disciplinary approach to the understanding of the awareness-behaviour-water quality pathway in order to inform awareness-focussed interventions (Okumah et al., 2019; Giri and Qiu, 2016). In this study, we take an interdisciplinary approach, where farmers and institutional stakeholders' perceptions of diffuse water pollution from agriculture and factors influencing actual (rather than intended) adoption of BMPs are considered alongside changes in water quality. By combining semi-structured in-depth interviews and water quality data from a case study in Wales (UK), we examine how farmers' awareness interacts with psychosocial, economic, agronomic, biophysical factors and adoption of BMPs and whether pesticide concentrations in three catchments in Wales have declined following an awareness-focussed trial aimed at reducing pesticide pollution. The pesticide of focus is MCPA (2-methyl-4-chlorophenoxyacetic acid), a chemical that is extensively used in agriculture to control broad-leaf weeds such as thistles, docks and the common rush (*Juncus effusus*). Due to the high solubility of MCPA and poor absorption to the soil matrix, it is prone to leaching directly into watercourses or via land drains, with a recent study showing that MCPA is frequently detected in watercourses and drinking water sources around the world (Morton et al., 2020), and is therefore not an issue particular to Wales. Although EU standards stipulate that the maximum concentration of any individual pesticide in drinking water remains below one tenth of part per billion (0.1 µg/L), the equivalent of one blade of grass in a 100,000 hay bale (Morton et al., 2020, Welsh Water, 2014), available data shows that between five to 10% of raw drinking water samples from surface water exceed 0.1 µg/L limit for MCPA in England and Wales (Defra, 2012).

Specifically, the study seeks to investigate: 1) whether MCPA concentration in drinking water sources declined significantly following an awareness-focussed intervention, 2) whether the decline in MCPA concentration can be attributed to adoption of BMPs, and 3) whether awareness contributed to adoption of BMPs. While the study is set in the context of pesticide pollution in Wales, it sets out to provide insights into the role of awareness-based interventions towards mitigating the environmental impact of land management practices on diffuse water pollution from agriculture more broadly. To our knowledge, this is the first study exploring the awareness-behaviour-water quality pathway in full, and one of the few in the field of sustainable land management (e.g. Pannell and Zilberman, 2020).

2. MATERIALS AND METHODS

2.1 Case study – Welsh Water's pesticide pollution reduction strategy

Dŵr Cymru Welsh Water (hereafter referred to as Welsh Water) is a water and waste utility operating in Wales (UK) responsible for the supply of high quality drinking water to over three million people, as well as treating and disposing of wastewater. In 2013, through their routine raw water monitoring programme, Welsh Water found that MCPA concentrations were increasing in drinking water sources (Welsh Water, 2014). Welsh Water's root cause analysis and discussions with stakeholders revealed that it was common practice for farmers to boom spray MCPA to tackle common rush (*Juncus effusus*) infestation (Welsh Water, 2014), which is mainly a problem in permanent pastures on poorly drained soils in high rainfall areas, especially after wet winters and/or summers. Although MCPA concentration were too low to pose a risk to those drinking the water, continuous increase in MCPA concentration in raw water may result in breaching EU Drinking Water standards and therefore were a concern for the utility company (Welsh Water, 2014). By safeguarding and improving raw water quality, before it gets to water treatment works can avoid the need for using additional chemicals and energy to ensure drinking water meets regulatory standard. This helps keep bills low for customers and safeguard the environment for generations to come (Welsh Water, 2014).

To address this issue, Welsh Water decided to work with the farming industry and other stakeholders in the land management sector, placing particular emphasis on providing farmers with advice and increasing their awareness of the problem and how to tackle it. Welsh Water argued that without the support of key industry partners, they were less likely to be successful. As a result, key industry partners were engaged at the beginning after their root cause analysis. They worked with them to identify solutions and to create a trial that was 'fit for purpose' for the target audience and to tackle the issue.

In 2015, Welsh Water launched a programme called the weed wiper trial in three targeted catchments (hereafter referred to as 'targeted catchments'); the Teifi, Towy and Wye, where routine water monitoring detected the most significant increase in MCPA concentrations. For example, between 2006 and 2015, 18 raw water samples exceeded the 0.1 ug/L MCPA limit. The location of the targeted and control catchments (Cleddau, Teme and Usk) which had not been in the trial are shown in Figure 1 and their characteristics presented in Table 1. Elevation range, average slope and average daily temperature is similar for all catchments. Mean annual rainfall is ~1600 mm for two of the control and two of the targeted catchments. The Towy has the highest annual rainfall of 1845 mm and the Teme, which is furthest east, the lowest annual rainfall. The Teme catchment is located mainly in England but provides source water to Welsh Water. The dominant bedrock in all catchments is Silurian mudstones and siltstones and the major soils associated with this geology are slowly permeable, seasonally wet, and have a loamy to loamy clay texture. Where Devonian old red sandstone is the dominant geology, the soils are more freely draining with a sandy loam texture. Some of the catchments contain small areas of limestone and/or mafic and felsic lava and tuffs. The main land use in all catchments is pasture that is used predominantly for sheep and beef grazing. One catchment in the targeted group (Wye) and another in the control group (Usk) contain 30% moorland, whereas the other catchments only contain between 6 and 12% moorland. Arable land is below 10% in all catchments except the Teme where it represents 32% of the area. Forestry represents between 5 and 15% of each catchment and is dominated by coniferous plantations.

The weed wiper trial was built on the principle of using a trusted third party organisation (Daltons ATV, who sell all-terrain vehicles such as quad bikes) who have good knowledge of the catchments and the farming community as brokers between Welsh Water, who want to improve water quality, and the farmers. The initiative encouraged farmers to sign up for the free hire of a weed wiper. A weed wiper is a technology where a wick wetted with herbicide is connected to a boom and dragged or rolled across the tops of the taller weed plants (Appendix A). This allows treatment of taller grassland weeds by direct contact, without affecting related but desirable shorter plants in the grassland sward beneath. The technology has the benefit of avoiding spray drift that occurs with other conventional methods (Appendix A) of application that use self-propelled sprayers equipped with long booms. In addition, only glyphosate based products are licenced to be used in the weed wiper. This is because, compared to MCPA that takes 15 – 25 days to break down in water, glyphosate takes considerably less time (three days) (Welsh Water, 2014). There was a total of 292 weed wiper hires between 2015 and 2019 across the three targeted catchments (Table 2).

In addition to Welsh Water attending a wider range of agricultural shows and various workshops to promote the weed wiper, information packs on the use of weed wipers and advice films on safe measures of pesticide application were distributed to farmers within and outside the three-targeted catchments to raise their awareness of BMPs and their benefits, including to water quality. Information regarding the weed wiper trial was advertised to farmers via a wide range of sources from agricultural magazines and newspapers to farm advisors. In addition to these, national regulatory and advisory authorities provided farmers with information on regulation and best pesticide management. Farmers' neighbours was also an important source of information. Between 2015 and 2019, a total of 628 information packs were distributed to farmers (Table 2), of which 444 packs (70.7% of total) were within the targeted catchments. Welsh Water encouraged farmers to use non-chemical techniques, such as topping with a rotary or flail mower before the rush plants produce seed, alongside targeted pesticide use via the weed wiper to achieve a long-term control of rushes. Thus, farmers were encouraged to take up pest management practices that could help tackle all possible sources of pesticide pollution to drinking water sources (see Appendix B for an overview of the practices).

The weed wiper trial is considered by Welsh Water to be a win-win solution that is expected to provide effective control for the farmer and lower risk of pollution to water sources. Welsh Water believed that by allowing farmers to hire the weed wiper and experience first-hand the technology would help farmers appreciate its benefits and raise awareness of the impact of poor pesticide management practices. It was hoped that by 'trying before buying', farmers would be more likely to adopt the weed wiper and other non-chemical techniques that could be used alongside (instead of pesticide) to provide longer-term control of pests and weeds (Welsh Water, 2014). The weed wiper trial is therefore 'advice-centred' and a voluntary approach that focusses on increasing farmers' awareness to stimulate their adoption of BMPs, with the specific intent to reduce pesticide leaching and thus improvement in water quality. This

201 makes the weed wiper trial a suitable case study for exploring the full awareness-behaviour-water quality pathway.

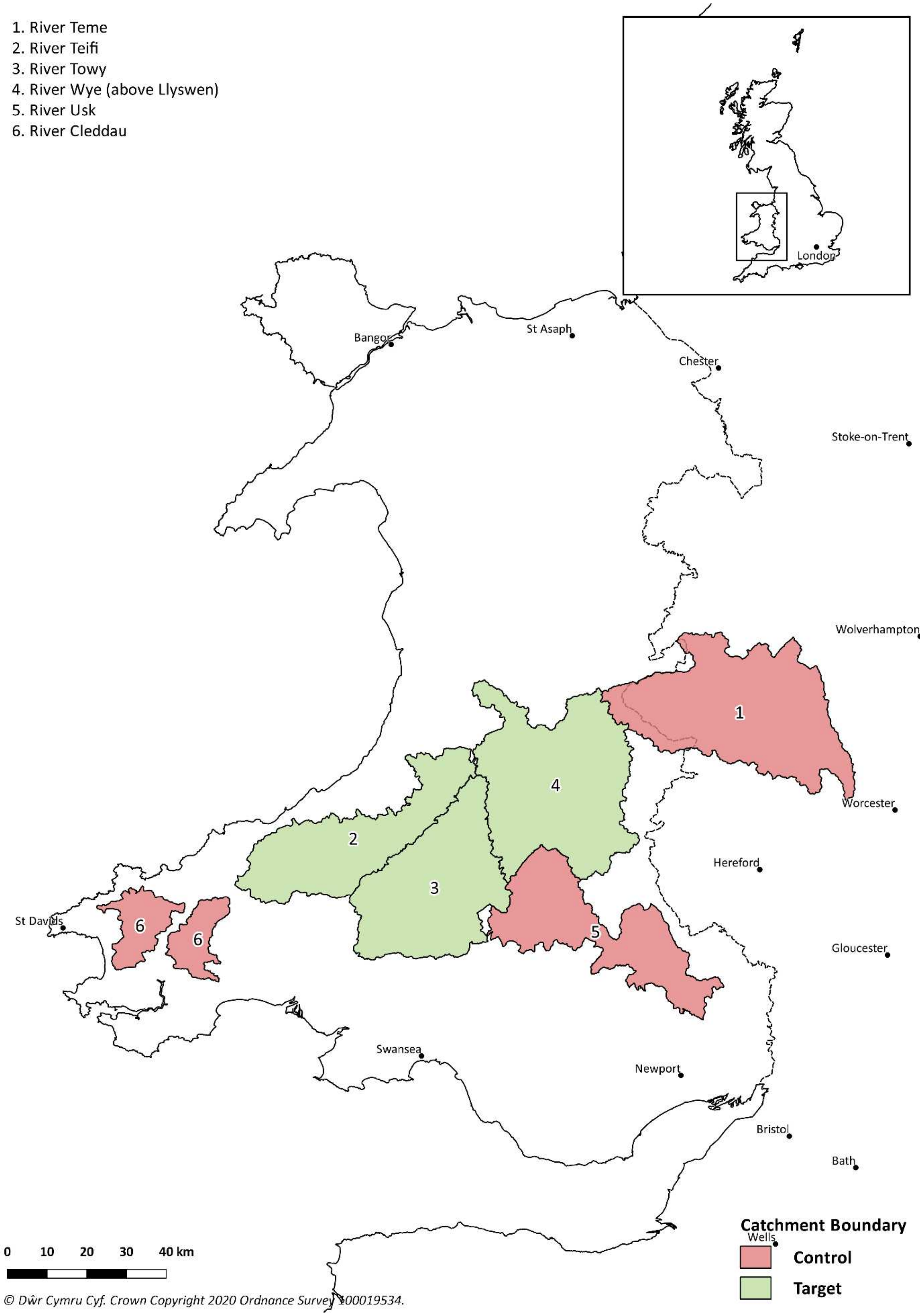

Figure 1: **Location of the six study catchments.**

Table 1: Catchment characteristics

	Wye	**Teifi**	**Towy**	**Teme**	**Usk**	**Cleddau**
Catchment Type	Targeted	Targeted	Targeted	Control	Control	Control
Average (2010-2019) annual rainfall (mm)	1625.78	1631.71	1845.31	989.89	1629.10	1624.14
Average (2010-2019) daily temperature (°C)	8.4	9.3	9.1	9.4	9.0	10.0
Elevation range (metres)	88.6 - 748.5	3.5 -571.7	8.8 - 799.7	25.2-544.5	14.5 - 883.6	3.3 - 535.1
Average slope (degrees)	8.51	6.15	8.64	6.15	8.75	4.45
Land area (km^2) and use (%)						
Land area	569	906	511	1,435	870	394
Pasture	47	81	72	51	49	78
Moors, heath, open land	30	10	12	8	31	6
Arable	7	1	0	32	9	10
Forestry	11	6	15	8	7	5
Others	5	2	0	2	3	1
Soil texture (% of catchment)						
Clay>loam	10.5	1.3	0.3	6.9	0.1	1.2
Loam	15.6	50.1	76.1	27.9	65.0	21.1
Loam>clay	61.8	33.3	0	53.0	29.3	66.3
Sand	0	0	0	0.0	0	4.2
Sand>loam	11.6	15.3	23.5	12.1	5.4	7.1
Others	0.4	0.0	0.2	0.1	0.2	0.0
Bedrock geology (% of catchment)						
Mudstone and Siltstone	82.6	63.1	68.7	91.6	77.0	91.6
Sandstone and Conglomerate Interbedded	16.6	36.9	31.0	3.7	20.1	0
Mudstone, Siltstone, Sandstone, Coal, Ironstone & Ferricrete	0	0	0	1.3	1.3	0
Limestone with subordinate sandstone and argillaceous rocks	0	0	0.3	2.7	1.5	0
Felsic, Mafic Lava and Tuff	0.8	0	0	0.7	0	8.4

Notes: Under Land use, "Other" includes e.g. urban, wetland, mines and industrial; under soil texture, "Others" include Loam>clay>sand, Sand>loam>clay, and Loam>sand>clay. Information on soil texture refers to that of the topsoil (5-20cm). Data on catchments were obtained from the following open sources: Meteorology Office (Historical Weather 2010-2020); Corine Land Cover (2018) European Environment Agency; British Geological Survey (Bedrock Geology 625k and Soil-Parent Material Model) (Russell, 2011).

Table 2: Summary of number of information packs distributed and weed wiper hires within and outside the targeted catchments

Year	Catchment: Teifi	Wye	Towy	Outside targeted catchments	Total
			Information packs distributed		
2015	79	57	0	55	191
2016	45	34	0	32	111
2017	37	36	44	44	161
2018	28	18	21	30	107
2019	15	12	18	23	68
Total	**204**	**157**	**83**	**184**	**628**
			Weed wiper hires		
2015	45	18	-	-	63
2016	41	22	-	-	63
2017	26	25	22	-	73
2018	18	16	13		47
2019	22	13	11		46
Total	**152**	**94**	**46**	**-**	**292**

Note: 1) In 2015 and 2016, farmers in Towy did not receive any packs and there were no hires as this catchment was only included in the scheme in 2017.

2.2 Methods

To determine whether Welsh Water's awareness focussed approach has resulted in a decline in MCPA concetrations in drinking water sources, and whether this can be related to an increased adoption of BMPs, we used two strands of data: water quality data (i.e., MCPA concentration) from Welsh Water's routine raw water programme, and qualitative data gathered via semi-structured in-depth interviews with farmers and other relevant regional stakeholders. This interdisciplinary approach aims at overcoming the limitations of partial mono-disciplinary methodologies unsuitable to addressing the complexity of 'wicked problems' such as diffuse water pollution from agriculture (Stoate et al., 2019; Termeer and Dewulf, 2019; Duckett et al., 2016; Martin-Ortega et al., 2015; Raymond et al., 2010).

2.2.1. Analysis of water quality changes

Welsh Water's monitoring assesses raw water quality based on a number of parameters, including MCPA concentration (measured in µg/L). Welsh Water provided MCPA data from 2006 to 2019 for all water treatment works (WTW) in the three targeted catchments (Towy, Tefi and Wye). In addition, they also provided MCPA data for all WTW within three control catchments (Cleddau, Teme and Usk) that had not been in the trial but were in a similar location (Figure 1) and of similar characteristics to the targeted catchments (Table 1). An overview of the water quality data provided by Welsh Water for each catchment is given in Table 3.For the Teifi and the Wye catchments, April 2015 served as the separation point between pre and post intervention, while April 2017 was used as the separation point for the Towy catchment; as this is when it became part of the weed wiper trial. For all the control catchments, April 2015 served as the separation point.

We explored the potential effects of the weed wiper trial on MCPA concentrations using factorial analysis of variance (ANOVA). Factorial designs are effective for examining treatment variations and to investigate interaction effects. Factorial designs enable us to effectively combine these data into one and examine the main and interaction effects of different variables. The Type III sum of squares estimation option was selected. This option allows us to evaluate the effect of each variable after other factors have been accounted for. Using this option has an advantage over estimation options such as Type I as the Type III option is not sample size dependent. The factorial ANOVA was ran using SPSS IBM version 23. In the model, MCPA concentration was classified as the dependent variable while condition (control or targeted), time (pre or post intervention) and catchment were included as independent categorical factors (Table 3). This allowed us to test whether there were differences in observed MCPA concentrations, whether such differences were statistically significant as well as the interaction between variables.

Table 3: Distribution of water samples provided by Welsh Water

Variable	Groups	Code	Number of water samples	Percentage
Condition	Control (C)	1	1339	43.5
	Targeted (T)	2	1738	56.5
Time	Pre intervention	1	1420	46.1
	Post Intervention	2	1657	53.9
Catchment	T-Towy	1	507	16.5
	T-Teifi	2	467	15.2
	T- Wye	3	764	24.8
	C Cleddau	4	488	15.9
	C-Teme	5	395	12.8
	C-Usk	6	456	14.8
Total	**-**	**-**	3077	-

2.2.3 Semi-structured in-depth interviews

Semi-structured interviews were conducted with sixteen farmers and six institutional stakeholders between July 2019 and February 2020 (see Appendix C for the interview scripts). In-depth interviews lasted up to about one hour and focussed on understanding interviewees perceptions on: 1) whether water quality outcomes can be attributed to land management practices, 2) whether and how awareness has contributed to adoption of BMPs, and 3) other factors that could influence land management practices and water quality outcomes. Relying on different stakeholders' perceptions enables us to gather different 'knowledges' from policymakers and local stakeholders as this could offer useful insights into understanding the complex factors influencing behaviours and diffuse water pollution from agriculture (Morgan, 2014). This helps to bridge the gap between science and society, elicit information that would otherwise be missed and help us to capture a more "ground-truthed" picture of reality (Tress et al., 2005). The value of qualitative data collected through the interviews lies in the deep insights it provides, not the 'number of persons explaining what', as the goal is not to generalise but to 'make sense' of the phenomenon that is under investigation (Onwuegbuzie and Leech, 2005, Rossman and Wilson, 1985). Consequently, as with any other qualitative social science study, sampling, analysis and study outcomes are not necessarily (motivated by and/or) dependent on sample size.

Farmers were our primary stakeholders as they were the ones whose knowledge and behaviours were expected to change through the weed wiper trial. At the same time, institutional stakeholders (e.g., representatives of farmer unions, local environmental organisations, and water utility) play important regulatory and advisory roles in land and water management and their views are therefore useful to further our understanding of the context and provide further insights (see Table 4a for the justification for their inclusion in this study and 4b for the characteristics of participating farmers). Of the sixteen farmers who participated in the interviews, eight had participated in the weed wiper trial while the remaining eight had not participated in it (although they had knowledge of the weed wiper trial and some had received information regarding the BMPs promoted). Implications of the views of these different farmers are considered in the discussion. Interviewees were predominantly livestock farmers (Table 4b).

Interviewees were recruited using a combination of connections with local partners (Welsh Water and Farming Connect, an advisory service that provides independent advice to farming businesses), face-to-face contact at the Royal Agricultural Welsh Show in Builth Wells in 2019 and snowballing, where some interview participants referred us to other stakeholders. Ten of the farmers and stakeholder interviews were conducted through phone calls while twelve were face-to-face at the Royal Welsh Show (Tables 4a and 4b describe interview participants). To enhance the credibility and validity of the data, we applied descriptive respondent validation (Byrne, 2001). This involved summarising key aspects of the interview and asking participants whether they represented their views or not. This was implemented either during or after the interview session. We applied the intelligent verbatim transcription method to transcribe the interviews (Golota, 2018).

Interviews were analysed using a grounded theory approach (Strauss and Corbin, 1998) to first perform an open coding of emergent themes, using NVIVO version 11. This was done by carefully reading through the interview transcripts and identifying recurring topics that emerged from the texts rather than on the basis of pre-defined topics. We identified statements that provided plausible explanations to the water quality results. Through an iterative process, 49 codes were generated (Appendix D), however, only 31 codes focused on the following topics: factors influencing awareness, factors influencing uptake of the weed wiper (and other BMPs), and factors that influence water quality. The other codes focussed on the role of agri-environment schemes, barriers to participation in agr-environment schemes as well as recommendations to improve awareness and uptake of BMPs (including the weed wiper, Appendix D).

All 31 codes were categorized under the three relevant topics. Next, using axial coding, we compared codes to establish similarities and differences and categorised them to identify the most dominant themes being discussed. In the case of factors influencing uptake of the weed wiper, the codes were further categorised under four main themes based on whether it is a resource issue, psychosocial issue, agronomic or geographical (Appendix D). To establish validity of our results, the procedure was reviewed in an iterative process until the results became stable. Results of the in-depth interviews are presented in Section 3 using a manifest style (Bengtsson, 2016), where key findings are presented and reference made to interviewees' statements.

Table 4a: List of stakeholders and justification for their inclusion in the interviews

#	Stakeholder	Justification for Inclusion
1	Farmers	Frontlines of land use and their farm activities may impact river water quality. Also, they are the ones that the weed wiper trial aimed to change their awareness and behaviours (see description of the farmers in Table 5b).
2	Welsh Water	Responsible for the supply of high quality drinking water to over three million people in Wales. They implemented the weed wiper trial.
3	Farming Connect	It is a knowledge transfer, innovation and advisory service for farming and forestry businesses in Wales funded through Welsh Government Rural Communities – Rural Development Plan 2014-2020.
4	National Farmers' Union	Representation body for agriculture and horticulture in England and Wales. They campaign for a stable and sustainable future for British farmers, including encouraging their members (farmers) to engage in best farming practices.
5	Natural Resources Wales	Advise and regulate the activities of farmers including practices that affect water resources.
6	Daltons ATV	Welsh Water's trusted intermediary and delivered the weed wipers to farmers. They also provide advice on best pesticide application techniques and how to use the weed wiper.
7	Lantra	Provide pesticide application training to farmers in Wales.

Table 4b: Profile of the farmer participants in-depth interviews

#	ID	Participated in weed wiper trial	Weed wiper use	Catchment	Tenancy	Farm type
1	P1	No	No*	Cleddau	Owner occupier	Arable
2	P2	No	No	Teifi**	Owner occupier	Livestock
3	P6	No	Yes	Towy**	Owner occupier	Livestock
4	P8	No	No	Usk	Rent (Tenant)	Livestock
5	P10	No	No	Severn	Rent (Tenant)	Livestock
6	P12	No	Yes	Teifi**	Owner occupier	Livestock
7	P13	No	No*	Teifi**	Rent (Tenant)*	Livestock
8	P14	No	Yes	-------	Rent (Tenant)*	Livestock
9	P15	Yes	No*	Towy**	Owner occupier	Livestock
10	P16	Yes	No*	Towy**	Owner occupier	Livestock
11	P17	Yes	No*	Teifi**	Owner occupier	Livestock
12	P18	Yes	No*	------	Owner occupier	Livestock
13	P19	Yes	Yes	Wye**	Owner occupier	Livestock
14	P20	Yes	Yes	Wye**	Owner occupier	Livestock
15	P21	Yes	No*	Teifi**	Owner occupier	Livestock
16	P22	Yes	No*	----	Owner occupier	Livestock

No* = farmer not using the weed wiper at the time of the interview but has used it in the past; * in tenancy types suggests that the farmer owns some portion of the land, with others being rented; ** targeted catchments; ------ = information not available.

3. RESULTS

3.1 Has MCPA concentration in drinking water sources declined significantly?

Between 2006 and 2019, 98.3% of all raw water samples at the WTW were below the 0.1 µg/L drinking water limit for MCPA in England and Wales. Concentrations exceeded 0.1 µg/L on 47 occasions; 26 in targeted catchments and 21 in control catchments. A seasonal pattern in concentrations was detected, with exceedances mostly evident during May, June, and July and again in September and October. This coincides with periods when MCPA is commonly applied to grassland for the control of ragwort, rush and thistle (Welsh Water, 2014).

Table 5 shows that before the weed wiper trial, the mean MCPA concentration in the targeted catchments (0.0137 µg/L) was higher than in the control catchments (0.0091 µg/L). Further results show that MCPA concentrations for both targeted and control catchments declined after the implementation of the weed wiper trial (see Table 5). However, the decline was significantly larger ($F(1) = 6.551$, $p<0.05$, n= 3077, Partial eta-squared (ηp^2) = 0.002) for the targeted catchments (mean = 45.2%) compared to the control catchments (mean = 10.9%). It was further revealed that the MCPA response post intervention varied between catchments: ($F(5) = 6.249$, $p < 0.001$, n= 3077), $\eta p^2 = 0.01$). Figure 2 shows that a substantial decline (between 3.1 and 55%) in MCPA concentration occurred in all three targeted catchments (with the highest decline observed in the Teifi catchment). In contrast, only one of the control catchments (the Teme) recorded a decline in MCPA concentration (mean % decline = 31.6%) while the Usk and the Cleddau catchments recorded an increase in MCPA concentration post 2015 (mean % increase = 20.2% and 31.6% respectively). Additional results indicate evidence of an interaction effect between the weed wiper trial and catchments: ($F(5) = 1.997$, $p < 0.1$, n= 3077), $\eta p^2 =$ 0.003), suggesting that the impact of the weed wiper trial on MCPA concentration depends on location or catchment characteristics.

Table 5: Mean concentration of MPCA for targeted and control catchments pre- and post-intervention

Period	Condition	Mean	Std. Deviation	Number of water samples
Pre-intervention	Targeted	0.0182	0.0968	783
	Control	0.0097	0.0285	637
Post-intervention	Targeted	0.0100	0.0231	955
	Control	0.0086	0.0181	702
Total	Targeted	0.0137	0.0673	1738
	Control	0.0091	0.0236	1339

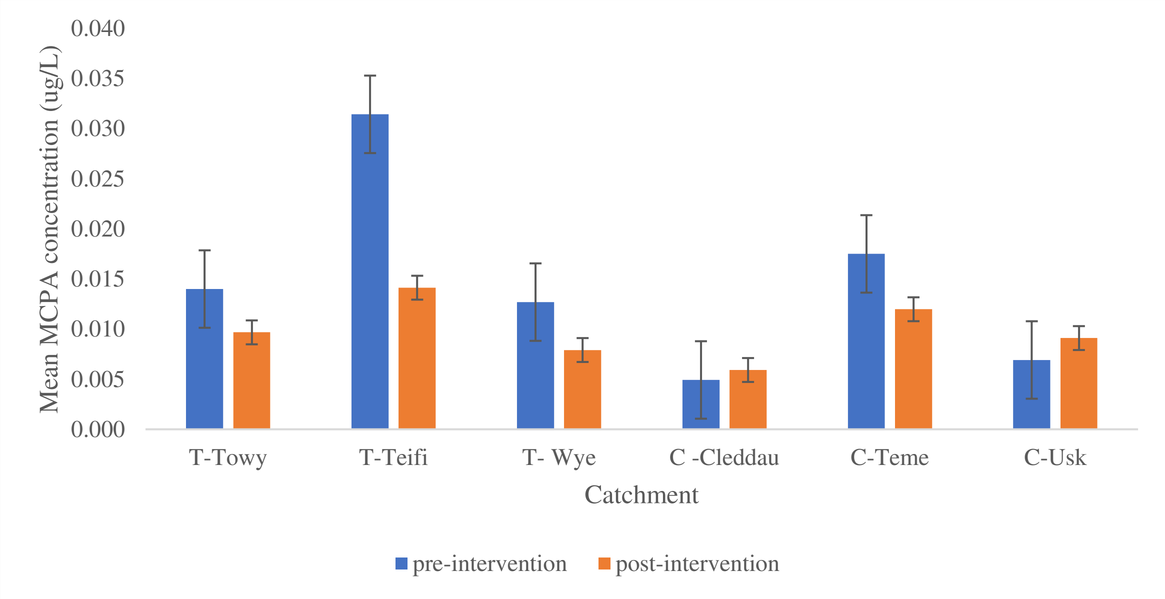

Figure 2: Average MCPA concentration in all catchments, pre and postintervention.
Notes: T. = Targeted catchments; C. = Control catchments

3.2. Has awareness and the adoption of BMPs contributed to a decline in MCPA concentration?

Results of the water quality analysis show that MCPA concentrations declined substantially in the catchments where the weed wiper trial had been carried out (mean = 45.2%) compared to the control catchments (mean = 10.9%). The interviews allowed us explore the role that awareness and behavioural change (through the adoption of BMPs), might have had on this effect. Statements from some farmers clearly showed an effect of the weed wiper trial and the adoption of more responsible pesticide practices beyond the trial. For instance, Participant 19 noted, "*I now only use a weed wiper and several of my neighbours have also bought their own weed wiper using grants*". Another added *"Yeah, I'm being very sort of responsible... The weed wiper only targets the weed so you are going to have less risk of any runoff or anything getting into watercourses. I think pretty much we're operating at a high standard. A lot of the businesses using chemicals and pesticides are operating at very high standards in terms of technology and precision. I think people have probably got more aware, rightly so*" (Participant 3).

Farmers believed that their practices (since their involvement in the trial and use of the information packs) contribute to reducing pesticide pollution because a lower amount of spray is used and it is only applied to the targeted weeds. This is reinforced by the positive relationship between number of weed wiper hires and percentage decline in MCPA concentration as catchments with more hires recorded the highest net reductions ($p < 0.05$, $R^2 = 0.60$, N = 6, see Figure 3). This is also backed up by the fact that catchments where more information packs had been distributed also recorded higher declines in MCPA concentration ($p<0.05$, $R^2 = 0.59$, N = 6, see Figure 4), although it should be noted that most weed wiper hires occured in the smallest target catchment; the Teifi which is 35% smaller than the Wye (see Tables 2 and 3).

From the interviews, we established that indeed, awareness – promoted through the weed wiper trial – seems to have contributed to uptake of the weed wiper, although it should be noted that weed wiper hires appear to have declined in the Teifi and Wye in 2018 and 2019 compared to the period 2015-2018 (Table 2). Statements on how applying chemicals near watercourses, failing to follow calibration standards for chemical applications, and applying excess chemicals particularly in wet conditions could result in on-farm pesticide pollution reflect farmers' awareness of the factors causing pesticide pollution. As Participant 14 noted "*….when you have a thunderstorm, like we did last night, heavy rain came in a matter of minutes from a dry condition to that. They could have just sprayed that ground with so much chemicals per acre, okay? All of a sudden comes down the rain, the surface wash off, goes into ditches, ends up in a water stream. That's pollution. Because the conditions were wrong at that specific moment. And there was heavily used chemicals… Or if there's a chemical spillage, you know, I mean, if somebody left the water running in a tank when they were filling, and they had already added the chemicals and ouch, over the top it came down the drain, and it found a ditch which then went to a river, then you'd have that. They are very minor ones and human error".* This clearly shows awareness, although responsibility is deflected mainly to weather conditions and human error.

On how awareness contributes to adoption, one farmer pointed out that the main reason they were engaged in best practice (including the use of the weed wiper) was because they were aware of the impacts of their practices on water quality and how best to mitigate pesticide pollution: "*…knowing what to do. We know there are issues of water supply so we're very conscious of where our water supply is on the farm and where our neighbouring water supply is, so we're not spraying near them as well. And then we'll watch the wind speed so there's no spray going into the watercourse as well"* (Participant 12). Another farmer, highlighting the role of the information pack said that "*the information pack was good and helped me…without this trial I wouldn't have tried out the [*weed wiper*] machine for myself and I'd probably still be using a knapsack*" (Participant 20). Other farmers indicated that "*the ability to try out one of the weed wipers for free before committing to buying one was the best way of me improving my knowledge and understanding of pesticide management. Without hiring one for free I would probably still be using a boom sprayer…The machine worked well for me, that's why I went to buy my own. I now only use a weed wiper*" (Participant 19). This view further points to the role of experiential learning, as a first-hand experience of the use of the weed wiper gave him/her the opportunity to appreciate the benefits of using the technology, which in turn contributed to his decision to acquire it.

All this evidence suggests that awareness promoted through the weed wiper trial played a crucial role in the adoption of the weed wiper. Further evidence shows that since the peak in MCPA concentration in 2014, concentrations have declined in both control and targeted catchments, but a substantial reduction was observed in the targeted catchments to such an extent that in 2019 mean MCPA concentration was lower for the targeted than control catchments for first time since 2010 (see Figure 5).

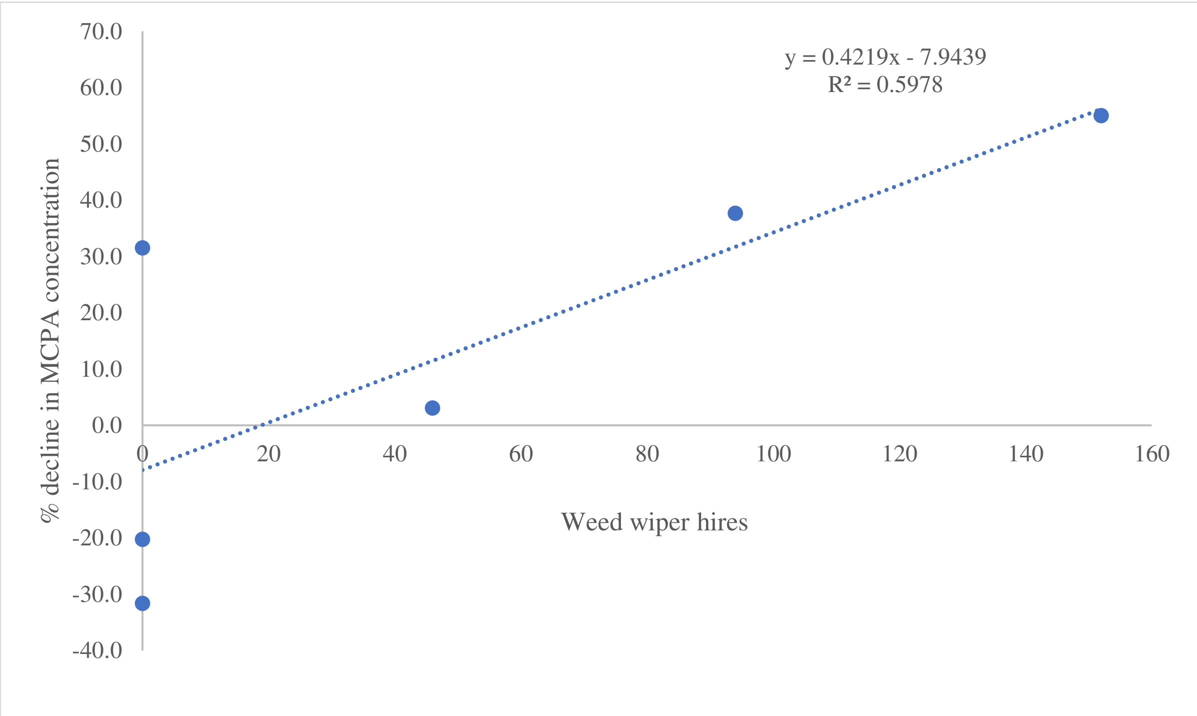

Figure 3: Relationship between weep wiper hires and % decline in MCPA concentration

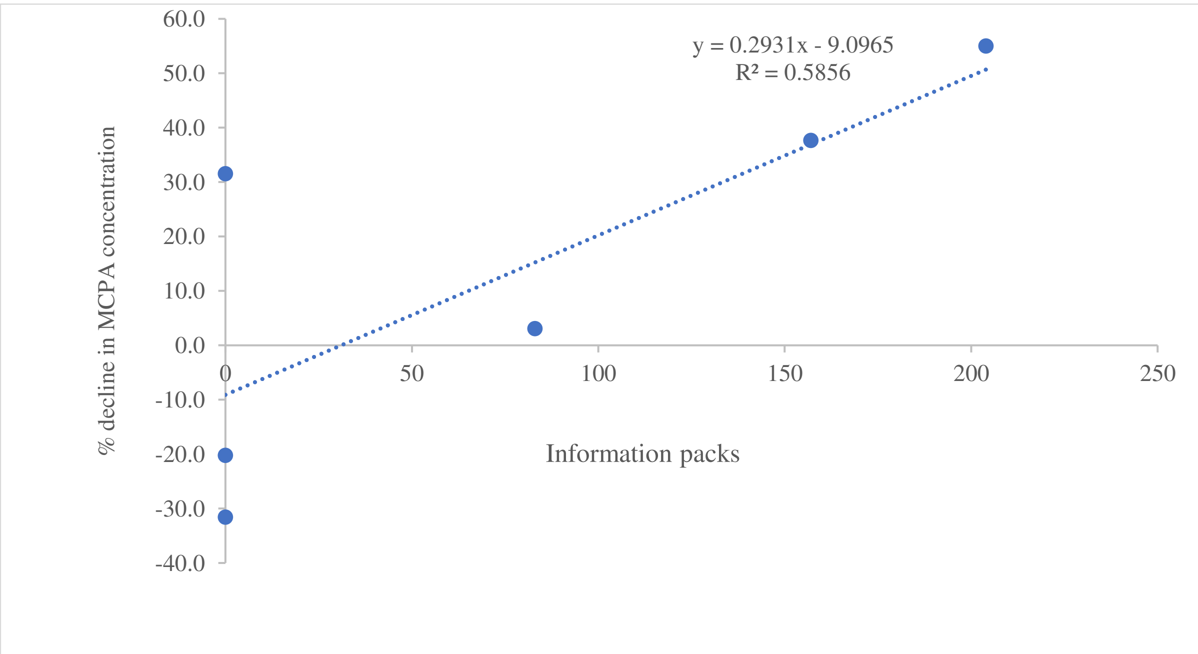

Figure 4: Relationship between number of information packs distributed in each catchment and % decline in MCPA concentration

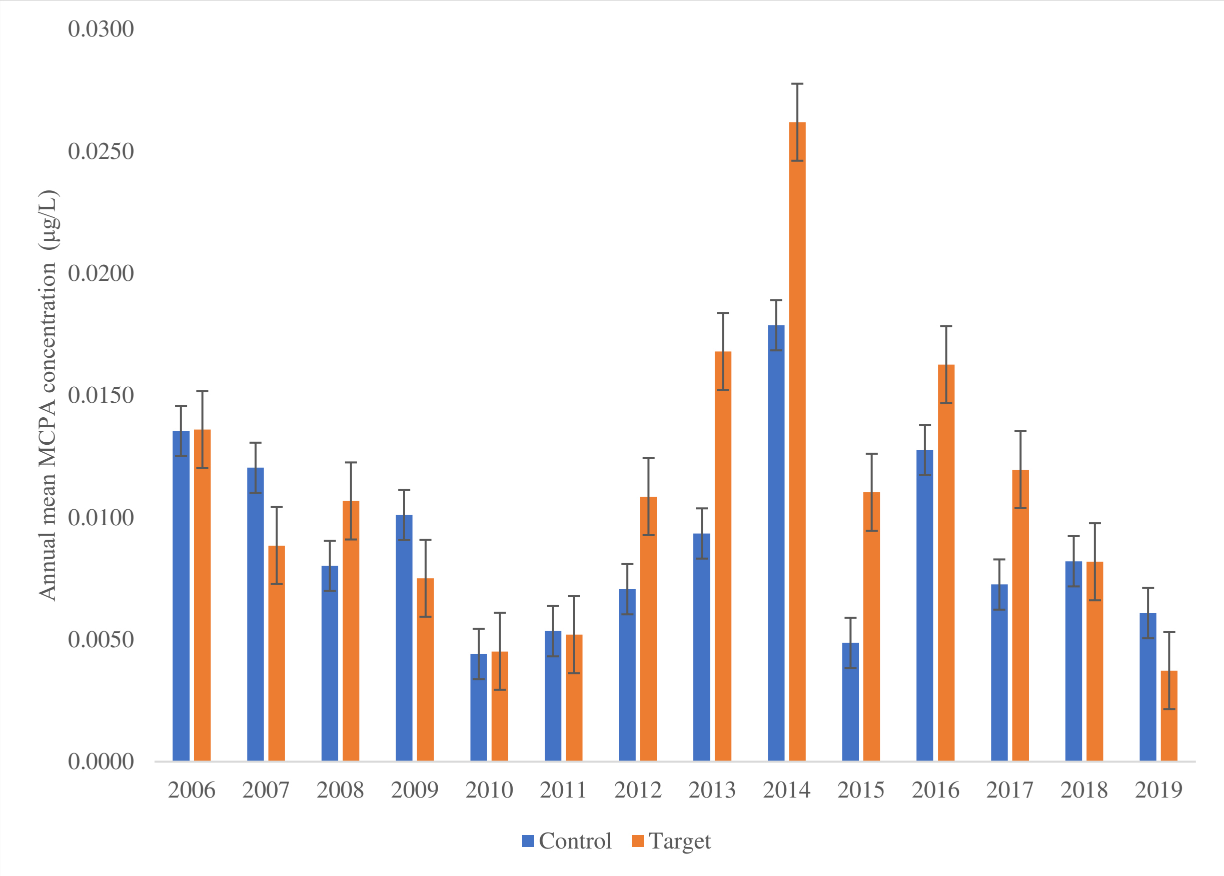

Figure 5: Annual mean MCPA concentration for both targeted and control catchments

3.3. Other factors contributing to adoption of BMPs

Awareness was not the only factor contributing to behavioural changes as this study identified other factors that contributed to the adoption of the weed wiper. For instance, we found that attributes of weed wiper technology played a very crucial role in its adoption as one farmer noted that "*this is probably one of the simplest machines that you could use. And you know, with the least amount of chemical use*" (Participant 14). Almost all farmers indicated that they found it "extremely easy to hire the weed wiper" and "very easy to use". This shows that ease of use of the weed wiper, the financial benefits associated with reduced input cost, and the fact that it does not require any substantial changes in farm operations are important drivers of uptake. These benefits of the weed wiper were disseminated among farmers through their neighbours, farm trials and other channels. Indeed, access to and assimilation of knowledge coupled with an improved understanding of the negative impacts poor pesticide management practices and of the benefits of best management practices improves environmental consciousness, boosts farmers' self-efficacy and may result in favourable environmental attitudes thus contributing to uptake of such practices.

Other important drivers of adoption of the weed wiper include psychosocial factors, such as social pressure, information source and trust, farmers' desire to protect their reputation, regulations, and beliefs towards old and new practices. Regarding social pressure, we found that neighbours' opinions have a role in encouraging or discouraging farmers in using the weed wiper. Similarly, perceived pressure from landlords was influential in farmers' decision to acquire the weed wiper. As Participant 14 noted "*the weed wiper was more acceptable with our landlords so we upgraded our old weed wiper and had a new one. Our landlords obviously wouldn't want us putting chemicals anywhere near water source*".

We also found that some farmers would not want to be associated with pollution problems and this desire to protect their reputation was influential in their decision to use the weed wiper. As participant 7 stated, *"it has to be in their [the farmers'] interests as well. I think because some farmers would want to make sure that they aren't kind of associated with any issues of pollution, maybe, you know, such as water runoff or similar, that would be in their interest".* The regulatory context, in this case the need to acquire a pesticide application license prior to the purchase of the weed wiper, was a hindrance to the uptake of the weed wiper. In responding to why some farmers may not be able to use the weed wiper, Participant 4 said *"...how difficult it is to take the licences before using the weed wiper and the use of that chemical, because it's a really strong chemical, Round up Glyphosate*", while Participant 8 noted that "*we haven't got our pesticide application licence and that's going to inhibit us from using the weed wiper*".

Some farmers are less likely to change practices because they feel uncomfortable about dealing with a new technology. They feel comfortable keeping practices that have been passed on from generations. This is illustrated in the account of participant 14 who indicated that one reason some farmers are not using the weed wiper is "*probably because they feel uncomfortable about something they've never used before. Maybe the older generation who don't like machinery and say, Oh, I can't do that. Because I've never done it before. A younger person will be more adaptable to things...It's only a generation thing reall*y".

Interview results also revealed that time and availability of resources such as technology (the weed wiper), complementary equipment (e.g., quad bike), the required herbicide (Glyphosate), and time were key factors driving the decision to use the weed wiper. These resources are all needed to be able to use the weed wiper, and are therefore conditional of its adoption. As Participant 1 noted, *"the other [barrier] would be availability of the technology such that farmers tend to be very busy now and some don't plan very well. And suddenly, I can do it today, well, the weed wiper is not available*". Participant 2 added that "*the main reason I didn't do it [participate in the trial] is I don't have a quad bike. I need something to pull it with*".

We found that agronomic factors such as the type of weed and extent of weed problem, type of crop, land use and farm size may also determine whether a farmer adopts the weed wiper, and sustains its use on his/her farm in the future . For example, when asked if they would use the weed wiper in future, one farmer responded "*…Yes, possibly! But the main weed that I control is dock. And the best way to control a dock is when it's small. So if you leave it until it's big enough to be controlled by a weed wiper, it's too big to kill it. You're supposed to kill docks when it's just starting to grow, in the spring. But you can't use a weed wiper for that*" (Participant 2). In relation to farm size, a participant of the weed wiper trial who had not pursued using the technology afterwards indicated that "*I have thought about buying more land and expanding my farm, if I did this, I would consider hiring the weed wiper. I'd consider using one in the future if I bought more land with more rush to treat*" (Participant 17). The fact that this farmer mentions additional land "with more rush to treat" suggests that the extent of weed problem may interact with farm size to influence the decision to adopt the weed wiper.

Other crucial agronomic factors include the need to not kill off the clover, keep healthy soil, and to apply a fast and easy weed management technique. Beyond these, perceived financial benefits were identified as a motivation for adoption while cost was a potential barrier. Participant 8 explaining why they were unable to use the weed wiper stated that "*...because there's no plenty of money for other things. Because we haven't got our pesticide application licence, we'd probably need a contractor to do it and I don't know how costly that is. So it's been a question of priorities and we got other things to do. When you got X amount to spend, you know, that might not be your concern. Maybe it's wrong, but it's a bit lower priority. If we had unlimited cash, we could do something different*". A participant of the weed wiper trial also indicated that "*we're not able to use the weed wiper [again] as we cannot afford to buy our own machine. If we were able to hire one for free again we definitely would as it was amazing*" (Participant 22). Financial constraint explains in part, why some farmers are unable to continue to use the weed wiper. While these farmers highlighted cost as a barrier, another farmer from the Wye catchment who participated in the weed wiper trial indicated that "*the low cost of using a weed wiper in comparison to other methods is the main driver, along with the good results. I can't think of anything that would prevent me from using one*" (Participant 20). This suggests that financial considerations can act both as a driver and a barrier depending on the farmers' circumstances, thus highlighting a potential moderating role of situational factors.

Season and weather conditions appear to influence weed management practices. Some farmers explained that wet seasons pose major challenges to them and this may determine the extent to which they are able to follow best practice. One farmer explained that, "*...season does have impact because our land is quite wet. So in a wet year, we struggle to get on with the tractor and the topper to do the topping. So some years we wouldn't touch because we can't basically get on there to top them. If we can't top them, they grow too strong...And then it's no good spraying them because they're too big; you* *need to spray them when they're small. So yeah, the season is important. Generally, in a wet year, we wouldn't do so much weed control. But in a dry year like this, we've got more opportunities to top the weeds*" (Participant 13, Farmer). Similarly, locational characteristics seem to influence practices as some farmers mentioned that very steep landscapes makes it difficult to in move spraying machines.

Just as the awareness-behaviour link is influenced by other factors, the relationship between adoption of BMPs and MCPA concentration is influenced by contextual factors. From the interviews, we identified other factors that could influence MCPA concentration. For instance, some interview participants indicated that MCPA concentration depends on the number of farmers implementing the recommended practices within a catchment, how long the practice has been implemented, external interventions (e.g., work from other companies within the catchment) and differences in land uses. In fact, Participant 9 suggested that the declining MCPA concentration recorded in the Teme, one of the control catchments, might be due to a different land use, which in turn contributes to different pesticides being applied in the catchment: "*…if you looked at other grassland pesticides, not just MCPA, that catchment [the Teme] will be really high. Because that's quite a heavy arable land area so they could be using more grassland herbicides, not necessarily MCPA*".

4. DISCUSSION

Results show that the mean MCPA concentration declined significantly in all the targeted catchments post the weed wiper trial (Figure 2); decreasing in all three targeted catchments by on average 45.2%%. In contrast, mean MCPA concentration displayed a variety of response in the control catchments; one declined and two increased (Figure 2). The largest decline in MCPA (55%) was observed in the Teifi catchment (Figure 3) where almost double the weed wiper hires occurred over the last five years than in the Upper Wye (152 and 94, respectively) and where most information packs were distributed (Table 2). In addition, the Teifi is the smallest of the target catchment. Therefore, these two factors (small catchment size and high uptake of weed wiper hires) is likely to account for why the largest decline in MCPA has been observed in the Teifi catchment. This is strong evidence that the weed wiper trial has resulted in the adoption of the weed wiper and that this is likely to account for the decline in MCPA concentrations in drinking water sources. By wiping pesticides directly onto the weeds, the weed wiper reduces spray drift and uses less chemicals, thereby reducing risk of runoff. This finding supports results of previous studies on measures that reduce spray drift to pesticide pollution (e.g., de Snoo and de Wit, 1998, see also, Kay et al., 2009 for a review), as they found that such BMPs could be highly efficient in reducing pesticide pollution, although none of these earlier studies focussed specifically on MCPA. Even more importantly, all weed wipers were only licensed for use with Glyphosate, thus the amount of MCPA being applied in the targeted catchments declined with increasing hires. As found by Baker et al. (1995), product substitution can potentially contribute to a reduction in pesticide pollution in surface waters although this depends on the efficacy of the new product (Reichenberger et al., 2007), which seems to have been the case here.

Another key factor that contributes to the success of the weed wiper trial in improving water quality relates to the type of pollutant being targeted. Due to its high solubility and poor adsorption to the soil matrix, MCPA is susceptible to rapid transport to surface water and thus it takes a relatively short timeframe to see the impact of increasing weed wiper use on water quality. In contrast, research on phosphorus has shown that it may take many years to realise the impacts of BMPs on water quality due to the build-up and retention of phosphorus in soils and river sediments (Stålnacke et al., 2003, Grimvall et al., 2000). In the case of nitrate, it can take several decades to see changes in surface water concentrations in catchments dominated by groundwater (e.g., Burt et al., 2011). This is because nitrate usually moves slowly through the aquifer. Therefore, the nature of the pollutant and catchment characteristics are important in controlling the time lag observed between intervention and improvement in water quality and the difference observed between the results of the weed wiper trial in this case study and those observed in other studies (e.g., Kroon et al., 2016; Meals et al., 2010). In the case of this research, the role of these other factors is reinforced by the small effect size (Partial eta-squared (ηp^2) = 0.002) obtained for the effects of the weed wiper trial on MCPA concentration (based on Cohen's indicators where small, medium, and large effects are reflected in values up to 0.10, 0.25, and 0.40, respectively (Cohen, 1973, 2013)). This raises an important question about what techniques might be needed to help farmers appreciate how water quality is responding to changes in land management practices for pollutants that take longer to respond to BMPs. Especially as slower changes in water quality may lead to farmers being less motivated to adopt BMPs. Vilas et al. (2020) have shown that real-time reporting of water quality data has the potential to tackle this problem, ultimately enhancing likelihood of BMP adoption among farmers.

Results from the in-depth interviews show that farmers had a good understanding of both pesticide pollution and BMPs. Farmers' awareness of pesticide pollution and BMPs could be attributed in part to the weed wiper trial. Moreover, Welsh Water used different information dissemination channels to reach many farmers including those who did not participate in the trial (29.3% of information packs were distributed among farmers outside the targeted catchments). Past studies have shown that dissemination mechanisms involving multiple channels are effective in reaching out to a wide audience and improving farmers' awareness particularly where the message is personally relevant (Dwyer et al., 2007). As observed in this study, even farmers who did not participate in the trial reported that they received information on pesticide pollution, the weed wiper and other BMPs from different sources including their neighbours (see section 2.1). For those that participated, they indicated how the information packs were useful in improving their understanding of safe measures of pesticide management.

While advice (via the information packs) seems to have improved farmers' awareness, experiential learning seem to have played a crucial role in further advancing farmers' understanding and contributed to uptake of BMPs (specifically the weed wiper). Experiential learning refers to learning-by-doing, and has been shown to be an effective mechanism for improving farmers' knowledge and uptake of BMPs (Suškevičs et al., 2019; Drangert et al., 2017). As some farmers noted, having the opportunity to use the weed wiper during the trial was critical in improving their knowledge of best pesticide management, and helped them to appreciate the benefits of adopting BMPs. Without this first-hand experience, they were more likely to be still using their old practices of weed management (e.g., knapsack and/or boom spraying). This finding consolidates the evidence that while information provision is important, farmers' are more likely to take up BMPs when given the opportunity to 'practise what they are taught' (Suškevičs et al., 2019, Okumah et al., 2019b, Dwyer et al., 2007). This can be linked to the reflective process that individuals go through when they engage in an activity, thus offering them the opportunity to learn from active experimentation, subsequently enhancing their chances of adoption (Kolb, 1984). In this case, adoption could be linked to two issues: first, a better understanding of the benefits (Kolb, 1984) and thus, the motivation to do it, and second, improved self-efficacy i.e., the confidence that they would be able to engage in the practice and do it well (Bandura, 1997). Consistent with these results, previous studies have demonstrated that farmers with a profound understanding of environmental pollution and BMPs are more likely to be environmentally concerned, have higher self-efficacy (Sewell et al., 2017) and are more likely to take up BMPs (Floress et al., 2017).

The extensive dissemination of information among farmers means that some farmers who did not participate in the trial had knowledge of the practices being promoted, with some of them acquiring and using a weed wiper (although the vast majority of information packs were distributed in the targeted catchments). This is not surprising, since farming communities do not operate in 'closed bubbles' and some permeability of information is to be expected. Moreover, other existing advisory services implies that farmers who did not participate in the scheme still had knowledge of BMPs from other sources. As some farmers and institutional interviewees indicated, there are ongoing efforts to raise awareness of BMPs to reduce diffuse water pollution from agriculture and farmers are increasingly taking advantage of the advice being provided. While it would have been interesting to point out potential differences in levels of awareness and behavioural changes between farmers who participated in the trial and those who did not, this was not possible with the available data. However, the results of this study still show that awareness does play a key role in explaining behavioural changes and improvements in water quality.

We also found that attributes of the weed wiper technology influenced its uptake. As Pannell and Zilberman (2020) have indicated, the advantages that a technology has over competing alternatives plays a key role in farmers' decisions and adoption behaviour. In this study, we found that some of the reasons for the adoption of the weed wiper was because there was less hassle to hire or acquire the machine, it was easy to operate or use, it yielded financial benefits due to reduced input cost and did not require significant changes in farm operations or management practices. This supports the growing evidence on the moderating role of contextual factors such as cost of compliance and 'goodness of fit' of practice on the awareness-behaviour link (Pannell and Zilberman, 2020; Okumah et al., 2018; Kroon et al., 2016; Barnes et al., 2009; Pannell et al., 2006). Farmers are more likely to adopt BMPs where the requirements fit the farm situation, especially when the costs of taking up such measures are low and the technology is easy to implement compared to more expensive and complicated technologies (Sattler and Nagel, 2010; Wynn et al., 2001; Morris et al., 2000; Wilson, 1997).

Pressure from neighbours, landlords and institutions seem to play a role in uptake of BMPs in our case. This evidence supports the findings of previous studies on the role of social norms. For some farmers, the decision to engage in sustainable practices depends on what their neighbours think or do, and their perceptions on what they ought to do (Dessart et al., 2019). This is particularly true for people with a strong tendency to conform to the majority (Asch, 1956) as well as 'conditional co-operators' – those who would do it if others do (Fischbacher et al., 2001). This is reinforced by the finding that some farmers do not want to be associated with pollution problems as they perceive other people's opinions to be important and sometimes need social approval (Talcott, 2013). Consequently, these farmers feel that engaging in bad practices could project them as 'bad' people (Defrancesco et al., 2008).

Openness to change is another important factor. We found that some farmers were less likely to change practices because they are not comfortable dealing with a new technology; they prefer to keep practices that have been passed on from generations. This corroborates the findings of previous studies on the role of 'resistance to change' in farmers' adoption of BMPs (e.g., Burton et al., 2008). We know from past empirical studies that farmers who score low on openness to engage in new experiences were more reluctant to change due to the status quo bias (George and Zhou, 2001), i.e., these farmers desire to keep existing practices as new ones are (sometimes) perceived to have negative consequences (Dessart et al., 2019; Samuelson and Zeckhauser, 1988). A recent study on the influence of status quo bias in adoption of agri-environment policy concluded that a large proportion of farmers do not accept change (Barreiro-Hurle et al., 2018), a potential reason for low adoption of BMPs in (some) farming communities.

While the use of the weed wiper appears to be promising in reducing MCPA concentration in drinking water sources, sustaining results of this initiative may be challenging particularly as the uptake of weed wiper hires appears to have declined in the target catchment over the last two years compared to the first three years of the initiative (Table 3). The decline in weed wiper hires over time might be related to the fact that farmers have only one opportunity to hire the machine for free. It could be that engaged farmers who were very keen to try the machine participated in the early years (2015-2017) of the trial.

As these farmers do not have the opportunity to hire the weed wiper again, further effort will be needed to reach out to less engaged farmers to encourage them to try it. This free hire aspect of the trial is very important as cost of hiring and/or acquiring the weed wiper was highlighted as a barrier to uptake by some farmers.

In addition to the above, the UK is at a major crossroads in terms of pesticide legislation and policy given Brexit (i.e., the UK's departure from the EU). It could decide to mirror the existing EU system and all its pesticide regulations and standards, or reduce regulations and weaken our existing standards or go further than the EU in protecting our environment from pesticide-related harms and deliver a 'Green Brexit'. There are currently political debates on phasing out glyphosate – the approved product for the weed wiper – in the agricultural sector by 2022 (European Parliament., 2017). If this should happen, an alternative pesticide would be needed, otherwise farmers are likely to return to the use of MCPA which may negate the water quality benefits Welsh Water have seen as a result of their weed wiper trial. In the midst of these uncertainties, additional efforts will be needed towards encouraging farmers to use Integrated Pest Management (IPM) methods for controlling weeds (i.e., the use non-chemical and targeted chemical). Although non-chemical methods were previously seen as less effective means of rush control, it is thought that modern farm technology could facilitate their use (Morton et al., 2020).

5. CONCLUSION

Efforts to tackle diffuse water pollution from agriculture are increasingly focusing on improving farmers' awareness under the expectation that this would contribute to them adopting BMPs and result in water quality improvements. To date, however, there are limited studies exploring the full awareness-behaviour-water quality pathway; with previous studies having mostly addressed the awareness-behaviour link relying on mono-disciplinary approaches. To address this important knowledge gap, we examined whether awareness-focussed approaches to mitigating diffuse water pollution from agriculture do result in increased adoption of BMPs and improved water quality, adopting an interdisciplinary approach to address the pathway in full. To do this, we worked with the Welsh water utility in the UK and their weed wiper trial to reduce levels of pesticide MCPA (2-methyl-4-chlorophenoxyacetic acid) in drinking water sources.

Analysis of MCPA concentrations from 2006 to 2019 shows a significant decline of 45.2% in MCPA concentration for the targeted catchments. Results from stakeholder interviews suggest that awareness – promoted through the weed wiper trial – had contributed to adoption of BMPs and that these are very likely to have resulted in the water quality improvements to drinking water sources. The combination of findings from this study provides some support for the emerging theoretical premise that the awareness-behaviour-water quality pathway exists but that this relationship may be mediated and/or moderated by other variables. This provides evidence that awareness-focussed approaches do work, however, policymakers and catchment managers need to consider the complex nature of the pathway and factors influencing it. Additionally, the findings of this study show promising results for awareness-focussed approaches not just in relation to diffuse water pollution from agriculture, but more generally for the uptake of BMPs and their impact in different environmental management areas.

The awareness-behaviour-water quality pathway is complex and dependent on several factors. We believe that this complexity can never be fully disentangled due to the 'wicked' nature of diffuse pollution problems and the psychosocial, agronomic, economic and biophysical factors influencing it. Nonetheless, we believe that it is extremely useful to start disentangling such complex relationships using the best available data as we have done in this study. To improve our understanding of the pathway, further research and data will be needed on other psychosocial, economic, agronomic factors, catchment and weather factors that interact to affect farmer's ability to implement BMPs and thus overall water quality improvements.

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6. APPENDICES

Appendix A: Common chemical control strategies to manage weeds

Equipment	Description
Boom sprayer	Most commonly used to apply liquid fertilizers or pesticides to crops during their vegetative cycle, boom sprayers distribute the product from a tank *through a* pipe with nozzles. The sprayer's height is adjustable. Using a boom sprayer, MCPA can be applied to grass. However, this must be applied with care, as MCPA could damage most broad-leaved plants, including clover.
Knapsack sprayer	Most commonly used to spray fungicides or insecticides, knapsack sprayer consists of a knapsack tank together with pressurising device, line, and sprayer nozzle. A knapsack sprayer is versatile and enables the farmer to target areas with rush. However, spray can drift in windy weather onto other plants and ultimately reach watercources.
Weed wiper	Using a weed wiper, Glyphosate can be applied, in conditions where rush plants are actively growing and stand higher than the surrounding grass. Because glyphosate has potentially less impact on water quality and broad-leaved plants than MCPA, the use of weed wipers (with glyphosate) is widely recommended than regular boom spraying with MCPA.

Appendix B: Summary of BMPs promoted as part of the weed wiper trial

Component	Recommended Practice
Storage	Keep pesticides in a clearly marked lockable, bunded store at least 10m away from any watercourse or drain.
	Keep pesticides in their original (clearly labelled) containers and legally dispose of any unwanted or out of date chemicals.
	Ensure you have a spill kit located near the store and/or filling area to contain any spillages.
In yard	Check application equipment is working correctly and has a valid National Sprayer Testing Scheme certificate where required.
	Ensure operator is suitably trained, competent and has required protective clothing e.g. overalls, gloves, masks.
	Ideally, fill equipment in a covered, concrete bunded area where drainage can be contained. Alternatively, fill on grass using a drip tray or portable bund.
In field	Carefully follow instructions for application. Do not over apply – this can wash off into drains or residues can stay in soils effecting the next crop grown.
	Do not fill at the entrance of a field or any bare earth especially if adjacent to a watercourse, or a road/track that could channel run-off water into a watercourse.
	Establish buffer strips adjacent to any ditches or watercourse.
	Do not apply pesticide prior to rainfall or in windy conditions or when ground is frozen.
	Plan your route through fields. Do not cross any ditches or streams to avoid accidents that could lead to involuntary pouring out of pesticides, and prevent pollution.
Disposal	Wash the outside of the sprayer before leaving the field, since there may remain residue on the machine or in the mud on tyres.
	Spray washings on to the crop or target area - be careful not to over apply.
	Ensure all cleaning activities take place away from watercourses.
	Return any unused pesticide to store. Alternatively, use a registered waste disposal company.
	Record all pesticide applications.

Appendix C: Interview scripts

<u>Skipping codes/questions</u>

Are you aware of Welsh Water's weed wiper trial? Did you participate in the trial?

<u>INTERVIEW: FARMERS WHO PARTICIPATED IN THE WW CAMPAIGN</u>

1. Please explain briefly how do you manage weeds on the farm?
2. If you use pesticides to control pests, how do you use them? What practices do you use? Do you often follow these same practices every year? When do you apply them? What type of pesticides do you use?
3. Have you always applied pesticide in this manner? Why? Or have you changed your practices over time?
4. There are reports that link pesticide use with a decline in water quality: do you believe this? Why?
5. Do you think your usage of pesticides is harmful to the environment? Why?
6. Thinking now about Welsh Water's weed wiper trial? Please are you able to describe it briefly for me? a) Describe what it consists of, b) whether and how it worked.
7. Have you changed any practices regarding your pesticide usage following the trial? Do you think you would have changed practices anyway even if you didn't participate in the trial? Why?
8. Would you say that your participation in the weed wiper trial has helped you improve your pesticide use? How?
9. Is there anything about the weed wiper trial that you believe was particularly useful in improving your understanding of best pesticide management? (e.g., how the messages were delivered, the amount of information that you received, how this information was portrayed)
10. Do you think the weed wiper is a good approach to pest management? Would you recommend it to your neighbours?
11. What might prevent/drive you (not) to use it in the future?

Catchment			
Farm type Arable [1]	Livestock [2]	Mixed farming [3]	Horticulture [4]
Which of the following best describes your status?			
Tenant Farmer [1]	Owner Occupier [2]	Associate (a partner) [3]	
Farm size in acres (all sites together).	< 50 Acres [1]	>= 50 Acres [2]	

<u>INTERVIEW: FARMERS WHO DID NOT PARTICIPATE IN THE WW CAMPAIGN</u>

1. Please explain briefly how do you manage weeds in the farm?
2. If you use pesticides to control weeds, how do you use them?
3. What practices do you use? Do you often follow these same practices every year? When do you apply them? What type of pesticides do you use? Have you always applied pesticide in this manner? Why? Or have you adopted any new practices over time?
4. There are reports saying pesticides affect water quality: do you believe this? Why?
5. Do you think your usage of pesticides is harmful to the environment? Why?
6. Have you changed any practices in your pesticide usage over the past 4 years (since April 2015)? Why?
7. Do you think it would have been good to have participated in the weed wiper trial? Why?
8. Do you think you'd have done things differently if you had participated in the weed wiper trial? Why? What will you do differently?
9. Would you like to use the weed wiper in the future? Why?

10. What might prevent/drive you (not) to use it in the future?
11. Would you recommend the weed wiper to your neighbours? Why?

Catchment				
Farm type	Arable [1]	Livestock [2]	Mixed farming [3]	Horticulture [4]
Which of the following best describes your status?				
Tenant Farmer [1]	Owner Occupier [2]	Associate (a partner) [3]		
Farm size in acres (all sites together).	< 50 Acres [1]	>= 50 Acres [2]		

INTERVIEW: (Welsh Water & Farming Connect)

1. Ask them to describe the trial: a) describe what it consists of, b) whether and how it worked c) general impression of it.
2. Can you explain how the wiper trial has improved the following?
   (a) Farmers' understanding of pesticide application
   (b) Pesticide management practices (which specific changes?)
   (c) MCPA concentration
3. Has any farmer reported major changes in pesticide handling and application? Which areas?
4. Show them water quality results and ask them to provide their views on what could explain those results.
5. Were your advice materials distributed among farmers in Teme?

Note: ***The interview script for institutions (Welsh Water and Farming Connect) was adapted for interviews with other institutions (based on their roles and involvement in efforts to mitigate diffuse water pollution from agriculture).***

Appendix D: Codes, themes and topics emerging from the analysis of interview transcripts

Codes	Theme
Topic: Factors influencing awareness	
Availability and access to scientific evidence	-
Availability and physical access to training opportunities	
Economic Access to training and learning opportunities	
Consistent engagement in best practice or consistent application of advice	
Topic: Factors influencing uptake of pesticide application measures	
Awareness/environmental consciousness	Psycho-social factors
Social pressure	
Desire to protect reputation	
Regulations	
Mind-set (beliefs regarding practices)	
Information source and trust	
Availability of the technology (e.g., weed wiper)	Resource Availability
Availability of complementary equipment (e.g., no quad bike)	
Availability of the chemical/herbicide used with the weed wiper	
Time required to implement practice	
Perceived financial benefits (a motivational factor for uptake)	Agronomic, farm characteristics and financial considerations
Perceived financial cost (as a potential barrier)	
Type of weed and extent of weed problem	
Type of crop (e.g., the variety of potato)	
Land use and Farm size	
The need to saves clovers	
The need to maintain good improve soil health or keep healthy land for growing grasses	
Need to use an application method that is faster (than other methods).	

Ease weed management	
Season and weather conditions	Location and climate characteristics
Location or landscape	
Topic: Factors interacting with behaviour to affect water quality	
Number of farmers implementing the recommended measures	-
Accidental pollution	
Pollution from other sources	
Land use	
How long measures have been implemented	
Possible external interventions	
Benefits of participating in agri-environment schemes	
Access to advice	-
Access to money	
Barriers to participating in agri-environment schemes	
Money is small	-
Lack of access to the right information	
Poor understanding of the point based system	
Recommendations to improve awareness and adoption of the weed wiper and (other BMPs)	
Provide scientific evidence	-
Attend shows	
Increase publicity; contact farmers	
Use case studies	
Do farm visits	
Make pesticide application course free for farmers.	
Increase funds/grants/incentives for courses	
Make the required herbicide more obtainable for people especially those around water catchment areas.	
Expand the weed wiper trial to include other catchments.	
Government should listen to farmers.	
Government should prioritise food production.	
Build relationship with land users to gain their trust and support.	
Work with trusted stakeholders to build trust and gain support.	