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Pesticide contamination of freshwater ecosystems: Mapping vulnerable areas and mitigation scenarios in the Prosecco DOCG wine production area

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Abstract

Freshwater ecosystems are the most vulnerable environments worldwide and the most biodiverse, providing essential ecosystem services. The role of land management in agriculture is paramount with the dramatic increase in pesticides: two million tonnes used worldwide (47.5% herbicides, 29.5% insecticides, and 17.5% fungicides) are jeopardising freshwater ecosystems. Concerns about the risk of pesticide contamination from viticulture have led to implementing nature-based mitigation measures (buffer strips and hedgerows) and technical improvements. The general aim is to assess spatial proximity among vineyards and river networks within the Prosecco DOCG area to identify potential critical areas for pesticide contamination. Specific objectives are: i) mapping vineyards within the Prosecco DOCG area, ii) identifying river banks with a higher probability of experiencing pesticide contamination, and iii) mapping critical areas potentially affected by pesticide contamination. Spatial modelling was based on very high geometric resolution ortophotos (0.5 m), LiDAR data (1 m), and morpho-hydrological parameters of the river network. Proximity and morpho-hydrological modelling showed that due to little distance from Prosecco croplands (5–20 m), freshwater ecosystems may be affected in different basins by spray drift pesticide contamination. Distances between vineyards and streams were shown to be critical, as 35.7% and 13.9% of river banks were within 20 m and 5 m distance from vineyards, respectively. Furthermore, 52% of basins presented river banks intersecting vineyards at 5 m, while 37% were within 20 m distance. Such hotspots should be investigated in the field for watershed-based quality assessment. However, mitigation scenarios indicate that spray drift contamination might be reduced by 75%, minimising the effect from 20 m to 5 m distance from vineyards and, therefore, avoiding reaching part of riparian and aquatic ecosystems. Geovisualisation of river banks proximity at watershed level offered insight into area with high probability of experiencing pesticide contamination from vineyards due to spray drift.

Keywords: freshwater ecosystems, viticulture, pesticide contamination, Prosecco, mitigation measures

Introduction

1.1 Ecological impacts of agricultural pesticides on freshwater ecosystems

Farmlands represent the world's largest terrestrial human-modified ecosystem, occupying about 37.4% (56.1 M km^2) of the 150 M km^2 of Earth land surfaces (Food and Agriculture Organization (FAO) 2016, 2017). Land management and practices are therefore paramount for a sustainable agro-food system that is able to preserve biodiversity as well as ecosystem functions and services (Newbold *et al.* 2016, Bernhardt *et al.* 2017). Achieving a better sustainability of food production is, therefore, a crucial challenge for the development of modern sustainable agriculture as well as reducing the impacts on ecosystems.

Together with the expansion and intensification of conventional agriculture, a notable increase in the production of pesticides has been widely documented. From 1955 to 2000, production increased by more than 750% (Tilman *et al.* 2001). At present, about two million tonnes of pesticides are used worldwide, among which 47.5% are herbicides, 29.5% are insecticides, 17.5% are fungicides, and 5.5% are others (Sharma *et al.* 2019, De *et al.* 2014).

Pesticide risks for human health are one of the main issues, as clearly stated by Directive (EC) 128/2009 on the sustainable use of pesticides. In particular, specific indications have been reported to minimise pesticide contamination of surface water bodies by considering their importance as sources of drinkable water for human consumption and the ecological relevance of aquatic and riparian ecosystems (European Parliament 2009).

Freshwater ecosystems are the most vulnerable environments worldwide, and they are the most biodiverse, providing essential ecosystem services such as water supply and quality control, habitat provision, erosion prevention, and supplying fertile soils for agriculture and places for drinking water and food (Vári *et al.* 2022, Rumschlag *et al.* 2020).

Although the progressive adoption of important protection measures (i.e. Directive EC 128/2009) has led to an improvement of surface water quality in Europe, pesticide contamination of surface water is still widely diffused. For example, pesticide contamination above the European official thresholds for drinkable water (0.1 µg/l for single pesticides and 0.5 µg/l for total pesticides) was detected in 21% of the sampling points of surface water bodies during a recent survey conducted in Italy in 2017–2018 (ISPRA 2020). As documented, even low pesticide concentrations can alter freshwater ecosystems (Berghahn *et al.* 2012, Maltby and Hills 2008), especially if the simultaneous presence of different active ingredients produces synergistic toxic interactions (Bjergager *et al.* 2011). Moreover, pesticide contamination in aquatic ecosystems can lead to progressive reduction of ecosystem functions and alteration of trophic chains affecting birds, fish, and other animals (Peters *et al.* 2013, Chagnon *et al.* 2014, Gibbons *et al.* 2014, Viant *et al.* 2006). Hallmann *et al.* (2014) observed faster declines in local populations of insectivorous birds in areas of the Netherlands with higher surface water concentrations of the insecticide imidacloprid. It is possible that pesticides might reach surface water bodies during or after field application via diverse transport processes, such as surface runoff, spray drift, and volatilisation. Such processes might result in chemical residuals found in river waters (Irace-Guigand *et al.* 2004, Claver *et al.* 2006) and groundwater (Lacorte and Barceló 1996), as well as lakes and coastal water (Konstantinou *et al.* 2006), highlighting that contamination can occur far away from the area of application.

Several environmental (i.e. wind speed, air temperature, rainfall events, crop stage, and canopy size) and technical (i.e. spray volume, nozzle type, sprayer characteristics and setting, air pressure, pesticide formulation) factors during and after pesticide application interact together to determine pesticide transport to no-target areas. Hence, predicting the potential risk of contamination of a certain pesticide application in a given crop at a given stage is difficult. Nevertheless, due to the high temporal frequency of pesticide applications (10-20) during the cropping season, characterised by high spray volume (500–1500 l/ha) and pressure (5-15 MPa) in horizontal or upward direction, some cropping systems, such as orchards and vineyards, present a higher risk as sources of diffuse pesticide contamination. Transport of large fractions of applied pesticides to non-target areas even at distances of several metres from the application point was observed in various studies in vineyards under different environmental conditions (Lefrancq *et al.* 2013, Otto *et al.* 2013, 2015, Vischetti *et al.* 2008).

1.2 The geography of the Prosecco DOCG area

1.2.1 Geomorphological framework

The Prosecco DOCG production area spans 214.92 km^2 within Treviso Province (Veneto Region, NE Italy), by forging a stretched shape of 24 km along SW-NE, according to the orientation of the hogback hills that characterise the landscape in the northern sector of the area (Figure 1a).

The whole area is characterised by a mean elevation of 183 m asl, a minimum of 50.5 m asl in the south-eastern sector within the city of Conegliano, and a maximum altitude of 632 m asl close to Valdobbiadene (western sector) in the southern slope of Pre-Alpine mountains.

The study area was divided into four main geomorphological zones: i) a system of hogbacks rising about 120–150 m of the plain, located in the northern sector; ii) a hilly landscape that alternates ridges N-S oriented to a few wide bottom valleys (north of Conegliano); iii) a hilly landscape characterised by gently slopes, according to the horizontal strata orientation; and iv) two wider plains corresponding to the alluvial plain of Vittorio Veneto (east sector) and the Quartier del Piave alluvial plain (Figure 1a).

1.2.2 The DOCG wine production territory

In the last decade, sparkling wine production globally increased by an annual rate of 7% in value and 6% in volume, making Prosecco a paradigmatic case of the most exported wine in the world (Pomarici et al. 2019, Tempesta et al. 2021, Consorzio di Tutela 2019).

In this area, due to a combination of global market demand and large investments in the Prosecco DOCG area, a remarkable increase in wine production is reported annually: from 40 M Prosecco DOCG bottles in 2003 to more than 100 M bottles in 2021, with an actual economic value of more than half billion euros (Pomarici 2019, Boatto et al. 2021, Federvini 2021). Such an increase is related to the notable expansion of Prosecco vineyards within the defined Controlled and Guaranteed Denomination of Origin production area, which drove severe Land Use Land Cover (LULC) changes and a considerable intensification of conventional agricultural activities (Visentin and Vallerani 2018, Basso 2019, Pappalardo et al 2019).

At present, vineyard cropland occupies about 32% of the whole surface of the DOCG area, and they represent about 50% of all farmlands, making de facto Prosecco a monoculture agro-system (Basso and Vettoretto 2020).

The Prosecco DOCG area encompasses 15 small–medium municipalities in a scattered urban–agricultural territorial matrix. For all municipalities, Prosecco viticulture is the most important economic activity; for instance, in the Refrontolo and San Pietro di Feletto municipalities, vineyards cover 32.3% and 40.8% of the total surface, respectively, including unsuitable areas for agriculture.

Since 2021, the Prosecco DOCG wine production area has been declared UNESCO's world heritage (Ponte 2021).

1.2.3 Pesticides and conventional viticulture

The expansion of Prosecco DOCG conventional viticulture has inevitably increased the use of pesticides in the area. According to an annual report from the Regional Environmental Protection Agency (ARPAV), based on the official seller declarations, pesticides sales increased, only within the Treviso Province, from about 3 million kg (of active principles) in 2011 to more than 4.5 million kg in 2019. By aggregating pesticide categories included in the seller declarations of the FAS Project (ARPAV 2021) an important growth in fungicide sales can be observed from 2010 to 2019 (Figure 2), probably due to the expansion of vineyard acreage within Treviso Province. By considering the distribution of active principles as territorial indicators for the sustainable use of pesticides, in 2019 Treviso Province presents a value of 16.5 kg ha^{-1} on the utilised agricultural area (ARPAV 2020).

Pesticide applications usually range between 12-13 application/year, in the case of dry years with low diseases pressure, and 20 or above in rainy years when diseases pressure is high. Most of these applications involved fungicides. Pesticide application usually begins in March-April and lasts until after the harvest in Autumn (Personal communication, 2021).

1.3 Aims of the study

This study adopted a GIS-based approach to assess spatial proximity and distances among vineyards and the river network as a first contribution to pesticide contamination monitoring and mitigation measures in the production area of Prosecco DOCG. To identify potential hotspots with a higher probability of experiencing pesticide contamination due to spray drift, the spatial relationships between vineyards and river networks were analysed by considering different spatial scenarios.

Specific objectives are: i) mapping vineyard rows within the Lierza basin and the Prosecco DOCG area; ii) identifying vulnerable river banks and watersheds potentially exposed to pesticide contamination by proximity; iii) highlighting vulnerable areas and mitigation scenarios by modelling a simple morpho-hydrological index into a high-resolution density map.

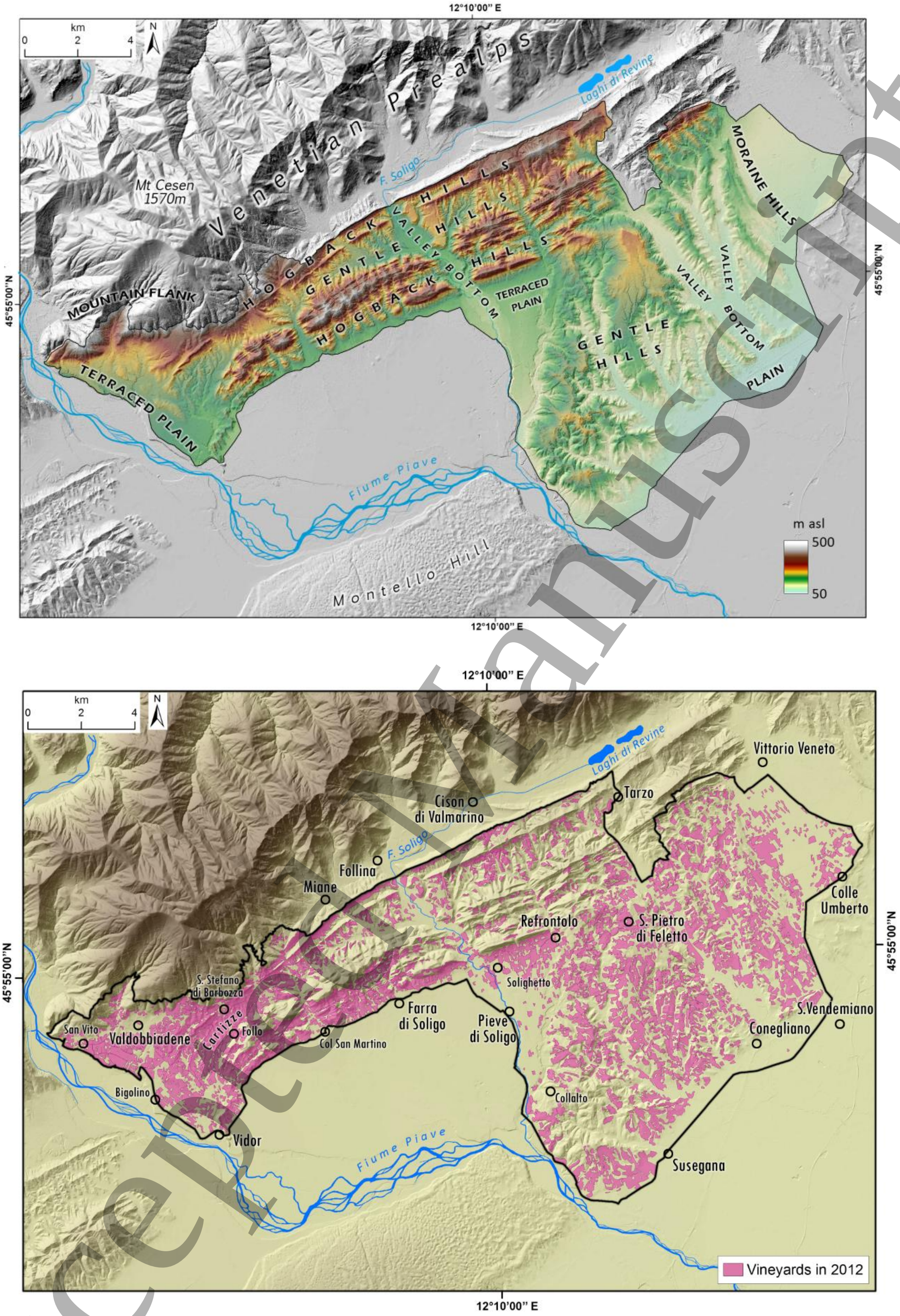


Figure 1: Prosecco DOCG area: (1a) geomorphological framework and elevation based on DTM LiDAR; (1b) vineyard distribution (30% of total study area) (Pappalardo et al. 2019)

Figure 2: Temporal evolution of pesticide categories in Treviso Province from 2010 to 2019, according to official seller records (data source: Arpav, 2020)

2 Data and methods

2.1 Spatial data

To perform territorial analysis and environmental modelling on the Prosecco DOCG area, we acquired official spatial data from the Veneto Region geoportal, such as vector shapefiles and raster.

For vineyard row extraction, we used multispectral orthophotos (RGB and NIR bands) at a very high geometric resolution (50 cm pixel size) from Veneto Region (2012).

We also used the latest updated LULC shapefile for vineyard distribution, with a nominal scale of 1:10,000, and land cover classes based on a minimum mapping unit of 0.16 ha; such a shapefile was derived from the same 2012 ortophotos (Veneto Region).

To perform hydrologic and morphologic analyses, we constructed a 1-m resolution digital terrain model (DTM) using the inverse distance weighted interpolation algorithm (Supplementary Material 1.1).

2.2 Vineyard row extraction and identification of spray drift areas

We firstly conduct spatial analysis at very high geometric resolution on a specific study case in the Lierza river basin. The results obtained with this study-case analysis were compared and validated with official data, then scaled up to the whole Prosecco DOCG area to obtain more general indications.

The Lierza river basin was selected due to its wide area (2,668 ha) and its geomorphologic variability, which is representative of the whole Prosecco DOCG area. Similarly, the different kinds of vineyards (terraced versus plain, small versus large) within this basin encompass the variability of agronomic conditions of viticulture in the Prosecco DOCG area.

We therefore mapped, by photointerpretation, all the visible vineyards within the Lierza river basin by digitizing every single vineyard row at 1:600–1:1,000 scale range, by using its centre as a draw line, in order to have a high accuracy.

To pursue a semi-automatic extraction of all vineyard rows on the whole Prosecco DOCG area, we also performed unsupervised classification techniques using the k-means and Isodata clustering models (Lillesand *et al.* 2015, Sun *et al.* 2017, Sirat *et al.* 2018) on the four spectral bands of the same ortophotos dataset (2012).

To identify areas potentially exposed to pesticide contamination due to spray drift, the polyline obtained after the extraction of vineyard rows was buffered at 5 (named DR5), 10 (named DR10), and 20 m (named DR20). This approach also expresses the mitigation effect as a reduction in the spray drift range (Table 1). These metrics are currently adopted for the calculation of the minimum width of the untreated buffer zones that are legally prescribed for the protection of non-target areas (Azimonti et *al.* 2017). In fact, the adoption of buffer zones (De Snoo and De Wit 1998), hedgerows (Otto *et al.* 2013, 2015), adequate sprayer settings and nozzles (Grella *et al.* 2017), target-sensing spray technologies (Brown *et al.* 2008), and anti-drift additives and formulations (Hilz and Vermeer 2013) were reported as effective mitigation measures to reduce the risk of pesticide contamination.

Table 1 summarises the three distances that represent three different scenarios for spray drift mitigation.

Measures	Buffer distance (m)	Spray drift reduction	Mitigation scenarios (buffer strips, hedgerows, technical improvements)
DR5	5	75%	High
DR10	10	50%	Medium
DR20	20	0%	Null

Table 1: Simulation of mitigation scenarios by the adoption of spray drift mitigation measures at different distances from Prosecco vineyards rows

2.3 Scaling up: from the Lierza basin to the Prosecco DOCG wine production area

To scale up vineyard spatial analysis from the Lierza basin to the whole Prosecco DOCG production area, we used a LULC shapefile from the Veneto Region dataset. From this shapefile, we extracted vineyard polygons (RV), and we compared these polygons with the vineyard buffers we mapped out and calculated within the Lierza basin area.

To identify areas potentially exposed to spray drift in the whole Prosecco DOCG, the 20 m buffer area from the vineyard rows must be identified. However, vineyard polygons RV delineate the perimeters of the entire vineyard parcel, not the actual crop row perimeters. Given that the outer parts of vineyards are usually occupied by roads or other uncultivated margins to have a spatial estimation, we assumed the presence of an average of 5 m buffer between the outer crop rows and the vineyard perimeter reported in the official dataset. A 15-m buffer towards the exterior (namely RV15) was therefore applied to vineyard polygons to identify the areas lying within 20 m from crop rows and consequently potentially exposed to spray drift.

2.4 Hydrographic network extraction and identification of surface water bodies potentially exposed to spray drift

Stream network polylines in the whole Prosecco DOCG production area were extracted from pre-processed DTM LiDAR data. The different morphologic characteristics of the stream were classified according to the stream hierarchic order (Strahler 1968, Cunha *et al.* 2016) and a buffer was applied to the stream network polylines to represent the spatial extension of water bodies. The specific values of this buffer were set according to the stream hierarchic order, which expresses the water supply, increasing from the lowest to the highest order (see Table 2) to account for the increasing width of surface water bodies belonging to the different orders. Even though such a procedure does not reflect the actual spatial extension of surface water bodies, it allows for a plausible estimation.

Stream Order	Buffer (m)
1	1.5
2	2.5
3	3.5
4	4.5
5	5
6	5
7	5

Table 2: Buffer values for Surface Water Bodies identification, based on hierarchic stream order applied to the stream network

The map of the whole hydrographic network, classified according to Strahler order, is represented in Figure 3. To identify the areas of surface water bodies potentially exposed to contamination by spray drift, the DR20, DR5 files (within the Lierza basin), and the RV15 file (for the whole Prosecco DOCG area) were intersected with the surface water bodies.

Moreover, the buffer along the hydrology network was converted from a polygon to a line file to obtain a linear value of each river bank potentially affected by spray drift from vineyard proximity; finally, the intersection between this line file and vineyard proximity value was replicated.

2.5 Calculation of the morpho-hydrological index and density maps

To better interpret the data, we considered the stream order related to the slope and the morphology of its basin. We assumed that higher hierarchic streams were capable of more water transport (due to hierarchy) and more water drainage (for higher slope values). Therefore, they might contribute to the wider contamination of freshwater ecosystems. The small mean area of the basins (4.19 ha) allowed us to obtain homogeneous shapes for every basin (i.e. the basins were in hilly landscape or in a plain one, and only in a few cases was there a mixed shape between these two main types). Hence, we considered the standard deviation of the basin heights to be a topographic index. According to Albaroot *et al.* (2018) and Koralay and Kara (2021), such an index is more performative and more accurate than the watershed relief used for measuring the height range of the watershed (H_{max}–H_{min}).

Therefore, this parameter, which properly describes the basin morphology for the aim of our study, was classified into 5 classes. Classes 1 to 5 describe decreasing standard deviation height value, that is, from basins with steep slopes to flat or quite flat basins in the plain or in the large valley bottom.

This topographic index of basin was associated with basin stream hierarchy by a simple times operation: a 19-value output was reclassified in a 6-class index that identifies basins with an increasing topographic and hydrographic drainage from the lower (1) to the higher (6). The higher this index value, the higher the probability that vineyard proximity will affect water quality. Using this morpho-hydrologic index (MHI) allows us to highlight different degrees of potential exposure and mitigation scenarios from pesticide contamination in freshwater ecosystems.

To obtain a synthetic map of a higher probability of experiencing pesticide contamination on surface water bodies, we performed a density calculation using the linear intersection between 5 m or 20 m vineyard buffers, as well as the hydrographic network on the whole Prosecco DOCG area. A more refined result in the density radius calculation was achieved by pre-processing the linear features with a densify tool fixing vertices every 2 m. The densified lines were then split into vertices. The density map was calculated with a 56.41 m and 564.1 m radius (to obtain 1 ha or 10 ha of area investigation, respectively). The value attributed to the line was its linear parameter (m), or the linear parameter multiplied by the basin value of the MHI.

The complete workflow including main data input, GIS geoprocesses, statistics and outputs is shown in Figure 4.

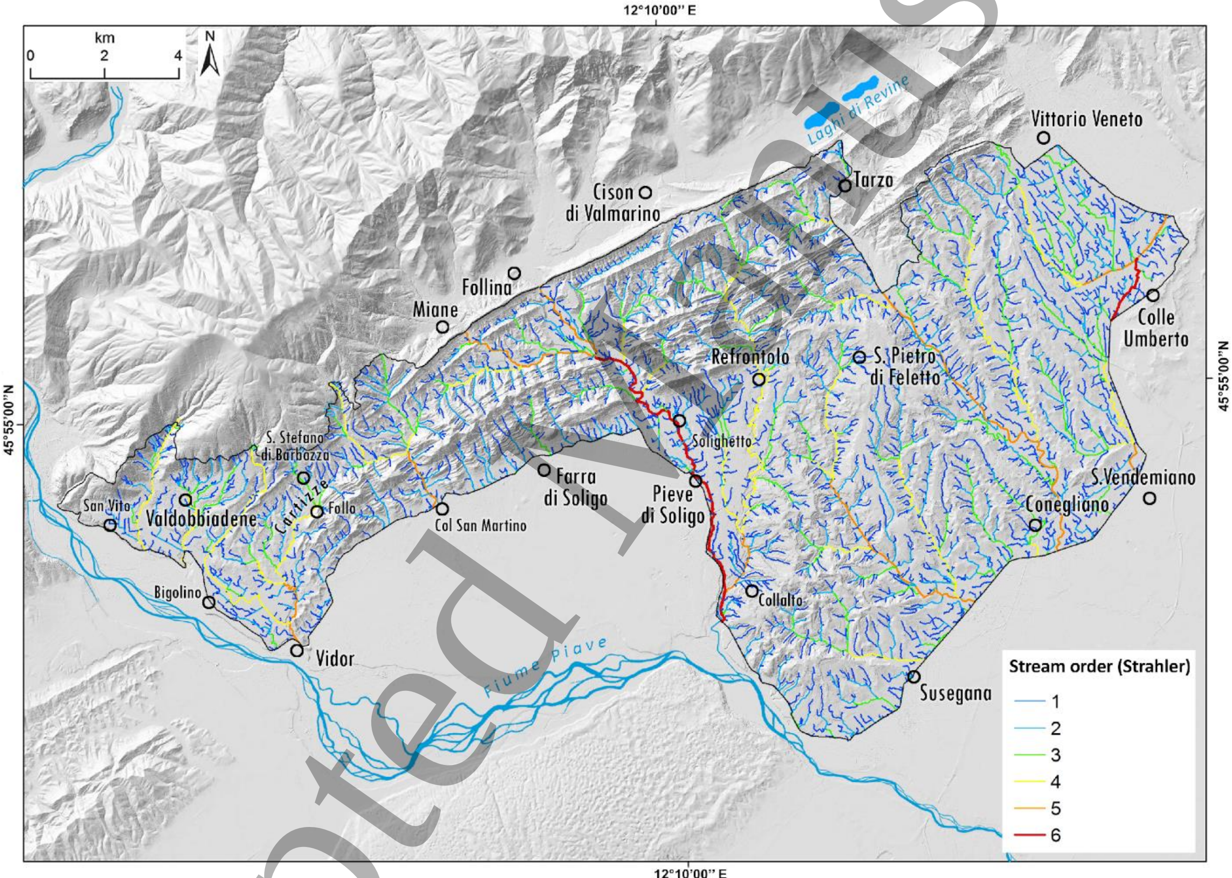


Figure 3: Extraction and classification of the hydrographic network within the Prosecco DOCG area.

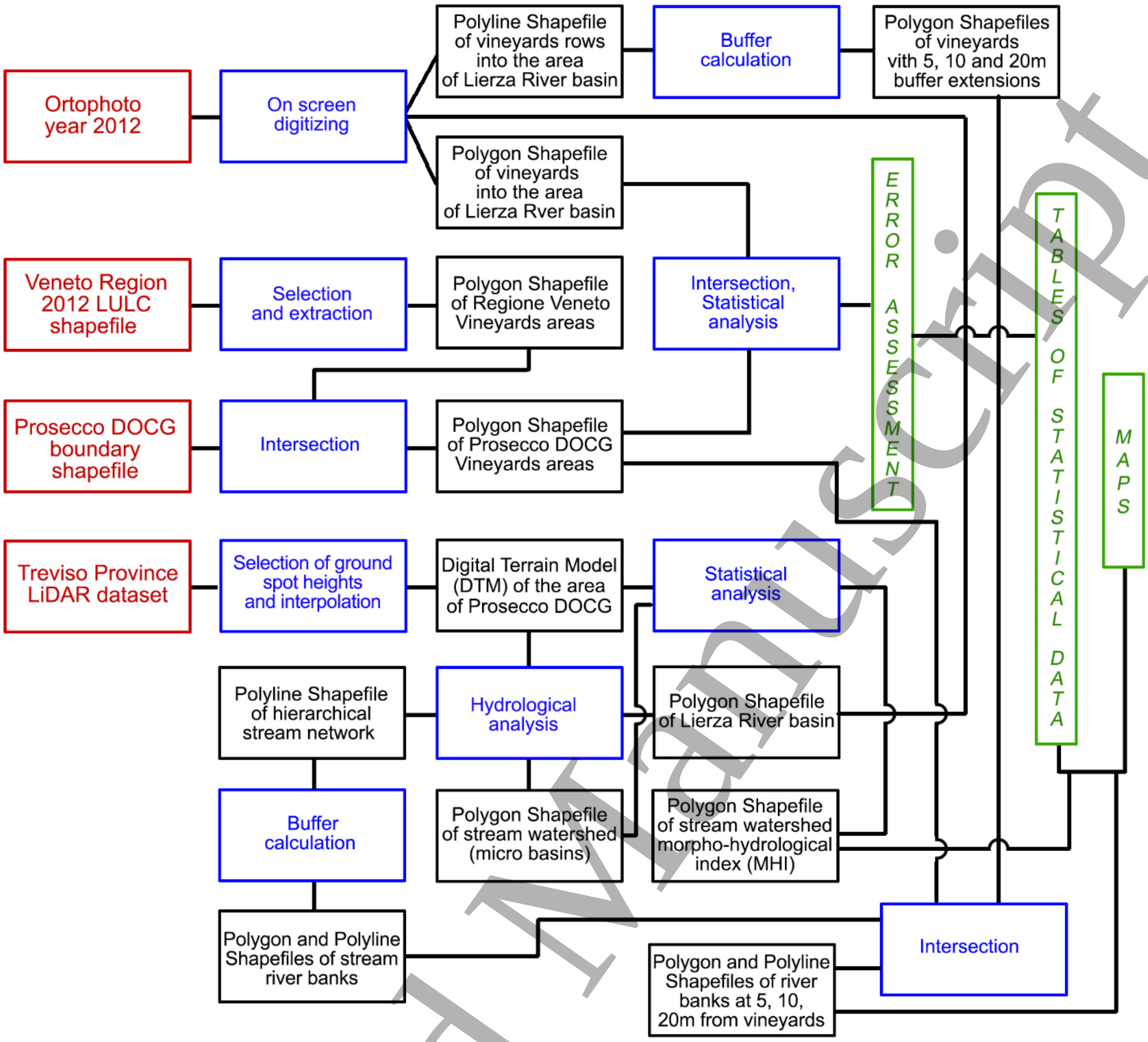


Fig. 4: Workflow of overall GIS analyses and main processes. In red input data, in blue GIS operations, in black intermediate and final geometries, and in green main results and outputs

3 Results

3. 1 Vineyard extraction and comparison

The automatic extraction of all vineyard rows by K-means and Isodata clustering algorithms allowed us to reclassify the image into discrete classes. The results were obtained from 16 to 5 classes (clusters). However, despite a high number of classes, results on vineyard row extraction showed high variability and mixed land use types due to the very similar spectral signatures of vegetation. Visual comparative analysis showed that if locally the difference between manually digitised rows and those extracted from the cluster analysis is very low, in different cases, geometric discrepancy is very high. Hence, we adopted manual extraction by image interpretation, which allowed us to map 27,901 vineyard rows for a total length of 1,630 km. The resulting shapefile was therefore clipped in the Lierza basin area, obtaining 1,587 linear km of vineyard rows. Two macro-area samples of vineyard rows extracted by photointerpretation from high-resolution ortophotos are shown in Figures 5 and 6.

Vineyard land use represents 19.1% of the total Lierza basin surface by a density of 3,005 m/ha.

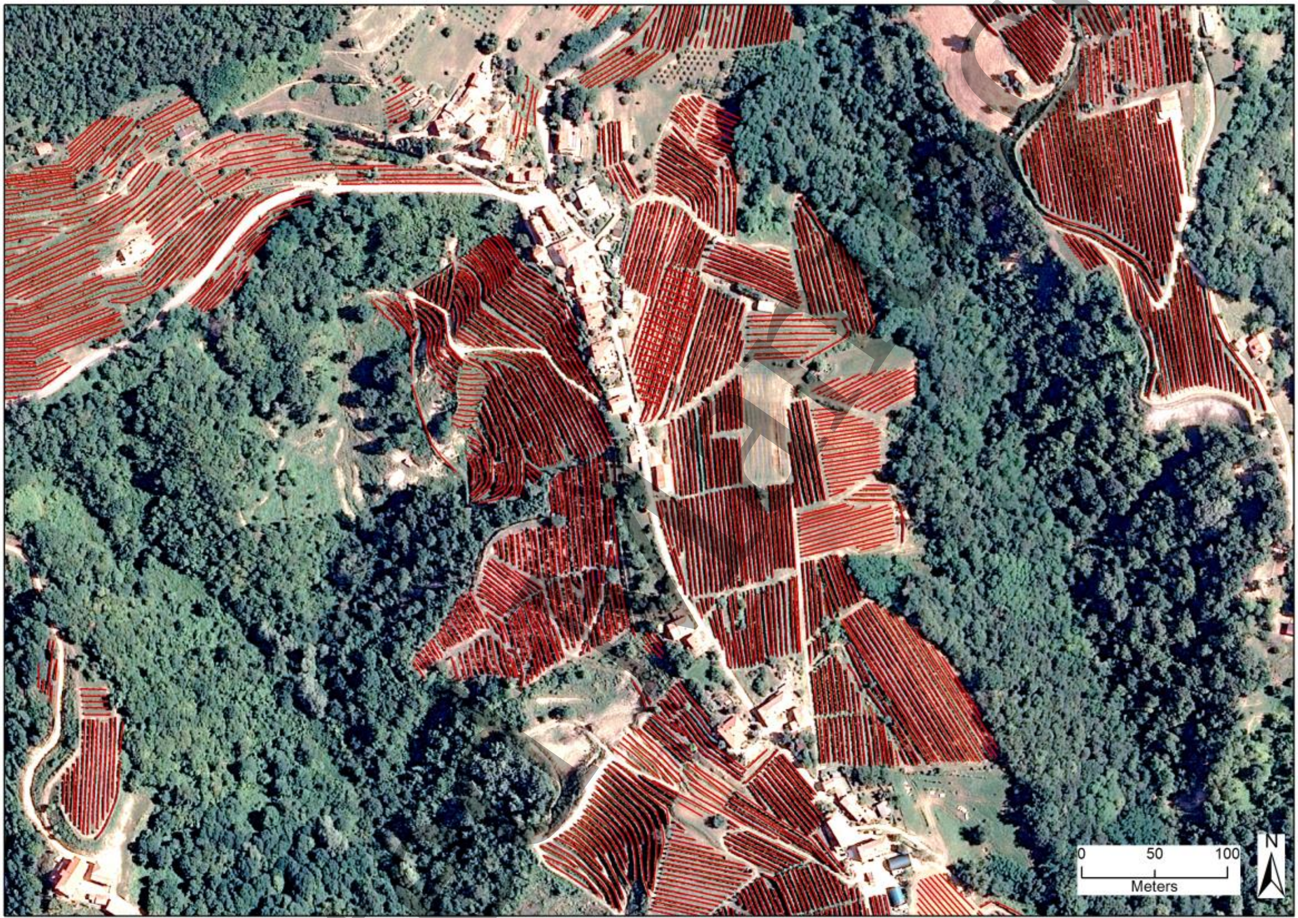


Figure 5: Vineyards in Lierza basin: extraction of vineyard rows by image photointerpretation on high-resolution ortophotos (2012, Veneto Region, 0.5 m image resolution)

The RV shapefile presented an area value very similar to the DR5 file (Table 3); this areal value comparison let us consider the RV shapefile as a vineyard perimeter with an applied buffer zone of 5 m. Moreover, the DR area with an applied buffer of 5 m was bigger (2.9%) than the RV area value. Hence, considering this latter value with a 5-m buffer allowed an underestimated, more conservative value. This conservative approach was also maintained for the 20 m buffer (15 m for the RV polygons), as shown in Table 3.

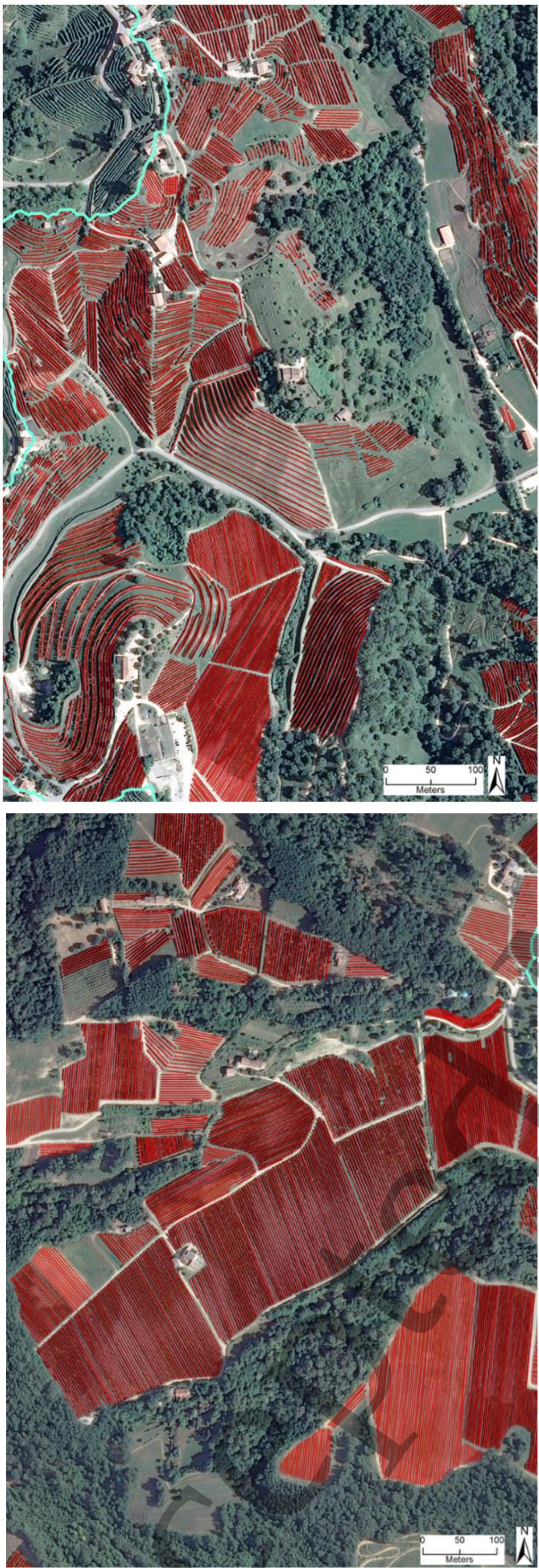


Figure 6: Vineyards in Lierza basin: extraction of vineyard rows by image photointerpretation on high-resolution ortophotos (2012, Veneto Region, 0.5 m image resolution)

Vineyards rows (km)	1,587
Vineyards area (ha)	528
Vineyards area + 5 m buffer (ha)	652.60
Vineyards area + 20 m buffer (ha)	971.35
Vineyards density (m/ha)	3,005.41
Vineyards from 2012 LULC (including 5 m buffer)	634.13
Vineyards from 2012 LULC 20 m buffer (ha)	912.47
Lierza basin area (ha)	2,665.37
Percentage of vineyards over the Lierza basin (%)	19.81

Table 3: Vineyards data comparison in the Lierza basin extracted by image photointerpretation on high resolution ortophotos (2012, Veneto Region, 0.5 m image resolution) and data from the 2012 LULC dataset of Veneto region

3.2 Stream network

The hierarchic hydrographic network extracted by the DTM topographic data was buffered and intersected with the vineyard-buffered polygons. The total stream network over the DOCG area measured about 1,050 linear km. Metrics about river networks and the Strahler order are shown in Table 4.

Stream Order	Number of streams	Total length (km)
1	2383	520.73
2	1194	277.08
3	542	123.88
4	328	79.763
5	185	35.42
6	73	12.91
Total	4705	1,049.7

Table 4: Hierarchy stream order values and length of the hydrographic network in the DOCG area

3.3 Streams/vineyards proximity and spatial interactions in the Lierza basin: Comparing data for scale-up analysis

We identified a few differences between DR5 and RV according either to the difference of their border or to new vineyard polygons mapped in DR files. DR5 geometry allowed us to detect 26.9 km (10.8%) of river banks from 5 m to vineyards against 31.4 km of the RV file (12.4%), which corresponded to a difference of 14.3% for river banks compared to DR data. The results of this intersection are shown in Table 5.

Furthermore, the area of this intersection was bigger for RV (5.9 ha) than for DR (4.8 ha). This was due to the less accurate vineyard delimitation in the RV dataset, which easily intersected stream drainage between the crops in the alluvial plain. The values were more similar considering the intersection between stream buffer and 20 m vineyard buffer. Here, the DR file intersected 67.1 km of river banks against 65.7 km of the RV file, a difference of 2.1%.

Hence, for the whole DOCG study area, where we used only RV data, we consider this result affected by a 14.3% uncertainty for the 5 m distance, and a 2.1% uncertainty for the 20 m distance between vineyards and streams (See Figure 2.1, Supplementary Materials 2.1).

Spatial relationships at 20 m and at 5 m distances among the external vineyard row and stream banks are shown in the two sample areas in Figure 7.

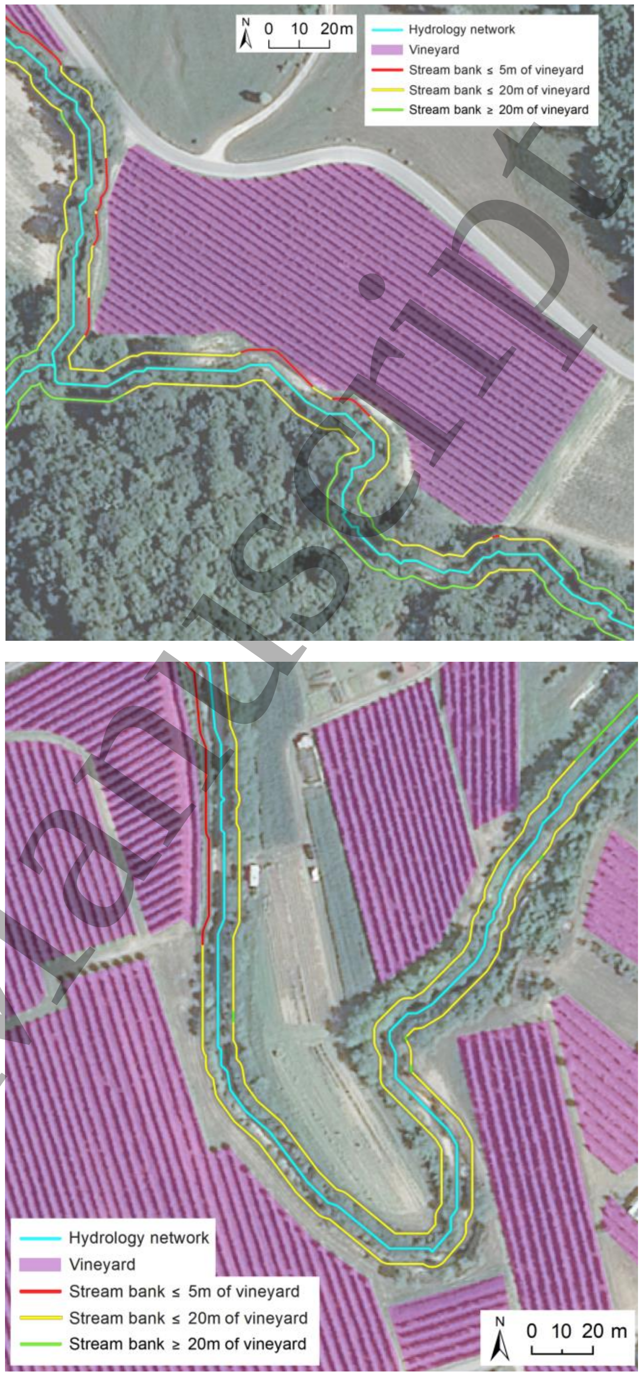


Figure 7: Potential exposure of stream banks to spray drift pesticide contamination at 20 m and 5 m distance from vineyard rows

Intersection between vineyards and streams in the Lierza basin	**DR**	**RV**	**DR %**	**RV %**
Freshwater ecosystem area within 20 m of vineyards (ha)	14.5	13.1	24.5	22.1
Freshwater ecosystem area within 5 m of vineyards (ha)	4.8	5.8	8.1	9.8
Length of river bank within 5 m of vineyards (km)	26.9	31.4	10.8	12.4
Length of river bank within 20 m of vineyards (km)	67.1	65.7	26.8	26.3

Table 5: Linear and areal values for streams – vineyards spatial interaction within the Lierza basin

3.4 Vineyards and freshwater ecosystems: Proximity analysis for river banks and watersheds in the Prosecco DOCG area

Considering an uncertainty of 14.3% we calculated in Lierza basin, the total length of river banks at a distance of 5 m from vineyards was about 340.5 ± 41 km (16.5%), whereas with 2.1% uncertainty and 20 m from vineyards, the estimated value was about 736.4 ± 15.7 km (35.7%). For a measure relative to the total stream network, we analysed these proximity values within every stream watershed. The results are presented in Table 6.

Intersection streams/vineyards	**Values**	**%**
Area within 20 m from vineyards (ha)	171.8	34.7
Area within 5 m from vineyards (ha)	69.0	13.9
Length of the river bank within a 20 m from vineyards (km)	736.4 ± 15.7	35.7
Length of the river bank within 5 m from vineyards (km)	340.5 ± 41	16.5

Table 6: Linear and areal values for streams-vineyards proximity in the Prosecco DOCG area

Proximity analyses at the basin and sub-basin levels showed that watersheds with river banks intersecting vineyards at 5 m, or even less, represented 37% (Figure 8): their surface extension accounted for 48% (103.1 km^2) of the total Prosecco DOCG area. Watersheds with all the river banks near vineyards (100% of river bank) represented 4.5% of the entire DOCG area (9.6 km^2) and 12.2% of the number of watersheds. Watersheds with at least one of its river banks at a distance of 5 m from vineyards (50% or more of river banks) were 15% of the DOCG area (32.2 km^2), and they represented 41.1% of the total number. Finally, 25% of the watersheds presented less than 10% of their river banks ≤ 5 m from the vineyards (value under or equal to 10%, see Figure 8).

The same analyses were performed at 20 m proximity between river banks and vineyards (Figure 9). The results showed that 52% of watersheds intersected vineyards, and they represented 63% (135.4 km^2) of the total Prosecco DOCG area. From this watershed, 28.5% of them have all their river banks (100% of river bank) near the vineyards (14.8% over the total number of prosecco DOCG watersheds).

Sixty-six of watersheds contains at least a river bank ≤ 20 m from vineyards (50% or more of river bank), representing 24.4% of the total number of basins in Prosecco DOCG area. Only 12% of watersheds had 10% or less of their river banks within 20 m distance from vineyards, unlike the 25% found within the 5 m distance (Figures 8, 9).

Geovisualisation of river bank proximity analysis at the watershed level highlights a higher probability of experiencing pesticide contamination from the vineyards due to spray drift, based on hydro-geomorphological assessment (Figure 10).

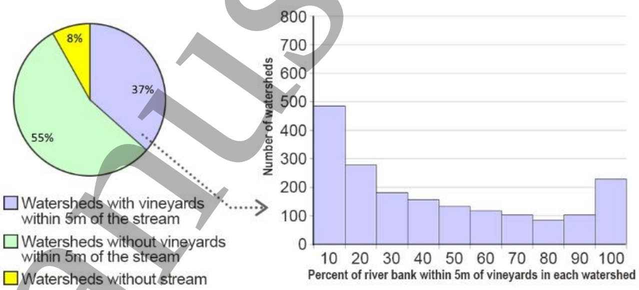


Figure 8: Distribution of watersheds in the Prosecco DOCG area with vineyard distance at 5 m from their stream/thalweg

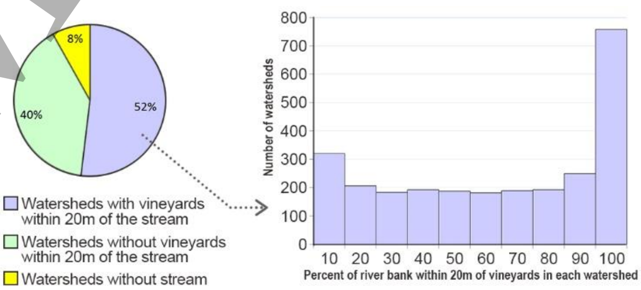


Figure 9: Distribution of watersheds in the DOCG area with vineyards at 20 m from their stream/thalweg

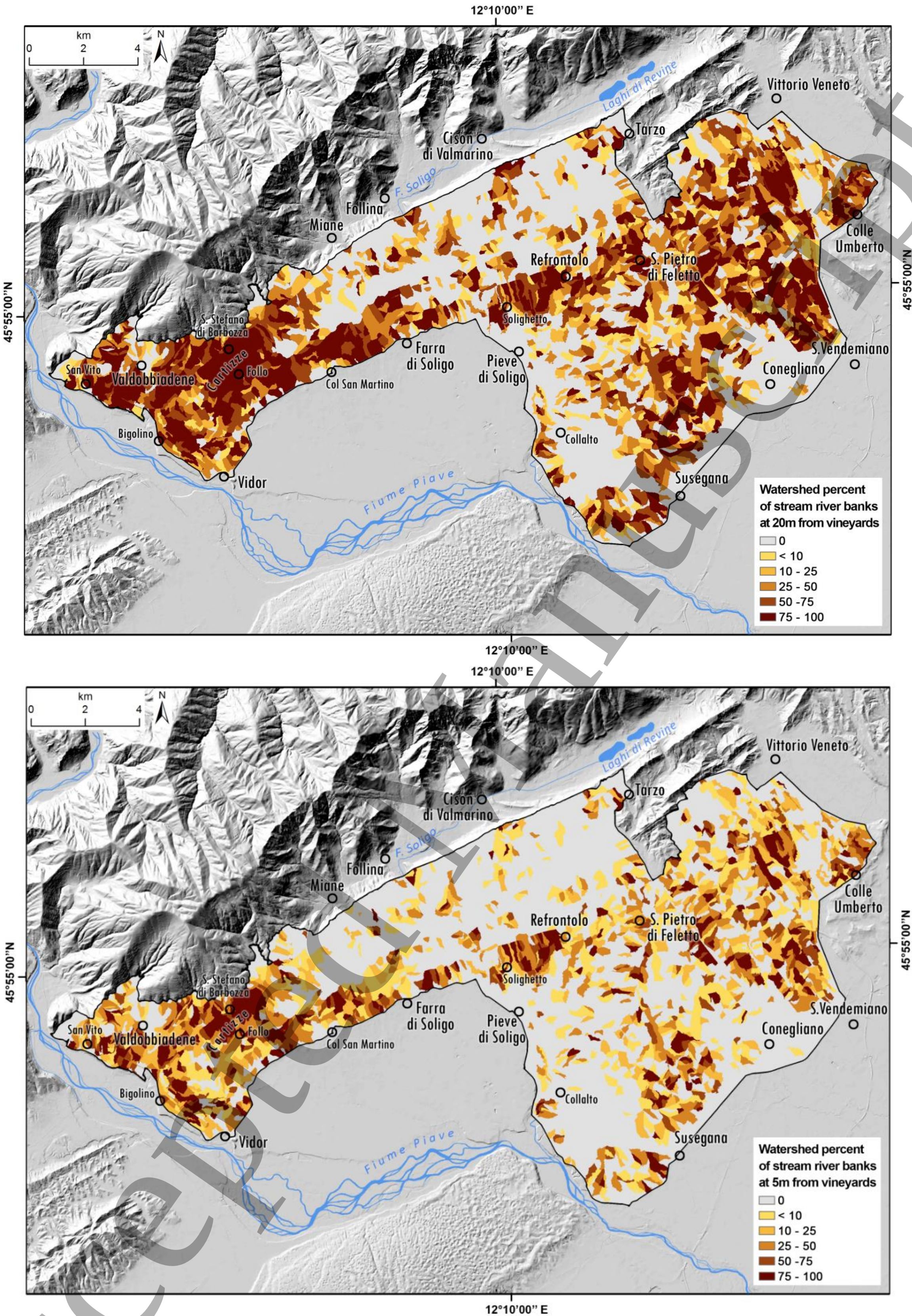


Figure 10: River banks with higher probability to experience pesticide contamination and potential mitigation effects from spray drift pesticide contamination at 20 m (10a) and 5 m (10b)

3.6 Modelling potential pesticide exposure on watersheds combining Morpho-Hydrologic Index into density maps

The MHI values allowed identification of the highest drainage basin transport by combining the morphology and stream order. The lowest MHI values were localised within the floodplain (classes 2, 3), whereas the highest values were along the hogback hills (NE sector) and the pre-alpine flanks (classes 3–5) (Figure 3.1, Supplementary Material).

By modelling river banks' proximity at 20 m and 5 m from vineyards, the density analysis provided a readable geovisualisation of critical areas with a higher probability of experiencing pesticide contamination due to spray drift and runoff (Figures 11a, 10b). Potential hotspots of pesticide contamination were mainly localised in the western sector (Barbozza and Cartizze), east of Valdobbiadene town. A higher probability of being exposed to pesticide contamination was also localised in the southern hogback sector, between Pieve di Soligo and Refrontolo (Col San Martino ridges), in the Feletto area, and within the plain area south of Vittorio Veneto.

Overall, spatial analyses based on morpho-hydrological assessment showed that, although integrated mitigation measures could be adopted to reduce up to 75% effect from spray drift, certain areas still remain potentially affected by pesticide contamination (Figure 11b).

4 Discussion

MHI methodology might be replicable and scalable in other similar geomorphological contexts if the baseline dataset for hydromorphological modelling is available at the same nominal resolution (LiDAR point density, orthophoto pixel size). In these cases, the adoption of the MHI is useful to provide a preliminary spatial assessment of the most vulnerable zones from pesticide contamination within a river network.

Proximity analyses combined with MHI modelling showed that due to their distance (5-20 m), freshwater ecosystems within the Prosecco DOCG area might be affected in different basins by spray drift pesticide contamination from conventional agricultural practices. We found distances between vineyards and streams to be critical, as 35.8% and 13.9% of river banks of the whole network were within 20 and 5 m from vineyards, respectively. Further, 37% of basins presented river banks intersecting vineyards at 5 m, while 52% were within 20 m distance. Areas with a higher probability of experiencing pesticide contamination due to spray drift, based on hydro-geomorphological assessment, were mainly located in hilly and steep slopes of the western sector, as well as on gently hills in the eastern sector, both northeast and southwest from Conegliano. These findings probably highlight the greater vineyard density in such zones (Figure 9).

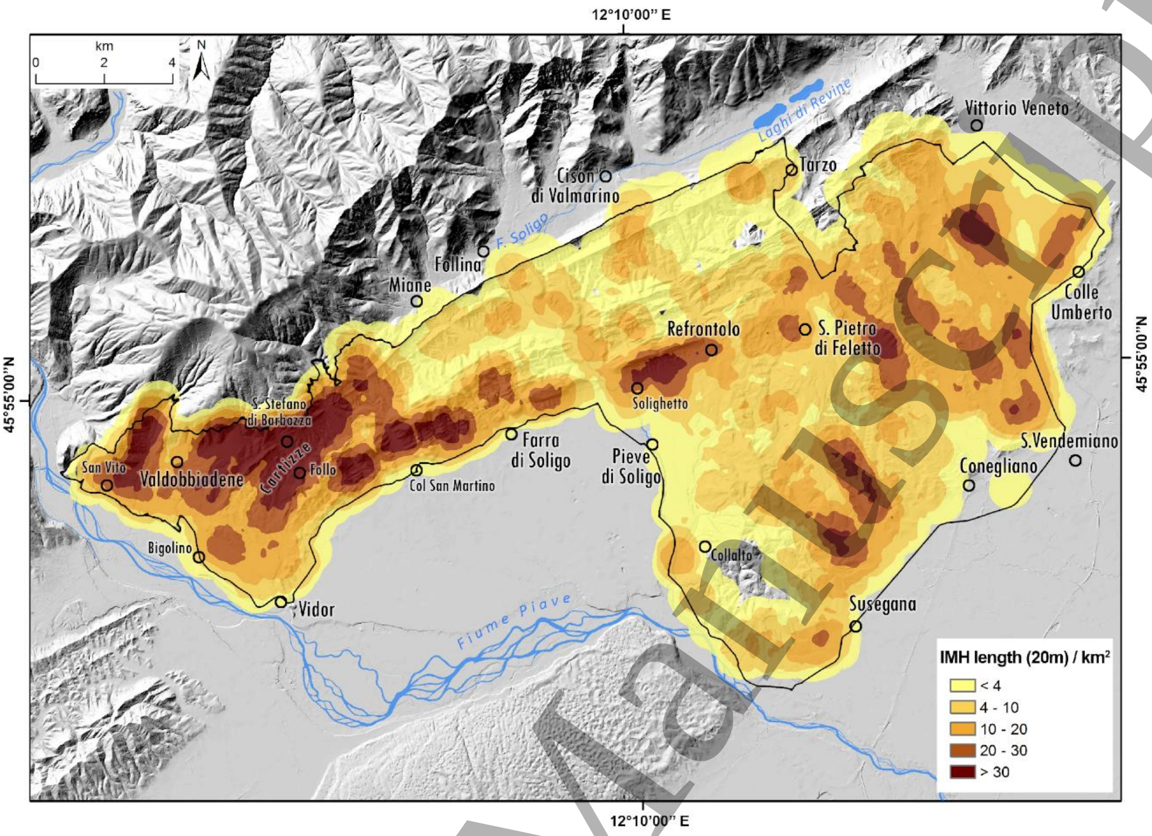
Further, the MHI density maps showed that in the highest mitigation scenario, pesticide contamination could potentially reach freshwater ecosystems in different hotspots due to the close proximity of vineyards to surface water bodies. In these cases, more performative mitigation measures should be adopted and integrated, and wider safety distances from the outer vineyard row should be considered. As reported on December 2021 by the UN Special Rapporteur on "the implications for human rights of the environmentally sound management and disposal of hazardous substances and waste", there is an increasing concern about the use of pesticides in the Veneto Region, particularly in the Treviso Province, within the Prosecco DOCG production areas (OHCHR 2021).

Modelled proximity analyses of river banks may also represent different mitigation scenarios if Nature-Based solutions, together with technical improvements, are implemented to control pesticide applications: buffer zones and hedgerows, adequate sprayer settings and nozzles, target-sensing spray technologies, and anti-drift formulations (Brown *et al.* 2008, Hilz and Vermeer 2013, Grella *et al.* 2017). In these cases, spray drift contamination might be reduced by 75%, minimising the effect on areas within 5 m of vineyards and therefore avoiding reaching part of riparian and aquatic ecosystems. Combining different mitigation measures in series increases and ensures the reduction of the risk of pesticide contamination in off-target zones (Otto *et al.* 2015). However, this combination should be arranged according to local environmental (weather trends, precipitation patterns, slope, presence of surface water bodies) and agronomic (number and pattern of pesticide applications, available sprayers, crop canopy management) practices.

Furthermore, the reduction of the risk of pesticide contamination in surface waters cannot be addressed solely at the field or farm level. An approach based on the catchment level is necessary, especially in areas as the Prosecco DOCG, characterised by a fragmented landscape with an alternation of orchards, vineyards, other cropped areas, natural areas, rivers, and ponds. A general concern for this area is also related to the LULC changes driven by Prosecco DOCG expansion, which increased from 4,000 ha in 2000 to 5,700 ha in 2010 and well beyond 8,000 ha in 2021 (Visentin and Vallerani 2018; ISPRA 2018; Basso and Vettoretto 2020; Consorzio Tutela Conegliano Valdobbiadene 2014, 2015, 2016, 2017).

Beyond the effectiveness of significantly reducing pesticide contamination sources, integrated off-field Nature-Based solutions should be considered by adopting an agroecological approach through the implementation of hedgerows and autochthonous vegetation along the river network. Such an approach may improve water quality and trigger an increase in aquatic and riparian biodiversity.

Our study provides the first contribution to identifying freshwater ecosystems that may be vulnerable to pesticide contamination due to their proximity to the outer vineyard row. Our results, therefore, highlight different potentially critical hotspots that should be monitored on-field by diffused sampling for an overall water quality assessment of river networks.



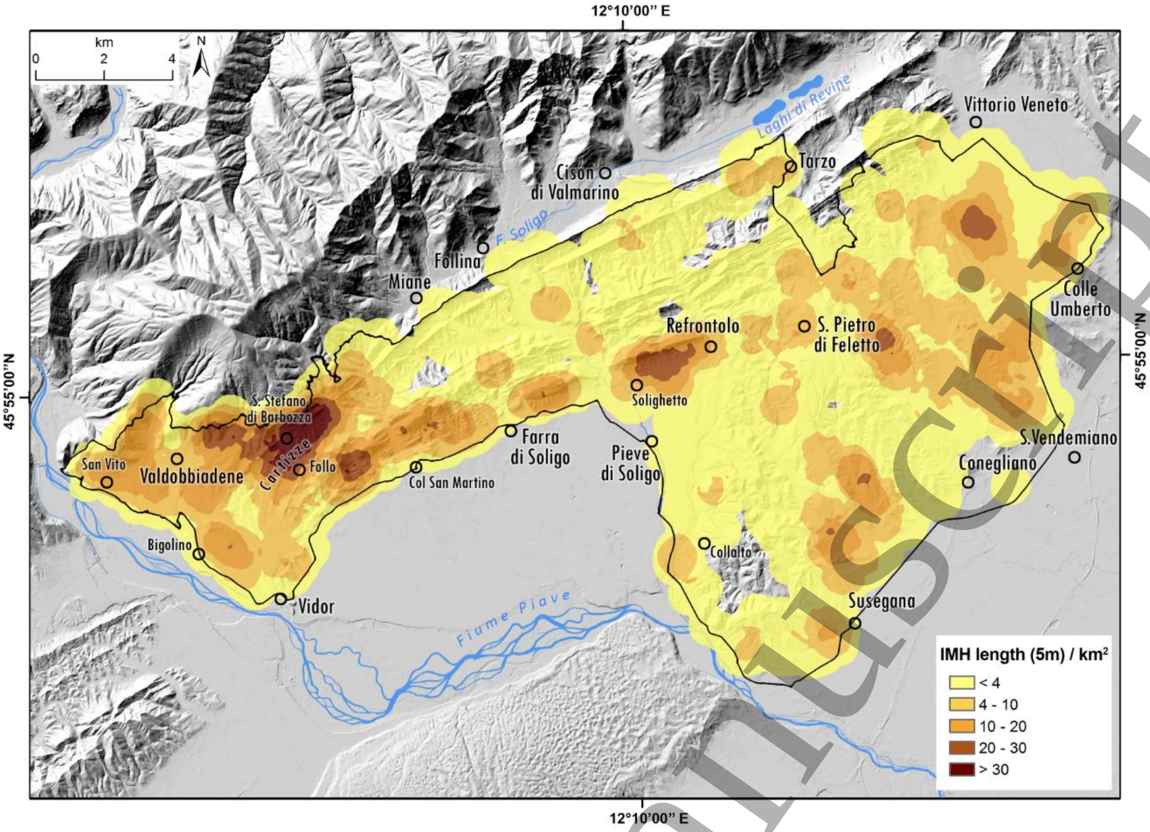


Figure 11: Density map combining Morpho-Hydrological Index (MHI) and vineyards proximity: 20 and 5 m proximity from vineyards for all watershed within the Prosecco DOCG area

5 Conclusion

This is the first study which investigated and modelled spatial proximity among vineyards and river networks within the Prosecco DOCG production area. Based on hydro-geomorphological assessment, our analysis highlights freshwater ecosystems with a higher probability of experiencing pesticide contamination due to spray drift from vineyards.

Modelled scenarios based on high-resolution spatial data such as LiDAR (2 points/m^2) and 0.2 m pixel size orthophotography allowed the detection of river banks and the identification of watersheds affected by vineyard proximity at 5 m and 20 m distance. Our findings suggest that various watersheds may be critical to pesticide exposure in the study area. However, integrated mitigation measures based both on NBs and in-field technical improvement could be adopted to drastically reduce surface water contamination and protect freshwater ecosystems and human health.

Our methodology, based on proximity analyses and on a simple morpho-hydrological index, can be replicated in similar agricultural contexts to screen critical areas and to assess the adoption of mitigation measures to reduce pesticide contamination.

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