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Elsa Martin (France)

Potential of artificial wetlands for removing pesticides from water

Abstract

The purpose of this paper is to investigate the potential of artificial wetlands (AW) as pesticide sinks. A micro-economic model is developed and completed by a numerical illustration, based on data from fungicide pollution by wine-growers. It enables us to calculate the value of an AW as a pesticide sink. Furthermore, the author shows that, for a given target mass of pesticides in water, the consideration of AW construction possibility can reduce overall abatement costs and can lower the input charge asked from farmers. This result remains true as long as the cost of constructing a wetland is not too high and it is a function of the target.

Keywords: water policy, constructed wetlands, agricultural pollution regulation.
JEL Classifications: Q25, Q58, K32.

Introduction

In the European Union, water policy is mainly driven by the Water Framework Directive (WFD) of 2000. One of its main targets is to work toward an environmental quality illustrating the best trade-off between economic and ecological interests. One consequence is that member states are looking for economic instruments allowing a pre-defined standard of water quality to be reached at the lowest cost possible. Furthermore, the Directive 2009/128/EC of the European Parliament and of the Council establishes a framework for Community action to achieve the sustainable use of pesticides. This Directive encourages the use of economic instruments like pesticide taxes.

The point of departure of our paper is the assumption that the lowest cost possible means of improving water quality with respect to pesticide pollution could involve the use of wetlands. What will be the effect of using wetlands on pesticide taxes and on the farmers' abatement effort? What is the potential value of wetlands as pesticide sinks? These are the main questions that we want to investigate in this work. To answer, we propose to build a micro-economic model that can be calibrated by using some "real" data.

Policy instruments for pesticide control have been long studied. Oskam, Vijftigschild and Graveland (1997) reviewed the policy instruments that can be used at the European level. Carpentier et al. (2005) formulated some recommendations for the French pesticide policy. To reduce pesticide pollution, they proposed to combine (1) the use of a taxation scheme, (2) the development of an innovation policy with respect to agricultural practices, and (3) the use of policy instruments that take into account local or agricultural production specificities. In our work, we want to consider the combination of (1) and the construction of a wetland by the regulator.

Byström (1998, 2000) estimated a replacement value for natural wetlands in Sweden in order to assess how effective natural wetlands are, relative to other abatement measures, in providing low cost reductions of nitrogen pollution. However, in his work farmers restore wetlands, which is not the case in ours where it is a regulator. Furthermore, we will concentrate on pesticide pollution and on Artificial Wetlands (AW). An AW is usually smaller than a natural wetland. It also acts as a natural filter: bacteria and plants having colonized the AW participate in pollutant assimilation. Recently, Grégoire et al. (2009) showed that the mass of pesticides assimilated depends on how long (in hours) the water lies in the AW; this duration is strongly linked to the size of the AW. In a static framework[1], the efficiency of an AW thus depends both on the mass of pesticides in water when it enters into the AW and on the size of the AW that can be adjusted by the regulator.

More particularly, we are going to consider a regulator who wants to reach a target mass of pesticides in water at the lowest cost possible. For this purpose, two types of mechanisms will be used: an incentive instrument (a pesticide tax) and a public investment (the AW). The whole regulation scheme will be assumed budget neutral: the cost of AW construction has to be financed by the tax. Such a setting is particularly policy relevant in the French framework because of the water agency system. Indeed, these agencies levy taxes on water (including the taxes concerned with pesticides) and could finance with them an AW construction, for instance. Furthermore, they have to achieve quality targets of water that are pre-defined.

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[1] A dynamic setting with a time step of hours does not make sense in economics.

To investigate how the consideration of the construction of an AW can affect the pesticide tax used in order to achieve a water quality target and to value the potential of AW as pesticide sinks, we will compare two cases: a benchmark one in which the regulator only implements a pesticide tax and an alternative one in which the regulator can additionally construct an AW in order to reduce pollution. We will calibrate our model to a case study located in the North-East of France that is concerned with fungicide pollution from wine-growers.

We will present our analytical framework in more detail in section 1. In section 2, we will present our results with respect to the potential of AW as pesticide sinks. In the final section, we will conclude with some policy implications and conclusions.

1. The analytical framework

We build an original framework that will able be to investigate the value of AW as pesticide sinks. To run a numerical illustration, we propose to focus on fungicide pollution from viticulture. In the framework of the LIFE Environment ARTWET project[1], Grégoire (Grégoire et al., 2009) and Imfeld (Imfeld et al., 2009) completed some experiments in a small catchment (of 28.9ha) in Alsace (North-East of France) in order to investigate the credibility of an AW for removing pesticides from water. We will concentrate on this catchment.

We will begin this section with some notations. Then we will introduce the calibration of our functional forms to our case study. Finally we will present the optimization models that will be run in order to simulate the economic behavior of the agents under consideration.

1.1. Notations. We consider a watershed with a fixed number n of wine-growers and a regulator.

x denotes the mass of fungicides used by a wine-grower. $\delta := \bar{x} - x$ is the fungicide abatement operated by the wine-grower with respect to the one corresponding to his optimal running, $\bar{x}$..[2] The fungicide abatement δ has a cost, $\kappa(\delta)$, which reflects the change in the wine-grower's profits resulting from this reduction. At the catchment scale, the total fungicide abatement is denoted Δ and the cost associated is denoted $K(\Delta)$.

The mass of fungicides in water downstream, M, is proportional to the total mass of fungicide usage: $M := \alpha X$ where $X := nx$ is the global mass of fungicides used upstream at the catchment level and $\alpha \in [0,1]$ is the transfer coefficient of the fungicides present in the water; $1\text{-}\alpha$ is usually called the natural assimilative capacity.

The regulator can decide to construct an AW of volume V, in order to eliminate some fungicides contained in water at the outlet of the watershed under consideration[3]. The construction of an AW has a cost that is assumed to depend on the volume converted: $c(V)$.

Concerning the physical process behind the reduction of the pollution with fungicides thanks to the construction of the AW, we are going to assume that the quantity, q, of fungicides assimilated by an AW of volume V, depends both on the total mass of fungicides in water at the exit of the AW, M, and on this size: $q := q(V,M)$.

To sum up:

- when the AW is not constructed, the mass of fungicides in water is proportional to the quantity applied by the wine-growers upstream: αX; and
- when it is constructed, the mass of fungicides in water is equal to the previous one minus the assimilation of fungicides by the AW: $\alpha X\text{-}q(V, \alpha X)$.

The target mass of fungicides is denoted $\overline{TM}$. It is a given constant.

1.2. The calibration of the functions. In Rouffach catchment, about $X = 20kg$ of fungicides are applied upstream by $n = 28$ wine-growers each year.

The assimilation rises when the size of the gravel filter that can be constructed in a pre-existing stormbasin increases. V will be the volume of this filter. Nevertheless, above a certain threshold, increasing the gravel filter more is useless. From the observation of 12 rain events from April 2009 to July 2009 by soil experts involved in LIFE Environment ARTWET project, we calibrated the assimilation function q according to the volume of the filter V and the mass of pesticides M as follows (see Appendix A, section 1 for more details):

$$q(V,M) = 10^{-4}(-0{,}45V^2 + 126V)M. \qquad (1)$$

In Appendix A, section 1, we also explain how we calibrated the natural assimilative capacity (without AW) as $\alpha = 6.10^{-3}$.

The gravel filter consists in quaternary gravel from the local Alsatian quaternary floodplain and a gabion barrier in front of the filter to block the gravel mass. We used data provided by the LIFE Environ-

[1] http://www.artwet.fr/artwet/.

[2] $\bar{x}$ could have been identified through the maximization of a profit function without changing anything.

[3] The regulator is assumed to own the land located downstream with respect to the farmers' fields.

ment ARTWET project in order to calibrate that the gabion barrier has a unit cost of 5000€ and the price of the gravel is about 15€ per m^3:

$$c(V) = 15V + 5000. \quad (2)$$

Leroy and Soler, within the Framework of a French project (see Bazoche et al., 2009), calibrated the reduction of the mean yield when the wine-growers use less fungicide. In calibrating this information with economic data of this catchment, we obtained the following function (see Appendix A, section 2 for more details):

$$\kappa(\delta) = 0{,}0224\delta^2 + 2\delta. \quad (3)$$

The fungicide abatement cost is calibrated as an opportunity cost (profit loss) when the fungicide usage decreases. In such a case, a part of the production is lost, because of disease increase.

1.3. The optimization models run. We simulate the economic behavior of the agents under consideration in two cases: a benchmark one in which AW cannot be constructed and an alternative one in which it can[1]. The final aim is to compare these cases. The decision process is decomposed into three steps in order to clarify the running of the process. However, since these steps reflect a decision process, they can be considered so close in time that it is possible to ignore discounting effects.

In the **first step**, in the *benchmark case*, the regulator chooses the proportional tax on fungicide usage, t, that minimizes the sum of the wine-growers' costs needed in order to achieve the target mass of pesticides. It has perfect and complete information but no profit maximization objective. As a consequence, it is perfectly able to anticipate the best reply of the wine-growers to this tax, $X^*(t)$, and there is no need for an optimization program in the benchmark case. In the *alternative case*, the regulator still chooses the proportional tax on fungicides, t. Furthermore, it chooses the volume of the AW, V, and now minimizes the sum of the costs of reducing the mass of fungicides used upstream and of AW construction downstream. The optimization program to be solved by the regulator in this case is thus the following one:

$$\min_{t,V} n\kappa(\bar{x} - x^{**}(t)) + c(V),$$
$$s.t. \ : \ \alpha X^{**}(t) - q(V, \alpha X^{**}(t)) = \overline{TM}. \quad (4)$$

In the **second step**, in *both cases*, each wine-grower chooses the mass of pesticides that minimizes his abatement costs, which then include the level of money levied through this proportional tax. In this work, we don't enter into the description of the decision process behind the fungicide usage reduction. Each wine-grower takes the tax rate as given since it is fixed by the regulator. The program that each wine-grower solves is thus the following one:

$$\min_{x} \kappa(\delta(x) + tx - \overline{ls}), \quad (5)$$

where $\delta(x) := \bar{x} - x$ and $\overline{ls}$ is a lump-sum transfer considered as fixed.

In the **third step**, the regulator balances its budget through transferring the amount of money collected in the previous step as a lump-sum transfer back to the wine-growers who are assumed myopic, i.e. they do not anticipate the exact value of this lump-sum transfer[2]. This transfer, ls, will be equal to $\frac{tX}{n}$ in the *benchmark case* and to $\frac{tX - c(V)}{n}$ in the *alternative case*.

Both cases will consist in solving the models backward. The reader can refer to Appendix B to check the mathematical robustness of the models.

2. Potential of AW as pesticide sinks

To investigate the potential of AW as pesticide sinks, we run the optimization models previously presented within the framework of the functional forms calibrated to Rouffach case study. After having presented the results of the computations, we will investigate the potential of AW as pesticide sinks. First we will derive a value of AW as pesticide sinks. Secondly, we will show the distributional impacts caused by the construction of AW. Finally we will investigate the impact of the target mass of pesticides in water on these results.

2.1. Results of the computations. The computations consist in solving the systems made up of the first order conditions presented in Appendix B, all the functions being calibrated as presented in the previous section[3].

Without any regulation, the maximum quantity of fungicides spread upstream, $\overline{X}$, is equal to 24,620g. One per 1000 reaches the AW zone, which treats again 40% of pesticides when there is no AW ($V = 0$). Then with $\overline{X}$ = 24,620 and V = 0, there remains $\overline{\alpha X}$ = 14,729mg of fungicides downstream of the AW.

[1] The asterisks * and ** will respectively denote the solution of the benchmark case and of the alternative case with AW construction possibility.

[2] We assume all along this paper that there are no regulation costs.

[3] We used Maple software. In the alternative case, we obtained a unique solution by not considering solutions with a complex part.

In the benchmark case, if we want, for instance, to divide this mass of pesticides by 10 ($\overline{TM}$ = 1,477mg), that is a particularly high target, we have to reduce the mass of pesticides usage from $\overline{X}$ = 24,620g to X^* = 2,462g. The total abatement cost associated to it is $K(\Delta^*)$ = 436,929€, the tax rate is t^* = 37.4€ per gram and the total amount of money collected is LS^* = $n.ls^*$ = 92,172€. They represent particularly high amounts of money mainly because of the restrictive target which is purely illustrative here.

In the alternative case, we introduce the possibility of constructing an AW. In this way, we can reach the same target of $\overline{TM}$ = 1,477mg with a total cost of $K(\Delta^{**})$ = 25,885€ by increasing the volume of the AW to V^{**} = 139.88 (the AW construction cost then equals $c(V^{**})$ = 7,098€) and reducing the global mass of pesticide usage to X^{**} = 20,860g (the fungicide abatement cost then equals $K(\Delta^{**})$ = 18,786€). The tax rate for the wine-growers becomes t^{**} = 8€ per gram of fungicides rejected and the difference between the total amount of money collected and the cost of the AW construction is equal to $LS^{**} = n.ls^{**}$ = 159,937€.

2.2. The value of AW as pesticide sinks. Within the framework of our example of dividing the mass of pesticides by 10 in Rouffach catchment, the value of the AW under consideration as a pesticide sink can easily be computed as:

$n\kappa(\delta^*) - n\kappa(\delta^{**}) - c(V^{**}) = 411{,}045€.$

Furthermore, we can observe that, thanks to the AW construction, the percentage reduction of the total cost induced in order to reach the target mass of pesticides is 94%.

We propose to illustrate this result with a graph that represents the simplified case in which all relations are assumed linear. In Figure 1, the target mass of pesticides $\overline{TM}$ is represented by the dotted line. The value of AW as pesticide sinks is represented by the area *BCD*. It is the difference between the total cost of achieving the target only with wine-growers' abatement upstream, $AC\overline{TM}$, and the total cost of achieving it by combining AW construction downstream and pesticide usage abatement by wine-growers upstream, $ABD\overline{TM}$.

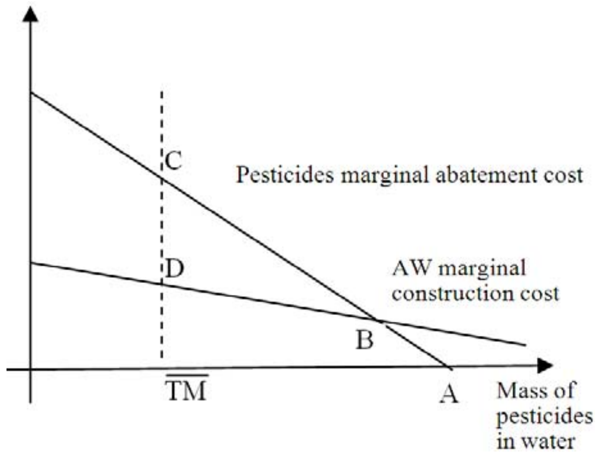

Fig. 1. The value of AW as pesticide sinks

More generally, the construction of an AW by the regulator generates a gain, $\Gamma := n\kappa(\delta^*) - n\kappa(\delta^{**})$. Since the use of a higher mass of pesticides reduces the cost, κ, of the deviation from the point, $\overline{X}$, which maximizes their profits. This gain accrues to the wine-growers:

$$\kappa_\delta > 0 \text{ and } n\delta^* > n\delta^{**} \Rightarrow n\kappa(\delta^*) > n\kappa(\delta^{**}) \text{ and } \Gamma > 0. \quad (6)$$

To quantify the value of AW as pesticide sinks, we also have to enter into the picture the global fiscal scheme (the proportional tax, t, but also the lump-sum transfer, LS) implemented by the regulator. As a consequence, we compare the global cost function of the wine-growers evaluated at the solution of each of our cases: $n\kappa(\delta^*)$ for the benchmark case and $n\kappa(\delta^{**})$ + $c(V^{**})$ for the case with AW since the fiscal schemes are respectively (t^*, LS^*) and (t^{**}, LS^{**}). According to the difference between the gains accruing to the wine-growers thanks to an AW construction and the costs induced, we can distinguish between two cases:

1. If $\Gamma > c(V^{**})$, constructing an AW in addition to a fiscal scheme is more cost-effective than not and the value of the AW as a pesticide sink is equal to $\Gamma - c(V^{**})$.
2. If $\Gamma > c(V^{**})$, constructing an AW is not cost-effective and the AW has not a value as a pesticide sink. Graphically and under a linearity assumption, such a situation would be different from the one represented in Figure 1: it would be such that the value *BCD* of the AW is less than or equal to zero.

2.3. The distributional effect of AW construction. The target mass is reached in both the benchmark case without AW and in the alternative case with

AW. However, the effort made by the wine-growers upstream in order to do so is quite different in each case. Indeed, in our case study we observe that, thanks to the AW constructed downstream, the percentage reduction of the fungicide abatement Δ is 83% and that of the tax rate is about 78.5%.

We use the same kind of graph as before in order to illustrate this result. The reduction of the effort to be made by the wine-growers upstream is illustrated in Graph 2 by the difference between the dotted line that intersects the horizontal axis at $\overline{TM}$ and the dotted and dash line that intersects the same axis at TM. Indeed, without AW construction downstream, the wine-growers have to make all the efforts in order to reach $\overline{TM}$ and with an AW construction the same target is reached but the effort asked from the wine-growers can be compared to the one aiming at reaching $TM > \overline{TM}$ since the pesticide units from TM to $\overline{TM}$ are removed by the AW whose marginal construction cost ($AWMCC$) is lower than the pesticide marginal abatement cost (PMAC) for those specific pesticide units. More particularly, a regulator who wants to reach the target $\overline{TM}$ in the benchmark case has to give to wine-growers incentives that make them move from $PMAC$ to $PMAC^*$. In the alternative case with AW construction, such a regulator has to make them move from $PMAC$ to $PMAC^{**}$. In the simplified case in which all relations are assumed linear, such movements can be obtained thanks to a pesticide tax equal to t^* in the benchmark case and to t^{**} in the alternative case with AW. We see that this tax is considerably reduced thanks to the AW construction.

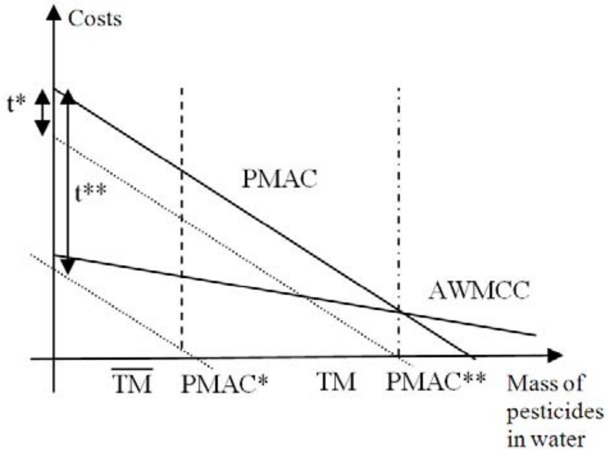

Fig. 2. The reduction of the effort to be made by the wine-growers

Within the more general framework illustrated by our theoretical model, we deduce from Appendix B that $q^{**} > 0$. It follows that the mass of pesticides used by the wine-growers in the benchmark case, $X^* = \frac{\overline{TM}}{\alpha}$, is lower than the one occurring when the regulator constructs an AW, $X^{**} = \frac{\overline{TM} + q^{**}}{\alpha}$, both at an individual and at an aggregate level: $X^{**} > X^* \leftrightarrow x^{**} > x^*$. As a consequence, AW construction downstream reduces the aggregate, $\Delta := n\delta$, and the individual effort, δ, that is made by the wine-growers of the catchment in terms of pesticide usage reduction in order to reach the target mass: $\Delta^* > \Delta^{**} \leftrightarrow \delta^* > \delta^{**}$.

We can also deduce from $\kappa_\delta > 0$ and $\kappa(\delta^*) > \kappa(\delta^{**})$ a general property of the tax levied on each unit of pesticide usage which it is higher in the benchmark case than in the alternative case with AW construction: $t^* > t^{**}$.

2.4. A potential variable according to the target. Table 1 represents the results of a sensibility study of Rouffach results above and below the target mass of pesticides in water (see the detailed results with and without AW in Appendix C). We can see that the magnitude of the savings made by the AW construction (total cost decrease column) increases with the target. This means that the lower the target mass of pesticides in water is, the lower the potential of AW will be.

Table 1. A potential increasing with the target

τ (€) decrease	Total cost decrease	$\overline{TM}$ (mg)
92%	98%	1,700
86%	97%	1,600
80%	95%	1,500
79%	94%	1,477
74%	92%	1,400
74%	92%	1,300
68%	89%	1,200

Bearing in mind the figures previously presented, this result is counter intuitive. Indeed, in Figure 1, we see that when $\overline{TM}$ increases, the area BCD that represents the value of AW as pesticide sinks decreases. This is the opposite result for the value obtained in the Rouffach case. However, as mentioned before, in Figure 1, we assumed that all relations are linear which is not likely to be the case. Figure 3 illustrates a case in which the *AWMCC* is non-linear with respect to the mass of pesticides in water. Here the value of AW as pesticide sinks is equal to the area: *ABC* – *BDE*. In such a case, if the target mass of pesticides in water is changed from $\overline{TM}_1$ to $\overline{TM}_2$, we see that the area *BDE* will decrease and, as a consequence, the value of AW will increase.

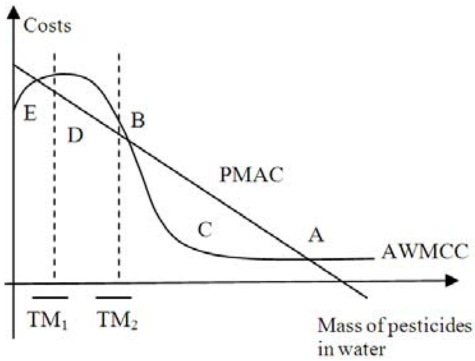

Fig. 3. A potential increasing with the target

Moreover, Table 1 shows that in the Rouffach catchment area, the pesticide tax decrease allowed by the AW increases with the target mass of pesticides. This result is again counter intuitive with respect to Figure 2. Once more, it is the non linearity in the functions (*AWMCC* but also *PMAC* here) that explains this.

Policy implications and conclusions

In this paper, we proposed to consider an original method of abatement of water pollution with pesticides using an AW construction. We showed that the consideration of AW construction downstream in order to reach a pre-determined target mass of pesticides in water can reduce both the effort that is made by the farmers upstream and the tax on pesticides that has to be implemented. This result remains true as long as the costs of constructing an AW are lower than the gains accruing to the farmers thanks to the AW construction. Finally, we showed that the potential of AW as pesticide sinks depends on the target mass of pesticides in water and that the sign of the relation depends on the characteristics of the case under study. This highlights the need for careful empirical investigation in each specific case. Our analytical framework is so generic that it could be applied to any case study.

Policy implications are of two natures. Firstly, our results abet the possibility for more stringent water quality standards at the national level since regulators can construct AW in order to reduce the mass of pesticides contained in water. Secondly, we know that, in real life, pesticide taxes are below their optimal level due to lobbying. When considering the possibility of constructing an AW in addition to classic regulations tools such as pesticide taxes, our results show that the pesticide taxes implemented in practice by policy-makers could come closer to the optimal pesticide taxes theoretically needed. Finally, in a context in which the empirical price elasticity of the pesticide demand can be quite small, the AW becomes an even more crucial instrument to be used in combination with pesticide taxes.

Nevertheless, the model constructed for this work has some usual limitations. Firstly, we focus on a deterministic setting with perfect and complete information of the regulator. In a setting where the regulator can set the level of the pesticide tax knowing perfectly the reaction of the farmers, the potential of wetlands for cleaning water in a cost-effective framework must be the worst one and if this potential is confirmed, it will also be the case in an imperfect information setting. Furthermore, we decided to leave the question of the uncertainty of the wetland abatement capacity to a future multidisciplinary work because we would need more data from scientists of other disciplines in order to establish a complete numerical illustration in an uncertain setting. Secondly, it would be of interest to include some dynamic effects in the assimilation process of the AW. However, the calibration phase of such an extension would also require considerable input from scientists of other disciplines and is why it is left for future works. Thirdly we assumed that farmers are identical and non-strategic. This has been done in order to keep the model easily tractable for a first numerical illustration but these assumptions could be relaxed in future works.

Finally, we did not enter into the picture the fact that AW can provide a lot of other services, in particular, ecological services. Considering ecological services provided by AW construction can be of major importance, the question would then be to know if the benefit of these services is greater than the benefit induced by a pesticide tax. Indeed, the benefit induced by a pesticide tax must include the effect on health of pesticide usage reduction in agricultural production. However, in the real world, the ecological services of wetlands and the effects of pesticide usage reduction on health are very difficult to evaluate and, from the best of our knowledge, no economic work concentrates on the AW services. This is why we limited our work to a cost-effective framework without any considerations in terms of welfare.

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Appendix A. Calibrations of the functions

1. The fungicide assimilative capacity of AW. All the data used here is provided from soils experts involved in the LIFE Environment ARTWET project. At the entrance of the public land (where the AW is constructed), only 1/1000 of the quantity X of fungicides rejected upstream remains. Without AW construction ($V = 0$), the soil could treat another 40% of fungicides. So we have: $\alpha = 6/10{,}000$.

On average, we know that the Rouffach AW assimilation increases from 40% to 80% with $V = 67.2\ m^3$, and to 90% with $V = 134.4\ m^3$. So, we look for a function that joins these points, with a derivative equal to zero for $\overline{V} = 140\ m^3$. Applying the polynomial trend curve function of Excel software that is based on the least square regression to these data, we obtain:

$$\frac{q}{X} = 10^{-7}[-0,27V^2 + 75,6V],$$

and

$$q(V, M) = 10^{-4}[-0,45V^2 + 126V]M,$$

since $M{:} = \alpha X$.

2. The fungicide abatement cost. First we obtained Table 2 from Leroy and Soler results (see Bazoche et al., 2009).

Table 2. Yields according to the number of fungicides applications

Yields (100kg/ha)	Number of fungicides applications
99	8
92.5	6
82.5	4
37.5	0

Then, applying again the polynomial trend curve function of Excel software on these data, we obtain the two first columns of Table 3.

Table 3. Abatement data for the whole catchment

Yields (%)	Number of applications	Fungicides quantity (g)	Sales (€)	Fungicides costs (€)	Other costs (€)	Profit (€)	Abatement (g)	Fungicides abatement cost (€)
38	0	0	370,920	0	479,005	-108,085	24,615	539,839
45	1	1,538	439,878	667	484,797	-45,587	23,077	477,341

Table 3 (cont.). Abatement data for the whole catchment

Yields (%)	Number of applications	Fungicides quantity (g)	Sales (€)	Fungicides costs (€)	Other costs (€)	Profit (€)	Abatement (g)	Fungicides abatement cost (€)
51	1	3,077	504,649	1,334	490,238	13,077	21,538	418,677
57	2	4,615	565,235	2,001	495,327	67,906	20,000	363,848
63	2	6,154	621,634	2,668	500,065	118,901	18,462	312,853
68	3	7,692	673,847	3,335	504,451	166,062	16,923	265,692
73	3	9,231	721,875	4,002	508,485	209,388	15,385	222,366
78	4	10,769	765,716	4,669	512,168	248,879	13,846	182,875
82	4	12,308	805,371	5,336	515,499	284,536	12,308	147,218
85	5	13,846	840,840	6,003	518,478	316,359	10,769	115,395
88	5	15,385	872,123	6,670	521,106	344,347	9,231	87,407
91	6	16,923	899,220	7,337	523,382	368,501	7,692	63,253
94	6	18,462	922,131	8,004	525,306	388,821	6,154	42,933
95	7	20,000	940,856	8,671	526,879	405,306	4,615	26,448
97	7	21,538	955,395	9,338	528,101	417,956	3,077	13,798
98	8	23,077	965,748	10,005	528,970	426,772	1,538	4,982
99	8	24,615	971,914	10,672	529,488	431,754	0	0

Furthermore, we know from the experts involved in LIFE Environment ARTWET project that, in the studied catchment, about 20 *kg* of fungicides are spread upstream each year by the 28 wine-growers. The vineyard average yield was 95% in 2008[1], which corresponds, on average, to 6.5 applications of fungicides. From this, we can compute the third column of Table 3. As a consequence, we calculate that the total usage of pesticides by all wine-growers is 3,077 *g* per application.

In the Upper-Rhine French administrative department, the viticulture sales are, on average, 293,000,000€ on 9,000 *ha*[2]. We estimate, then, that in the 28.9 *ha* of our studied catchment, the sales are 940,856€. Therefore, we estimate that a yield equal to 95% corresponds to sales equal to 940,856€. From this, we deduce the fourth column.

To find the wine-growers profits, we deduce the costs from the sales. First, we know from the experts involved in LIFE Environment ARTWET project that the fungicide costs are estimated at 1,334€ per application in the whole catchment. The fifth column is deduced from this. The other costs represent, on average, 56% of the sales: 85% are fixed and 15% are proportional to the yield[3]. The sixth and seventh columns are computed from this.

The eighth column is computed by considering that the abatement is equal to the difference between the fungicide quantity that corresponds to the maximum yields, namely 24,615 g, and the fungicide quantity under consideration. Finally, the total fungicide abatement cost is the difference between the profit with a maximum yield and the profit with the fungicide quantity under consideration. Applying again the polynomial trend curve function of Excel software on the data of these two last columns, we obtain:

$$K(\Delta) = 0.0008\Delta^2 + 2\Delta.$$

We then deduce the individual fungicide abatement cost function from:

$$28\kappa(\delta) = K(28\delta),$$

$$\Leftrightarrow 28(\beta_1\delta^2 + \beta_2\delta) = 0.0008(28\delta)^2 + 2(28\delta),$$

$$\Leftrightarrow \beta_1 = 0.0224 \text{ and } \beta_2 = 2.$$

Thus, the individual fungicide abatement cost function is the following one:

$$\kappa(\delta) = 0.0224\delta^2 + 2\delta.$$

Appendix B. Robustness of the optimization programs in the general case

1. Additional theoretical assumptions needed. The cost of fungicide usage reduction is assumed to increase with the mass of pesticides removed, at an increasing rate (it is convex): $\kappa_\delta > 0$ and $\kappa_{\delta\delta} > 0$ where subscripts of functions indicate partial derivatives. Furthermore, no reduction induces no cost, $\kappa(0) = 0$; small reductions are not very costly,

[1] Source: "Agreste" national data 2008.
[2] Source: http://www.haut-rhin.chambagri.fr/AGRI68/FILIERES/filiere_viticole.PDF.
[3] Source: http://www.haut-rhin.chambagri.fr/AGRI68/FILIERES/filiere_viticole.PDF.

$\lim_{\delta \to 0} \kappa_\delta = 0$; but large ones are disheartening, $\lim_{\delta \to \underline{x}} \kappa_\delta = +\infty$. $\delta \to 0$ means that the mass of fungicide usage is at its maximum, $\bar{x}$, and $\delta \to \bar{x}$ that it is at its minimum, 0.

We assume that the suitable land area that can be converted into an AW is such that the volume cannot be higher than $\bar{V}$, since the regulator does not hold infinite property rights on land. The construction of an AW has a cost that is assumed to depend on the volume converted: $c(V)$. It is increasing, $c_V > 0$, and convex, $c_{VV} > 0$, and there is no cost when no AW is constructed: $c(0) = 0$. Furthermore, small constructions are not very costly, $\lim_{V \to 0} c_V = 0$, but large ones are disheartening[1], $\lim_{V \to \bar{V}} c_V = +\infty$.

We expect that q increases with the size of the AW (at a decreasing rate: $q_{VV} < 0$) and also with the mass of fungicides (q_M and $q_V > 0$). q_M can be interpreted as the efficiency of a pre-determined AW with respect to the fungicide assimilation; it is positive and we assume that the mass of fungicides assimilated by the AW increases less than one unit when the mass of fungicides entering into it increases by one unit: $1 > q_M > 0$. No molecule of fungicide induces no assimilation and neither does no AW construction: $q(0,M) = q(V,0) = 0$. The total size of AW available, $\bar{V}$, is assumed so high that, next to this point, each additional unit of AW becomes inefficient, $\lim_{V \to \bar{V}} q_V = 0 \forall X > 0$, and when no AW is constructed, the efficiency of constructing the first unit is assumed strictly positive, $\lim_{V \to 0} q_V > 0 \forall X > 0$.

The pollution induced by the minimum mass of fungicide usage is assumed always lower than the target mass: $\overline{TM} > 0$. Furthermore, the AW is assumed to be unable to assimilate the mass of fungicides corresponding to the wine-growers' maximum profits up to the target mass: $\alpha \bar{X} - q(V, \alpha \bar{X}) > \overline{TM} \forall V > 0$, where $\bar{X} = n\bar{x}$. As a consequence, the pollution induced by the maximum mass of fungicide usage is always higher than the target mass: $\alpha \bar{X} > \overline{TM}$.

2. The benchmark case: the artificial wetland is not constructed.

(1) The total mass of fungicide usage in the catchment area exists, is unique and decreases with the tax rate.

Proof. From the first order condition of the second step of our model, we define the following function:

$$\Psi(t,x) := -\kappa_\delta(\bar{x} - x) + t.$$

We deduce from our assumptions $\lim_{\delta \to 0} \kappa_\delta = 0$ and $\lim_{\delta \to \underline{x}} \kappa_\delta = +\infty$ that $\lim_{x \to \underline{x}} \Psi > 0$ and $\lim_{x \to 0} \Psi < 0$ $\forall t > 0$. Furthermore, we know that $\Psi_x = \kappa_{\delta\delta} > 0$. The implicit function theorem tells us that $\exists ! x | \Psi(t, x(t)) = 0$ and that:

$$x_t^* = -\frac{\Psi_t}{\Psi_x} = -\frac{1}{\kappa_{\delta\delta}} < 0.$$

As a consequence of the fact that $X^*(t) := nx^*(t)$, we obtain:

$$X_t^* < 0.$$

(2) When the tax rate is zero, the mass of fungicide usage in the catchment area is maximum and when the tax is very high, it goes down to its minimum.

Proof. If we put our assumptions $\lim_{\delta \to 0} \kappa_\delta = 0$ and $\lim_{\delta \to \underline{x}} \kappa_\delta = +\infty$ into the first order condition of the second step of our model, we find that $\lim_{t \to 0} x^*(t) = \bar{x}$ and $\lim_{t \to +\infty} x^*(t) = 0$. Finally, we find: $\lim_{t \to 0} nx^*(t) = n\bar{x} = \bar{X} = \lim_{t \to 0} X^*(t)$ and $\lim_{t \to \infty} nx^*(t) = n\underline{x} = \underline{X} = \lim_{t \to \infty} X^*(t)$. It directly follows from this lemma that $X^*(t)$ [0, $\bar{X}$].

(3) The solution of the benchmark case (X^*, t^*) exists and is unique.

Proof. Since we assumed that the information of the regulator is perfect and complete, it is able to anticipate the best-response of each wine-grower to the tax: $x^*(t)$. Furthermore, the lump-sum transfer and the proportional tax compensate themselves in such a way that the optimization program to be solved is the following one, where $X^*(t) := nx^*(t)$:

[1] Bearing in mind that V is the volume of the gravel filter, this means that above the volume $\bar{V}$, infinite additional costs are induced in order to increase the height of the filter for instance.

$$\min_t n\kappa(\bar{x} - x^*(t)),$$
$$s.t. \;:\; \alpha X^*(t) = \overline{TM}.$$

We then construct the following Lagrangian equation:

$$\Lambda(t,\lambda) = n\kappa(\bar{x} - x^*(t)) + \lambda[\alpha X^*(t) - \overline{TM}].$$

We know from the (1) and $\alpha\overline{X} > \overline{TM} > 0$ that the constraint qualification is checked since: $\exists t \left| \begin{cases} \alpha X_t^* < 0 \\ \alpha X^*(t) = \overline{TM} \end{cases} \right\}.$

If t^* is a solution of the regulator problem then there exists a unique λ^* such that the following first order conditions are satisfied:

$$X_t^*[-\kappa_\delta^* + \alpha\lambda^*] = 0, \tag{1}$$

$$\alpha X^* - \overline{TM} = 0. \tag{2}$$

The convexity of the Lagrangian equation is checked thanks to the (1):

$$(-\kappa_\delta X_t + \lambda^* \alpha X_t)_t = \kappa_{\delta\delta} X_t^2 - \kappa_\delta X_{tt} + \lambda^* \alpha X_{tt} = \kappa_{\delta\delta} X_t^2.$$

So, (t^*, λ^*) is a global minimum. Our assumptions on the target mass, $\alpha\overline{X} > \overline{TM} > 0$, insure that $X^*(t) \in [0, \overline{X}]$ and the interiority of the tax rate, i.e. $t^* \in [+\infty, 0]$, then directly comes from (2). It follows that $\lambda^* > 0$. It then directly follows that:

$$(2) \Leftrightarrow X^* = \frac{\overline{TM}}{\alpha}.$$

$$(1) \Leftrightarrow \lambda^* = \frac{\kappa_\delta^*}{\alpha}.$$

3. The alternative case: the artificial wetland is constructed. When the regulator considers the possibility of constructing an AW in order to reduce the mass of fungicides in water, a local solution of the model $(X^{**}, V^{**}, \lambda^{**}, t^{**})$ exists.

Proof. To define the solution of this problem, we construct the following Lagrangian equation, where $X^{**}(t) := nx^{**}(t)$:

$$L(t,V,\lambda) = n\kappa(\bar{x} - x^{**}(t)) + c(V) + \lambda[\alpha X^{**}(t) - q(V, \alpha X^{**}(t)) - \overline{TM}].$$

The constraint qualification is checked since we know from one of the previous subsection, and the assumptions $1 > q_M > 0$, $q_V > 0$ and $\alpha\overline{X} - q(V, \alpha\overline{X}) > \overline{TM} \;\; \forall V > 0,$ that:

$$\exists t, V \left| \begin{cases} \alpha X_t^{**}[1 - q_M^{**}] < 0 \\ \alpha X^{**}(t) - q(V, \alpha X^{**}(t)) = \overline{TM} \\ -q_V^{**} < 0 \end{cases} \right\}.$$

If (t^{**}, V^{**}) is a solution of the regulator problem then there exists a unique λ^{**} such that the following first order conditions are satisfied:

$$X_t^{**}[-\kappa_\delta^{**} + \alpha\lambda^{**}(1 - q_M^{**})] = 0, \tag{3}$$

$$c_V^{**} - \lambda^{**} q_V^{**} = 0, \tag{4}$$

$$\alpha X^{**} - q(V^{**}, \alpha X^{**}) - \overline{TM} = 0. \tag{5}$$

Let H denote the Hessian matrix of $L(t, V, \lambda^{**})$:

$$H = \begin{bmatrix} X_t(\kappa_{\delta\delta} X_t - \alpha\lambda^{**} q_{MM} X_t) + X_{tt}(-\kappa_\delta + \lambda^{**}(1 - q_M)) & -\alpha\lambda qvx \\ -\alpha\lambda qxv & c_{VV} - \lambda^{**} q_{VV} \end{bmatrix}.$$

We deduce from the evaluation of this matrix at the optimum that the minimum, defined by the previous first order conditions, is a local one, since:

$$H^{**} = \begin{bmatrix} \kappa_{\delta\delta}^{**} X_t^{**2} & 0 \\ 0 & 0 \end{bmatrix}$$

Our assumptions on the target mass, $\alpha\overline{X} - q(V, \alpha\overline{X}) > \overline{TM} \ \ \forall V > 0,$ insure that $X^{**}(t) \in [0, \ \overline{X}\ ]$ and the interiority of the tax rate, i.e. $t^{**} \in \ [+\infty, 0]$, then directly comes from (2) of the previous subsection. It follows that $\lambda^{**} > 0$. Putting now the assumptions $\lim_{V \to 0} q_V > 0 \forall X > 0$ and $\lim_{V \to 0} c_V = 0$ along with $\lim_{V \to \overline{V}} q_V = 0 \forall X > 0$ and $\lim_{V \to \overline{V}} c_V = +\infty$ in the first order equation related to V, we have $V \in \ [0, \ \overline{V}\ ]$. It then directly follows that:

$$(5) \Leftrightarrow \overline{TM} = \alpha X^{**}(t) - q^{**}.$$

$$(3) \Leftrightarrow \lambda^{**} = \frac{\kappa_{\delta}^{**}}{\alpha(1 - q_M^{**})} > 0.$$

$$(4) \Leftrightarrow c_V^{**} = \lambda^{**} q_V^{**}.$$

Appendix C. Sensibility study above and below the target

Table 4. Sensibility study in the benchmark case

X (g)	V (m3)	τ (€)	K (€)	C (€)	Total cost	$\overline{TM}$ (mg)
2,833	0	36.9	423,116	0	423,116	1,700
2,667	0	37.1	429,280	0	429,280	1,600
2,500	0	37.4	435,489	0	435,489	1,500
2,462	0	37.4	436,929	0	436,929	1,477
2,333	0	37.7	441,741	0	441,741	1,400
2,167	0	37.9	448,039	0	448,039	1,300
2,000	0	38.2	454,381	0	454,381	1,200

Table 5. Sensibility study in the alternative case with AW construction

X (g)	V (m3)	τ (€)	LS (€)	K (€)	C (€)	Total cost	$\overline{TM}$ (mg)
24,010	139.72	3	64,162	1,503	7,096	8,598	1,700
22,599	139.83	5	111,007	7,285	7,098	14,383	1,600
21,186	139.88	7	151,500	16,262	7,098	23,360	1,500
20,860	139.88	8	159,937	18,786	7,098	25,885	1,477
19,769	139.90	10	185,713	28,476	7,098	35,574	1,400
18,359	139.91	12	213,380	43,818	7,099	50,917	1,300
16,952	139.92	14	234,656	62,309	7,099	69,408	1,200