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Processes of pesticide dissipation and water transport in a Mediterranean farmed catchment

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Abstract The contamination of soil and runoff water by diuron was monitored over several years at the field and the catchment level in a Mediterranean vineyard zone. Several aspects of pesticide behaviour in semiarid environments were observed. Pesticide dissipation in the soil was largely influenced by periods of drought, and large temporal changes in pesticide desorption properties occurred. The main pathway of pesticide losses at the field scale was the intense overland flow generated by heavy Mediterranean rainfalls. Soil treatment had a major influence on herbicide losses. Conventional tillage limited the contamination of surface waters in comparison to no-tillage, since it increased infiltration and restricted the use of herbicides. At the catchment scale the concentrations in pesticides of surface waters were similar to those at the field scale, due to the dominant Hortonian behaviour of the catchment. However, over a season the pesticide losses by runoff water were much smaller at the catchment scale because of important channel losses.

Key words catchment scale; field scale; herbicides; overland flow; semiarid climate; tillage; vineyard

INTRODUCTION

Pesticides are widely used in modern agriculture in most countries throughout the world, and in a large range of environments. However, environmental monitoring increasingly indicates that trace amounts of pesticides are present in surface and underground water bodies, far from the sites of pesticide application. To find strategies for limiting the contamination of the surrounding environment, the processes affecting the persistence and transport of pesticides have been studied widely for many years. However, so far, the majority of studies has been performed in temperate or humid conditions, and consequently there is a need for studies about pesticide behaviour in other environments. This is especially so in semiarid or Mediterranean areas for two main reasons. Firstly, the risk of contaminating waterbodies by pesticides is not less severe in semiarid climatic conditions (e.g. Albanis *et al.*, 1992; Lennartz *et al.*, 1997) than in others (e.g. Franck & Sirons, 1979; Ng *et al.*, 1995), and it has potentially large social consequences given the limited water resources. In effect, the intense rainfall events of semiarid climates, combined with often discontinuous soil cover by crops,

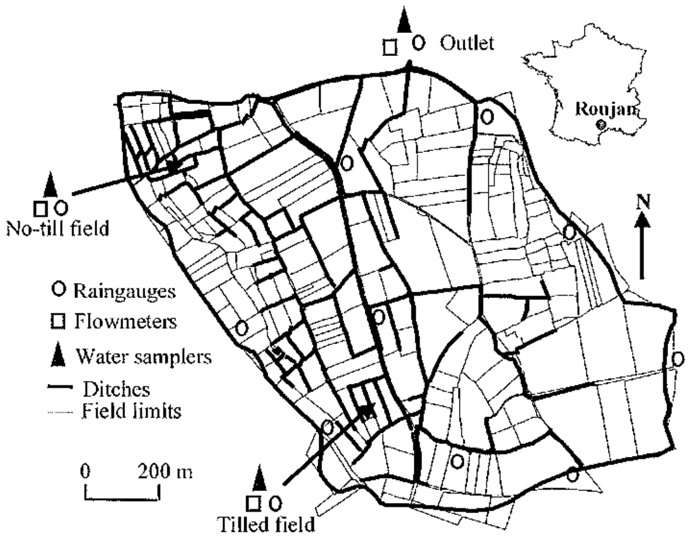

Fig. 1 Field limits, network of ditches and location of monitoring sites on the Roujan catchment.

are well known to cause intense overland flow and erosion, and thereby high leaching potential of pesticides. Secondly, the specific characteristics of semiarid areas require the re-evaluation of pesticide behaviours observed in other conditions.

In this paper we illustrate some aspects of the behaviour of pesticides in semiarid agriculture by analysing patterns of pesticide persistence and pesticide transport at the field and catchment scales which we have monitored in the vineyard-growing area of southern France since 1995.

MATERIAL AND METHODS

The experimental site is a 91 ha catchment located in southern France (43°30′N, 3°19′E) (Fig. 1). The main crop is grapes. The site is primarily man-made, with terraced slopes, a major network of ditches collecting the runoff water, and a finely divided land register of more than 150 fields. In geological terms, the substrata derive from marine, lacustrine or fluvial sediments. According to the FAO soil classification system, the main soil types are luvisols, regosols and cambisols.

The climate is sub-humid Mediterranean, with a prolonged dry season. Average annual rainfall is 650 mm and average annual Penman potential evapotranspiration is 1090 mm. There is a large year-to-year variability in rainfall. Monthly maximum precipitation is registered in February and October. Average summer (June–August) precipitation is 84 mm. Rainfall mainly occurs as storm events, with an average rainfall intensity of 31 mm h^{-1} and maximum intensity of 177 mm h^{-1}, as measured over time steps of 5 min.

The basic hydro-meteorological equipment has been in place since May 1992 (Fig. 1) It consists of a rainfall measurement network (13 rain gauges), a piezometric measurement network (14 sites), a system for monitoring water flows, suspended solids and pesticides at the outlet of the catchment and of two fields with different soil

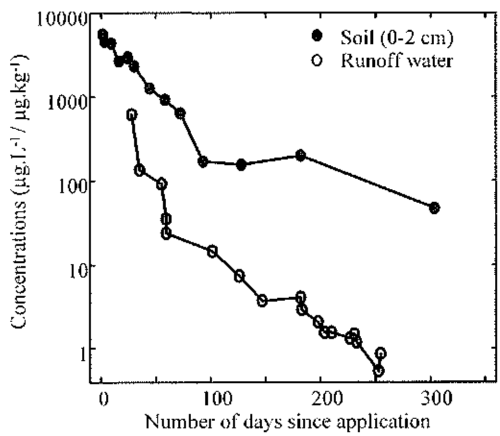

Fig. 2 Evolution of average diuron concentration in topsoil (0–2 cm) and in storm flow water during 1997 (after Louchart *et al.*, 2000).

treatments. In one field, named hereafter the no-till field, herbicides are applied over the whole vineyard without any tillage; in the other field, named herafter the tilled only and tillage is operated between the rows. To determine herbicide persistence in the soil, the soil surface (0–2 cm) of the monitored fields was sampled according to a spatially-stratified random scheme and to fixed time intervals since application. The study was focused on the herbicide diuron, since it is one of the most widely used herbicides for controlling weeds in vineyards in southern France. The results presented hereafter concern mainly the period 1995–1998. Full details of the sampling designs can be found in Lennartz *et al.* (1997) and Louchart *et al.* (2001).

RESULTS AND DISCUSSION

Patterns of herbicide dissipation and transport at the field scale

Figure 2 shows the typical evolution of herbicide concentrations in the soil surface and in the overland flow water that can be observed after application in a vineyard field in the Roujan catchment. The herbicide concentration of the surface soil exhibits a constant decrease with two phases. In the first, the decay of diuron is fast, whereas in the second, the decay slows down and may even stop temporarily. The transition between the first and second phase occurs mainly in June, at the start of the dry summer conditions, which are known to limit or stop soil microbial activity. These observations show that the dry conditions that can prevail in semiarid climates favour the persistence of pesticides in the surface layer of the soil at the field scale during several months after application, and thereby increase the length of the period during which there is a risk of water contamination. The period of risk will be even longer at the catchment scale since there is a large variation in application dates between the fields of a given catchment area.

The temporal pattern of herbicide concentration in overland flow water is closely related to that in the soil. The large water contamination during the rainfall events after

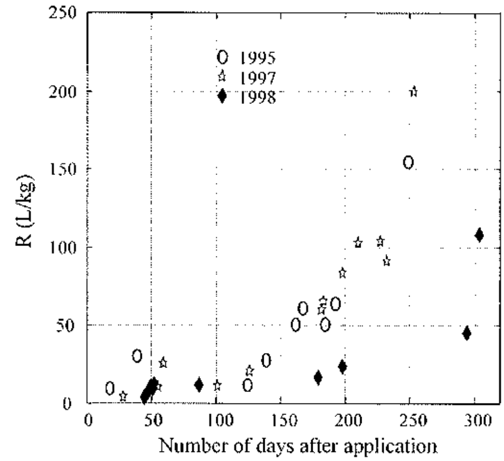

Fig. 3 Evolution of the ratio R between diuron concentration in topsoil (0–2 cm) and in storm flow water during three years of monitoring (after Louchart *et al.*, 2000).

application is worth noticing, but also the persistence of a significant level of contamination more than 250 days after application. This is to be related both to the large intensities of rainfall in the Mediterranean area, which wash off the soil surface, and to the slow degradation of diuron in the soils, as stressed above. A difference in slope between the herbicide decays in soil and water can also be observed. It suggests a decrease with time of the extractability of diuron by overland flow. Figure 3 shows the computed ratios between diuron concentrations in topsoil and in overland flow water for all runoff events of three monitoring years. These ratios correspond to apparent linear distribution coefficients K_{app} between solid and liquid phases in a desorption process (Louchart *et al.*, 2000). The observed values of K_{app} increased in a rather similar way each year and were 1.8 to 75 times larger than the distribution coefficient K_d measured in batch conditions. These results indicate that it is necessary, under the specific conditions of the present study site, to consider a time-dependent K_d value in pesticide transport modelling.

The patterns of herbicide transport at the field scale are also largely influenced by soil treatment. Table 1 indicates the range of diuron losses that could be observed between the tilled and non-tilled fields. The losses, expressed in percentages in order to account for the difference in applied quantities between the two fields, are two to three times larger on the non-tilled field. This arises from the fact that tillage increases the soil infiltration capacity of the vineyards, whereas no-tillage practices favour the presence of permanent crusts of small permeability on the soil surface. Andrieux *et al.* (1996) observed on the Roujan catchment that overland flow is twice as large at the annual scale on the non-tilled field than on the tilled fields.

Patterns of herbicide transport at the catchment scale

Figure 4 shows that the outflow at the outlet of the catchment is clearly event-dominated. This is representative of the hydrological cycle in the Mediterranean zone.

Table 1 Variation in losses in diuron concentrations at the field and catchment scales during three years of monitoring. The values are expressed as percentages of applied quantities. At the field scale, two values are given which indicate the observed range of variation between the tilled and no-till fields.

	Field scale	Catchment scale
1995	0.4–1.4 %	0.05%
1997	0.9–3.3 %	0.50%
1998	3.8–6.0 %	0.30%

The catchment's very short times of response to rainfall pulses indicate that water flows during rainfall are primarily dominated by Hortonian overland flow. This was confirmed by hydrochemical tracing (Ribolzi, 1996) which showed on some events that up to 80% of the peak flow was due to overland flow. Despite the event-dominated nature of outflow, some seasonal characteristics are apparent. Three periods can be distinguished. The first corresponds to the period during which the water table in the depression of the basin is high, namely from October to May. In that instance, the network of ditches drains the water table, which produces a permanent, although minor, baseflow. The second period is summer, during which rainfall is rare, the water table comes down and baseflow ceases. In that situation, the intense summer storms of the Mediterranean climate rarely affect the catchment's outflow. This is because either soil moisture is low and thus no runoff is produced at the field scale, or because field runoff is captured by the ditches and re-infiltrates to the groundwater (see also Marofi, 1999). The third period corresponds to the transition between the dry and wet periods. It is very short, as can be seen in Fig. 4. The first main rainfalls in autumn replenish the groundwater of the catchment in less than 1–2 days.

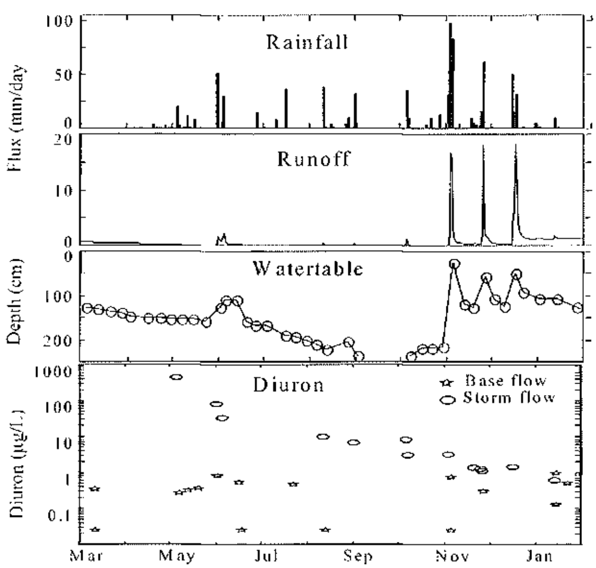

Fig. 4 Observed values of daily rainfall: (a) catchment runoff, (b) and average concentrations in diuron, and (c) in storm flow and baseflow in 1997 (after Louchart *et al.*, 2001).

The contamination of runoff water during storm flow and base flow is shown in the bottom graph of Fig. 4. The concentrations of diuron in storm flow are almost of a similar magnitude to those measured in overland flow at the field scale, which confirms the predominance of Hortonian flow in catchment flow during the runoff events. There is therefore no significant dilution effect by antecedent water between the field and the catchment scale, and in turn the average level of water contamination at the outlet of the catchment seems to be larger than that observed in other catchment studies in which Hortonian flow is less dominant (e.g. Franck & Sirons, 1979; Ng *et al.*, 1995). The concentrations of diuron in base flow are always one or more orders of magnitude less than in storm flow, and additionally do not fluctuate very much even after the great flushes of diuron that occur during the first runoff events after application. To explain this dynamic of the contamination of base flow, which in fact corresponds to the average contamination of the groundwater, there are two hypotheses (Louchart *et al.*, 2001). One is that inertia of the groundwater, namely the ratio between its water store and the amount of recharge by surface waters during a given runoff event, is large. Another is that adsorption and degradation processes occur in the groundwater, which limit the increase of water contamination.

Comparing in Table 1 the losses of pesticides between the field and catchment scales shows large differences. They are mainly due to the fact that a significant part of the overland flow exiting the field re-infiltrated in the soils and the groundwater of the catchment by seepage in the ditch network.

CONCLUSIONS

This study of the behaviour of herbicides in a Mediterranean catchment covered mainly by vineyards shows several points that should be considered for pollution monitoring designs and transport modelling approaches in semiarid environments.

The concentrations of pesticides in topsoil decline irregularly after application according to the succession of rainy and droughty periods. Decay models taking into account water content and temperature effects on pesticide transformation are required.

The main pathway of pesticide losses to runoff water at the field scale is the intense overland flow that is generated by the heavy rainfalls of the Mediterranean climate. Losses by percolation through the soil can be assumed to be small given the overall water deficit in semiarid regions.

The observed temporal patterns of pesticide concentration in runoff water appeared to be related to the decay of pesticide residues at the soil surface, but also to temporal changes in pesticide sorption properties and to overland flow intensity which seem to have a large influence in semiarid conditions.

Soil treatment is a main factor of variation of herbicide losses by overland flow in vineyards, since it modifies the infiltration properties of the soil surface. In this respect conventional tillage clearly limits the contamination of surface waters in comparison to no-tillage practices, since it increases infiltration and restricts the amount of applied herbicides.

At the catchment scale the contamination of surface water is irregular, very large during storm flow periods and moderate during base flow periods. Consequently most pesticide losses occur during the runoff events.

Although the concentrations in pesticides of surface waters are similar at the field and catchment outlets due to the dominant Hortonian behaviour of the catchment, over a season the pesticide losses by runoff water are much smaller at the catchment scale because of the important channel losses that are characteristic of the hydrological behaviour of semiarid catchments.

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