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Using Habitat Equivalency Analysis to Assess the Cost Effectiveness of Restoration Outcomes in Four Institutional Contexts

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Abstract :

At the national level, with a fixed amount of resources available for public investment in the restoration of biodiversity, it is difficult to prioritize alternative restoration projects. One way to do this is to assess the level of ecosystem services delivered by these projects and to compare them with their costs. The challenge is to derive a common unit of measurement for ecosystem services in order to compare projects which are carried out in different institutional contexts having different goals (application of environmental laws, management of natural reserves, etc.). This paper assesses the use of habitat equivalency analysis (HEA) as a tool to evaluate ecosystem services provided by restoration projects developed in different institutional contexts. This tool was initially developed to quantify the level of ecosystem services required to compensate for non-market impacts coming from accidental pollution in the US. In this paper, HEA is used to assess the cost effectiveness of several restoration projects in relation to different environmental policies, using case studies based in France. Four case studies were used: the creation of a market for wetlands, public acceptance of a port development project, the rehabilitation of marshes to mitigate nitrate loading to the sea, and the restoration of streams in a protected area. Our main conclusion is that HEA can provide a simple tool to clarify the objectives of restoration projects, to compare the cost and effectiveness of these projects, and to carry out trade-offs, without requiring significant amounts of human or technical resources.

Keywords : Wetland restoration, Equivalency tool, Ecosystem services, Cost effectiveness

1 Introduction

According to economics, the welfare of populations at a given time is a function of the utility released by the consumption of goods and services available at this time (Ramsey, 1928). Goods and services are produced using a certain amount of capital as input through a production process. Future consumption and future welfare are thus a function of the actual stocks of capital (Mäler et al., 2008).

There are different types of capital involved in the production function: manufactured capital (material goods), human capital (individuals working capacity) and natural capital. Natural capital is constituted of the limited stocks of natural resources, physical and biological, that yield the flow of goods and services from ecosystems (Costanza and Daly, 1992).

In the context of project planning, economists are supposed to assess what is the best allocation of resources among alternative scenarios of substitution between natural capital, human capital and manufactured capital. This assessment requires a unit of equivalency. If manufactured and human capital have long been assessed in monetary terms, it is still in debate for natural capital. This debate is largely associated to the debate between weak sustainability (strong substitutability between natural capital and manufactured capital) and strong sustainability (weak substitutability between natural capital and manufactured capital) (Stern, 1997; Ekins et al., 2003; Bithas et al., 2011). Standard environmental economy considers that the different types of capital are substitutable (Pearce and Atkinson, 1993). As a result, it is focused on the monetary value of natural capital in comparison with the monetary value of manufactured capital. In this way, monetary valuation provides economic units of equivalency allowing to measure the benefits provided by alternative scenarios regarding the substitution of one category of capital by another. Ecological economy contests this position and argues that substitution is only possible at the margin and that there is a portion of natural capital that is essential to human survival and for which there is no adequate substitute, defining critical natural capital (Ekins et al., 2003). Furthermore, it denounces the limits of monetary valuation which are of three types: (1) methodological limits to value ecological services due to non-commercial use value or non-use value (Heal, 2000) ; (2) limits to respect all the constraints of strong sustainability, even when all externalities are internalised (Bithas et al., 2011) ; (3) the lack of institutional contextualization of monetary values that limit their informative scope (Norgaard and Bode, 1998 ; Vatn 2010).

The idea that there is a minimum level of natural capital necessary to support human welfare seems more and more obvious to policy makers, which is why there is a growing number of institutional frames fixing strong ecological objectives, for example through European environmental directives: Water Framework Directive or the Marine Strategy Framework Directive (Good Ecological States), Natura 2000 Directive (Protected Species and Habitat Lists), Environmental Impact Studies Directive (Avoid-Reduce-Compensate ecological impacts), Environmental Liability Directive (no net loss of biodiversity and ecological services). They fix minimum quality standards in ecological terms for aquatic ecosystems, implying reduction of pressures and restoration of damaged ecosystems. In this context, the challenge for ecological economists is to be able to provide biophysical units of equivalency which are substitutable enough to provide a simplified picture of what the level of natural capital is. The aim of this paper is to assess how it is possible to use the Habitat Equivalency Analysis (HEA) to evaluate restoration projects developed in alternative institutional contexts. Originally, HEA is a tool developed to size restoration projects for the compensation of accidental impacts using ecological services units (Dunford et al., 2004 ; Bruggeman et al., 2005 ; Roach and Wade, 2006 ; Zafonte and Hampton, 2007). Recent publications have highlighted how it is possible to use equivalency tools in order to provide ecosystem valuations in ecological services biophysical units (Dumax et al., 2011; Vaissière et al., 2013). These publications, however, are based on hypothetical case studies. The goal of this paper is to use HEA for real restoration projects carried out in France during the last years in order to discuss the results both from a theoretical and a practical point of view.

The first section of this paper will be dedicated to the presentation of the method and the economic arguments that defend its broader use. We will, in the second section, present the results of its application in four restoration projects in France, based on different institutional frames, and finally discuss these results in perspective of their institutional goals in the third section.

2 Material and method

2.1 Adapting HEA

In the US, the Habitat Equivalency Analysis (HEA) was developed for the Natural Resource Damage Assessment that evolved from a monetary and welfare valuation to an estimation based on the cost of compensatory restoration projects that enhance or improve natural resource services in a sufficient amount to compensate the public (Burlington, 2002 ; Dunford et al., 2004).

Facing difficulties to obtain valid monetary damage estimates, resource trustees chose to prefer compensatory scaling methods based on ecological services. Service-to-service methods such as HEA, are based on the principle that the values humans place on natural resources are - as an approximate - proportional to the ecological services these resources provide. Damage affects natural resources and associated services and, using a biophysical indicator, one can estimate the loss of ecological services (due to damage) and gain in ecological services (due to the compensatory restoration project).

In this view, HEA is used to determine the appropriate scale of compensatory restoration through a procedure in four steps (Roach and Wade, 2006):

1 - The choice of one or more biophysical metric(s) to be used as indicators of the services provided by ecosystems;

2 - The estimation of the interim ecological service loss from the natural resource injury until it is restored to baseline conditions;

3 - The identification of a range of compensatory restoration projects;

4 - The choice of one or more compensatory restoration projects that provide a present value of service gain equal to the present value of service loss from the natural resource injury.

In the end, HEA values the ecological services produced by a restoration project in the perspective of its institutional objective: the compensation of the loss of ecological services. Compensation can be considered as an institutional objective that will change according to the nature of the impact. In this paper we want to determine if HEA can be used in the context of other institutional objectives. As we aim at valuing ecological service gains associated with restorations that would not take place in the context of compensation, we need to adapt the procedure to calibrate the HEA method to each restoration action.

The rationale of the HEA can be described through Equation (1) (Dunford et al., 2004 ; Zafonte and Hampton, 2007 ; Levrel et al., 2012 ; Vaissière et al., 2013) and is observable on Figure 1. HEA quantifies gains and losses as Discounted Services Acres Years (DSAYs).

$$\boldsymbol{V_I A_I I_t (1+r)^{-T_I} = V_R A_R R_t (1+r)^{-T_R}} \quad (1)$$

V_I is the value of the ecological services on the impacted site and V_R is the value of the ecological services on the compensatory restoration site.

A_I is the surface impacted, the damaged area and A_R the surface compensated, the restoration area.

I_t is the intensity of damage and R_t the intensity of restoration. They vary according to time and this variation is called recovery function on the impact site and maturity function on the restoration site.

r is the discount rate.

$-T_I$ is the time scale of the impact and $-T_R$ is the time scale of the compensatory restoration.

FIGURE 1 - Changes in ecological services provision on sites of injury and compensation (adapted from Vaissière et al., 2013)

From the initiation of procedure to the calculation of equivalency, HEA relies on some key elements that justify its use for the determination of the compensation of public loss of ecological services. These elements are associated to the calculation of ecological services in Equation (1) and have to be adapted.

First, HEA relies on different hypothesis on the value of ecological service (Dunford et al., 2004 ; Zafonte and Hampton 2007). In the end it assumes that humans derive utility from natural resources in proportion to the ecological services they provide. As so, the services from restoration project designed for compensation, should provide approximately the level of utility expected to reach the objective of compensation of public loss from the injury (Roach and Wade, 2006). Under the same assumptions, the level of utility provided by restoration with another objective could be evaluated in the lights of its expected objectives. This will be the assumption operationalized in our analysis. This assumption is adopted in the expanded HEA.

There is also the possibility for an operator to apply a "compensation ratio" to insert relative preferences for services on impacted sites over services on restoration sites (or the opposite). Equation 1 can be manipulated so as to help operators determine the size of restoration (Equation 2). It is thus possible to apply the ratio of the value of damaged services to the value of restored services ($\frac{V_I}{V_R}$). Ratios can be applied, for example, to give preferences on the type of actions chosen to implement compensatory restoration (Levrel et al., 2012).

$$A_R = \frac{V_I}{V_R} \times \frac{A_I I_t (1+r)^{-T_I}}{R_t (1+r)^{-T_R}} \quad (2)$$

The second key element is time consideration. In HEA, the application of a discount rate reflects the "social rate of time preference, which reflects society's willingness to shift the 'consumption' of public goods (such as natural resource services) over time" (Dunford et al., 2004, p. 62). As a consequence, it betrays social preference for services produced today rather than tomorrow. In this case, discounting is not applied on the monetary value of ecological services but directly to the biophysical quantity of ecological services. In the case of NRDA procedures, a discount rate of 3% is generally applied and the time reference is usually based on the year of the impact (NOAA, 1997). The same assumption is used for the adapted HEA. The year of reference will be based on the institutional frame and we will calculate all projects on a 25-year period.

The third element is the question of the measurement of the level of ecological services through a specific metric. As it is hard and costly to measure all components of an ecosystem, HEA relies on the use of a metric. Generally, the choice of metric is oriented toward an ecological parameter that is representative of the damaged habitats and/or natural resource. This metric is central in the process as it will be used for the determination of losses resulting from damage and the gain associated to compensatory restoration. Thus HEA results will be very sensitive to this choice (Strange et al., 2002, Vaissiere et al., 2013). As we can see on Table 1, various metrics can be found in literature depending on the type of ecosystems and the targeted services or functions. From the observation of the metric, HEA measures ecosystem services as an estimated percentage. Quantification of gains is conducted in perspective of the level of services on the site of injury in its baseline condition. In the adapted HEA, the idea is to adopt a baseline depending on the institution frame in which the assessment makes sense: the good ecological states for the MSFD or the WFD, the no net loss for the Environmental Liability directive and so on.

Source	Ecosystem	Targeted function or service	Choice of metric
Fonseca et al.	Seagrass	Food source, shelter,	Seagrass density (number of

(2000) ; Bell et al. (2008)		sediments stabilisation and nutrients cycles	roots per unit of surface)
Strange et al. (2002)	Salt marsh	Primary production	Biomass
		Habitat	Canopy structure of vegetation
		Soil development and biogeochemical cycling	Organic matter
		Support of food chain	Infauna
		Secondary production	Shellfish and fish density
Milon and Dodge (2001)	Coral reef	Habitat	Reef surface
Sperduto et al. (2003)	Seabirds	Bird population	Abundance
Penn and Tomasi (2002)	Salt marsh	Habitat	Qualitative observation, expert judgement and specific species abundance
French McCay and Rowe (2003)	Coastal species	Habitat participation to food web	Primary or secondary production
Cacela et al. (2005)	Estuary	Sediments quality	Toxic element concentration and effects on biota
Bruggeman et al. (2005) ; Scribner et al. (2005)	Unspecified	Habitat at metapopulation scale	Abundance and genetic variability
Roach and Wade (2006)	Coastal wetlands	Habitat	Establishment of a model to estimate impacts of chemicals
		Damages on wildlife (birds, mammals and reptiles)	

Table 1 - Review of possible metrics for HEA and their associated ecosystem and ecological services in the scientific literature

All these elements are of key importance for the application of the method and they are all taken from observations of the damages on natural resources. Table 2 summarizes how the expansion of HEA has been carried out in order to be applied to other type of institutional frame (Table 2).

	HEA for compensation	Translation in a broader use
Institutional context	Natural Resource Damage Assessment	Multiple (Water Framework Directive, Marine Strategy Framework Directive, Positive actions, Compensation...)
Actor responsible for restoration	The party responsible of the impact	Multiple (Private investor, public actor, NGO...)
Value of services	Possible use of ratio to frame compensation options	Possible use of ratio to frame restoration options
Choice of metric	Depending on the nature of the impact to compensate	Depending on the nature of the objective for restoration
Baseline for measurement	Initial level of ecological services on impacted site	Reference level of ecological services to produce
Time reference	Time of the impact	Time of the initiation of the restoration planning

Table 2 - Calibration of HEA for the expansion of its use

In this paper we will apply HEA to the valuation of actions of restoration of ecological services in perspective of their institutional objectives. This work will rely on case studies from four sites in France.

2.2 Study sites

Site selection resulted of opportunities resulting from cooperation with a public agency specialized in water and aquatic ecosystem management, the ONEMA (The French National Agency for Water and Aquatic Environments) and Water Agencies. We selected four different case studies in France taking place in different institutional context (Figure 2, Table 3).

	Libellule® zone	Environmental measures of Port 2000	Kervigen marsh	Vurpillères stream

Geographical context	Saint-Just and Saint-Nazaire-de-Pézan Pop. 3,068 Languedoc-Roussillon Mediterranean	Le Havre Pop. 300,000 Upper Normandy Oceanic	Châteaulin and Porzay and surrounding communities Pop. 15,000 Brittany Oceanic	Labergement-Sainte-Marie Pop. 1,000 Franche-Comté Continental
Goal of the restoration project	Creating a market for environmental mitigation or natural water treatment system	Acceptance of the ecological impacts coming from the extension of the Port of Le Havre in the Seine estuaries	Avoiding green tides	Ecological restoration of Vurpillères stream
Type of action	Creation of a wetland at the outlet of a sewage treatment plant	Home-birds (shorebirds): creation of an island in the sea, creation of a resting place on dune -Production of mudflats: creation of a meander	Producing a service for assimilative decrease of nitrogen	Restoration of meanders in the stream
Size of projects	1.5 ha	45 ha for the resting place 1.5 ha for the island 300 ha for the meander	22 ha	1.1 km of stream

Table 3 - Presentation of the four case studies

FIGURE 2 - Location of the four case studies in France

3 Results

This part will present the application of HEA to the calculation of the gain of ecological services associated to each of our projects (synthesized in Table 6). As we assert that HEA is a good tool for valuation of a project according to its institutional context and objectives, we will have to synthetically introduce each project.

3.1 Libellule® Zone

In 2007, the towns of Saint-Just and Saint-Nazaire-de-Pézan undertook the renovation of their wastewater treatment plant (WWTP). Because of their location in the watershed of a protected Mediterranean lagoon exposed to eutrophication problems (the Or lagoon), partners proposed to create a lagoon system to apply tertiary treatment while securing the rejection of the WWTP. The company in charge offered to support the costs of establishing the lagoon system in exchange for the opportunity to implement the Libellule® zone in place of the original project which merely consisted of a pond planted with reeds. This new system, in addition to the initial objectives, included innovative projects - research program on micro-pollutants, joint production of a rich biodiversity or credit production for wetland and biodiversity offsets - with the view of using this pilot project to develop a market for implementation of Libellule® zone. It has been operational since 2009. Part of the water leaving the WWTP reaches a succession of wetland habitats - phytoplankton basin, reed marsh, meandering zone, anastomosing array and free zone - complemented by a humid meadow, an alluvial zone, a brush planted with trees and a sand filter (Figure 3).

FIGURE 3 - Map of the Libellule® zone (Image: Biotope)

As the goal of the project manager of the Libellule® zone is the creation of a market for this project, it can be valued in perspective of different objectives corresponding to different institutional contexts that would require implementation of similar projects. On the basis of the data available and the potential targeted markets we can select the elements to calibrate HEA for the calculation of gains of ecological services (Table 4).

If we consider the Libellule® zone in the context of the production of a lagoon system for WWTP, it can be valued in perspective of its objective of tertiary treatment. The reason why the project's initiators decided to implement a constructed wetland in this area was the Or lagoon's great sensitivity to eutrophication. Thus we can use information taken from monitoring of the Or lagoon for the application of HEA. Data availability on both sites and discussions with local experts led us to choose dissolved oxygen as a metric of the activity of vegetal species, among the major drivers of purification capacity of the Libellule® zone. Equation 3 shows the calculation of intensity of restoration ($\boldsymbol{R}$ in Equation 1), we measured the level of dissolved oxygen at the entrance ($\boldsymbol{O_i}$) and at the exit ($\boldsymbol{O_f}$) of the Libellule® zone and in the Or lagoon ($\boldsymbol{O_{Or}}$). Gains valued through HEA are thus measured in perspective of the institutional context in which the project takes place as the enhancement associated to the metrics is measured relatively to the level of the metrics in the Or lagoon. We then calculated the gains using HEA, between the start of the works on WWTP in 2007 and 2032 (on a 25-year period length). We valued an amount of 1.26 DSAYS between 2007 (start of the works on the WWTP) and 2032.

$$\boldsymbol{R} = \frac{\boldsymbol{O_f - O_i}}{\boldsymbol{O_{Or}}} \quad (3)$$

We also valued the project in perspective of other objectives such as offset production or security of the WWTP rejects as presented on Table 4. As a result we obtained 9.57 DSAYs and 6.44 DSAYs for the valuation of Libellule® zone in the perspective of offset production for habitat and biodiversity respectively and 6.92 DSAYs in perspective of security of the WWTP rejects.

Objective for valuation	Metrics	Determination of baseline	DSAYs
Tertiary treatment	Dissolved oxygen : Presence of dissolved oxygen is an indication of the chemical activity of vegetal species in water.	Dissolved oxygen in the Or lagoon.	1.26
Offset production (Habitats)	Coverage of hydrophytes: Composite proxy considering surface and deep hydrophytes.	Coverage of 100% of available surface.	9.57
Security of the WWTP rejects	Surface of wetland: The total area occupied by wetland in the entire Libellule® zone.	Coverage of 100% of the entire Libellule® zone.	6.92

Offset production (biodiversity)	<u>Species richness (odonates) :</u> Indicator of the number ofspecies of dragonflies inventoried on the site	Maximum of species inventoried on one area in France[a] from 1970 to 2006.	6.44

Table 4 - Application of HEA to measure the environmental gains on the Libellule® zone, using different proxys ([a] French society of odonatology, source: INVOD, ESRI)

As shown in Table 4, valuation using HEA is very sensitive to the choice of assumptions for the calculation of gains (particularly for the metric and the reference state). Each of these assumptions can be disputed, thus there is not much sense in considering these results in absolute values. In this view we propose to discuss these values in perspective of the institutional objectives in which these projects take place. DSAYs could then be used as a unit for comparing projects in terms of cost efficiency analysis or enter in multi-criteria analysis.

The implementation of Libellule® zone is conducted to create new markets (e.g. market for mitigation of emerging pollutants such as micropollutants) or to propose a new offer on existing markets (e.g. tertiary treatment of water sewage). These markets are characterized by specific performance criteria and can provide good metrics and reference states for projects, as shown in our example of dissolved oxygen. These markets can also be oriented toward the production of wetlands habitat or biodiversity offsets, for which gains should be valued in perspective of potential impacts on similar ecosystems (for more information on emerging markets for biodiversity see Hough and Robertson [2009], McKenney and Kiesecker [2009] or Coggan et al. [2013]). In this way, HEA can be an interesting tool as it provides a unit for exchange between compensation bankers and project developers.

3.2 Environmental measures of Port 2000

The Seine estuary refers to the part of the river that is subject to tidal influence. It is a densely populated region and home to a variety of economic activities. The estuary is characterized by the presence of a high biological diversity (birds, fish, etc.) and included in the Natura 2000 network. It is also protected by the existence of the Nature Reserve of the Seine Estuary. Because of the construction of Port 2000, the Le Havre harbor had to set up two types of environmental measures to offset impacts on local biodiversity: compensatory measures and accompanying measures.

Compensatory measures that focused on the creation of a resting place on dune - a resting area of 45 ha consisting of a basin subject to tidal influence and a large dry area - and an islet resting place - an islet of 5 hectares at low tide which is reduced to 1.5 ha and three smaller islets at high tide (Figure 4). As the objective of the islet is to welcome shorebirds at high tides, we retain the surface of 1.5 ha in all calculations. These measures were designed to compensate for the destruction of a disused deposition chamber which had been colonized by seabirds - particularly shorebird species.

Among the accompanying measures we study a rehabilitation project of mudflats. This project involved the creation of an artificial meander to restore 100 ha of mudflats which had undergone a decrease of their surface area at a rate of 20 hectares per year since 1980.

We applied HEA to value these projects in two different ways, first considering the compensatory measures and second considering accompanying measures.

First we focus on the valuation of the two compensatory measures : the repositories for shorebirds. Valuation of projects using HEA is similar to its initial use in the NRDA framework, with the difference that the impact is not accidental and temporary but authorized and permanent. As a result, the objective for valuation of both repository area and islet is the compensation of loss of habitat for shorebirds. According to data availability, we used the global population of shorebirds in the estuary as metric. In 1997, objectives were set for compensatory restoration to compensate loss of population of shorebirds due to port development. We used data produced by Wetland International on observation of the evolution of shorebirds population on the estuary (Aulert et al, 2009) between 1985 and 2007. Works of Port 2000 were finished in 2005, we then assume that after this year, all evolution of the shorebird population at the scale of the estuary will be due to compensatory measures. As we do not have available information after 2007, we have to make assumptions on the maturity curve associated to the intensity of restoration. We assume that because of the last adjustment and good management practice, compensation measures will work and that shorebird population will recover its 1997 level in 2011 with a linear growth from 2007 to 2011. We can then calculate the gains associated to both repositories between 2005 and 2030 using HEA, result is of 0.131 DSAYs.

Considering the accompanying measure, the objective of the project is to restore 100 ha of mudflats by an action on 300 ha. Although mudflats didn't appear at the expected place, 60 ha appeared elsewhere, we assume that it is directly linked to the project and use the surface of mudflat as a metric to calculate gains with HEA. According to local observation of Aulert et al. (2009), surface of mudflats appeared is of 45 ha in 2008. We have to make assumptions to reconstitute intensity of restoration in time. Works ended in 2005, as a result we assume that apparition of mudflats started in 2006, letting one year for system stabilization after works. We then assume linear growth between 2006 and 2008 (45 ha) and between 2008 and 2012

(60 ha) and a stabilization of the system in 2012. Calculation of the ecological gains using HEA gave a result of 9.12 DSAYs for the rehabilitation of mudflats.

As we mentioned in the previous part, these two values make no sense in absolute terms, but we can consider them relatively to each project's objectives. In the case of compensatory measures, we can value the temporal loss of services associated to port development (using the loss side of Equation 1). We measured a total loss of 2.16 DSAYs. According to Equation 2 and the quantity of DSAYs associated to the action of compensation, 16.4 ha of additional compensation would be necessary for the compensation of temporal losses. If we rely on the replacement cost principle, as 46.5 ha cost around 9.9 million EUR, we can value the temporal loss of services associated to shorebirds compensation to an additional 3.3 million EUR.

FIGURE 4 - Aerial view of Port 2000 and the environmental measures accompanying the project (Image: Google Earth - Cnes/Spot Image 2013)

3.3 Kervigen marsh

The Kervigen marsh is located in the bay of Douarnenez in Brittany. It is a 22-hectares marsh separated from the sea by a coastal dune. It is crossed by the river Kerharo, whose watershed is known for its intensive agriculture. In the 1960s, adjustments were made to drain the swamp for agriculture. This led to the rectification of the river and the raising of the dune. However, agricultural activity ceased in 1975. In 1990, because of the intense exposure of Douarnenez Bay to green tides, Kervigen marsh became the subject of an experiment to take advantage of its performance in purifying nitrates. The success of this experiment led to the acquisition of land from the local government and the establishment of a rehabilitation program: restoration of the dune and diversion of part of the flow of the river into the marsh with the installation of two systems of sluices for water level management (Figure 5).

FIGURE 5 - Aerial view of Kervigen marsh (Image: Google Earth - DigitalGlobe 2013)

Facing the high purification capacity of the marsh, a broad program of restoration has been included in the nitrate mitigation strategy of the watershed of the Douarneney bay. This program aims at reducing by 50 tons per year the quantity of nitrate in the bay with marsh rehabilitation. We will use this objective for the calibration of HEA for valuation of the Kervigen marsh.

Purification performances of the Kervigen marsh varies between 2 and 4 kg per day per hectare, as the marsh is used 110 days per year (when the water level in river is high enough to allow fish circulation despite deviation in the marsh). Calculation of ecological gains using HEA gave us 0.079 DSAYs and 0.158 DSAYs for performances of 2 and 4 kg per day per hectare respectively.

The strategy of restoration fixes an objective of reduction of 50 tons of nitrate per year, this can be considered as a deficit of ecological services: if nothing is done 100% of services will be lost, corresponding to 18.41 DSAYs between 2012 and 2037. Considering the gains associated to the Kervigen marsh rehabilitation we can propose discussion on the different strategies for restoration of marshes (Table 5). Using HEA we can dimension the need of restoration to reach 50 tons of nitrate reduction. We can see that changing the time limit for the objective will change the total surface of project, because of the application of a discount rate that gives preference for services produced in 2012, rather than later.

Strategy for marsh restoration	Surface to restore per year	Total surface to restore
Objective in 2012	234 ha	234 ha
Objective in 2015	64 ha	254 ha
Objective in 2020	33 ha	294 ha

Table 5 - Dimensioning restoration plan according to different strategy scenario for a selected performance of 2 kg.day^{-1}.ha^{-1}

3.4 Vurpillères stream

The Vurpillères stream is located in the upper Jura mountains, in the Nature Reserve (NR) of Lake Remoray. It is a little over one kilometer long, supplied by a watershed with no anthropogenic activity. It crosses low marshes and peat lands. In the 1960s, with the aim of draining the marshes for agriculture, the stream was channeled. Without releasing usable land, this rectification resulted in a loss of diversity of habitats and species. When the Nature Reserve was established in 1980, public access to the wetlands was completely banned and in 1997 the first management plan enabled the reserve manager to launch the restoration of Vurpillères stream (Figure 6).

Valuation of this restoration project was conducted using HEA. For calibration of the model we used information on monitoring of small invertebrates of the communities : plecoptera, trichoptera and ephemeroptera. Monitoring on the restored stream was conducted in 1993, 1998, 2002 and 2007 (Redding, 2009). We chose the species' richness of these communities as a metric for the calculation ; and the number of species at the last observation (2007) as a baseline, assuming that the stream had reached its initial level of services. The application of HEA for the calculation of gains gave 5.79 DSAYs between 1997 date of the project and 2022.

In the same way, we can calculate the loss associated to the channelization of the stream in 1966 with HEA. We obtain a total of 25.95 DSAYs lost. This underlines that the restoration of ecosystems never takes into account the temporal loss associated with past impacts. In the case of Vurpillères stream, compensation of total losses would have implied a project 4.5 times more important.

FIGURE 6 - Aerial view of the Vurpillères stream (Image Google Earth -GeoEye 2013)

	Libellule® zone	Environmental measures of Port 2000		Kervigen marsh	Vurpillères stream
		Mudflats rehabilitation	Repositories		
Objective for valuation	Depending on the targeted market	Creation of 100 ha of mudflat	Ecological neutrality of Port 2000 on the shorebirds in the estuary	Reduction of 50 kg nitrate per year through restoration of marshes	Ecological restoration of the site to its itinial state
Metrics	e.g. Dissolved oxygen	Surface of mudflats	Abundance of shorebirds in the estuary	Absorbed nitrate	Species richness
Initial level	State of metric before works	Null	Number of shorebirds before impact	Absorbed nitrate without the marsh	Number of species before restoration
Intensity of restoration	Evolution of metrics during time	Surface of mudflats observed in 2008 and 2012, we assume linear growth between observations	Variation of number of birds from 2005 and return to the baseline in 2010.	Purification performance associated to the latest measures in 2008.	Number of observed species in 1993, 1998, 2002 and 2007, we assume linear growth between observations
Hyptohsesis on the final level	Management plan maintains level of service to its 2011 state.	Site is stabilised in 2012.	Return to the baseline in 2010.	Management plan maintains performance to its 2008 state.	In 2007, level of service is back to its initial level.
Reference state	Dissolved oxygen in the Or lagoon	Objective of mudflat creation (100 ha)	Number of birds in the estuary in 1997	Nitrate reduction objective (50 tons per year)	Species richness in 2007
Reference date	Beginning of works (2007)	Beginning of works (2005)	Beginning of impact (1997)	Beginning of project (2010)	Start of project (1997)
DSAYs	1.26	9.12	0.131	0.079	5.79

Table 6 - Synthesis of the application of HEA for valuation of actions of restoration of aquatic ecosystems

3.5 Comparative results

As we mentioned, results of valuation using expanded HEA do not have much sense in absolute value and must be conducted in comparative terms. Table 7 shows the results of a cost-benefit analysis conducted on the basis of the benefits expressed in DSAYs and the cost per hectare of projects. The cost of the project was determined based on the cost of investment and annual costs associated to management and monitoring (when scheduled). Total costs for the project was calculated over the same time period as the one used for DSAYs calculation, i.e. on a 25 year period.

		Objective	Cost of project (EUR/ha)	DSAYs	Cost/Benefit Ratio (10^3)
Libellule® zone		Market of lagoon systems	1,338,000	1.26	1062
		Offset for biodiversity	1,338,000	6.44	207
Environmental measures of Port 2000	Mudflats rehabilitation	Production of mudflats	77,000	7.589	10
	Repositories	Compensation of shorebirds	213,000	0.21	1014
Kervigen marsh		Mitigation of nitrate	13,600	0.0495	275
Vurpillères stream		Restoration	10,600[b]	10.38	1

Table 7 - Comparisons of costs and benefits of projects ([b] Restoration was applied on 1100 meters of the river, piezometric level was improved on riverbanks on a strip of 10 to 20 meters large on each side of the river. We retain a width of 15 meter on each side to calculate the surface impacted by the restoration project)

4 Discussion

HEA can provide a simple tool to clarify the objectives, the means to achieve them and a tool to assess the efficacy of actions to achieve these objectives. It enables us to assess the ecological benefits of alternative restoration programs in biophysical units and to compare them in a strong sustainability way.

4.1 Results

Comparison of projects using expanded HEA then raised the question of the substitutability of DSAYs. At the level of investment in natural capital, we can compare projects amongst themselves. Such a comparison means to determine the best investment in ecological services regardless of location, ecosystem type or institutional frame. In this way, prioritizing investment at constant budget would imply to choose the project with the lowest cost-benefit ratio. In this way, the more interesting project is the restoration of Vurpillères stream (Table 7).

When we introduce more precise considerations, comparison needs to be conducted with caution. Indeed, as we can see on Table 7, the Libellule zone appears to be the worst project when we consider its benefits in perspective of tertiary treatment of WWTP, whereas it becomes a more interesting investment than bird repositories when we consider its benefits in perspective of offset production for biodiversity. In the same way projects are implemented on specific location, restricting investment to a specific area narrows the set of solution. In this way, the question of the best investment on the Seine estuary would lead to prefer mudflats rehabilitation over bird repositories restoration (Table 7). These issues are related to methodological assumptions that need to be discussed.

4.2 Methodology

As mentioned earlier, the HEA methodology relies on key assumptions that need to be discussed in perspective of our proposal for expansion of its use.

First, the value of ecological services is supposed to be constant over time, which might be true for short periods but is more difficult to argue for longer periods as retained by HEA (Zafonte and Hampton, 2007). The question of constant value is also asked regarding the spatial dimension. We have considered this same assumption for our calculation.

Second, HEA applied a discount rate to the ecological services in order to integrate the human time preference for the present. There is an extended literature discussing the problems regarding discount rates and proposing modifications and alternatives (Henderson and Bateman, 1995 ; Weitzmann, 1998 ; Frederick et al., 2002; Young and Hatton McDonald, 2006). As a result, since the time reference is the year of impact, projects implemented earlier have a greater value. In the context of our extended approach, this can raise issues. For example in the case of the use of HEA to value production of biodiversity offset, a project implemented before impacts could accumulate enough ecological services to compensate impacts on larger area which seems to be the opposite of the objective of the legislation.

Third, HEA allows the application of a ratio, which can be applied to illustrate preference for some action over another (Levrel et al., 2012) or to weight on the location of compensation regarding the location of the impact. We have not applied any ratio in our calculations, but application of HEA in a decision procedure could consider application of ratio. For example, in the case of the meander, we stated that restoration outcome did not appear at the expected location. A ratio could be applied to underline the inadequacy of the outcomes to the institutional frame and to decrease the value of the project's benefits.

Fourth, the quantity of DSAYs we calculated using HEA is heavily dependent of the choice of metrics (Strange et al., 2002). This is part of the strength of HEA into the NRDA framework, it allows to focus discussion on the choice of the metrics. Adoption of HEA resulted from a will of simplification of the calculation of costs since previously, the complexity and opacity of calculations systems limited implementation of compensation measures.

Fifth, we note that calculation of DSAYs relies on assumptions about the maturity function or the observation of metrics. All assumptions on the value of the metrics explicitly stated in this paper were conducted according to data availability but only rely on authors' arbitration. In its genuine use HEA relies on a more participatory process which helps reduce uncertainty accumulated through assumptions.

All these elements are associated to the fact that the HEA is usually integrated into a specific procedure of decision: the NRDA. This procedure gives a framework for the use of HEA and justifies all the conventions associated to the calibration of the assumptions of the model. Our work only consisted in an exploratory application of the tool. Although results seem interesting, it is now impossible to conclude toward the good integration of HEA into a specific decision process.

4.3 What place for this new tool?

The objective of this paper is to discuss the perspective of expanding the use of the HEA to value in biophysical terms the benefits of investment in aquatic ecosystems in perspective of their institutional objectives.

In the end we obtained for each of our study sites a quantity of DSAYs calculated considering the institutional objective of every action. As we mentioned, this quantity of DSAYs has no meaning in absolute terms, it has to be considered in relative terms. In this view valuation with HEA can be used in 3 ways:

-(1) *ex ante* to size an action in order to produce the exact quantity of ecological services required;

- (2) *ex ante* to help the arbitration between several projects in order to choose the most adapted project under a specific context;

- (3) *ex post* to illustrate the benefits of an action under a specific context.

Our proposition is strongly rooted toward the consideration of institutions as they constitute the frame of reference for valuation. Thus we can only discuss the results of valuation using HEA under the objective fixed by the relevant institutions. A restoration project that doesn't meet its objective when implemented for a specific purpose can't be considered as more valuable even if it has a more important monetary value. In this way, the valuation of restoration projects in biophysical terms shows some advantages as it doesn't meet the usual critics addressed to monetary valuation and can thus be a good complement.

Institutional economics considers several obstacles to monetary valuation that can be overcome using biophysical indicators. Vatn and Bromley (1994) described three major obstacles to monetary valuation: cognition problem, incongruity problem and composition problem.

The cognition problem refers to the impossibility for humans to achieve perfect knowledge, which can lead to disregarding some valuable attributes. The use of biophysical indicators can minimize this risk as it carries in itself attributes associated to the functioning of ecosystem.

The incongruity problem relates to the fact that different attributes of natural capital assets can be incompatible with each other in the assessor's mind. For example, increasing filtration capacity can sometimes be at odds with biodiversity conservation when management implies mowing during nesting period (e.g. from Kervigen marsh). Valuing a project in perspective of its institutional objective can help overcome these issues as it helps ranking these attributes.

Finally, the composition problem is associated to the fact that "the value of individual ecosystem components should not be derived from their perceived utility to humans but rather from their functional contribution to maintaining the integrity of the whole system" (Rees et al., 2007, p 230). This echoes our objective to use biophysical indicator to value an ecosystem toward the achievement of a broader objective.

Our proposition of tool follows the path of scientists from different origins involved in environmental management issues, who promote integrative approaches crossing ecology, economics and institutional analysis. Such as those of the Natural Capital Project founded on the use of multi-criteria analysis and biophysical indicators to provide guidance for investment in natural capital (Goldstein et al., 2008 ; Nelson et al., 2009), the approach of the Restoration of Natural Capital (Aronson et al., 2007) and the Ecological Footprint (Wackernagel et al., 1999) that recognize structural and cognitive barriers to investment in natural capital that can be overcome using valuation in physical terms (Wackernagel and Rees, 1997).

The expansion of HEA as a new ecological services valuation tool is in full agreement with those authors and offers a new tool to improve guidance for investment in natural capital through restoration of aquatic ecosystems. A deeper analysis of the fundamental assumptions of the model can also enlighten concrete dimensions of strong sustainable development: the time dimension, the space dimension, the human power dimension (action for investment), the indicator dimension and the institutional dimension (procedure and governance). If the first four are already the subject of an extended research both generally and especially for HEA, the last dimension still needs some development specifically regarding the procedure associated to the application of the HEA in a concrete decision context that would go over its genuine use.

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Tables

Source	Ecosystem	Targeted function or service	Choice of metric
Fonseca et al. [2000] ; Bell et al. [2008]	Seagrass	Food source, shelter, sediments stabilisation and nutrients cycles	Seagrass density (number of roots per unit of surface)
Strange et al. [2002]	Salt marsh	Primary production	Biomass
		Habitat	Canopy structure of vegetation
		Soil development and biogeochemical cycling	Organic matter
		Support of food chain	Infauna
		Secondary production	Shellfish and fish density
Milon and Dodge [2001]	Coral reef	Habitat	Reef surface
Sperduto et al. [2003]	Seabirds	Bird population	Abundance
Penn and Tomasi [2002]	Salt marsh	Habitat	Qualitative observation, expert judgement and specific species abundance
French McCay and Rowe [2003]	Coastal species	Habitat participation to food web	Primary or secondary production
Cacela et al. [2005]	Estuary	Sediments quality	Toxic element concentration and effects on biota
Bruggeman et al. [2005] ; Scribner et al. (2005)	Unspecified	Habitat at metapopulation scale	Abundance and genetic variability
Roach and Wade [2006]	Coastal wetlands	Habitat	Establishment of a model to estimate impacts of chemicals
		Damages on wildlife (birds, mammals and reptiles)	

TABLE 1 - Review of possible metrics for HEA and their associated ecosystem and ecological services in the scientific literature

	HEA for compensation	Translation in a broader use
Institutional context	Natural Resource Damage Assessment	Multiple (Water Framework Directive, Marine Strategy Framework Directive, Positive actions, Compensation...)
Actor responsible for restoration	The party responsible of the impact	Multiple (Private investor, public actor, NGO...)
Value of services	Possible use of ratio to frame compensation options	Possible use of ratio to frame restoration options
Choice of metric	Depending on the nature of the impact to compensate	Depending on the nature of the objective for restoration
Baseline for measurement	Initial level of ecological services on impacted site	Reference level of ecological services to produce
Time reference	Time of the impact	Time of the initiation of the restoration planning

TABLE 2 - Calibration of HEA for the expansion of its use

	Libellule® zone	Environmental measures of Port 2000	Kervigen marsh	Vurpillères stream
Geographical context	Saint-Just and Saint-Nazaire-de-Pézan Pop. 3,068 Languedoc-Roussillon Mediterranean	Le Havre Pop. 300,000 Upper Normandy Oceanic	Châteaulin and Porzay and surrounding communities Pop. 15,000 Brittany Oceanic	Labergement-Sainte-Marie Pop. 1,000 Franche-Comté Continental
Goal of the restoration project	Creating a market for environmental mitigation or natural water treatment system	Acceptance of the ecological impacts coming from the extension of the Port of Le Havre in the Seine estuaries	Avoiding green tides	Ecological restoration of Vurpillères stream
Type of action	Creation of a wetland at the outlet of a sewage treatment plant	Home-birds (shorebirds): creation of an island in the sea, creation of a resting place on dune -Production of mudflats: creation of a meander	Producing a service for assimilative decrease of nitrogen	Restoration of meanders in the stream
Size of projects	1.5 ha	45 ha for the resting place 1.5 ha for the island 300 ha for the meander	22 ha	1.1 km of stream

TABLE 3 - Presentation of the four case studies

Objective for valuation	Metrics	Determination of baseline	DSAYs
Tertiary treatment	Dissolved oxygen : Presence of dissolved oxygen is an indication of the chemical activity of vegetal species in water.	Dissolved oxygen in the Or lagoon.	1.26
Offset production (Habitats)	Coverage of hydrophytes: Composite proxy considering surface and deep hydrophytes.	Coverage of 100% of available surface.	9.57
Security of the WWTP rejects	Surface of wetland: The total area occupied by wetland in the entire Libellule® zone.	Coverage of 100% of the entire Libellule® zone.	6.92
Offset production (biodiversity)	Species richness (odonates) : Indicator of the number of species of dragonflies inventoried on the site	Maximum of species inventoried on one area in France[a] from 1970 to 2006.	6.44

TABLE 4 - Application of HEA to measure ecological services according to different metrics ([a] French society of odonatology, source: INVOD, ESRI)

Strategy for marsh restoration	Surface to restore per year	Total surface to restore
Objective in 2012	234 ha	234 ha
Objective in 2015	64 ha	254 ha
Objective in 2020	33 ha	294 ha

TABLE 5 - Dimensioning restoration plan according to different strategy scenario for a selected performance of 2 $kg.day^{-1}.ha^{-1}$

	Libellule® zone	Environmental measures of Port 2000		Kervigen marsh	Vurpillères stream
		Mudflats rehabilitation	Repositories		
Objectif de valorisation	Depending on the targeted market	Creation of 100 ha of mudflat	Ecological neutrality of Port 2000 on the shorebirds in the estuary	Reduction of 50 kg nitrate per year through restoration of marshes	Ecological restoration of the site to its initial state
Metrics	e.g. Dissolved oxygen	Surface of mudflats	Abundance of shorebirds in the estuary	Absorbed nitrate	Species richness
Intensity of restoration	Evolution of metrics during time	Observations in 2008 and 2012, we assume linear growth between observations	Variation of number of birds from 2005 and return to the baseline in 2010.	Purification performance associated to the latest measures in 2008.	Observations in 1993, 1998, 2002 and 2007, we assume linear growth between observations
Hypothesis on the final level	Management plan maintains level of service to its 2011 state.	Site is stabilised in 2012.	Return to the baseline in 2010.	Management plan maintains performance to its 2008 state.	In 2007, level of service is back to its initial level.
Référence state	Or lagoon	Project objective (100 ha)	Metric in 1997	Policy objective (50 $t.year^{-1}$)	Species richness in 2007
Reference date	Beginning of works (2007)	Beginning of works (2005)	Beginning of impact (1997)	Beginning of project (2010)	Start of project (1997)
DSAYs	1.26	9.12	0.131	0.079	5.79

TABLE 6 - Synthesis of the application of HEA for valuation of actions of restoration of aquatic ecosystems

		Objective	Cost of project (EUR/ha)	DSAYs	Cost/Benefit Ratio (10^3)
Libellule® zone		Market of lagoon systems	1,338,000	1.26	1062
		Offset for biodiversity	1,338,000	6.44	207
Environmental measures of Port 2000	Mudflats rehabilitation	Production of mudflats	77,000	7.589	10
	Repositories	Compensation of shorebirds	213,000	0.21	1014
Kervigen marsh		Mitigation of nitrate	13,600	0.0495	275
Vurpillères stream		Restoration	10,600[b]	10.38	1

TABLE 7 - Comparison of costs and benefits of projects

([b] Restoration was applied on 1100 meters of the river, piezometric level was improved on riverbanks on a strip of 10 to 20 meters large on each side of the river. We retain a width of 15 meter on each side to calculate the surface impacted by the restoration project)

Figure

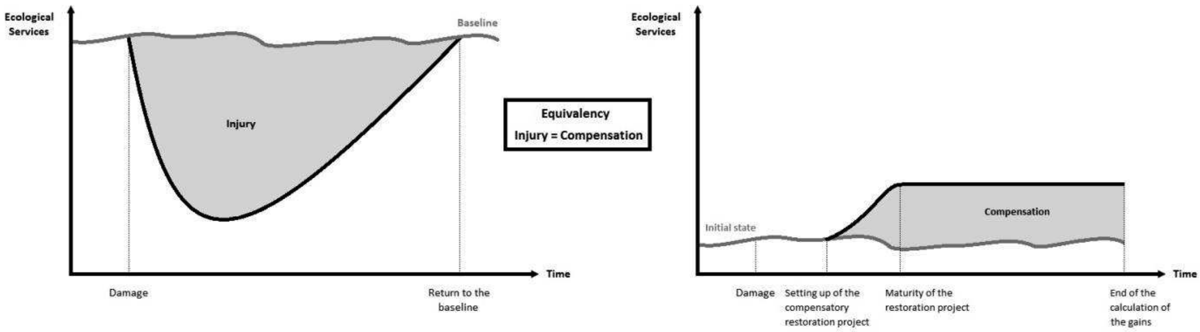

FIGURE 1 - Changes in ecological services provision on sites of injury and compensation (adapted from Vaissière et al., 2013)

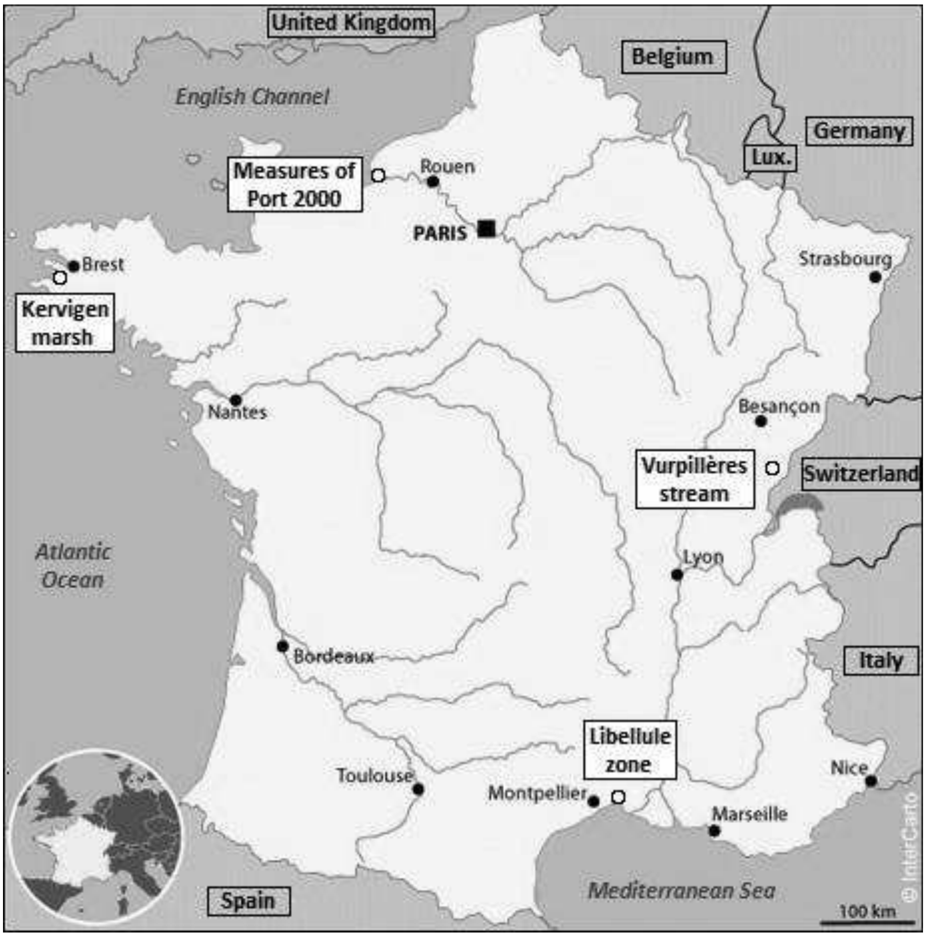

FIGURE 2 - Location of the four case studies in France

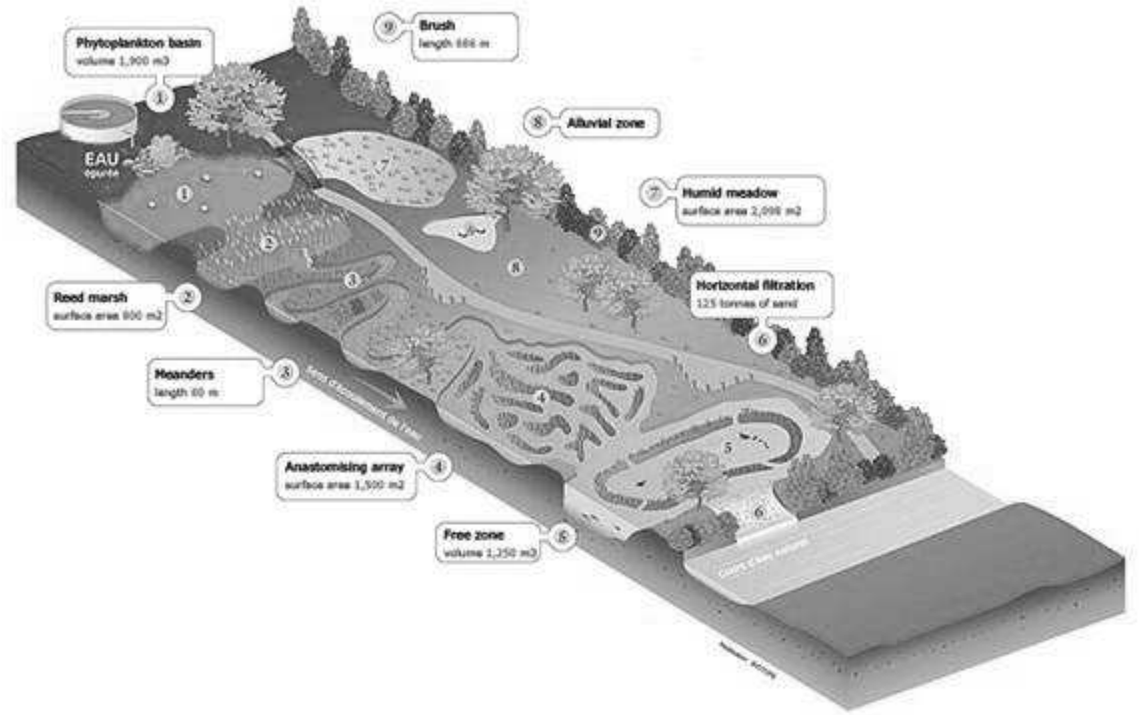

FIGURE 3 - Map of the Libellule® zone (Image: Biotope)

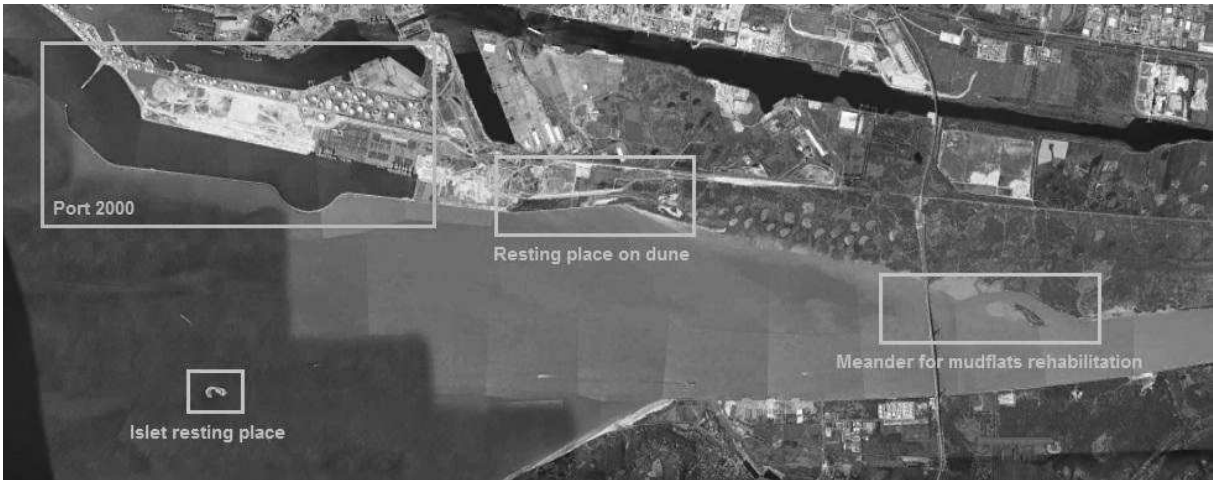

FIGURE 4 - Aerial view of Port 2000 and the environmental measures accompanying the project (Image: Google Earth - Cnes/Spot Image 2013)

FIGURE 5 - Aerial view of Kervigen marsh (Image: Google Earth - DigitalGlobe 2013)

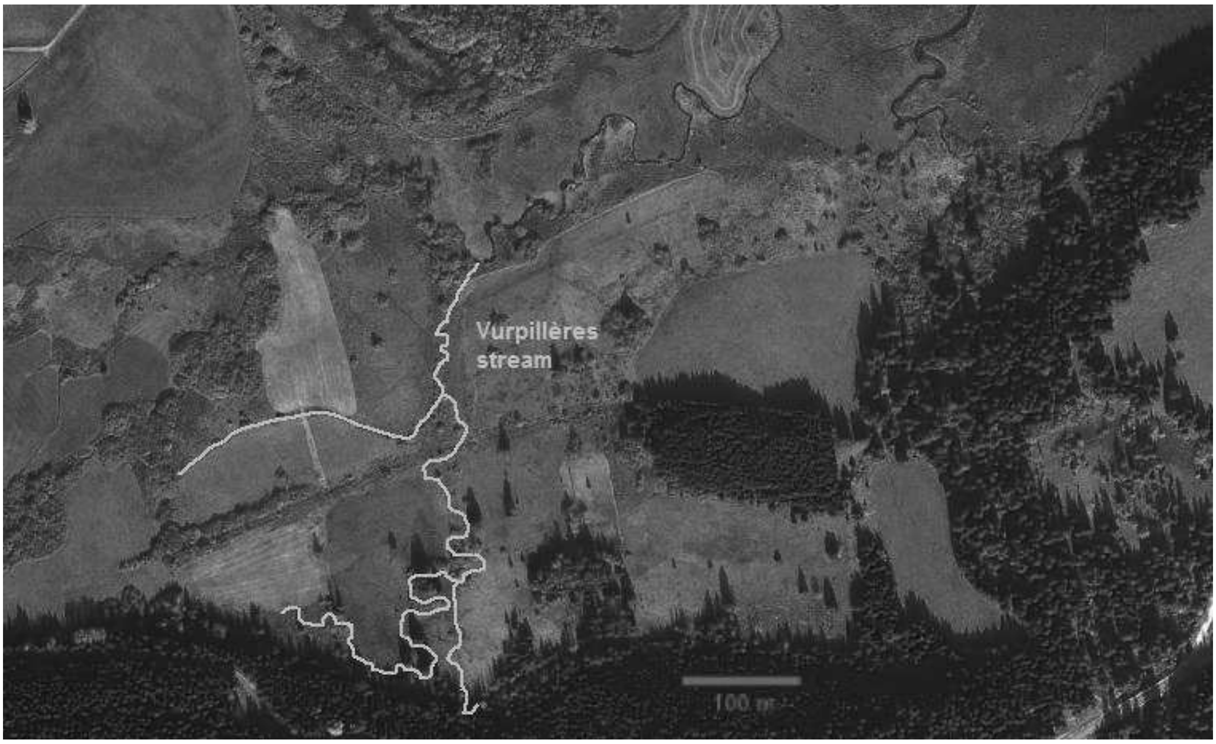

FIGURE 6 - Aerial view of the Vurpillères stream (Image Google Earth -GeoEye 2013)

Supplementary material

This document provides the details of the calculation realized in the article. For each site we will present the calculation of DSAYs associated to benefits of the project and the calculation of costs of projects.

Calculation of DSAYs associated to restoration project will be conducted according to formula (1). Calculation will be explained so as to underline what are the elements necessary for calibration of the model and for calculation.

$$\mathbf{G} = \boldsymbol{V_R} \times \sum_{t=i}^{t=n} [\boldsymbol{R_t}(\mathbf{1}+\boldsymbol{r})^{-\boldsymbol{t}}] \qquad (1)$$

V_R designate the value of the services produced on the restoration site, we don't apply any modifier for the value of services ($V_R = 1$).

R_t is the intensity of restoration at year t, it designates the level of services gained through the project, usually it is calculated as the value of the gains associated to the state of the metrics at year t (the difference between initial and final state) divided by the value of the metric on the reference site. The variation of R_t during time is called maturity curve. The difference between initial and final state is selected to catch the effect of the restoration project, the difference between the situation without restoration action and the situation with the action.

r is the discount rate, we apply a value of 3%.

Calculation is done for each year between the initiation of the project (i) and a selected horizon (n). In our calculations, the initiation date correspond to the year of the initiation of the project, for coherence, all calculation will be conducted on a 25 years period.

For all examples, information needed to the calculation will be summarized in tables, the first one will presents the assumptions needed for the calibration of the model to a specific objective, the second one will present the maturity function (the rate of intensity of restoration during time) and the third one will present the matrix of calculation of DSAYs.

1 *Libellule® Zone*

1.1 *Tertiary treatment measured through dissolved oxygen*

Project	Libellule® Zone
Objective	Tertiary treatment
Metric	Dissolved oxygen
Reference state	Level of metric in the Or lagoon

Maturity curve	The project is initiated in 2007, production of services starts in 2010 and reaches its maximum level of services in 2011 and we have data on the metric for 2010 and 2011 (Table 1.1.2)
Initiation year	2007
Final year	2032

Table 1.1.1 - Assumptions and information needed for calculation of DSAYs to value the benefits of Libellule® zone toward its objective of tertiary treatment

	Dissolved oxygen at the entrance of Libellule zone	Dissolved oxygen at the exit of Libellule zone	Dissolved oxygen in the Or Lagoon	Value of the metric
2007 - 2009	No data	Supposedly unchanged	No data	0
2010	9,2	9,9	10	0,074
2011	9,1	9,9	9,9	0,079
2012 - 2032	9,1	9,9	9,9	0,079

Table 1.1.2 - Maturity curve of the restoration project, values of the metric of dissolved oxygen values during time

We can then calculate the benefit associated to the objective of tertiary treatment using the dissolved oxygen as proxy of the level of ecological services (Table 1.1.3).

	Level of services gains associated to the project		Mean gain of services	Discount factor	Unitary gains
	Δ(Input/Output) Dissolved oxygen / Dissolved oxygen in the Or lagoon		(3) = (1) + (2) / 2	(4) = $(1+r)^{(2007-t)}$	(5) = (3)x(4)
	Initial (1)	Final (2)			
2007	0,000	0,000	0,000	1,00	0,000
2008	0,000	0,000	0,000	0,97	0,000
2009	0,000	0,074	0,037	0,94	0,035
2010	0,074	0,079	0,077	0,92	0,070
2011	0,079	0,079	0,079	0,89	0,071
2012	0,079	0,079	0,079	0,86	0,069
2013	0,079	0,079	0,079	0,84	0,067
2014	0,079	0,079	0,079	0,81	0,065
2015	0,079	0,079	0,079	0,79	0,063
2016	0,079	0,079	0,079	0,77	0,061
2017	0,079	0,079	0,079	0,74	0,059
2018	0,079	0,079	0,079	0,72	0,057
2019	0,079	0,079	0,079	0,70	0,056
2020	0,079	0,079	0,079	0,68	0,054
2021	0,079	0,079	0,079	0,66	0,053
2022	0,079	0,079	0,079	0,64	0,051
2023	0,079	0,079	0,079	0,62	0,050
2024	0,079	0,079	0,079	0,61	0,048

2025	0,079	0,079	0,079	0,59	0,047
2026	0,079	0,079	0,079	0,57	0,045
2027	0,079	0,079	0,079	0,55	0,044
2028	0,079	0,079	0,079	0,54	0,043
2029	0,079	0,079	0,079	0,52	0,041
2030	0,079	0,079	0,079	0,51	0,040
2031	0,079	0,079	0,079	0,49	0,039
2032	0,079	0,079	0,079	0,48	0,038
				DSAYs	**1,26**

Table 1.1.3 - Calculation of the DSAYs to value the benefits of Libellule® zone toward its objective of tertiary treatment

1.2 Offset production for habitat measured through vegetation coverage

Project	Libellule® Zone
Objective	Offset production (Habitat)
Metric	Coverage of hydrophytes
Reference state	Hypothetical maximum coverage of 100%
Maturity curve	The project is initiated in 2007, production of services starts in 2010 and reaches its maximum level of services in 2011 and we have data on the metric for 2010 and 2011 (Table 1.2.2)
Initiation year	2007
Final year	2032

Table 1.2.1 - Assumptions and information needed for calculation of DSAYs to value the benefits of Libellule® zone toward its objective of offset production for habitat

	Coverage of hydrophytes without Libellule zone	Coverage of hydrophytes in the Libellule zone	Hypothetical maximum of 100% coverage	Value of the metric
2007 - 2009	0	0	1	0
2010	0	0,41	1	0,41
2011	0	0,61	1	0,61
2012 - 2032	0	0,61	1	0,61

Table 1.2.2 - Maturity curve of the restoration project, values of the metric of hydrophytes coverage values during time

	Level of services gains associated to the project	Mean gain of services	Discount factor	Unitary gains

	% Coverage of hydrophytes / 100		(3) = (1) + (2) / 2	(4) = $(1+r)^{(2007-t)}$	(5) = (3)x(4)
	Initial (1)	Final (2)			
2007	0,00	0,00	0,00	1,00	0,00
2008	0,00	0,00	0,00	0,97	0,00
2009	0,00	0,41	0,21	0,94	0,19
2010	0,41	0,61	0,51	0,92	0,47
2011	0,61	0,61	0,61	0,89	0,54
2012	0,61	0,61	0,61	0,86	0,53
2013	0,61	0,61	0,61	0,84	0,51
2014	0,61	0,61	0,61	0,81	0,50
2015	0,61	0,61	0,61	0,79	0,48
2016	0,61	0,61	0,61	0,77	0,47
2017	0,61	0,61	0,61	0,74	0,45
2018	0,61	0,61	0,61	0,72	0,44
2019	0,61	0,61	0,61	0,70	0,43
2020	0,61	0,61	0,61	0,68	0,42
2021	0,61	0,61	0,61	0,66	0,40
2022	0,61	0,61	0,61	0,64	0,39
2023	0,61	0,61	0,61	0,62	0,38
2024	0,61	0,61	0,61	0,61	0,37
2025	0,61	0,61	0,61	0,59	0,36
2026	0,61	0,61	0,61	0,57	0,35
2027	0,61	0,61	0,61	0,55	0,34
2028	0,61	0,61	0,61	0,54	0,33
2029	0,61	0,61	0,61	0,52	0,32
2030	0,61	0,61	0,61	0,51	0,31
2031	0,61	0,61	0,61	0,49	0,30
				DSAYs	9,57

Table 1.2.3 - Calculation of the DSAYs to value the benefits of Libellule® zone toward its objective of offset production for habitat

1.3 Security of the wastewater treatment plant's rejects through the surface of wetland

Project	Libellule® Zone
Objective	Security of the wastewater treatment plant's rejects (WWTP)
Metric	Surface of wetland in the total Libellule® zone
Reference state	Hypothetical maximum surface of 100%
Maturity curve	The project is initiated in 2007, production of services starts in 2010 and reaches its maximum level of services in 2011 and we have data on the metric for 2010 and 2011 (Table 1.3.2)

Initiation year	2007
Final year	2032

Table 1.3.1 - Assumptions and information needed for calculation of DSAYs to value the benefits of Libellule® zone toward its objective of security of the WWTP's rejects

	Area of wetland without the Libellule® zone	Area of wetland in the total Libellule® zone	Hypothetical maximum of 100% area of wetland	Value of the metric
2010	0	6500	15000	0,43
2011	0	6500	15000	0,43
2012 - 2032	0	6500	15000	0,43

Table 1.3.2 - Maturity curve of the restoration project, values of the metric of wetland area values during time

	Level of services gains associated to the project		Mean gain of services	Discount factor	Unitary gains
	% Area of wetland / 100		(3) = (1) + (2) / 2	(4) = $(1+r)^{(2007-t)}$	(5) = (3)x(4)
	Initial (1)	Final (2)			
2007	0,00	0,00	0,00	1,00	0,00
2008	0,00	0,00	0,00	0,97	0,00
2009	0,00	0,43	0,22	0,94	0,20
2010	0,43	0,43	0,43	0,92	0,40
2011	0,43	0,43	0,43	0,89	0,39
2012	0,43	0,43	0,43	0,86	0,37
2013	0,43	0,43	0,43	0,84	0,36
2014	0,43	0,43	0,43	0,81	0,35
2015	0,43	0,43	0,43	0,79	0,34
2016	0,43	0,43	0,43	0,77	0,33
2017	0,43	0,43	0,43	0,74	0,32
2018	0,43	0,43	0,43	0,72	0,31
2019	0,43	0,43	0,43	0,70	0,30
2020	0,43	0,43	0,43	0,68	0,30
2021	0,43	0,43	0,43	0,66	0,29
2022	0,43	0,43	0,43	0,64	0,28
2023	0,43	0,43	0,43	0,62	0,27
2024	0,43	0,43	0,43	0,61	0,26
2025	0,43	0,43	0,43	0,59	0,25
2026	0,43	0,43	0,43	0,57	0,25
2027	0,43	0,43	0,43	0,55	0,24
2028	0,43	0,43	0,43	0,54	0,23
2029	0,43	0,43	0,43	0,52	0,23
2030	0,43	0,43	0,43	0,51	0,22
2031	0,43	0,43	0,43	0,49	0,21
2032	0,43	0,43	0,43	0,48	0,21
				DSAYs	**6,92**

Table 1.3.3 - Calculation of the DSAYs to value the benefits of Libellule® zone toward its objective of security of the WWTP's rejects

1.4 Offset production for biodiversity measured through species richness of odonates

Project	Libellule® Zone
Objective	Offset production for biodiversity
Metric	Indicator of the number of species of dragonflies inventoried on the site
Reference state	Maximum of species inventoried on one area in France[1] from 1970 to 2006
Maturity curve	The project is initiated in 2007, production of services starts in 2010 and reaches its maximum level of services in 2011 and we have data on the metric for 2010 and 2011 (Table 1.4.2)
Initiation year	2007
Final year	2032

Table 1.4.1 - Assumptions and information needed for calculation of DSAYs to value the benefits of Libellule® zone toward its objective of offset production for biodiversity

	Species richness of odonates without the Libellule zone	Species richness of odonates on the Libellule® zone	Maximum species richness observed on one territory in France from 1970 to 2006	Value of the metric
2007 - 2009	3	0	70	-0,04
2010	3	28	70	0,36
2011	3	34	70	0,44
2012 - 2032	3	34	70	0,44

Table 1.4.24 - Maturity curve of the restoration project, values of the metric of species richness of odonates values during time

	Level of services gains associated to the project		Mean gain of services	Discount factor	Unitary gains
	Δ(Before/After) Species on the site / Maximum species in France		(3) = (1) + (2) / 2	(4) = $(1+r)^{(2007-t)}$	(5) = (3)x(4)
	Initial (1)	Final (2)			
2007	-0,04	-0,04	-0,04	1,00	-0,04

[1] Société française d'odonatologie, source: INVOD, ESRI.

2008	-0,04	-0,04	-0,04	0,97	-0,04
2009	-0,04	-0,04	-0,04	0,94	-0,04
2010	-0,04	0,36	0,16	0,92	0,14
2011	0,36	0,44	0,40	0,89	0,36
2012	0,44	0,44	0,44	0,86	0,38
2013	0,44	0,44	0,44	0,84	0,37
2014	0,44	0,44	0,44	0,81	0,36
2015	0,44	0,44	0,44	0,79	0,35
2016	0,44	0,44	0,44	0,77	0,34
2017	0,44	0,44	0,44	0,74	0,33
2018	0,44	0,44	0,44	0,72	0,32
2019	0,44	0,44	0,44	0,70	0,31
2020	0,44	0,44	0,44	0,68	0,30
2021	0,44	0,44	0,44	0,66	0,29
2022	0,44	0,44	0,44	0,64	0,28
2023	0,44	0,44	0,44	0,62	0,28
2024	0,44	0,44	0,44	0,61	0,27
2025	0,44	0,44	0,44	0,59	0,26
2026	0,44	0,44	0,44	0,57	0,25
2027	0,44	0,44	0,44	0,55	0,25
2028	0,44	0,44	0,44	0,54	0,24
2029	0,44	0,44	0,44	0,52	0,23
2030	0,44	0,44	0,44	0,51	0,22
2031	0,44	0,44	0,44	0,49	0,22
2032	0,44	0,44	0,44	0,48	0,21
				DSAYs	6,44

Table 1.4.3 - Calculation of the DSAYs to value the benefits of Libellule® zone toward its objective of offset production for biodiversity

2 Environmental measures of Port 2000

2.1 Compensatory measures: repositories for shorebirds

Project	Environmental measures of Port 2000
Objective	Ecological neutrality of Port 2000 on the shorebirds in the estuary
Metric	Abundance of shorebirds in the estuary
Reference state	Number of shorebirds in the estuary in 1997
Initial state	Difference between the number of shorebirds in 1997 and the number of shorebirds in 2005.
Maturity curve	Works begin in 2001 on the dune repository and 2004 on the islet. We assume that we can start to measure the effects of the compensatory measures at the end on

	the first phase of works of Port 2000, in 2005. Calculation of gain will thus begin in 2005. The value of the metric is assumed using the variation of the total population of shorebirds on the estuary. From 2005, all variation of shorebird population is associated to the compensatory measure. Using the work of Aulert et al. (2009) we know the variation of the population of shorebirds from 1997 to 2008. We assume that after 2007, the level of service will reach the 1997 baseline in 2010 with a linear growth.
Initiation year	1997 is the reference year associated to the impact
Final year	2030

Table 2.1.1 - Assumptions and information needed for calculation of DSAYs to value the benefits of repositories for shorebirds in the Seine estuary

	Number of shorebirds on the estuary	Number of shorebirds without the project (2004)	Number of shorebirds on the estuary in 1997	Value of the metric
2004	7000	7000	16000	0
2005	7000	7000	16000	0
2006	7000	7000	16000	0
2007	5000	7000	16000	-0,13
2008	8700	7000	16000	0,11
2009	12400	7000	16000	0,34
2010 - 2030	16000	7000	16000	0,56

Table 2.1.25 - Maturity curve of the restoration project, values of the metric of abundance of shorebirds on the estuary

	Level of services gains associated to the project		Mean gain of services	Discount factor	Unitary gains
	Number of birds due to action / Number of birds in 1997		(3) = (1) + (2) / 2	(4) = $(1+r)^{(2005-t)}$	(5) = (3)x(4)
	Initial (1)	Final (2)			
2005	0,00	0,00	0,00	0,79	0,00
2006	0,00	0,00	0,00	0,77	0,00
2007	0,00	-0,13	-0,06	0,74	0,00
2008	-0,13	0,11	-0,01	0,72	0,00
2009	0,11	0,34	0,22	0,70	0,00
2010	0,34	0,56	0,45	0,68	0,01
2011	0,56	0,56	0,56	0,66	0,01
2012	0,56	0,56	0,56	0,64	0,01
2013	0,56	0,56	0,56	0,62	0,01
2014	0,56	0,56	0,56	0,61	0,01
2015	0,56	0,56	0,56	0,59	0,01

2016	0,56	0,56	0,56	0,57	0,01
2017	0,56	0,56	0,56	0,55	0,01
2018	0,56	0,56	0,56	0,54	0,01
2019	0,56	0,56	0,56	0,52	0,01
2020	0,56	0,56	0,56	0,51	0,01
2021	0,56	0,56	0,56	0,49	0,01
2022	0,56	0,56	0,56	0,48	0,01
2023	0,56	0,56	0,56	0,46	0,01
2024	0,56	0,56	0,56	0,45	0,01
2025	0,56	0,56	0,56	0,44	0,01
2026	0,56	0,56	0,56	0,42	0,01
2027	0,56	0,56	0,56	0,41	0,00
2028	0,56	0,56	0,56	0,40	0,00
2029	0,56	0,56	0,56	0,39	0,00
2030	0,56	0,56	0,56	0,38	0,00
				DSAYs	0,131

Table 2.1.3 - Calculation of the DSAYs to value the benefits of repositories for shorebirds in the Seine estuary

2.2 Accompanying measures : rehabilitation of mudflats

Project	Environmental measures of Port 2000
Objective	Rehabilitation of 100 ha of mudflat
Metric	Surface of mudflats
Reference state	Objective of mudflat rehabilitation (100 ha)
Initial state	Null
Maturity curve	Project is associated to the rehabilitation of 60 ha of mudflats in 2012. Using the work of Aulert et al. (2009), we know that the project can be associated to the rehabilitation of 45 ha in 2008. Works ended in 2005, we assume linear growth of the surface of mudflat from 2006 to 2008 (45 ha) and from 2008 to 2012 (60 ha).
Initiation year	2005 is the beginning of the works
Final year	2032

Table 2.2.1 - Assumptions and information needed for calculation of DSAYs to value the benefits of the rehabilitation of mudflats in the Seine estuary

	Surface of mudflats that appeared	Objective of 100 ha of rehabilitation project	Value of the metric
2005	0	100	0
2006	15	100	0,15
2007	30	100	0,3
2008	45	100	0,45

2009	48,75	100	0,4875
2010	52,5	100	0,525
2011	56,25	100	0,5625
2012 - 2030	60	100	0,6

Table 2.2.2 - Maturity curve of the restoration project, values of the metric of surface of mudflats rehabilitated

	Level of services gains associated to the project		Mean gain of services	Discount factor	Unitary gains
	Area of mudflat due to action / Area of mudflats expected		(3) = (1) + (2) / 2	(4) = $(1+r)^{(2005-t)}$	(5) = (3)x(4)
	Initial (1)	Final (2)			
2005	0,00	0,00	0,00	1,00	0,00
2006	0,00	0,15	0,08	0,97	0,07
2007	0,15	0,30	0,23	0,94	0,21
2008	0,30	0,45	0,38	0,92	0,34
2009	0,45	0,49	0,47	0,89	0,42
2010	0,49	0,53	0,51	0,86	0,44
2011	0,53	0,56	0,54	0,84	0,46
2012	0,56	0,60	0,58	0,81	0,47
2013	0,60	0,60	0,60	0,79	0,47
2014	0,60	0,60	0,60	0,77	0,46
2015	0,60	0,60	0,60	0,74	0,45
2016	0,60	0,60	0,60	0,72	0,43
2017	0,60	0,60	0,60	0,70	0,42
2018	0,60	0,60	0,60	0,68	0,41
2019	0,60	0,60	0,60	0,66	0,40
2020	0,60	0,60	0,60	0,64	0,39
2021	0,60	0,60	0,60	0,62	0,37
2022	0,60	0,60	0,60	0,61	0,36
2023	0,60	0,60	0,60	0,59	0,35
2024	0,60	0,60	0,60	0,57	0,34
2025	0,60	0,60	0,60	0,55	0,33
2026	0,60	0,60	0,60	0,54	0,32
2027	0,60	0,60	0,60	0,52	0,31
2028	0,60	0,60	0,60	0,51	0,30
2029	0,60	0,60	0,60	0,49	0,30
2030	0,60	0,60	0,60	0,48	0,29
				DSAYs	9,12

Table 2.2.3 - Calculation of the DSAYs to value the benefits of the rehabilitation of mudflats

3 *Kervigen marsh*

Project	Kervigen marsh
Objective	Reduction of 50 kg nitrate per year through restoration of marshes

Metric	Absorbed nitrate
Reference state	Nitrate reduction objective (50 tons per year)
Initial state	Absorbed nitrate without the marsh (null)
Maturity curve	Purification performance associated to the latest measures in 2008, it gives a performance between 2 and 4 kg per day per hectare, we present result for the lowest value.
Initiation year	2010 is the beginning of the works
Final year	2035

Table 3.1.1 - Assumptions and information needed for calculation of DSAYs to value the benefits of the rehabilitation of Kervigen marsh

	Performances of nitrate mitigation (t/year/ha)	Objective of mitigation of 50 t/year	Value of the metric
2012 - 2030	0,22	100	0,044

Table 3.1.2 - Maturity curve of the restoration project, values of the metric of nitrate mitigation performance

	Level of services gains associated to the project		Mean gain of services	Discount factor	Unitary gains
	Nitrate mitigation capacity of the marsh / Total objective of mitigation		(3) = (1) + (2) / 2	(4) = $(1+r)^{(2012-t)}$	(5) = (3)x(4)
	Initial (1)	Final (2)			
2012	0	0,0044	0,0	1,00	0,002
2013	0,0044	0,0044	0,0	0,97	0,004
2014	0,0044	0,0044	0,0	0,94	0,004
2015	0,0044	0,0044	0,0	0,92	0,004
2016	0,0044	0,0044	0,0	0,89	0,004
2017	0,0044	0,0044	0,0	0,86	0,004
2018	0,0044	0,0044	0,0	0,84	0,004
2019	0,0044	0,0044	0,0	0,81	0,004
2020	0,0044	0,0044	0,0	0,79	0,003
2021	0,0044	0,0044	0,0	0,77	0,003
2022	0,0044	0,0044	0,0	0,74	0,003
2023	0,0044	0,0044	0,0	0,72	0,003
2024	0,0044	0,0044	0,0	0,70	0,003
2025	0,0044	0,0044	0,0	0,68	0,003
2026	0,0044	0,0044	0,0	0,66	0,003
2027	0,0044	0,0044	0,0	0,64	0,003
2028	0,0044	0,0044	0,0	0,62	0,003
2029	0,0044	0,0044	0,0	0,61	0,003
2030	0,0044	0,0044	0,0	0,59	0,003
2031	0,0044	0,0044	0,0	0,57	0,003
2032	0,0044	0,0044	0,0	0,55	0,002
2033	0,0044	0,0044	0,0	0,54	0,002
2034	0,0044	0,0044	0,0	0,52	0,002

2035	0,0044	0,0044	0,0	0,51	0,002
2036	0,0044	0,0044	0,0	0,49	0,002
2037	0,0044	0,0044	0,0	0,48	0,002
				DSAYs	**0,079**

Table 3.1.3 - Calculation of the DSAYs to value the benefits of the rehabilitation of Kervigen marsh

4 *Vurpillères stream*

Project	Vurpillères stream
Objective	Ecological restoration of the site to its initial state
Metric	Species richness of plecoptera, trichoptera and ephemeroptera
Reference state	Species richness in 2007
Initial state	Number of species before restoration
Maturity curve	According to the work of Redding [2009], we select the number of observed species in 1993, 1998, 2002 and 2007, we assume linear growth between observations.
Initiation year	1997 is the beginning of the works
Final year	2022

Table 4.1.1 - Assumptions and information needed for calculation of DSAYs to value the benefits of the rehabilitation of Kervigen marsh

	Species richness without project	Species richness on the site	Species richness at reference (1967)	Value of the metric
1997	25	25	48	0
1998	25	25	48	0
1999	25	29	48	0,08
2000	25	29	48	0,08
2001	25	30	48	0,10
2002	25	30	48	0,10
2003	25	31	48	0,13
2004	25	34	48	0,19
2005	25	37	48	0,25
2006	25	40	48	0,31
2007	25	44	48	0,40
2008 - 2018	25	48	48	0,48

Table 4.1.2 - Maturity curve of the restoration project, values of the metric of species richness

	Level of services gains associated to the project		Mean gain of services	Discount factor	Unitary gains
	Δ(Input/Output) Dissolved oxygen / Dissolved oxygen in the Or lagoon		(3) = (1) + (2) / 2	(4) = $(1+r)^{(2012-t)}$	(5) = (3)x(4)
	Initial (1)	Final (2)			
1997	0,00	0,00	0,00	1,00	0,00
1998	0,00	0,08	0,04	0,97	0,04
1999	0,08	0,08	0,08	0,94	0,08
2000	0,08	0,10	0,09	0,92	0,09
2001	0,10	0,10	0,10	0,89	0,09
2002	0,10	0,13	0,11	0,86	0,10
2003	0,13	0,19	0,16	0,84	0,13
2004	0,19	0,25	0,22	0,81	0,18
2005	0,25	0,31	0,28	0,79	0,22
2006	0,31	0,40	0,35	0,77	0,27
2007	0,40	0,48	0,44	0,74	0,33
2008	0,48	0,48	0,48	0,72	0,35
2009	0,48	0,48	0,48	0,70	0,34
2010	0,48	0,48	0,48	0,68	0,33
2011	0,48	0,48	0,48	0,66	0,32
2012	0,48	0,48	0,48	0,64	0,31
2013	0,48	0,48	0,48	0,62	0,30
2014	0,48	0,48	0,48	0,61	0,29
2015	0,48	0,48	0,48	0,59	0,28
2016	0,48	0,48	0,48	0,57	0,27
2017	0,48	0,48	0,48	0,55	0,27
2018	0,48	0,48	0,48	0,54	0,26
2019	0,48	0,48	0,48	0,52	0,25
2020	0,48	0,48	0,48	0,51	0,24
2021	0,48	0,48	0,48	0,49	0,24
2022	0,48	0,48	0,48	0,48	0,23
				DSAYs	5,79

Table 4.1.3 - Calculation of the DSAYs to value the benefits of the restoration of Vurpillères stream

5 *Calculation of cost of projects*

For each project cost are calculated based on the fixed cost of project and the yearly variable cost associated to monitoring and management. Results are summarized in table 5.1

Project	Fixed cost ($.ha^{-1}$)	Variable cost ($.ha^{-1}$)	Variable cost on 25 years ($.ha^{-1}$)	Total cost ($.ha^{-1}$)
Libellule® Zone	233,000	60,000	1,105,000	1,338,000
Environmental measures of Port	77,000	0	0	77,000

2000 - Mudflats rehabilitation				
Environmental measures of Port 2000 - Repositories	Dune repository (97% in 1 ha): 42,200 Islet repository (3% in 1 ha): 5,300,000	0	0	213,000
Kervigen marsh	8,600	273	5,000	13,600
Vurpillères stream	10,600	0	0	10,600

Tableau 5.1 - Calculation of costs per hectare for each project