Nutrient allowances market and wetland abatement

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Abstract

The buffering function of wetlands is one of the most efficient mechanisms for regulating agricultural runoffs and water pollution. The aim of this paper is to show how farmers could use wetland abatement as a way to achieve pollution targets set by a regulator in a nutrient allowance market. The introduction of allowances into farmers' maximisation programs creates an incentive to either reduce fertilizer use per hectare of crops, or to restore wetlands on agricultural land. Comparative statics results express a negative correlation between the quantity of allowances per farmer and the fertilizer use. Furthermore, the quantity of allowances per farmer is negatively correlated to the wetland surface area.

Key words: Nutrients, wetlands, agriculture, permit market, regulation, allowances, runoffs

JEL Classification: Q15, Q28

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1 Introduction

Wetlands offer a wide range of ecosystemic goods and services, and ensure such ecosystemic functions as nutrient absorption. Wetlands trap, eliminate, or transform undesirable chemical substances flowing from the land into water bodies, thereby protecting the land. Wetlands, nowadays considered as one of the most important environmental ecosystems in the world, long suffered from being insufficiently understood. This meant that their ecological and economic importance were neglected, with most wetlands being used for agricultural purposes. Wetlands, however, not only remove chemical nutrients from agricultural runoffs, but also provide ancillary benefits for wildlife habitats and exercise flood control. The buffering function of wetlands, one of their most important mechanisms, particularly useful for regulating agricultural runoffs and for limiting water pollution. Agriculture, with its intensive use of fertilizers, constitutes a major source of nutrient pollution (Ribaudo et al., 2001; Simonit and Perrings, 2005, 2011), one of the leading causes of water quality impairment in the U.S. (Ribaudo et al., 2001).

The use of fertilizers is designed to increase agricultural productivity. Nutrients, naturally present in the soil, are essential for plant growth. Thus, increasing nutrients for more intensive agricultural activity is aimed at providing more nutrients to plants and improving soil efficiency. One problem, however, is that this nutrient overload has negative effects on soil and water and induces pollution. This question has been extensively studied, particularly when a regulating agency is introduced (Crépin, 2005; Elofsson, 2011; Heberling et al., 2010; Sutton et al., 2011). Heberling et al. (2010) address the problem of reducing nutrients by introducing subsidies into a water quality trading program. In our paper, we consider another way of reducing agricultural pollution: establishing a permit market which induces changes in the yield process. The introduction of allowances offers farmers one of two alternatives: they can reduce runoffs by limiting their use of fertilizers, or they can restore wetlands on their land. If they choose the former solution, agricultural runoffs will decrease, and so will pollution. We have to assume that agricultural yield will decrease, too, because of a decrease in nutrients. Thus, farmers will produce less on their unchanged surface. If farmers choose the latter solution, however, by restoring wetlands on their land, those wetlands would reduce nutrient pollution. Because of the resulting loss of cultivable surface area, farmers would certainly like to compensate for yield loss. Farmers who try to optimise agricultural crops per unit of land may use more fertilizer to achieve their goals, as shown in the conclusions of Heberling et al. (2010). Their model, unfortunately, seems unable to confirm final outcomes in the water quality trading programs. The authors do not show how farmers evolve in their use of fertilizers, or how runoffs are affected by the introduction of subsidies.

We address these questions in what follows. Section 2 first presents a review of the literature. Then we develop the model in Section 3, before studying its properties (Section 4). We then conclude in Section 5.

2 Literature review

Nutrients, such as nitrogen and phosphorus, are essential for plant and animal growth and nourishment, and play a key role in determining the presence of different species in wetlands. The overabundance of certain nutrients in water can cause a number of adverse health and ecological effects (Russi et al., 2013; Simonit and Perrings, 2005; Kahn and Kemp, 1985; Heinle, 1982; Hansen and Hansen, 2013). Agriculture, because of its use of fertilizers, constitutes a major source of nutrient pollution in freshwater and estuaries (Simonit and Perrings, 2011; Ribaudo et al., 2001; Simonit and Perrings, 2005). Nutrient pollution is the leading cause of water quality impairment in lakes and estuaries, and the second leading cause in rivers (Ribaudo et al., 2001; Nirascou, 2006). Intensive farming also affects the nutrient load in territorial waters (Simonit and Perrings, 2011). The fertilizer used in agriculture is mainly composed of nitrogen and phosphorus. These elements can accelerate the development of algae on the surface of the water, resulting in a variety of problems, including clogged pipelines, greater fish mortality, and reduced recreational opportunities (Ribaudo et al., 2001). The areas most affected are those closest to land on which intensive farming is practiced.

Agricultural pollutants have a harmful impact on land as well as toxic effects on humans. The assessment carried out by the European Nitrogen Assessment (ENA) in 2011 estimate at between 70 and 320 billion euros (on a European scale) the annual damage caused by nitrogen (more than twice the benefits from the agricultural use of nitrogen) (Sutton et al., 2011). In France, the annual treatment cost of runoff surpluses represents about 54 billion euros per year, according to Bommelaer and Devaux (2011). The ENA proposes solutions in terms of changes in agricultural practices - while underlining the importance for economic efficiency of wetlands restoration (Sutton et al., 2011). Russi et al. (2013) stress that the calculated marginal cost for nitrogen retention in active floodplains reaches approximately 252 million euros per year, and 72 million euros per year for phosphorus in Germany. Gren (1995), Pinay and Tremolieres (2000) and Byström et al. (2000) conclude that ecological engineering approaches, such as the construction or restoration of wetlands for nutrient retention, should have their place as an alternative, together with more conventional water pollution control technology. A study conducted by MacGibbon et al. (2010) on Lake Rotorua estimates that the sum of 1 million dollars is needed for wetlands restoration, which could absorb 1.34 tons of nitrogen per year (+/- 16%) and 0.033 tons of phosphorus per year (+/-38%). Their analysis has shown that wetlands can constitute a realistic option within a package of interventions to reduce nitrogen and phosphorus loads into Lake Rotorua. MacGibbon et al. (2010) show that the restoration/protection of all identified wetland sites across the studied area would cost 54.4 million dollars and would remove about 59.1 tonnes nitrogen/yr (+/- 15%), corresponding to about 26% of the nitrogen reduction target sought from the catchment. Another experiment was carried out to assess nitrogen flux depletion in a Breton coastal marsh next to farmland. The measured nitrate stripping is about 60% on average, i.e. 4 kg N/ha of marsh/day (Piriou et al., 1999).

Nutrient loads from agriculture runoffs can be reduced by the natural capability of wetlands to filter nitrogen from the water (Mitsch et al., 1999). Wetlands are among the most important ecosystems on Earth. They provide a range of ecosystemic functions and services and are particularly valuable as sources, sinks and transformers of a multitude of chemical, biological and genetic materials (Mitsch and Gosselink, 2007; Mitsch et al., 1999). Pinay and Tremolieres (2000) explain the sink role of wetlands: the plants present in wetlands are very effective in absorbing nutrients. A wetland is considered a sink if it has a net retention of an element or a specific form of that element - i.e. if the inputs are greater than the outputs (Simonit and Perrings, 2011; Piriou et al., 1999; Ribaudo et al., 2001; Mitsch et al., 1999). Both kinds of wetlands, natural and constructed, have been shown to be effective sinks for nutrients, especially when the nutrient loads are not excessive (Mitsch and Gosselink, 2007). Wetlands act as buffer zones, trapping the nitrogen contained in runoffs and 'processing' it through plant uptake or denitrification into the atmosphere. This means that if wetlands are localised between an agricultural zone and a river, these zones can absorb agricultural runoffs and limit river pollution.

Both constructed and natural wetlands are used for treatment of wastewater because of their consistent performance in pollutant removal. Wetlands degrade most forms of organic matter into carbon dioxide, releasing trace elements in the process. Piehler and Smyth (2011) demonstrate that wetlands present significant rates of natural denitrification. The nitrogen removal function of these habitats constitutes an important contribution to the estuarine ecosystem function. Potentially toxic metals and soluble metals are trapped and retained to varying degrees by the complex biology and chemistry of wetlands (Knight, 1997). If sufficient nitrate and organic carbon are available, high rates of denitrification ($> 100gm^{-2}yr^{-1}$) are physically possible. It also appears that, on a per unit-area basis, wetlands have a greater potential than riparian forests for nitrate-nitrogen reduction by denitrification (Mitsch et al., 1999). Studies by Brunotte et al. (2009), and also by Scholz et al. (2012) demonstrated that, in Germany, the overall potential of active floodplains for nitrogen retention is approximately 42,000 tons per year and, for phosphorus retention, approximately 1,200 tons per year (Russi et al., 2013).

Heberling et al. (2010) have studied water trading quality (WTQ) programs and propose to incorporate the use of wetlands in these programs in order to meet national wetlands goals. To participate in a WQT program, a farmer could employ wetlands as his nutrient management practice. However, the farmer has no incentive to restore wetland on his land. In order to create incentives for wetland creation and restoration, Heberling et al. (2010) propose to integrate a wetland subsidy in the farmer profit function. Despite the water quality enhancement properties of wetlands, the model reveals that implementing a wetland subsidy would not necessarily translate into water quality improvements. So "a wetland subsidy acts like a fertilizer subsidy", as explained by Heberling et al. (2010). Thus, the final outcome in the water quality trading program depends on how the factors are interrelated in each market. Although the subsidy would increase the use of wetlands, Heberling et al. (2010) cannot confirm how farmer behaviour might change in terms of fertilizer use or how runoff would ultimately be affected by the subsidy. The present paper aims to address this question but, unlike Heberling et al. (2010), it integrates a regulator aimed at reducing runoffs, combined with an economic regulation tool - a permit market. Furthermore, we take imperfect competition into account, considering pollution in terms of point source pollution for each farmer. This could eventually be determined by calculating the quantity of fertilizer bought by farmers. We do not, however, consider external non-point source pollution.

3 The model

We are interested in the question of wetlands restoration and runoff reduction via a model which integrates many farmers and a regulator. We assume identical farmers, with the same costs and income, farming similar land with similar farming practices, on land offering the same productivity. The model is in imperfect competition in the goods market (as suggested by Ribaudo et al., 2001), and in perfect competition in the allowance market.

3.1 Crop yield and runoff

The crop yield Y_i of the n identical farmers, denoted by $i = 1...n$, is assumed to depend on the share $(1-\omega_i)$ of land $\bar{L}_i$ devoted to agriculture equal to $(1-\omega_i)\,\bar{L}_i$ and the amount of fertilizer used x_i, expressed by:

$$Y_i = x_i^{\alpha}\left((1-\omega_i)\,\bar{L}_i\right)^{\beta} \tag{1}$$

where $0 \leq \omega_i \leq 1$ stands for the share of land devoted to wetlands. When the share tends to one ($\omega_i \to 1$), the land is totally devoted to wetlands and the yield is nil. When the share of wetlands is nil ($\omega_i \to 0$), the yield is at its maximum. Coefficient α measures yield elasticity with respect to the fertilizer. Under conditions $0 < \beta \leq 1$ and $0 < \alpha \leq 1$, the yield function is positive and decreasing with the fertilizer ($Y_x > 0\,; Y_{xx} < 0$), and also with the wetland share $(Y_\omega < 0\,; Y_{ww} < 0)$. To simplify the notation, the land area is assumed to be fixed and then normalised to one ($\bar{L}_i = 1$).

The crop yield creates runoff R_i, which depends positively on the use of fertilizer and agricultural surface used:

$$R_i = b_i^{-1}\,(1-\omega_i)^{\varphi}\,x_i^{\mu} \tag{2}$$

When the land is devoted exclusively to wetlands, i.e. $\omega_i \to 1$, the runoff is nil ($R_i = 0$), since crop yield is also nil ($Y_i = 0$). However, when there is no wetland, i.e. $\omega_i \to 0$, crop yield and runoffs are at their maximum, with $Y_i = x_i^{\alpha}$ and $R_i = b_i^{-1}x_i^{\mu}$. The constant parameter b_i represents soil quality, and is negatively correlated to R_i. The better the soil quality, the more efficient the retention function is. Under condition $0 < \varphi \leq 1$, runoff is negative and decreasing with wetland size ($R_w < 0$ and $R_{ww} > 0$). This means that runoff can be reduced by wetland abatement, but at a decreasing rate. As in Heberling et al. (2010), condition $\mu > 1$ (Komárek et al., 2009; Mitsch and Gosselink, 2007), necessary for our model, ensures that runoff is positive and increasing with the use of fertilizer ($R_x > 0$ and $R_{xx} > 0$). This can be explained by the accumulation process of nutrients. Wetlands absorb nutrients and maintain the chemical equilibrium of the land, but the bioaccumulation phenomenon induces an accumulation of nutrients. Finally, conditions on the elasticities imply $R_{x\omega} < 0$, which states that fertilizer use and wetlands interact in runoff yield as technical substitution factors. We can note that our first and second order conditions are also present in Heberling et al. (2010).

Equations (1) and (2) highlight the dilemma faced by farmers trying to reduce their runoff, either by limiting their use of fertilizer or by increasing wetland abatement (a rise in ω_i). In both cases, the lower runoff means lower crop yield. Without regulation, it is easy to see that farmers have no incentive to devote their land to wetlands, since doing so would mean a loss in crop yield. Hence, the choice between wetland and fertilizer will depend on the relative efficiency of these two factors.

Demand for crops is given by:

$$Y^d = P^{-\epsilon},\, \epsilon > 1 \tag{3}$$

where P is the endogeneous price of crops and ϵ stands for the elasticity-price of demand.

The establishment of a permit market controlling agricultural runoffs can significantly reduce runoffs. If we assume that agricultural techniques and fertilizer efficiency remain unchanged, farmers could reduce the quantity of runoffs either by restoring wetlands on their own land - which would improve the retention function of the wetland - or by reducing fertilizer use on an unchanged cultivated surface. The main question raised by Heberling et al. (2010) concerns the possibility of farmers increasing their use of fertilizer in order to compensate for the loss of cultivated land. Since farmer reaction remains unknown, the water quality trading program cannot provide conclusions about runoff reduction. Our model addresses this issue by introducing a regulating agency to limit the quantity of runoff via a permit market. Thus, even if farmers increase their use of fertilizer per hectare, following wetland restoration on their own land, the total pollution would be reduced thanks to the permit market. This is what we will see in the following subsections.

3.2 Regulating agency

As the aim of the regulating agency is to reduce runoffs coming from intensive farming, a nutrient allowance market is introduced. To regulate runoffs is a strong hypothesis. A primary difficulty with runoff regulation is that multiple sources mix together, making a targeted liability analysis difficult (Kochan, 2006). However, following EPA (2003), Kochan (2006) and Hansen and Hansen (2013), we consider that, even if we cannot escape the reality that controlling runoff may require regulation, we can reasonably expect that some barriers can be overcome. For example, an estimation of nutrient loading is possible with model simulations. Several mathematical models have been developed to estimate nutrient loadings in watersheds (Zhang and Jörgensen, 2005). In addition, Cason et al. (2003) propose an incentive mechanism to encourage the reduction of non-point source pollution using an experimental model. Their results show that landholder profits are higher when environmental quality is revealed to sellers. Finally, the nutrient allowance market we consider is comparable to the fishery tradable permit market or to the tradable permit system in irrigated agriculture (Latinopoulos and Sartzetakis, 2011).

The supply of allowances is given by $Q^s = \overline{Q}$, while the demand of allowances is measured by the farmers total runoff $Q^d = \sum_i R_i$. The clearing market condition implies $\overline{Q} = \sum_i R_i$. The allowance market is assumed to be competitive. Each farmer receives an initial amount of allowances $\overline{Q}_i$ with $\overline{Q} = \sum_i \overline{Q}_i$. To fulfil the runoff target set by the regulator, farmers can decide to reduce their fertilizer use or to restore wetlands on agricultural lands.

The introduction of allowance credits would modify the maximization program of the farmer, as we will see in the next subsection.

3.3 Farmer behaviour

Following Marcoul (2002), Bimonte et al. (2009) and Dubois (2009), we consider an oligopolistic market in which farmers are assumed to maximize their payoff, depending on crop yield, fertilizer use, the allowance market and the land surface devoted to agriculture. The maximization program of farmer i is given by

$$\max_{\omega_i, Y_i} \pi_i = PY_i - c_{x,i}x_i - m\left(R_i - \overline{Q}_i\right) - c_{l,i}$$

We consider the demand for crops given by $P = Y^{-\frac{1}{\epsilon}}$ and the fertilizer use function $x_i = Y_i^{\frac{1}{\alpha}}(1-\omega_i)^{-\frac{\beta}{\alpha}}$, coming from (1). We pose the parameter ϕ_i expressing that farmer i takes the consequences of its production on those taken by other farmers into account when maximising profit (Pereau and Sanz, 2011)[1]. Taking into account the following farmers reaction function in imperfect competition (following Sen and Dutt, 1995):

$$\frac{\partial}{\partial Y_i}\left(\sum_{j\neq i} Y_j\right) = \phi_i$$

This gives

$$\max_{\omega_i, Y_i} \pi_i = Y^{-\frac{1}{\epsilon}} Y_i - c_{x,i} Y_i^{\frac{1}{\alpha}} (1-\omega_i)^{-\frac{\beta}{\alpha}} - m\left(b_i^{-1}(1-\omega_i)^{\left(\varphi - \frac{\beta\mu}{\alpha}\right)} Y_i^{\frac{\mu}{\alpha}} - \overline{Q}_i\right) - c_{l,i}$$

with m standing for the price of allowance, $c_{x,i}$ the price of fertilizer, $c_{l,i}$ the rent of land. Converting land to agriculture or back to wetlands is assumed to be costless. The solution of this program gives the optimal amount of wetland area and fertilizer use. The first order conditions with respect to the two decision variables ω_i and Y_i are

$$-\frac{\beta}{\alpha} c_{x,i} Y_i^{\frac{1}{\alpha}} (1-\omega_i)^{-\frac{\beta}{\alpha}-1} + m\left(\varphi - \frac{\beta\mu}{\alpha}\right) b_i^{-1} (1-\omega_i)^{\left(\varphi - \frac{\beta\mu}{\alpha} - 1\right)} Y_i^{\frac{\mu}{\alpha}} = 0 \tag{4}$$

$$P + Y_i \frac{\partial Y^{-1/\epsilon}}{\partial Y_i} - \frac{1}{\alpha} c_{x,i} Y_i^{\frac{1}{\alpha}-1} (1-\omega_i)^{-\frac{\beta}{\alpha}} - \frac{\mu}{\alpha} m b_i^{-1} (1-\omega_i)^{\left(\varphi - \frac{\beta\mu}{\alpha}\right)} Y_i^{\frac{\mu}{\alpha}-1} = 0 \tag{5}$$

From (4) and (5), we obtain the optimal wetland area of farmer i and the goods supply of farmer i respectively:

$$\omega_i = 1 - \left(\frac{(\alpha\varphi - \beta\mu)}{\beta} m b_i^{-1} c_{x,i}^{-1}\right)^{\frac{-\alpha}{\beta(1-\mu)+\alpha\varphi}} Y_i^{\frac{1-\mu}{(\beta-\beta\mu+\alpha\varphi)}}$$

$$Y_i = \left(\frac{P}{1+\psi}\right)^{\frac{\beta(\mu-1)-\alpha\varphi}{\beta(1-\mu)+\varphi(\alpha-1)}} c_{x,i}^{\frac{\alpha\varphi-\beta\mu}{\beta(1-\mu)+\varphi(\alpha-1)}} \left(m b_i^{-1}\right)^{\frac{\beta}{\beta(1-\mu)+\varphi(\alpha-1)}} K$$

with $K = \left(\frac{\alpha}{\mu}\left(\frac{\alpha\varphi-\beta\mu}{\beta}\right)^{\frac{\alpha\varphi-\beta\mu}{\beta(1-\mu)+\alpha\varphi}} + \frac{1}{\alpha}\left(\frac{\alpha\varphi-\beta\mu}{\beta}\right)^{\frac{-\beta}{\beta(1-\mu)+\alpha\varphi}}\right)^{\frac{\beta(\mu-1)-\alpha\varphi}{\beta(1-\mu)+\varphi(\alpha-1)}}$ is a positive constante and where $\psi = -\frac{\phi_i+1}{\phi_i - n\epsilon + 1} > 0$ is the mark-up. Considering the positive relation between Y_i and P, we pose

[1]Following Pereau and Sanz (2011), we can note that the case of price-taking behaviour with perfect competition is represented by $\phi_i = 1$, while the opposite case of monopoly is expressed by $\phi_i = 0\,;\, n = 1$.

$\mu < 1 + \frac{\alpha\varphi}{\beta}$. Thus, we can express the positive correlation between the price of allowance and the wetland surface allows by $\mu < \frac{\alpha\varphi}{\beta}$.

At symmetric equilibrium, where $b_i = b$, $c_{x,i} = c_x$, $\omega_i = \omega$, $\phi_i = \phi$, $Y = nY_i$, we obtain the optimal wetland area of a representative farmer:

$$\omega = 1 - \left(\frac{(\alpha\varphi - \beta\mu)}{\beta} m b^{-1} c_x^{-1} \right)^{\frac{-\alpha}{\beta(1-\mu)+\alpha\varphi}} Y^{\frac{1-\mu}{\beta(1-\mu)+\alpha\varphi}} \tag{6}$$

and the goods supply

$$\frac{Y^s}{n} = \left(\frac{P}{1+\psi} \right)^{\frac{\beta(\mu-1)-\alpha\varphi}{\beta(1-\mu)+\varphi(\alpha-1)}} c_x^{\frac{\alpha\varphi-\beta\mu}{\beta(1-\mu)+\varphi(\alpha-1)}} \left(m b^{-1} \right)^{\frac{\beta}{\beta(1-\mu)+\varphi(\alpha-1)}} K \tag{7}$$

Substituting (7) in (6) gives the optimal wetland area, the function of the price of the yield, the price of allowances, the price of the land and the cost of fertilizer:

$$\omega = 1 - \left(m b^{-1} \right)^{\frac{1-\alpha}{\beta(1-\mu)+\varphi(\alpha-1)}} c_x^{\frac{\alpha-\mu}{\beta(1-\mu)+\varphi(\alpha-1)}} \left(\frac{P}{1+\psi} \right)^{\frac{\mu-1}{\beta(1-\mu)+\varphi(\alpha-1)}} \tag{8}$$

To simplify the expression, the multiplicative constants are omitted.

The optimal fertilizer use can be expressed:

$$x = \left(m b^{-1} \right)^{\frac{\beta}{\beta(1-\mu)+\varphi(\alpha-1)}} c_x^{\frac{\varphi-\beta}{\beta(1-\mu)+\varphi(\alpha-1)}} \left(\frac{P}{1+\psi} \right)^{-\frac{\varphi}{\beta(1-\mu)+\varphi(\alpha-1)}} \tag{9}$$

Expressions for goods supply, fertilizer demand and land allocation between agricultural soil and wetlands are defined for a given allowance price and a given price of crops. With a given m and a given P, we can express some partial results that will be confirm by the comparative statics in the general equilibrium situation., i.e. $\frac{\partial w}{\partial b} > 0$; $\frac{\partial w}{\partial c_x} < 0$; $\frac{\partial x}{\partial b} < 0$; $\frac{\partial x}{\partial c_x} < 0$. We add to these results the positive correlation observed between the price of crops and the fertilizer use, the allowance price and the wetland surface. We will now study the partial equilibrium allowance price.

3.4 Nutrient allowance market

After determining the optimal part of wetland and the optimal level of fertilizer use, the clearing market condition on the nutrient market allows us to obtain the equilibrium allowance price. At symmetric equilibrium, the aggregate runoff is:

$$R = nb^{-1}(1-\omega)^{\varphi} x^{\mu}$$

From $R = \overline{Q}$, and replacing x by its expression (9), $(1-\omega)$ by (8) and R by $\overline{Q}$, we obtain the expression of the equilibrium allowance price :

$$m = \left(\frac{P}{(1+\psi)}\right)^{\frac{\varphi}{\varphi(1-\alpha)+\beta\mu}} \left(\frac{\overline{Q}}{n}\right)^{\frac{\beta(1-\mu)+\varphi(\alpha-1)}{\varphi(1-\alpha)+\beta\mu}} c_x^{\frac{\beta\mu-\alpha\varphi}{\varphi(1-\alpha)+\beta\mu}} b^{\frac{\beta}{\varphi(1-\alpha)+\beta\mu}} \tag{10}$$

This expression allows us to express the general equilibrium of variables ω and x and, thus, $\frac{Y}{n}$ and P, as we will see in the following section. Before that, we observe, in partial equilibrium, the positive relation between P and m and b and m and the negative relation between c_x and m. These intermediate results confirm the comparative statitics that we will study in general equilibrium.

4 General equilibrium

In order to determine the optimal level of yield and the optimal price of yield, we replace m given by (10) in Equations (7), (8) and (9). This allows us to express the decision variables in relation to$\left(\overline{Q}/n\right)$. We can write the following expressions for ω and x:

$$\omega = 1 - \left(\frac{P}{(1+\psi)}c_x^{-1}\right)^{\frac{-\mu}{\varphi(1-\alpha)+\beta\mu}} \left(\frac{\overline{Q}}{n}b\right)^{\frac{1-\alpha}{\varphi(1-\alpha)+\beta\mu}} \tag{11}$$

$$x = \left(\frac{P}{(1+\psi)}c_x^{-1}\right)^{\frac{\varphi}{\varphi(1-\alpha)+\beta\mu}} \left(\frac{\overline{Q}}{n}b\right)^{\frac{\beta}{\varphi(1-\alpha)+\beta\mu}} \tag{12}$$

Replacing variables m, ω and x by (10), (11) and (12) in the expression of the supply curve, we obtain the global supply curve expression, function of P and $\frac{\bar{Q}}{n}$:

$$\frac{Y}{n}=\left(\frac{P}{(1+\psi)}c_x^{-1}\right)^{\frac{\alpha\varphi-\beta\mu}{\varphi(1-\alpha)+\beta\mu}}\left(\frac{\overline{Q}}{n}b\right)^{\frac{\beta}{\varphi(1-\alpha)+\beta\mu}} \tag{13}$$

Using $Y^d=P^{-\varepsilon}$, the global demand curve expression, we determine the value of the equilibrium price:

$$P=(1+\psi)^{\frac{\alpha\varphi-\beta\mu}{\Omega}}\,c_x^{\frac{\alpha\varphi-\beta\mu}{\Omega}}\left(\frac{\overline{Q}}{n}b\right)^{\frac{-\beta}{\Omega}} \tag{14}$$

where $\Omega=\varphi(\alpha+\varepsilon-\alpha\varepsilon)+\beta\mu(\varepsilon-1)>0$.

Equation (13) shows that the equilibrium supply curve is a positive function of the quantity of distributed allowances, whereas the equilibrium demand curve is a negative function of the quantity of distributed allowances. From (Y,P), we obtain the optima levels of variables x, ω and m and, thus, the optimal part of wetland, the optimal level of quota and the optimal price of allowances. To do this, we substitute (14) in (11) and (12), so that:

$$\begin{aligned}
\omega^* &= 1-((1+\psi)\,c_x)^{\frac{\varepsilon\mu}{\Omega}}\left(\frac{\overline{Q}}{n}b^{-1}\right)^{\frac{\alpha+\varepsilon-\alpha\varepsilon}{\Omega}} && (15)\\
x^* &= ((1+\psi)\,c_x)^{\frac{-\varepsilon\varphi}{\Omega}}\left(\frac{\overline{Q}}{n}b^{-1}\right)^{\frac{\beta(1-\varepsilon)}{\Omega}} && (16)\\
m^* &= b^{\frac{\beta(1-\varepsilon)}{\Omega}}\,c_x^{\frac{(\beta\mu-\alpha\varphi)(1-\varepsilon)}{\Omega}}\,(\psi+1)^{\frac{-\varepsilon\varphi}{\Omega}}\left(\frac{\overline{Q}}{n}\right)^{\frac{\beta(1-\mu)+\varphi(\alpha-1-\beta)}{\varphi(1-\alpha)+\beta\mu}} && (17)
\end{aligned}$$

The expression of $Y,\ P,\ \omega^*$, x^* and m^* allows us to study the comparative statics of variables. The table below summarizes this. Results show that the optimal part of wetland ω^* is positively correlated with the soil quality b, and negatively with the quantity of distributed allowances $\overline{Q}/n$. An interesting result appears for this variable : ω^* is negatively correlated with the price of fertilizer c_x. We can interpret this result by the fact that if fertilizer prices increase, the farmer is more prone to reduce his fertilizer use than to restore wetland. The elasticities observed for Y and P are coherent with economic intuitions: the positive correlation between the optimal yield of crops and the quantity of allocated allowances, and between the optimal yield of crops and soil quality, are easily understandable, as well as the negative correlation between the optimal price of crops and these same parameters. The farmer will produce more crops with an increase in allocated allowances and improved soil quality, and inversely for P. We find the same results as previously, with the optimal quantity of fertilizers x^* being positively correlated with the quantity of allowances. Finally, the optimal price of allowances m^* is negatively correlated with the quantity of allowances, and positively with the fertilizer price.

	Y	P	w^*	x^*	m^*
$\overline{Q}/n$	+	-	-	+	-
b	+	-	+	-	+
c_x	-	+	-	-	-

Table 1: Comparative statics of variables Y, P, w^*, x^* and m^*

Finally, having determined and interpreted the comparative statics of our model, we now illustrate the evolution of the variables Y and P in the case of decreasing allocated allowances. Variables Y and P move in opposite directions relative to $\overline{Q}/n$, b and c_x. In Figure 1, we see that a restriction in the number of allocated allowances induces a move of the supply curve to the left which, in turn, induces a decrease in the quantities offered and, therefore, an increase in price. Also, as we can see, diminishing the number of allowances has no consequences on economic efficiency but just serves as an environmental target. As ω^* is negatively correlated to $\overline{Q}/n$, a decrease in the number of allocated allowances encourages wetland restoration. The reduction in the number of allocated allowances induces a move of the equilibrium point to the left, which signifies lower crop yield, and to the top, which signifies an increase in crop price.

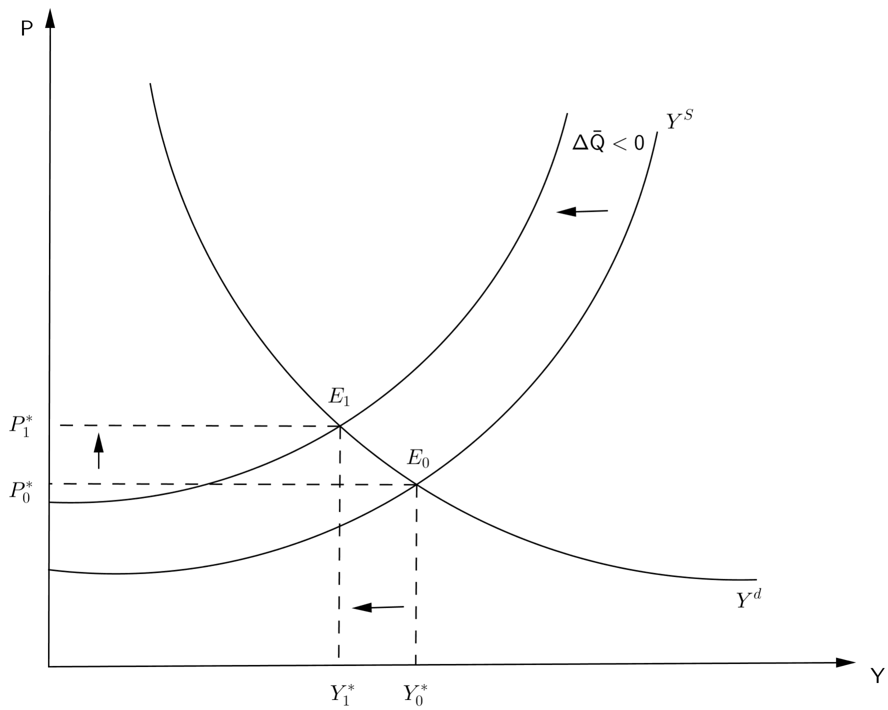

Figure 1: Evolution of Y and P with a decrease in allocated allowances

As shown in the table of comparative statics, a reduction in the number of allowances induces a decrease in fertilizer use $\left(\frac{\partial x^*}{\partial \overline{Q}/n} > 0\right)$, and is favourable to wetlands restoration $\left(\frac{\partial w^*}{\partial \overline{Q}/n} < 0\right)$. A restrictive policy which induces, therefore, a restriction in the number of allowances, induces a decrease in crop yield. If we assume a fixed price, the restrictive policy could induce a greater decrease in yield than was previously the case. As we can see in the figure below, if the price of crops is no longer an adjustment variable, the reduction in the number of allowances will induce a significant decrease in crop yield.

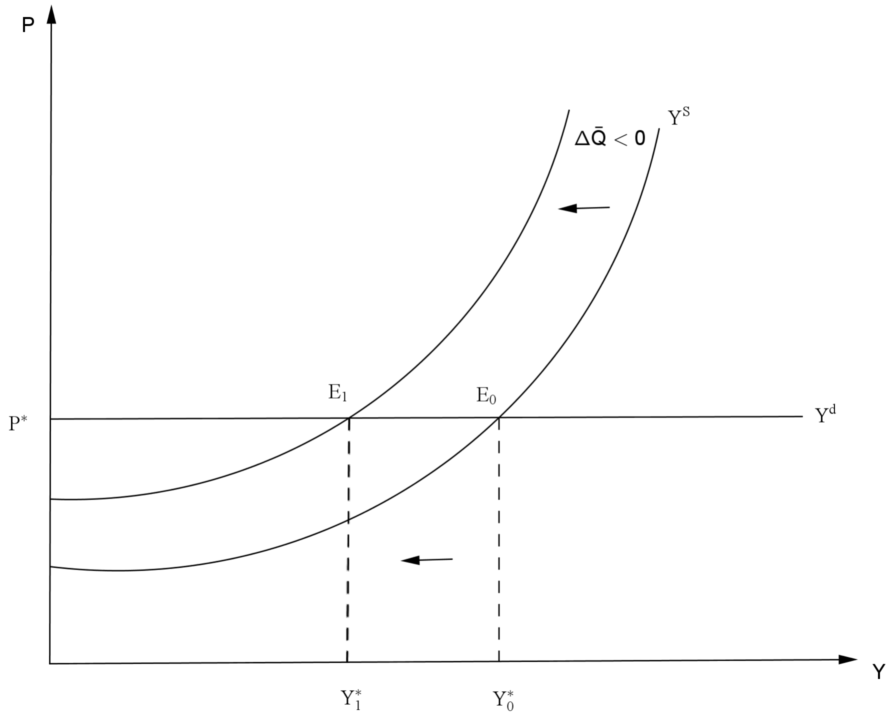

Figure 2: Evolution of Y with a decrease in allocated allowances and a fixed price

A restriction on the number of allowances is much more efficient than an action on the fertilizer price. If the regulator chooses to increase the fertilizer price, following the objective of reducing runoffs, effects are a reduction on fertilizer use, but also a reduction on wetlands surface. We can conclude on the permit market efficiency which induces both a reduction on fertilizer use and an increase on wetlands surface. Finally, we can highlight the importance of wetlands, and thus the importance of having a policy encouraging the increase of wetlands, by considering ancillary benefits provided by wetlands and the positive impact of wetlands on water and soil quality.

5 Conclusion

The wetland buffering function is one of its most efficient mechanisms for regulating agricultural runoffs and for limiting water pollution. In order to achieve these targets, the establishment of wetlands to reduce nitrogen and phosphorus loads resulting from neighbouring intensive farming practices is currently being considered. In our model, wetlands restoration is encouraged by the intervention of a regulator which decides to reduce agricultural pollution *via* a permit market. Our model, based on Heberling et al. (2010), tries to respond to the "farmers' dilemma", i.e. choosing to reduce runoffs by limiting fertilizer use or to restore wetlands on their lands. Reducing fertilizer use brings about an immediately apparent result. By contrast, the restoration of wetlands leaves some questions unanswered about the final quantity of nutrients. Farmers lose a part of their cultivable surface, so we can easily suppose that they would like to compensate for their loss of yield. Thus, we might wonder whether farmers would compensate with a bigger consumption of fertilizer, even if returns to scale could decrease; or choose not to compensate and accept lower total yield, motivated by the possibility of obtaining allowances quotas.

Our model resolves this question by introducing a permit market to control runoffs. This means that those farmers who prefer to compensate for the loss of land by increasing their use of fertilizers, should do so within limits imposed by the permit market. Thus, even if they increase their use of fertilizer per hectare, total pollution would be diminished. Comparative statics reveals interesting elements: we can see a negative correlation between the price of fertilizers and crop yield, the use of fertilizers, the wetland surface and the price of allocated quotas. Furthermore, the quantity of individual allocated quotas is negatively correlated to the wetland surface and the price of quotas, and positively to crop yield and the use of fertilizers.

Our approach is based on a restrictive policy regulated by allowances in imperfect competition. For future research, we could envisage introducing an incentive policy, such as the one studied by Crépin (2005), in which wetlands creation is motivated by subsidies. We could also integrate a study of hierarchical governance, as in Elofsson (2011), in order to define the optimal governance of our model. Introducing an incentive instrument giving more weight to the wetlands restoration solution could be one way of improving our model. This could be done by introducing the notion of ancillary benefits, and subsequently determing their economic value. We can reasonably assume that the incentive policy would be supported by the regulator, because of the presence of public goods. The introduction of ancillary benefits provided by wetlands could further encourage the restoration of wetlands.

References

Beattie, B. R., Taylor, C. R., Watts, M. J., 1985. The economics of production. Wiley New York.

Bimonte, S., Miralles, A., Pinet, F., 2009. Atelier "systèmes d'information et de décision pour l'environnement".

Bommelaer, O., Devaux, J., 2011. Coûts des principales pollutions agricoles de l'eau. Tech. rep., Commissariat Général au Développement Durable, Etudes & Documents n°52.

Byström, O., Andersson, H., Gren, I.-M., 2000. Economic criteria for using wetlands as nitrogen sinks under uncertainty. Ecological Economics 35 (1), 35 – 45.

Cason, T. N., Gangadharan, L., Duke, C., 2003. A laboratory study of auctions for reducing non-point source pollution. Journal of Environmental Economics and Management 46 (3), 446–471.

Crépin, A.-S., 2005. Incentives for wetland creation. Journal of Environmental Economics and Management 50 (3), 598–616.

Dubois, S., 2009. Vers la déchéance alimentaire de l'humanité? Revue internationale et stratégique (3), 141–146.

Elofsson, K., 2011. Delegation of decision-rights for wetlands. Environmental and Resource Economics 50 (2), 285–303.

EPA, 2003. Nonpoint source program and grants guidelines for states and territories. 68 Fed. Reg. 60,653, 60,653.

Gren, I.-M., 1995. Costs and benefits of restoring wetlands: two Swedish case studies. Ecological Engineering 4 (2), 153 – 162.

Hansen, L. B., Hansen, L. G., 2013. Can non-point phosphorus emissions from agriculture be regulated efficiently using input-output taxes? Environmental and Resource Economics, 1–17.

Heberling, M. T., Garcia, J. H., Thurston, H. W., 2010. Does encouraging the use of wetlands in water quality trading programs make economic sense? Ecological Economics 69 (10), 1988 – 1994.

Heinle, D., 1982. Historical Review of Water Quality and Climatic Data from Chesapeake Bay with Emphasis on Effect of Enrichment. US Environmental Protection Agency, Center for Environmental Research Information.

Kahn, J. R., Kemp, W. M., 1985. Economic losses associated with the degradation of an ecosystem: The case of submerged aquatic vegetation in chesapeake bay. Journal of Environmental Economics and Management 12 (3), 246–263.

Knight, R. L., 1997. Wildlife habitat and public use benefits of treatment wetlands. Water Science and Technology 35 (5), 35 – 43.

Kochan, D. J., 2006. Runoff and reality: Externalities, economics, and traceability issues in urban runoff regulation. Chapman Law Review 9 (2), 409–433.

Komárek, M., Vaněk, A., Chrastnỳ, V., Száková, J., Kubová, K., Drahota, P., Balík, J., 2009. Retention of copper originating from different fungicides in contrasting soil types. Journal of hazardous materials 166 (2), 1395–1402.

Latinopoulos, D., Sartzetakis, E., 2011. Optimal exploitation of groundwater and the potential for a tradable permit system in irrigated agriculture.

MacGibbon, R., Turner, J., Tozer, C., 2010. Wetland feasibility for nutrient reduction to Lake Rotorua.

Marcoul, P., 2002. Information sharing and oligopoly in agricultural markets: The role of bargaining associations. Tech. rep.

Mitsch, W. J., Day Jr, J. W., Gilliam, J. W., Groffman, P. M., Hey, D. L., Randall, G. W., Wang, N., 1999. Reducing nutrient loads, especially nitrate-nitrogen, to surface water, ground water, and the Gulf of Mexico. Tech. rep., National Oceanic and Atmospheric Administration National Ocean Service Coastal Ocean Program.

Mitsch, W. J., Gosselink, J. G., 2007. Wetlands. NJ: John Wiley & Sons, Inc.

Nirascou, F., 2006. Les pesticides dans les eaux - données 2003 et 2004. Les Dossiers IFEN, Institut français de l'environnement (5), 38.

Pereau, J.-C., Sanz, N., 2011. Bycatch ITQ management in oligopolistic fisheries. Tech. rep., CEREG-MIA, Université des Antilles et de la Guyane.

Piehler, M., Smyth, A., 2011. Habitat-specific distinctions in estuarine denitrification affect both ecosystem function and services. Ecosphere 2 (1), art12.

Pinay, G., Tremolieres, M., 2000. La retention et lelimination de lazote. Fonction et valeurs des zones humides. Dunod, Paris, 129–142.

Piriou, J.-Y., Coic, D., Merceron, M., 1999. Abattement de l'azote par le marais côtier de kervigen et potentiel breton. In: Pollutions diffuses: du bassin versant au littoral, Saint-Brieuc, Ploufragan (France), 23-24 Sep 1999.

Ribaudo, M. O., Heimlich, R., Claassen, R., Peters, M., 2001. Least-cost management of nonpoint source pollution: source reduction versus interception strategies for controlling nitrogen loss in the Mississippi Basin. Ecological Economics 37 (2), 183 – 197.

Russi, D., ten Brink, P., Farmer, A., et al., 2013. The economics of ecosystems and biodiversity for water and wetlands. IEEP, London and Brussels; Ramsar Secretariat, Gland, 84 p.

Sen, A., Dutt, A. K., 1995. Wage bargaining, imperfect competition and the markup: Optimizing microfoundations. Economics Letters 48 (1), 15–20.

Simonit, S., Perrings, C., 2005. Indirect economic indicators in bio-economic fishery models: agricultural price indicators and fish stocks in Lake Victoria. ICES Journal of Marine Science: Journal du Conseil 62 (3), 483–492.

Simonit, S., Perrings, C., 2011. Sustainability and the value of the 'regulating' services: Wetlands and water quality in Lake Victoria. Ecological Economics 70 (6), 1189 – 1199.

Sutton, M. A., Howard, C. M., Erisman, J. W., 2011. The European nitrogen assessment: sources, effects and policy perspectives. Cambridge University Press.

Zhang, J., Jörgensen, E. S., 2005. Modelling of point and non-point nutrient loadings from a watershed. Environmental Modelling & Software 20 (5), 561–574.