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LESSONS GAINED FROM FRENCH R&D PROGRAMS FOR PESTICIDES DISSIPATION BY USE OF CONSTRUCTED WETLANDS

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ABSTRACT Pesticide pollution is a major threat of surface water quality in France. To comply with the European Water Framework Directive (2000/60/EC), authorities have decided to implement a Phyto-Pharmaceutic Products or pesticide reduction plan. It targets a 50% reduction of pesticide inputs by 2018. This plan only considers actions on farming practices and does not foresee any actions on transfers through catchments, assuming that pre-existing buffer strips are efficient. This assumption is not verified on a significant part of the territory for which complementary solutions for the control of pesticide transfer have to be found. Thanks to two R&D research programs regarding constructed wetlands, we got the opportunity to improve the state of the art, assess the performance of constructed wetlands and find economical, legal and social incentives for further nationwide extension. Two constructed wetlands were tested at both pilot and field scales. On-site wetlands were located at the outlet of sub-surface artificially drained catchments. Two contrasting regions have been chosen as well. In all cases climatic parameters, and water and pesticide flows in and out have been measured and monitored. We also recorded the conditions of implementation since we were very close to real conditions. For this purpose inquiries addressing the various actors were carried out by sociologists. The results of the performance regarding pesticide dissipation are shortly given. Sociologic approaches and amenities assessments have revealed unsuspected relations of the farmers with the society and the environment, and vice versa. The implementations have resulted in a co-construction where each actor had personal involvement. Even if co-construction should be a driving line, solutions for appropriate incentives and land reallocation tools should be discussed with politics and authorities in order to facilitate further realizations.

Keywords: Drainage, Non point pollution, Pesticides, Co-construction, Mitigation, Constructed wetlands.

INTRODUCTION Pesticide pollution is a major threat of surface water quality in France. To comply with the European Water Framework Directive (EWFD, 2000/60/EC), which requires a "Good Ecological Status" for all waterbodies in 2015, French policy adopted a Phyto-Pharmaceutic Products’ or pesticide reduction plan (ECOPHYTO 2018 plan). This program aims at inciting farmers to halve the annual amount of pesticides used. Nevertheless, the question of pesticide transfer is not solved. Presently the "zero pesticide" solution is not achievable for technical and economical reasons. About 10% of the French arable land is drained by subsurface drainage. The main role of the buried pipes is to control shallow water table in waterlogged soil during winter period. It concerns generally cereal crops such as winter wheat, barley and rape. This technique is mainly used in a context of intensive agriculture. The conjunction of pesticide's use for agricultural purpose and preservation of surface water quality is a new challenge for sustainable drained agriculture. One of the specifities of drainage is to collect water in pipes thus transforming non-point source application to point source pollution. This particularity is an advantage to introduce the buffer zone concept, which is well developed for nitrogen in the US, northen Europe, but new for pesticide issues.

This study gathers conclusions obtained from two applied research projects: Life ArtWET (06 ENV/F/000133) and TRUSTEA (Rustic Treatment of Agricultural Water). This paper will discuss the potential efficiency of artificial wetlands to mitigate pesticide pollution and detail an example involving actual stakeholders.

LITERATURE REVIEW OF MITIGATION SOLUTIONS FOR DIFFUSE POLLUTION CONTROL AND FIRST OPERATIONAL CONCLUSIONS

Literature review A recent review (Reichenberger et al. 2008) made an inventory of all the actions that could be implemented at the watershed level: reduction of pesticide application rates, vegetative filter strips etc. Nevertheless, in case of subsurface artificially drained soil, pipes shortcut water directly transferring it to natural receiving waters. The concept of buffer zones thus includes not only runoff mitigation measures like vegetative strips, but systems collecting and treating water coming from subsurface artificially drained areas as well. Among existing buffering solutions, constructed or artificial wetlands seem to answer this challenge. Indeed artificial wetlands could play a buffering role between the pipe’s outlet and natural water bodies, by intercepting and treating surface water.

Figure 1 shows the result of a literature review about pesticide mitigation efficiencies measured in artificial wetlands. Fifteen of the papers focused on pesticide mitigation in wetlands viewed as black boxes. The authors only compared inlet to outlet pesticide concentrations or loads. Results showed a huge variability (between 10 to 90% of pesticide removal) mainly due to pesticide properties and specific hydrological context (in situ study vs. laboratory mesocoms). All the experiments were carried out under controlled conditions (i.e. steady state inlet hydraulic head, tracers…). None of these studies assessed the ratio of water flows intercepted by the artificial wetland to the total amount of water produced by the watershed.

The vast majority of existing studies (e.g. Schulz and Peall, 2001) suggests that constructed wetlands are very effective in reducing pesticide inputs in surface waters. A potential drawback is that they can be quite area-consuming: the largest investigated wetland was 134 m long and 36 m wide (Moore et al., 2002). However, smaller, less area-demanding wetlands (e.g. 50 m long and 1.5 m wide; Moore et al., 2001) were found to be very effective in removing pesticides from the water passing through the wetland. Yet, it has to be noted that almost all available studies dealt with strongly sorbing insecticides (e.g. chlorpyrifos) with a strong tendency to adsorb to macrophytes,

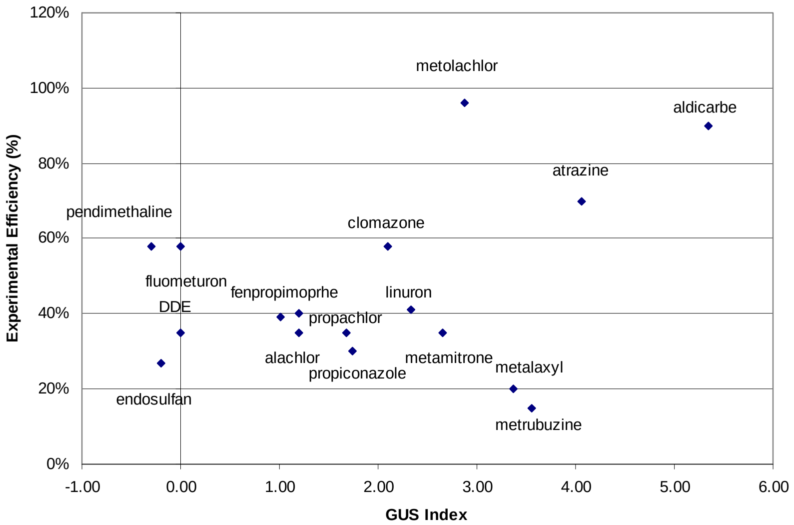

Figure 1. Review of experimental efficiency for pesticide dissipation by artificial wetlands (GUS index is calculated considering adsorption coefficient and degradation properties).

suspended particles or bed sediments. Only one study (Moore et al., 2000) investigated the fate and transport of atrazine, a moderately sorbing herbicide in constructed wetlands. Moore et al. (2000) found that a travel distance of 100 - 280 m through the wetland would be necessary to achieve effective runoff mitigation. It can therefore be concluded that more research on the effectiveness of constructed wetlands for removing moderately and weakly sorbing pesticides must be conducted.

The expected processes involved in this kind of system are photodegradation, chemical degradation (such as photolysis, hydrolysis, oxydo-reduction reactions), biodegradation, adsorption. Because of a large number of active ingredients and a wide variety of dissipation pathways, these processes are all working together in artificial wetlands.

From the literature review, we can conclude that:

- Vegetalized wetlands are more efficient than non vegetalized ones (Rose et al., 2006; Moore et al., 2002).
- Retention rate is linked to hydraulic residential time and hence to wetland water storage capacity (Rodgers and Dunn, 1992; Dierberg et al., 2002)..
- Efficiency rate is linked to pollutant load (Moore et al., 2000; Moore et al., 2001; Schulz and Peall, 2001).
- Wetland efficiency is inversely correlated to velocity (Dierberg et al., 2002; Haarstad and Braskerud, 2005).
- Efficiency depends on the whole system: substrate, vegetation and physico-chemical conditions (Blankenberg et al., 2006; Braskerud and Haarstad, 2003).
- Efficiency depends on initial concentrations:(Blankenberg et al., 2006) and hydraulic residential time is the main factor controlling pesticide degradation.

Specificities of drainage hydrology As shown previously, residential time is a crucial parameter for pesticide mitigation. This point is strongly linked to drainage hydrology. Pesticides are mostly transferred via subsurface pipe drains during the first floods following their application. In case of winter crops, pesticide major application periods are November (for herbicides like isoproturon), March to May (herbicides, fungicides like expoxiconazole, and insecticides like lambda-cyhalothrine). These periods particularly match the start of the hydrologic year for drainage (fall) and spring drained flows. The largest amounts of water at an artificially drained watershed outlet in France are measured from December to February (Tournebize, et al. 2008). This winter period corresponds to that during which no pesticide is applied. The period of common occurrence between pesticide transfer occurrence and drainage functioning is then reduced to November and March to May months. Branger et al. (2009) showed that 90% of pesticide loads is due to the first three flow events after application. This means that there is no use trying to treat all water volumes. Focusing on the first flows after pesticide application may help mitigating a high proportion of total pesticide loads in reduced water volumes. Moreover during this period, peak flows are relatively small (0.5 to 1 L/s/ha) compared to those recorded from December to February (1.5 to 3 L/s/ha).

First operational conclusions In addition to the reduction of pesticide use at the farm scale, buffer zones's implementation between arterial drainage network and natural receiving waters is expected to meet the objective of pesticide transfer limitation. Land availability is the key issue. Currently a 1-2% wetland area to watershed area ratio is an achievement we will optimize in further works by use of modeling. For wetland surface area being restricted, a water management strategy has to be established in order to catch the maximum pesticide loads within the minimum drained water volumes. Passeport et al. (2010) introduced one of our views in the drainage context. Due to seasonality of pesticide transfer, a parallel wetland option appeared to be better than a "in a series" one. This parallel wetland is connected to the arterial ditch by a buried pipe whose diameter was voluntarily restricted to only let 1 L/s/ha discharge pass through the wetland (see figure 2). In the context of rural area, for farmers being themselves in charge of wetland construction fees, design rules should favor low cost and rustic material.

EXPERIMENTAL ASSESSMENT OF EFFICIENCY OF ARTIFICIAL WETLAND As part of the TRUSTEA project, two complementary experiments were carried out in order to evaluate the potential of pesticide retention in artificial wetlands. The former one called "Evieu test", assessed the inlet-outlet pesticide mitigation in a horizontal subsurface flow wetland. The second experiment, herein called "column test" focused on pesticide mass balance in pilot-scale mesocosms.

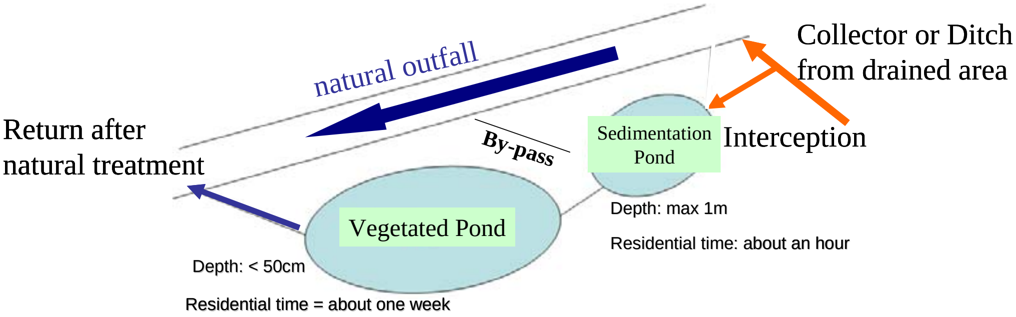

Figure 2. Proposed diagram of artificial wetland for pesticide mitigation in subsurface artificially drained areas.

Table 1. Measured removal efficiencies of conservative tracer (Bromide), and a cocktail of pecticides (DIU=Diuron, IPU=Isoproturon, TBZ=Tebuconazole, AZS=Azoxystrobine) in a horizontal subsurface flow constructed wetland under controlled conditions.

	Bromide	DIU	IPU	TBZ	AZS
Injected Concentration (µg/L) ([a] mg/L)	300[a]	82	104	60	67
Koc (g/cm^3 ; laboratory)		428	120	1027	423
DT50 (j ; from Agritox)		29	17	107	12
% outlet load*	89%	63%	73%	10%	24%
maximum concentration in % measured at outlet*	8,4%	4,1%	6,7%	0,5%	1,5%

* calculated from inlet values

Tracer experiment under controlled conditions: Evieu Test Evieu's site is a constructed wetland which has been designed as a wastewater treatment plant designed for 200-people equivalents and equipped for experimental purpose (Molle et al. 2008). A multi-pesticides tracer (diuron, isoproturon, tebuconazole, azoxystrobine, and bromide as conservative tracer, see table 1) was spread in the last pond considered as horizontal subsurface flow constructed wetland during 2.33 h. Reeds (phragmite australis) covered 100% of the 66 m² (length = 17 m, width = 3.9 m, depth = 0.6 m) surface area. The steady state (4.5 m^3/day) was maintained by pumping. The wetland outlet has been monitored for discharges and pesticide and bromide concentrations for 3 weeks.

Results from table 1 shows that removal efficiency is linked to pesticide properties, from sorptive (76% for azoxystrobine and 90% for tebuconazole) to non sorptive (27% for isoproturon and 37% for diuron) molecules. This on-site experiment highlighted the potential efficiency of constructed wetlands under steady state conditions. However, no information concerning the fate of those pesticides within such a wetland was available. Further experiments are described below.

Pesticide behavior in experimental columns. An experiment was carried out in columns to assess absorbed pesticide in reed (phragmite austalis) tissues. Seven columns were filled respectively with (1) washed granular only, (2) granular and organic matter, (3) a mixed of granular, organic matter and reeds in three replicates. These substrates came from the Evieu experimental wetland mentioned above. A similar cocktail of pesticides than that used for the previously described on-site tracer experiment was added to the columns. The objectives of these columns experiments were to characterize vegetation uptake, influence of gravel+organic matter versus gravel alone on pesticide degradation and adsorption during one week. Table 2 shows pesticide retention in the different columns. No difference was noticed between the conditions including reed or not when gravel and organic matter were mixed. Gravel alone column showed a relatively low retention as compared to the other ones. Pesticide chemical analysis of stems and roots from reed did not reveal high pesticide storage (less than 1% of the input mass). Nevertheless, extraction analysis from macrophyte were made, and showed that a higher level of pesticide content, but still low, was observed in root system compared to stems for more sorptive compounds (azoxystrobine and tebuconazole compared to diuron and isoproturon).

Table 2. Pesticide amounts dissipated in experimental column after one week.

Dissipated mass (in %)	DIU	IPU	TBZ	AZS
Gravel+organic matter+reed	49	26	56	56
Gravel+organic matter	50	31	56	55
Gravel	23	9	32	33

Results highlighted that reed vegetation addition did not provide direct larger pesticide removal quantities; whereas, organic matter seemed to be the key component controlling pesticide mitigation.

Potential mitigation from artificial wetlands. These experiments demonstrated that constructed wetlands have a considerable potential for pesticide mitigation. But wetland pesticide reducing efficiency was not similar for all pesticides. It strongly depends on chemical properties and organic matter content. Wetland vegetation plays an indirect role in pesticide retention. The main processes of dissipation are adsorption by substrates (vegetation, straw, sediments, clay) and chemical or biological degradation which are linked to redox conditions and organic matter content.

SOCIOLOGICAL ASSESSMENT This assessment comes from a real case study sociologists were involved with.

Brief description of the watershed The anonymous aquifer provides water for about half million of inhabitants in the suburb of a major city in France. Location names are voluntary not given. The specificity of this aquifer lies in its recharge. About 70% of it comes from direct reload through sinkholes making a link between surface water and groundwater. In this area, headwatersheds of the hydrogeological catchment are generally subsurface artificially drained because of shallow impervious layer located in the upper reaches. In these particular watersheds, drained water collected by arterial network is directly infiltrated through sinkholes in the aquifer. The example herein detailed, is a 400 ha fully drained watershed. Crop distribution is split into 57% of winter wheat, 14% of sugar beet, 15% of bean, and 5% of rape, 2% of corn and 7% of other crops.

Stakeholders and their involvement: sociological contribution Water management at this scale involves a large range of stakeholders. The water agency is in charge of the EWFD application. Local authority is responsible for the supply of drinking water to citizens at the lowest possible treatment. The main concern of the ten farmers in the watershed is food production. A new regulation (Dec 2006) sets lowered threshold for pesticide concentration in ground water (below 0.1 µg/L per molecule). Actions should be taken at the watershed scale. Unfortunately, few methodologies are available to stakeholders besides application rates reductions. Therefore this water quality issue became an operational research project.

From 2005 up to now, different steps were managed in the project. The first one was to convince reluctant farmers about the evidence of pesticide transfer at the watershed level. The outlet of the watershed (before the sinkholes) was monitored for discharge and water quality. This monitoring (figure 3) was used to characterize pesticide dynamics from subsurface artificially drained areas and quantify annual pesticide loads. For instance (figure 3) Ehtofumesate, an herbicide applied on sugar beet, on 14% of the total

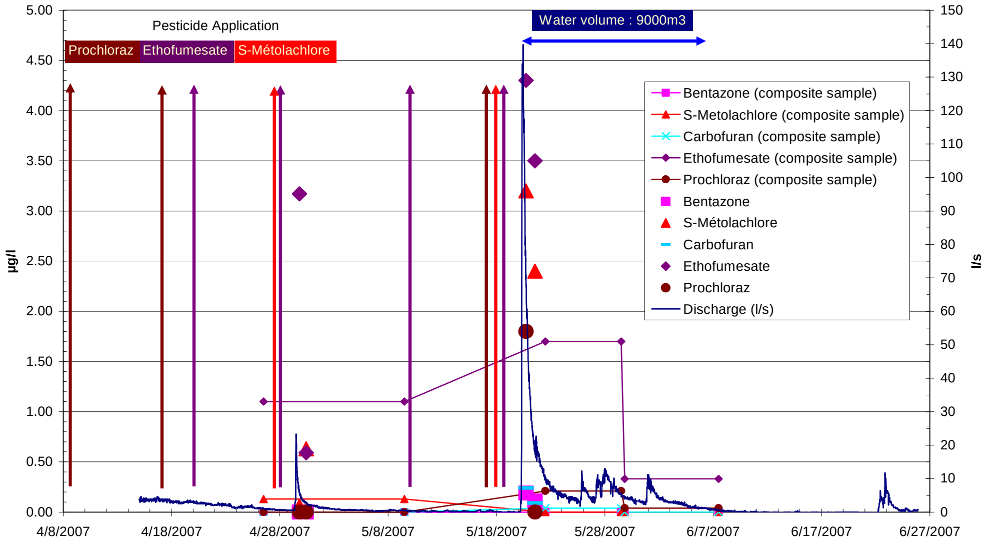

Figure 3. Example of discharge, and pesticide concentration monitoring at the outlet of the 400 ha artificially drained watershed in May 2007.

cultivated area, generated a peak after application up to 4.43 µg/L and a total flux of 1% of applied amount. Farmers were aware of the impact of their own agricultural activities. The first action plan specifically focused on pesticide application rates reduction at the watershed scale. Ten farmers were involved in this approach. The second action mainly dealt with transfer limitation by artificial wetlands implemented on the watershed.

The second step was to propose and discuss several theoretical solutions. The concept of buffer zones was introduced and explained to the different stakeholders. This led to a co-constructed solution. The following three steps were topographical and geotechnical survey, funding research and design contractor proposal. Finally, the last step consisted in the construction of the final solutions.

Mitigation strategy The final co-constructed solution, after negotiations led to only three individual artificial wetlands managed by farmers themselves and one collective terminal artificial wetland. The solution gathered public and private structure ownerships. Upstream, farmers remained the main actors of their own artificial wetlands. Their involvement was necessary because they know exactly the date of pesticide application and pesticide concentration at the drainage system’s outlet. But it was not possible to create sufficient buffer zones to treat all water volumes because of farmers' acceptability, topographical issues and land availability. Hence downstream, a river water management authority had to take in charge the final artificial wetland to polish all drained water. The total wetland area rises to 0.7% of the total watershed area. It is quite low compared to what scientists recommended at the beginning of the negotiation process.

Water management is a key in the functioning of artificial wetland for pesticide mitigation in a drained watershed. Indeed, the parallel wetland should be operated during the month after pesticide application (November and March to May). The pipe (figure 1) linking the main ditch to the artificial wetland should be opened and closed by the farmer himself.

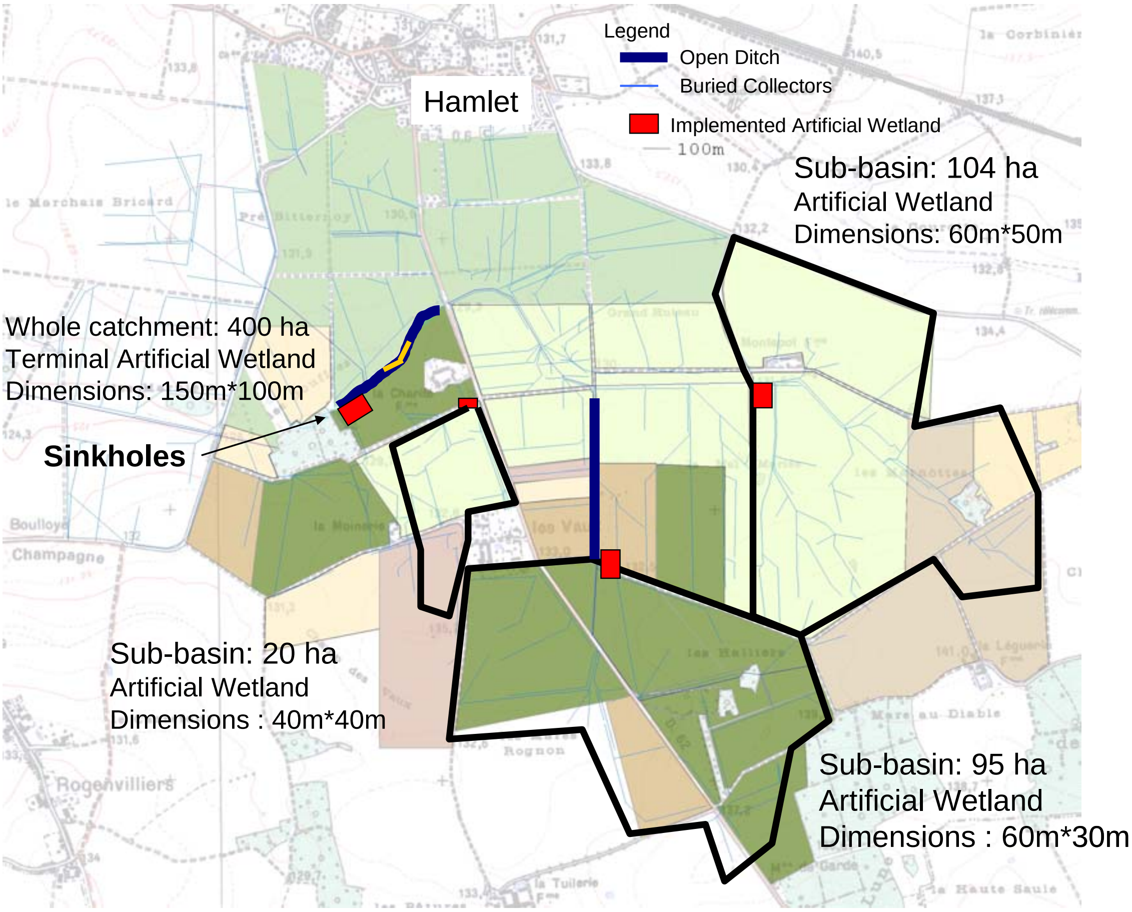

Figure 4. Diagram of artificial wetlands' location in a real case of water protection (France)

Sociological account A social scientist from TRUSTEA group, was invited to observe meetings with scientists, farmers and local authorities at the different stages of the project. She also conducted several in-depth interviews with each one of these stakeholders. The aim was to understand what would facilitate or impede their participation in the making of strip zones and their implementation. She insisted from the very beginning that the project should not be presented as ready made by the "experts". On the contrary, she argued that sufficient space should be let for negotiation and change. Indeed, in the case of R&D projects, as the literature on scientific and technical innovation have shown (Akrich, et al., 1988 [1,2]; Pinch et Bijker 1989), co-construction and the recognition of various sources of expertise (including farmers' knowledge) are important conditions for success and legitimacy. In this case, it was a prerequisite as farmers were asked to give away a share of their land for the construction of the mitigating device and are meant to be its future main users.

Fieldwork confirmed this hypothesis. Scientists and engineers realised very fast that their request for 1% of the land would encounter much resistance. Despite the fact that the farmers agreed on the usefulness of strip zones from the very beginning, they questioned regularly its specifications (size, location) and the proceedings (management and organisation of the project), thus causing much distress among the instigators of the project, scientists, engineers but more specifically, the local representatives of an association in charge of the defence of the aquifer. As a result of bargaining and reorientation of research, some adjustments could finally be made. Scientists made lab tests that allowed them to propose a hold on the land of 0.5% only which facilitated the espousal of the farmers.

On the other hand, farmers gained back some room of manoeuvre from it and could raise a few relevant issues. For instance, they wondered about the legal status of the buffer zones and liability in case of an accident, which were not addressed beforehand. They also required long term monitoring and support to make sure the device would be efficient. In case it wouldn't be, they asked that the excavated earth should be kept close to make the whole thing reversible.

Not talking about gaps of knowledge, the uncertainties on its very name (artificial wetland / constructed wetland / buffer or strip wet zone?), with possibly diverse legal entanglements (do they really change the agricultural vocation of the land?), the hesitations of the farmers which are already complying with input reducing measures but do not really question the dominant production model they are part of, all of these elements condition the future of strip zones and their socio-environmental fate. If we do not want its users to see them only as a means to compensate for the effects of intensive farming and maintain the related production model, regular advice for better practices and reducing inputs of pesticides should be provided (Henke 2008). It should also help to keep all stakeholders lined up and committed to its success.

CONCLUSION Pesticide issues in subsurface drained watershed are not a fate. Complementary actions should be set up at watershed scale such as reduction of pesticide pressure at plot scale, and reduction of pesticide transfer. This study show that an artificial wetland, as a buffer function, is a solution aiming to limit pesticide transfer from plot outlet to natural waterbodies. By presenting two experiments in subsurface drained context, an artificial wetland has a real potential to dissipate pesticide coming in. The efficiency strongly depends on pesticide properties. Implementation is driven by three key points: land availability (at least 1% of agricultural watershed) which controls hydraulic residential time, organic matter within the wetland which stimulates microbial activities; and water management which involves the farmer himself and allows him to target higher pesticide fluxes. The sociological part of the study highlights the importance of a co-construction process between all involved stakeholders, even if it is time consuming. Theoretical solution should be adapted not only to hydrological aspects but also to the socio-economical context.

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