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CL:AIRE's INSPIRATION bulletins describe practical aspects of research which have direct application to the management of contaminated soil or groundwater in an agricultural context. This bulletin describes a methodology to help reduce pesticide pollution.

Identification of priority areas to target pesticide pollution mitigation measures

1. Introduction

Sustainable Intensification of Agriculture (SIA) is needed to increase production so that natural resources are managed sustainably. However, at present, agriculture remains a primary cause of water-related problems (EEA, 2015). Within the EU, the Water Framework Directive (2000) was established to improve water quality and resource management. Despite efforts, many European rivers and aquifers still show pollution from agricultural sources (EEA, 2015) and pesticide residues frequently occur in surface waters (Casado *et al.*, 2019) which can have deleterious impacts on aquatic organisms and ecosystems.

Hence, there is a continuing interest in the implementation of measures in agriculture to reduce the impact of pesticides on water quality. However, there is no one-size-fits-all solution to deal with pesticides input to the aquatic environment and budget constraints trigger the need to prioritise actions that lead to water quality improvement in a cost-efficient way.

A methodology that helps practitioners identify priority areas to reduce pesticide pollution is needed and represents a step towards developing knowledge for catchment management strategies for water quality programmes.

2. Background

Pesticides are chemical compounds that are used to kill pests, including insects (ie. insecticides), rodents (ie. rodenticides), fungi (ie. fungicides) and weeds (ie. herbicides) as defined by the World Health Organization (n.d.). Once applied, pesticides can enter surface water via diffuse sources such as surface runoff, drain flow, spray-drift, atmospheric deposition and groundwater flow or via point sources (Holvoet *et al.*, 2007). The source and the pathways pesticides follow can have implications on the type and the effectiveness of mitigation measures. The relevance of different entry routes must be assessed and matched with suitable mitigation strategies. Surface runoff can be the dominant process of contaminant transfer as a significant portion of pesticides applied to agricultural fields can move into aquatic ecosystems during rainfall (Tang *et al.*, 2012). Pesticides dissolved in water or sorbed to sediment particles can be transported during a rainfall event (Holvoet *et al.*, 2007). Moreover, the fate of pesticides is affected by their physical and chemical properties, and interactions with soil, weather and agricultural practices (Reichenberger *et al.*, 2007).

Mitigation measures can be defined as all actions that lead to a decreased likelihood of pesticide contamination and should be selected according to the input pathways that contribute most to the reduction of risk at the relevant receptors. Vegetated treatment systems like field or riparian grass buffer strips, hedgerows and, constructed or stormwater wetlands, are landscape feasible solutions for runoff and erosion (Reichenberger *et al.*, 2007). The primary objective of landscape-related measures is to reduce pesticide transfer with the use of buffers or retention zones, and they have been effective at reducing pesticide pollution in water (Pätzold *et al.*, 2007). Arguably, the position of landscape elements influences the amount of pesticides, from a given field, reaching a watercourse (Reichenberger *et al.*, 2007). Furthermore, not all fields within a catchment are considered critical regarding diffuse pollution; some areas, known as Critical Sources Areas (CSAs) contribute a disproportionately large fraction of the polluting load (Frey *et al.*, 2009). CSAs correspond to areas of pesticide application that are hydrologically active and connected to the stream network (Doppler *et al.*, 2014). Mitigation options applied to CSAs can bring higher positive impacts at catchment level. Therefore, the identification of priority areas where mitigation measures can be implemented is an essential step when pesticide loads need to be reduced.

Some alternative methods have been employed to establish priority areas that involve 1) the use of hydrological physically-based models to approximate contaminant transport (Bach *et al.*, 2002), 2) the use of long-term pesticide monitoring data (Di Guardo and Finizio, 2018), 3) a combination of indicators and multi-criteria analysis (Macary *et al.*, 2014), and 4) GIS modelling to prioritise catchments or streams within a watershed (Zhang *et al.*, 2008). Previous approaches have been applied at larger scales, mainly to identify extensive critical zones. However, changes in agricultural practices and/or implementation of mitigation measures mainly take place at farm level. The catchment scale considering detailed field data is useful for the implementation of actions by farmers or local groups. Previous studies do not consider the microscale or parcel scale required for recommendations within a small catchment.

This bulletin was prepared by Gisela Quaglia from VITO and Ghent University with assistance from Ingeborg Joris, VITO and University of Antwerp; Steven Broekx, VITO; Nele Desmet, VITO; Kim Koopmans, pcfuit npo and Piet Seuntjens, VITO, University of Antwerp and Ghent University. For further information please email: gisela.quaglia@vito.be.

Inspiration

The methodology developed includes very detailed landscape data, such as topography, crop cover, use of pesticide, erosion risk and hydrological connectivity, among other relevant factors to derive a theoretical risk map for pesticide pollution. The emissions of pesticide that could reach surface water were calculated for each field. The maximum cumulative runoff area was also estimated to evaluate the connectivity of each field to the waterbody. The resulting maps, emission and connectivity were added to obtain a theoretical risk map.

The approach was applied in a case study in Belgium to establish an action plan to mitigate pesticide pollution followed by five years of water quality monitoring.

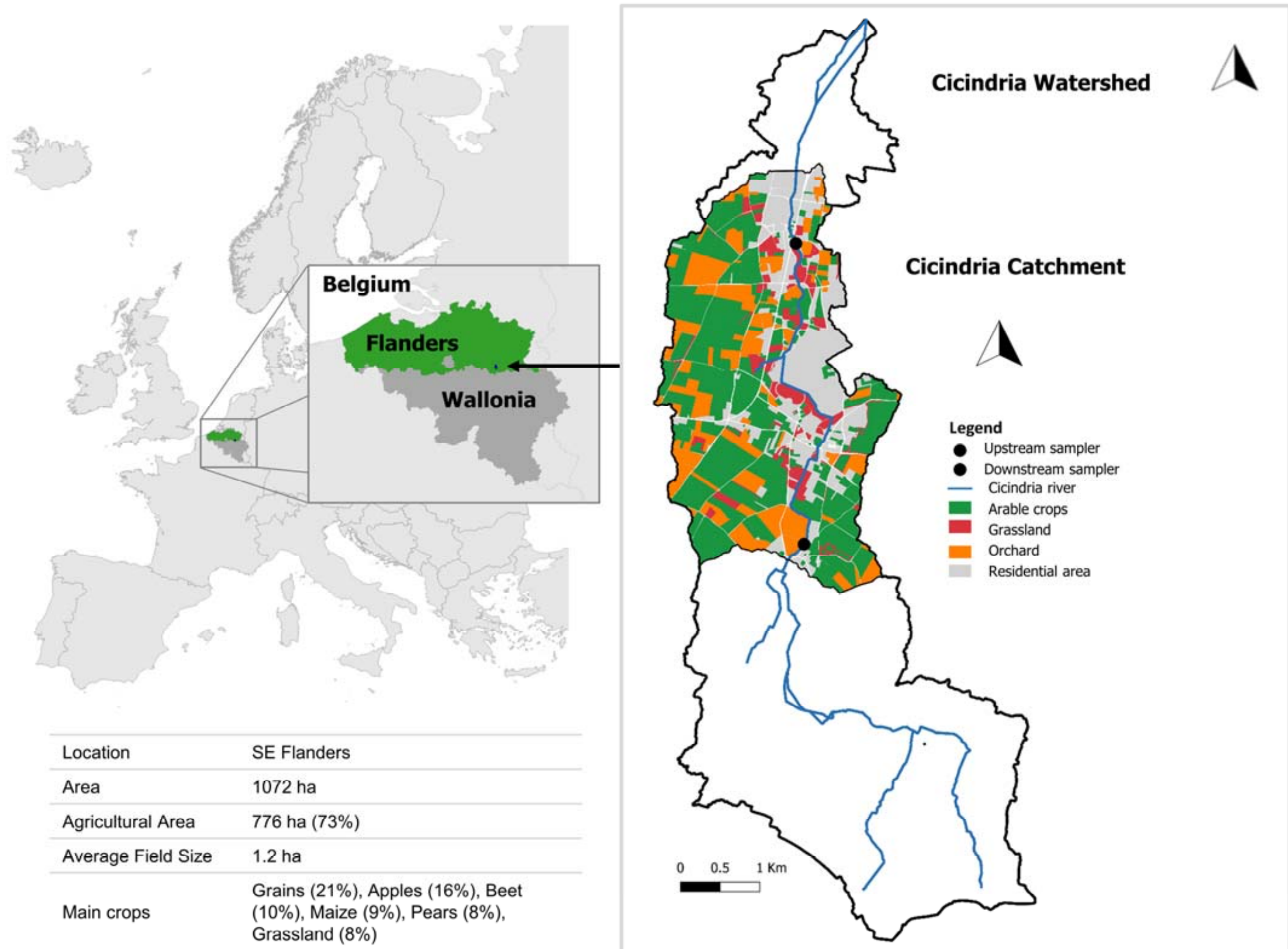
3. Materials and Methods

A study site in SE Flanders (Belgium) was used to test the methodology (Figure 1). The Cicindria catchment has an area of 1075 ha, predominantly used for agriculture (72%). The site is characterised by hilly topography and loamy soils, resulting in a high vulnerability to erosion. Soils are well-drained and usually have no artificial drainage systems.

Glyphosate was the pesticide selected for this case study. This product is one of the most used herbicides worldwide and intensively applied to agricultural fields to kill weeds. This substance is applied to the majority of crops and frequently detected in waterbodies (VMM, 2017).

Gross emissions of pesticide to surface water are calculated using the emission factors (EF). EF represents the fraction of the applied dose that follows a particular pathway (spray-drift, erosion, drainage, interception, volatilisation). Pesticide losses for each pathway are estimated separately based on methods developed in previous studies (De Schampheleire *et al.*, 2007; Gustafson, 1989; Linders *et al.*, 2000; Webb *et al.*, 2016). The crop cover and the related dose was considered in the calculation. The relevant pathways towards a watercourse (drift, erosion and drainage) were added for each parcel and further classified in 6 classes, obtaining an emission risk map.

The topography is a dominant factor controlling surface runoff, and it is typically used to understand the structural connectivity of a system and to identify possible sensitive areas. The hydrological connectivity of each parcel is evaluated using the runoff upslope contributing area. A multiple flow direction (MDF) map was used, provided by the Department of Land and Soil Protection, Subsoil, Natural Resources based on a Digital Elevation Model (DEM) with 5 m resolution and the Flemish Hydrographic Atlas. The runoff map shows the zones that can potentially produce runoff and is a static representation of runoff generation (Bracken and Croke, 2007). The hydrological



Location	SE Flanders
Area	1072 ha
Agricultural Area	776 ha (73%)
Average Field Size	1.2 ha
Main crops	Grains (21%), Apples (16%), Beet (10%), Maize (9%), Pears (8%), Grassland (8%)

Figure 1: Cicindria catchment location, land use (2016) and relevant characteristics.

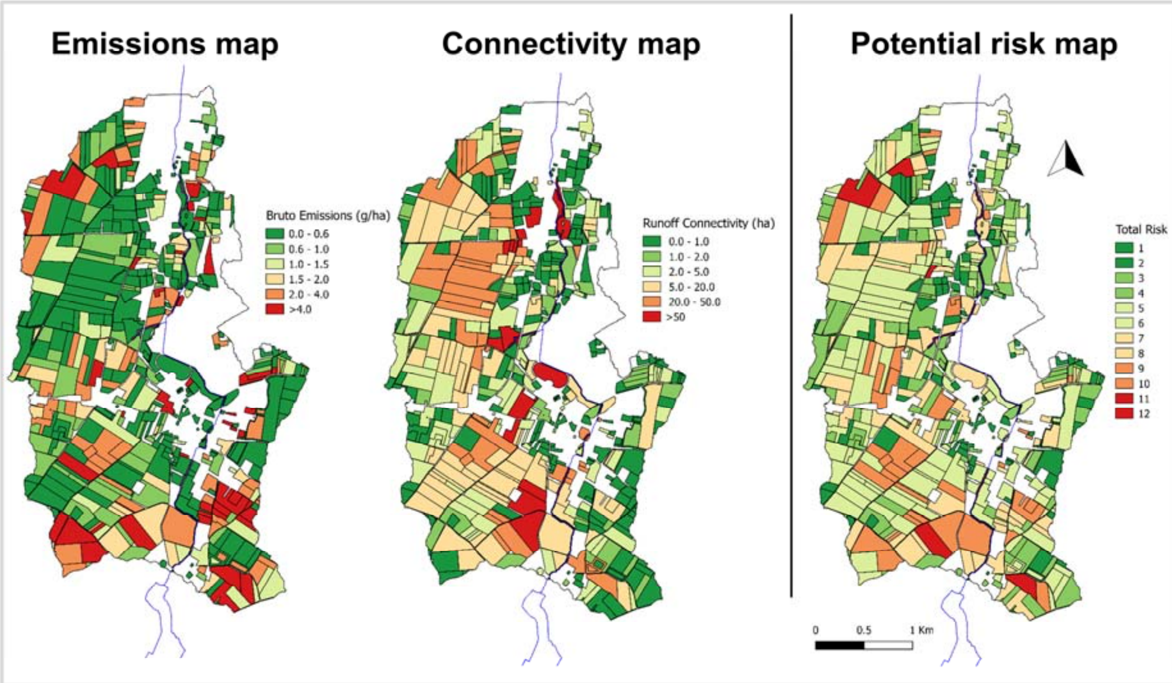


Figure 2: Potential risk map (right) for 2012 obtained by the addition of the two intermediate maps, emissions (left) and connectivity (centre). Figure from Quaglia *et al.* (2019) reprinted with permission from the copyright holders, Elsevier Ltd.

connectivity of each land parcel was evaluated using the flow accumulation (runoff) map, and further classified in 6 classes obtaining a connectivity map.

The theoretical risk map is obtained after adding the intermediate maps, emission and connectivity. Each parcel has a score from 2 (low risk) to 12 (high risk). Additional details of the methodology can be found in Quaglia *et al.* (2019).

4. Results and Discussion

The potential risk map includes potential pesticide emissions and the hydrological connectivity of each parcel, as shown in Figure 2. The evaluation was performed for the land cover present in 2012. Parcels with higher scores have higher priority for mitigation measures. These parcels could potentially contribute to higher emissions and are better connected to the river.

The results obtained were used to identify, raise awareness and motivate farmers to implement mitigation measures such as grassed buffer strips voluntarily. It was a helpful tool to explain the sources and pathways of pesticides to farmers and to discuss the best location for risk reduction measures. The effect of these measures on the glyphosate loads in the river is being assessed by a five year (2014-2018) monitoring campaign.

5. Future Steps

During the five-year monitoring campaign (2014-2018), mitigation measures were implemented within the catchment (Figure 3 and Figure 4). The analysis of the datasets will allow glyphosate loads and the influx from agricultural land through runoff and erosion during storms to be estimated.

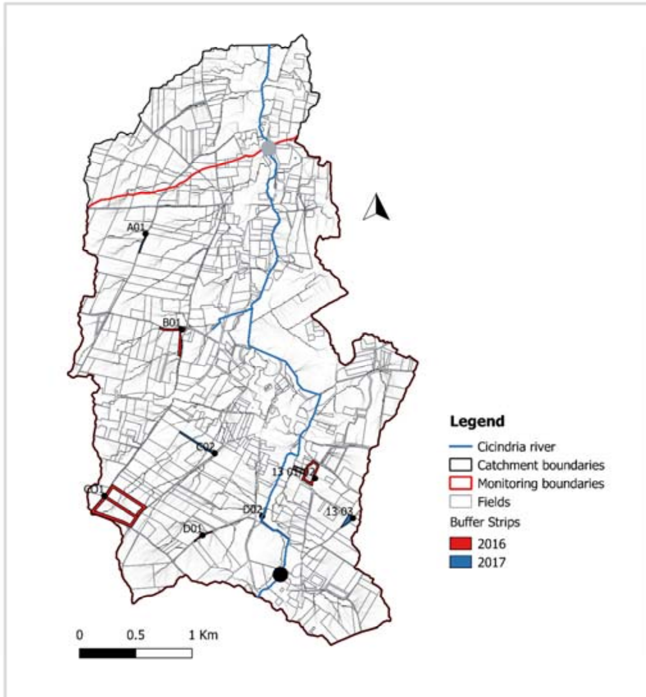


Figure 3: Map with the location of the grassed buffer strips implemented in the study area (2016-2017) as part of a voluntary programme.

The contribution of different pathways to the estimated loads and the efficiency of mitigation measures needs to be further explored using a pesticide fate and transport model. This model will evaluate the efficiency of management strategies for the reduction of pesticide loads. To this end, the model has to link the use and emissions from the field to surface waters. The model will contribute to a framework that evaluates cost-efficient measures to reach a particular pesticide reduction goal at the outlet of the catchment.

Figure 4: Grassed buffer strips implemented in the catchment (2016-2017).

The final step of this research is a decision-support framework (DSF) for spatial targeting of landscape mitigation measures. The tool will assess the impact of different strategies in multiple locations for pesticide reduction.

6. Conclusions

A GIS-based tool for water resource managers has been developed that provides a first picture of the potential impact of pesticides on surface water bodies. The approach could help in the identification and prioritisation of critical risk areas, where mitigation measures may be applied. The tool is relatively simple to apply and uses geospatial data that is often typically available or easy to obtain. It identifies areas in which mitigation measures seem necessary and could, therefore, contribute to improving water quality.

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