Critical natural capital, ecological resilience and sustainable wetland management: a French case study.

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Abstract:

This paper aims at building an analytical economic framework to address the functioning of an ecosystem using a functional approach of critical natural capital while accounting for the ecological resilience property. This framework is then operationalised to study the sustainability of wetlands ecosystems in the Gironde Estuary region (France).

Keywords: criticality, wetlands, ecological resilience, functionalities, ecological services, ecosystem, sustainability, critical natural capital.

JEL Classification: Q01, Q56, Q57.

Titre : Capital naturel critique et gestion durable des zones humides : une approche bioeconomique fondée sur la résilience écologique

Résumé :

Cet article a pour objet d'analyser le fonctionnement des zones humides à partir d'une propriété particulière : la résilience écologique. La méthodologie développée permet de caractériser l'interface services-fonctionnalités, le potentiel de résilience écologique ainsi que la durabilité de l'écosystème étudié. Une application aux zones humides de l'estuaire de la Gironde est proposée et discutée.

Mots clés : criticité, zones humides, résilience écologique, fonctionnalités, services écologiques, écosystème, durabilité, capital naturel critique.

1. Introduction

Despite its various meanings in the literature, the concept of critical natural capital (CNC hereafter) is always closely linked to the sustainability issue of development. Indeed, an important challenge for the conservation of natural resources in the context of sustainability relies on the fact that some components of natural capital have to be maintained because they are of critical importance for the preservation of life and ecosystems survival. This challenge is all the more acute as economic activities have an increasing impact on nature and may bring irreversible damages both directly and on the long run. It follows that a central question is how much we are in need of the maintenance of natural capital to sustain the development of a society. This point is closely connected to the well-known debate on weak and strong sustainability (Victor, 1991; Chiesura et al., 2003). On the first hand, weak sustainability refers to the perfect substitution possibilities between all the kinds of capital, without any concern for the question of scale or of the natural dynamics of the complex systems involved (Limburg et al., 2002). The strong sustainability approach, on the other hand, assume a complementary relationship between man-made capital and natural capital which is usually defined as a heterogeneous stock of renewable as well as non-renewable resources including the provision of ecosystem services and life-support functions (De Groot, 1992; MacDonald *et al*, 1999; Daly *et al.*, 2004). The preservation objective of these natural components is at the core of the CNC concept according to which some elements of natural capital cannot be declining or deteriorated as they are unique and irreplaceable: "*[CNC] ought to be maintained in any circumstances in favour of present and future generations*" (Brand, 2009, p.606). By the same token, it ensues that CNC is a cornerstone of the strong sustainability approach.

It must be noted, however, that little attention is usually paid in this approach to the way the various elements of this capital contribute to the provision of environmental services as well as how the impact of economic activities may lead to qualitative change in the functioning of the environmental systems under study. Those issues may be important to tackle however, especially for specific environmental systems whose major role has been recently emphasized regarding the well-being of human societies. This is notably the case of ecosystems that provide a large set of services while being subject to heavy pressures mainly stemming from economic activities (MEA, 2005 ; Sukhdev, 2008 ; Salles et al., 2009). Those evolutions may appear all the more damageable as the functioning of those systems rests upon the use of specific renewable resources for which there is no substitute.

In line with these concerns, this paper aims at addressing some of the previous issues by considering the case of a specific ecosystem, namely wetlands. To do so, it first aims at building a simple modelling framework of an ecosystem which rests upon a functional approach of natural capital and CNC. By doing so, the usual analysis of CNC is extended through the taking into account of core ecological features which characterise the functioning of the ecosystem. Those elements appear to be important if we want to tackle the way the system may react to economic pressures affecting natural capital and adapt to them (this property being captured by the concept of ecological resilience). With this representation at hand, we thereby aim at providing a useful framework for investigating the economic sustainability of the ecosystem from a theoretical as well empirical viewpoint. Indeed, we try to use such a framework to analyse sustainability issues in the case of estuarine wetlands of the Gironde Estuary region.

The paper proceeds as follows. Section 2 presents and discusses the functional approach of CNC, shedding light on its main features and how it relates to and extends the standard approach to this concept. It shows how the ecological resilience concept may be called upon within this approach so as to provide a qualitative assessment of the performances of the ecosystem. Section 3 deals with the building of a modelling framework of the ecosystem functioning based on the functional approach of CNC. Section 4 applies this framework to the analysis of the case of wetlands in the Gironde Estuary region. An operational approach so as provide data-based indicators of ecological resilience potentials as well as of sustainability of these ecosystems is proposed and discussed. Section 5 concludes.

2- Critical natural capital and ecological resilience

2.1- A functional approach of critical natural capital

Various categorizations of CNC are found in the literature (Chiesura *et al.*, 2003; de Groot *et al.*, 2003 ; MacDonald *et al.*, 1999). First, and according to Ekins *et al.* (2003), CNC may be defined as “*natural capital which is responsible for important environmental functions and which cannot be substituted in the provision of these functions by manufactured capital*” (p.169). This approach is close to the one of Faucheux and O'Connor (1998) as well as Noël and O'Connor (1998) for whom CNC is "*a set of environmental resources which at the prescribed geographical scale performs important environmental functions and for which no* *substitute in terms of manufactured, human or other natural capital exists*", or, in a more extended way, "*a subset of natural capital including ecological life support systems and irreplaceable cultural artefacts*" (Costanza and Daly, 1992). In the EU-funded project on strong sustainability - CRITINC-, CNC is the "*set of environmental resources which performs important functions and for which on substitutes in terms of human, manufactured, or other natural capital currently exist*" (Ekins et al, 2003). In such a context, some thresholds and management rules are needed to avoid the decrease of the resources (stock) provided by the environmental system.

This first set of definitions emphasizes the essential role of the ecological functions that environmental systems components (plants, animals...) and processes (biogeochemical cycles) provide. In this respect, and following Pearce and Turner (1990), the features of CNC are organized in terms of source, sink, life-support and well-being functions. The source function is related to the productive area (harvesting) and depends on various uses. The sink function refers to the assimilative capacity of environmental systems to deal with waste and pollutions. The life-support function is based on the regulation capacity of natural processes (local and global levels). The well-being function addresses the quality of life (to which natural capital contributes) and its determinants -use and non use values of the resources- which may refer to socio-economic issues.

Another example of the functional approach of CNC is provided by De Groot et al. (2002). These authors suggest a classification of environmental systems as well as of the services and goods they provide through four environmental functions: regulation, habitat, production and information functions. According to De Groot (1992), those functions capture "*the capacity of natural processes and components to provide goods and services that satisfy human needs directly or indirectly*". Regulation functions relate to the capacity of environmental systems to regulate ecological processes and life support systems (climate regulation, waste treatment, water regulation...). Habitat functions refer to conservation of biological and genetic diversity. Production functions concern the provision of natural resources for populations (food, raw materials, energy resources, genetic materials...). The information function exemplifies the contribution of environmental systems to support cognitive development of human (recreation and cultural experiments...). The first two functions are essential for human survival and, as such, dominate the last two ones.

From the preceding, it follows that various conceptions of critical natural capital prevail in the literature, each shedding specific light on the way economic activities affect the quality of the environmental systems involved. As a consequence there is not a unique measure for criticality of natural capital. Moreover, CNC appears to be, to a significant part of the components it refers to, a non monetary valuable asset. Indeed, as long as the criticality of natural capital is anchored on the complementary hypothesis between man-made and natural capital (strong sustainability), there is no place for a direct monetary valuation process (Azqueta et al. 2007). The assessment of the criticality of natural capital has instead much to do with ecological relationships and indicators (number of species, links between various species living within the system...) and, as such, should rely upon a biophysical evaluation process in the first hand (MacDonald et al., 1999)

A first way to assess the criticality in this perspective would go through defining some minimum values (thresholds), beyond which some components of natural capital have to be maintained in order to avoid the decrease in the provision of the related services (Pearce and Turner, 1990). Those conditions may be called criticality conditions. For instance, regulation function (climatic function) associated with a particular environmental system (tropical forests) may be operational only if the size of such an environmental system is maintained over a minimal critical level, otherwise the function will not run in a proper way. It may be possible then that some environmental services will no more be provided to the society.

A second way to assess the criticality, closely related to the first one, focuses on the analysis of the various functions fulfilled by natural capital. According to De Groot et al. (2003), two main criteria have to be considered in this respect. First, the criticality of natural capital may be assessed from the perspective of the ecological, socio-cultural and economic 'importance' taken by natural systems. This point is shared by Turner (1993) who focuses more directly on the regulation functions of environmental systems (here ecosystems) as being essential for human activities and human life: these functions are "*the primary values of ecosystems for general biospheric functioning*".

Second, criticality has also to take into account the degree of 'threat' which natural capital is exposed to. Note that natural capital can threatened although it may not be vital for human welfare (certain animal species without human use or key-role played within a given ecosystem), or it can be both important and threatened (tropical rainforests, climate change).

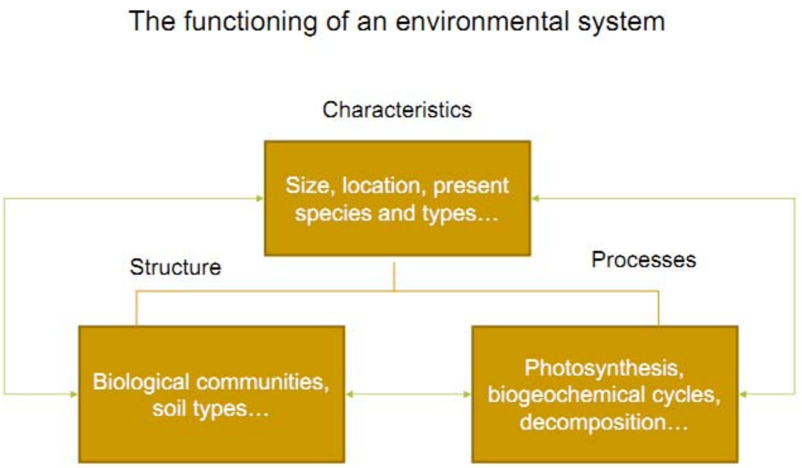
Both aspects of criticality should thus be combined to provide a measure of the degree of criticality of natural capital. Ten Brink (2000) adopts such an approach. In his work, the “importance dimension” is assessed through a large number of criteria drawing on ecological, socio-cultural and economic functions fulfilled by CNC. If a monetary valuation of the "importance" dimension is possible under restrictive conditions (which include the fact that the ecosystem functions are directly related to economic activities (De Groot *et al.* 2003)), it is not the case for the "threat" dimension whose measurement is based on both quantitative and qualitative aspects which are embedded in a natural capital index. Basically, the index is defined by combining an ecosystem quantity indicator which is defined as the size of the ecosystem or habitat (as the percentage of a given area of a region/country) and a quality one which is defined as the ratio between the current state and a postulated baseline state (as a percentage). In particular, the quality is related to the pressures exerted on the ecosystem (as an example of which, we may think about human population density, activities of production and consumption, eutrophication, acidification...).

However, this approach does not analyse the functioning of an environmental system. This goes mainly through investigating how the components of natural capital that are involved in this system activate specific ecological functions that are, in turn, at the source of the environmental services provided to the society.

Any environmental system (as a given ecosystem or the biosphere) may be decomposed into three types of elements: characteristics, structure and processes (see figure 1). Those elements reflect both the interactions between the natural capital components and the mechanisms involved as well as between the functions they activate. Characteristics are descriptive properties which include the biological, chemical and physical aspects such as present species, size, soil properties, and vegetation. The structure refers to the existence of communities of plants and animals, and is closely related to the existence of biotic and abiotic webs (interactions between vegetation, soil types, living species, biomass...). The processes operating within the ecosystem are referring to the dynamics of transformations involving energy and matter flows (photosynthesis, biogeochemical cycles...).

As we have mentioned, some functions may play a more important role than others in this setting, as their activation is essential for the maintenance of the integrity of the system. In this respect, two functions are generally favoured: the regulation and the habitat functions (De

Groot, 1992). For those functions, the criticality conditions that pertain to the natural capital components have to be fulfilled if we want the system to be sustainable.



Source: adapted from Turner et al. (2000)
Figure 1

2.2 Towards a qualitative approach of natural capital criticality: the ecological resilience

The functional approach of natural capital (we have presented so far) has to be complemented by an analysis of its properties if we want to address the performances of the environmental system under concern. Usually, such a performance may be tackled through the concept of ecological resilience.

Numerous definitions of resilience are present in various disciplines (Hein, 2010 ; Brand et al. 2007; Brand, 2009 ; Folke, 2006) since the seminal paper of Holling in 1973. Two approaches of this concept can be identified.

The first one called by Holling himself as "*engineering resilience*" is related to the rate of return of a system to some equilibrium state after a small disturbance. This definition has been mainly applied for the analysis of environmental system stability near an equilibrium steady state.

The second one, which we refers to as the Holling approach, deals with the potential for a system to maintain its structure and functions in the face of disturbance and to adapt itself by absorbing disturbance (re-organization). More precisely and according to (Brand et al., 2007), the original definition adopted by Holling implies that resilience is "*a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables*". Such a definition may apply to the conditions of an environmental system which locates far from its equilibrium steady state and even can flip into another regime of behaviour (or steady state). Thus, while the engineering resilience definition is suitable with system facing gradual changes, the Holling definition seems to be more applicable to systems subject to multiple states and thresholds (Hein, 2010).

Insofar as we analyse environmental systems (and ecosystems) by focusing on CNC dimension, it appears relevant to adopt the Holling resilience approach for addressing the properties of natural capital involved in such systems. According to Arrow et al. (1995), ecological resilience is a necessary condition for the sustainability of economic activities: "[those] *are sustainable only if the life-support ecosystems upon which they depend are resilient*".

An application of Holling approach of resilience has been notably suggested by Brand (2009) and by Deutsch et al. (2003). In those studies, ecosystems are defined as complex dynamic systems: the dynamics relies on an organizational and temporal complexity, while the links between the ecosystems and the social systems may be addressed with the concept of resilience. In this respect, Brand mentions that "*an ecosystem amount of ecological resilience is directly linked to the degree of threat this ecosystem may face*", suggesting that the ecological resilience concept is able to catch the impact of economic activities on the quality of ecological services provided by the ecosystem.

However, ecological resilience cannot be measured directly. Brand (2009) has nevertheless shown that it can be estimated through the distance between the current value taken by a slow variable which characterizes the state of the ecosystem (a key controlling variable) and the predicted value of the related ecological threshold (critical level). Implicitly, this variable refers to the set of components of the natural capital involved in the ecosystem under study. As an example of a slow variable, we may consider the current value of nutrient concentration - such as phosphate - for a shallow lake, or the abundance of woody plants in rangelands. The amount of ecological resilience is in this case inversely related to the degree of threat.

However, this threshold method can be used to estimate the ecological resilience only if ecosystems can shift between different stable states and if the ecosystem dynamics can be understood with the identification of a few key variables. Indeed, such a resilience measure is defined regarding the behaviour of *slowly* changing variables (land use and agricultural practices, nutrient stocks, soil properties, water quality...) that determine the thresholds beyond which disturbances (harvesting, polluting activities...) may push the system into another (stable) state (Deutsch et al., 2003).

On the whole, ecological resilience appears to be an important device to apprehend the quality of the functioning of an ecosystem. Indeed, this property allows connecting the provision of services, the environmental functions fulfilled within the ecosystem and the pressures that anthropic activities may exert on the natural capital components involved (see figure 2)

Ecological resilience and the functioning of an ecosystem

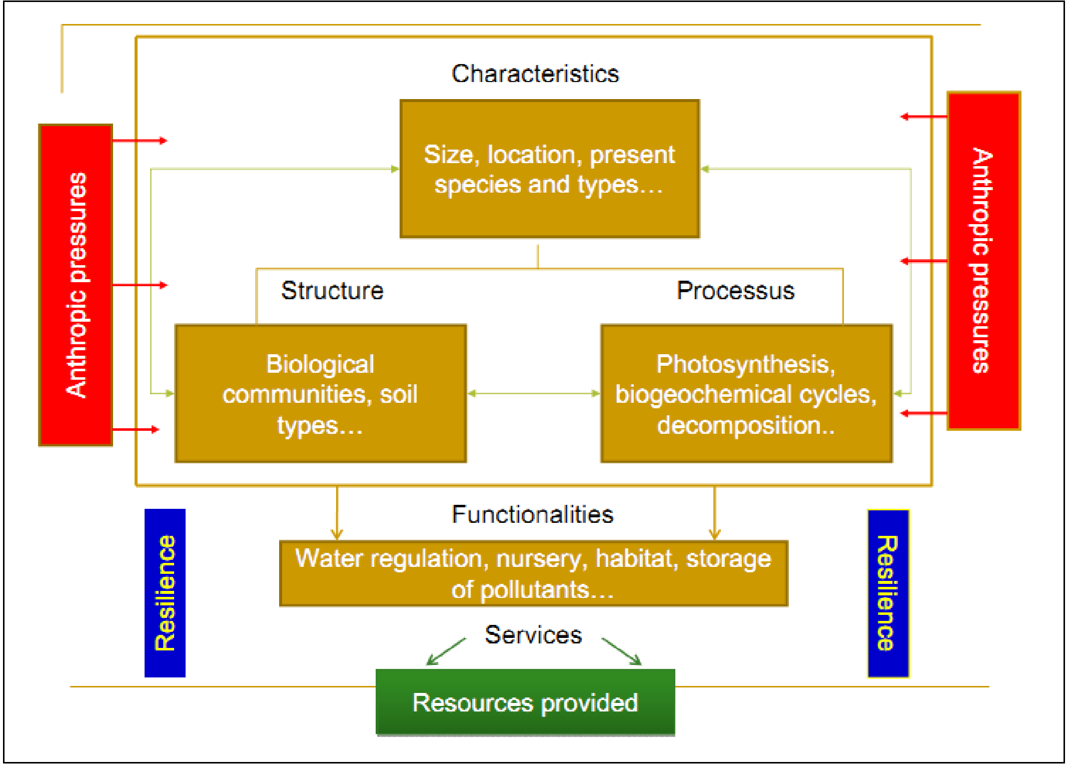


Figure 2

3- Accounting for CNC and ecological resilience in a simple economic model of the functioning of an ecosystem

Following the previous, methodological discussions, the aim of this section is twofold. The first is to build a simple representation of the functioning of an ecosystem which includes a functional approach of CNC while accounting for the ecological resilience property. With these features at hand, the second objective is to show how this representation may be used to address some economic issues raised by the functioning of ecosystems (sustainability, optimal management). Albeit simple, this representation may thereby serve as a useful framework to operationalise the previous notions within a given case study. We intend to perform such an exercise in section 4, using this kind of representation to analyse the case of wetlands..

Building the aforementioned representation may proceed according to three main steps:

1- The first step consists in considering the main elements that frame the functioning of the ecosystem *i* under concern. The analysis we have conducted so far suggests three cornerstones in this respect:

(1) The components of natural capital that are used within the ecosystem. Those components may be tackled through state variables. Those variables may be associated with stocks of resources or as binary indicators which reflect specific qualitative attributes of the components or aspects of natural capital (soil types, hydrological features…). In the following, we note by C^i the whole set of the *p* components that are involved in the functioning of the ecosystem *i* such that $C^i = \{c_k^i;\ \ k = 1,..., p\}$.

(2) The functionalities that refer to the ecological functions that are fulfilled by the ecosystem. The activation of those functionalities is performed through different mechanisms (biological, chemical, physical…) that play in interaction and, more importantly do involve and combine different natural capital components (see figure 1 *supra*). In this respect, a given component may be necessary for the activation of several functionalities or may be functionality-specific. As mentioned in the previous section, some functionalities may be more important than others (notably those pertaining to regulation and habitat ecological functions). In the following, we assume that the functioning of the ecosystem *i* may be tackled through one set of *m* functionalities noted as F^i such that $F^i = \{ f_h^i;\ \ h = 1,..., m\}$.

(3) The services that are provided by the ecosystem. This provision rests upon the activation of the functionalities and therefore on the use of the different components of natural capital that are considered within the ecosystem. We may suppose at this stage that all the ecosystem services may be valued from an economic viewpoint so that maintaining this set of services does not imply favouring economic services at the expense of other ones. However, even if we restrict the set of services of interest as such, a choice may be done between these services according to specific objectives (cf. *infra*). Lastly, as for the natural capital components that are used by the functionalities, the provision of different services may call upon the activation of common functionalities while some functionalities may be univocally involved in the provision of certain services. We note by S^i the whole set of the *l* services (of interest) which are provided by the ecosystem so that $S^i = \{s_j^i;\ \ j = 1,..., l\}$.

2- The second step consists in drawing a specific representation of the functioning of the ecosystem given the three core elements that characterize it (natural capital components, functions, services). We may consider several ways to proceed in this respect which may be ranked by order of complexity depending on the objective we assign to this representation.

At this stage, we will only require that the representation tackles the state of the functioning of the ecosystem at a given time period. This state of functioning may be directly measured through the provision of the services (and this is why this indicator would be probably favoured from an economic viewpoint). Depending on how this provision has been contemplated in the first step of our approach, however, it is clear that this state of functioning does more fundamentally relate to the functionalities that have been activated and to the natural capital components that are involved in this process.

Moreover, even if we base the measure of the state of functioning on the provision of services, this provision may be assessed through two different but complementary dimensions: the number of services and the quantity of services which are provided. In our framework, we only focus on the former dimension meaning that we look at the effective delivery of the service trough an indicator value (1 or 0). The important feature to emphasize here however is that, in either case, we apprehend the state of functioning of the ecosystem through *conditional* relationships that link together the provision of services with the activation of the functionalities as well as the use of the natural capital components. In other terms, observing a given *number* of services implies that a given set of functionalities have been activated and that some natural capital components have been used. It suggests the following causality sequence:

$$S^i \leftarrow F^i \leftarrow C^i \quad (1)$$

We might go further by making explicit the relationships between the elements under concern, drawing, from example, on the analytical insights of some ecological models. We may also adopt a dynamic approach of this functioning allowing for feedbacks between the provision of services and the evolution of the natural capital components. Those extensions are left for further research however. Here, we stick to one simple and static setting in as much as the former rests upon the conditional relationships considered *supra*.

3- The final step consists in addressing the issue of ecological resilience in this representation and in investigating the different uses we may draw from such a property when providing an economic analysis of the ecosystem and its functioning.

Ecological resilience puts a direct qualification on the functioning of the ecosystem as it aims at tackling its capacity to adapt to different pressures that affect the natural capital components. Addressing this property within the representation we may consider implies addressing two elements at least.

First, there is the question of how the pressures may be taken into account in the representation. One answer would go through the introduction of a set of conditions put on the different components of natural capital. We could then assume that, depending on the kind of pressures under concern and on their intensity, the conditions may be or may be not fulfilled by the components. Accordingly, the level of pressures would then determine a *resilience potential* which could be measured as the number of conditions which are satisfied (with respect to the whole number of components involved in the ecosystem). We may model this set of conditions as:

$$c_k \geq \underline{c}_k \;\; \forall \; k = 1, 2, ..., p \qquad (2)$$

This set of conditions (2) may be introduced beforehand, the fulfilment of which depending on the presence and intensity of the pressures. In this case, those conditions can be interpreted as *criticality* conditions (with respect to the functioning of the ecosystem), as the pressures would then imply one threat to the mere existence of the ecosystem (or at least the provision of the services).

The threshold ($\underline{c}_k$) may be interpreted differently according to the kinds of components which are considered. For example, they may pertain to the disappearing of one component ($\underline{c}_k = 0$) or more generally to a minimal value above which the component should be maintained.

Finally, one aspect we do not address at this stage is the fact that the fulfilling of the criticality conditions may be endogenously determined: the reaction of the ecosystem to the pressures may indeed feedback on the dynamics of the natural capital components.

Secondly, the capacity of the ecosystem to adapt (its “resilience”) would *de facto* be conditioned by its resilience potential and the way the conditional relationships may interact with it. Indeed, depending on whether the whole (or part of the) set of the criticality conditions are satisfied or not, the ecosystem would be put in a different state of functioning, as the way the functionalities are activated would then be affected as well as, in turn, the provision of ecosystem services.

We may draw some interesting economic insights from such a framework, especially if we focus on the analysis of the sustainability of the ecosystem.

Sustainability concerns suggest, indeed, to consider the maintenance of a given number of services by the ecosystem to ensure the satisfaction of human needs. This sustainability condition can be written as: $Card\left(S\right) \geq S_{\min}$ with $S_{\min}$ the number of services set by a regulator. Backward reasoning implies, in this case, that we could search for the resilience potential(s) which would comply with this given level of sustainability.
Sustainability concerns may also be combined with the quest for an optimal management of the ecosystem. In this respect, it would be interesting to look at the minimum level of the resilience potential ensuring the maximal number of services provided by the ecosystem.

To solve for these two problems, we need to introduce additional notations. Let $c_{h,k}$ be one of the *k* components that is required to activate the functionality *h*, and $C_h = \left\{c_{h,k}\right\}$ the set comprising all of these necessary components (for the functionality *h*). In the same way, let define $f_{j,h}$ one the *h* functionalities which are necessary to ensure the provision of the service *j* and $F_j = \left\{f_{j,h}\right\}$ the set comprising all of these necessary functionalities (for the service *j*) .
We also need to reconsider the case for the criticality conditions which have been defined with respect to the c_k's. Looking at the $c_{h,k}$'s imply that the criticality conditions should now be contemplated in terms of these necessary components. In this case we will consider:

$$c_{h,k} \geq \underline{c}_{h,k} \tag{3}$$

When several components are involved in the activation of more than one functionalities, they can be subject to different threshold values depending on the functionalities at stake. When the threshold value are compatible, we consider that $\underline{c}_k = \max_k \left\{\underline{c}_{h,k}\right\}$. However when these values are conflicting, we have to distinguish each critical component associated to every functionality.

Looking first at the resilience potential(s) that would comply with a given level of sustainability, we then note that problem amounts to search for the whole set of the $c_{h,k}$ which fulfil the *criticality* conditions $c_{h,k} \geq \underline{c}_{h,k}$ while ensuring[1] $Card\left(S\right) \geq S_{\min}$.

Secondly, looking at the minimum level of the resilience potential ensuring the maximal number of services provided by the ecosystem which are solution of the following program:

$$\begin{aligned} &\max_j Card(s_j) = \max_h \min_k \cup_h \cup_k c_{h,\,k} \\ &s.t. \quad c_{h,k} \geq \underline{c}_{h,k} \end{aligned} \qquad (4)$$

Box : ecosystem functioning, ecological resilience and sustainability

We illustrate how one simple representation of the functioning of an ecosystem (such as the one we have designed so far) may be used to draw some insights on the economic aspects related to the sustainability of this ecosystem.

As illustrate by figure 3, suppose that the ecosystem core features are given as follows. Its functioning rests upon[2]:
(1) the involvement of three natural capital components noted (c_1, c_2, c_3), with $C=(c_1, c_2, c_3)$;
(2) the activation of three functionalities (f_1, f_2, f_3), with $F=(f_1, f_2, f_3)$;
(3) the provision of three services (s_1, s_2, s_3), with $S=(s_1, s_2, s_3)$.

The conditional relationships linking those elements may be expressed as follows:

The activation of f_1 requires the involvement of all the three natural capital components, so that $C_1 = \left\{c_{1,1}, c_{1,2}, c_{1,3}\right\}$,
The activation of f_2 requires the involvement of c_1 and c_3, so that $C_2 = \left\{c_{2,1}, c_{2,3}\right\}$,
The activation of f_3 requires only the involvement of c_3, so that $C_3 = \left\{c_{3,3}\right\}$,
And
The provision of s_1 requires the activation of f_1 and f_2 so that $F_1 = \left\{ f_{1,1}, f_{1,2} \right\}$,
The provision of s_2 requires the activation of f_2 and f_3 so that $F_2 = \left\{ f_{2,2}, f_{2,3} \right\}$,
The provision of s_3 requires only the activation of f_3 so that $F_3 = \left\{ f_{3,3} \right\}$.

Given this representation, we would first be able to measure the resilience potential as:

$$\underset{k}{card}\left(c_{h,k} > \underline{c}_{h,k}, \forall k = 1,2,3\right)$$

We may also look at sustainability properties:

1- we may first look for the resilience potential(s) which would comply with a given level of sustainability (S_{min}).

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[1] The notation *Card(S)* refers to the number of elements included in the set *S*.
[2] We omit the subscript *i* relative to the ecosystem under concern, so as to simplify the notations.

Let assume that this condition is at least satisfied for a given level of utility corresponding to the provision of one service. For a given service *j*, this provision would correspond to the set $\cup_h \cup_k \underline{c}_{h,k}$.
We observe the following cases: for S_1, the solution set involves the components $\{c_1,c_2,c_3\}$; for S_2, the solution set involves $\{c_1,c_3\}$ and for S_3 it restricts only to $\{c_3\}$. Accordingly, we obtain several levels for the resilience potentials as solutions.

Now if the sustainability condition is associated with the provision of two services, then the solution sets would be $\{c_1,c_2,c_3\}$ for both (s_1, s_2) and (s_1, s_3) and $\{c_1,c_3\}$ for (s_2, s_3). Thus, the related set of resilience potentials has been reduced.

Second, we could look for the minimal level of the resilience potential which ensures the maximal number of services provided by the ecosystem. Applying the *maximin* strategy will provide the results given by equation (4).

Consider first that only one component fulfils the criticality condition. The involvement of c_3 would allow one service given by s_3. If two criticality conditions are fulfilled (c_1 and c_3), we can reach an amount of two services s_2 and s_3. To get the whole set of services implies the fulfilment of all the criticality conditions by the components. Let us remark that if the threshold value are compatible, we have $\underline{c}_k = \max_h \{\underline{c}_{h,k}\}$.

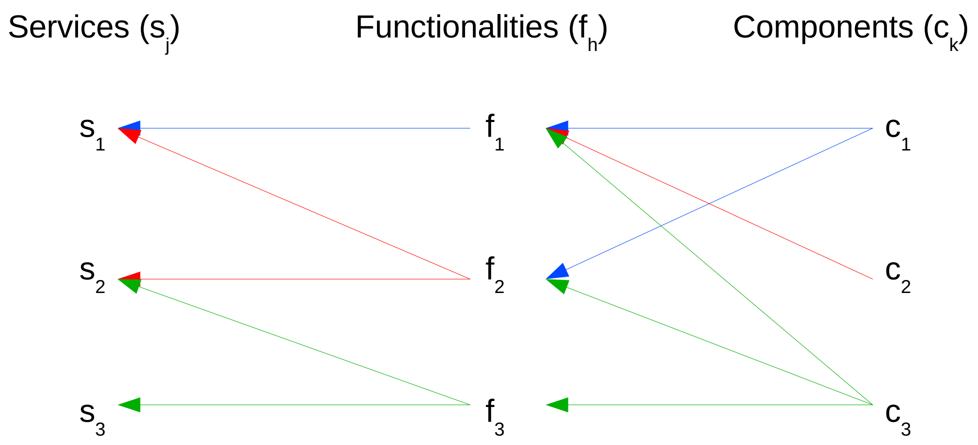


Figure 3

4- Assessing the sustainability of wetlands

In what follows, we draw from framework developed by Turner et al. (2000) to analyse wetlands. We then try to adopt an operational approach so as provide data-based indicators of ecological resilience potentials as well as of sustainability of these ecosystems.

4.1- Wetlands as ecosystems

Wetlands are a good candidate for a critical natural capital approach because they may be considered as complex, adaptive ecosystems with a strong multidimensional nature which is supported by their relationships among groundwater, surface water and vegetation type (Plummer and al. 2007).

Several classifications of wetland types can be found in the literature (Mitsch et al., 2007) given the diversity which is observed in the nature. One common feature shared by wetlands is however the fact that there is a predominance of water during some period of time and, accordingly, that the structure of this ecosystem is mainly influenced by the hydrologic regime (Turner et al., 2000). In this respect, wetlands constitute a diverse group of ecosystems which have been defined by the Ramsar Convention in 1975 as "*areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres*".

Wetlands are usually sorted in three main parts: marine and coastal wetlands including estuaries, lagoons, inter tidal marshes, coral reefs…, inland wetlands such as lakes and rivers, waterfalls, marshes, peatland or flooded meadows, the third category includes artificial or man-made wetlands, e.g. canals, ponds, water storage or wastewater treatment areas.

French Legal definition of wetlands (art L.211-1 “Code de l’environnement”) slightly differs from the one retained by Ramsar as it states that wetlands are "*farmed or unfarmed lands usually flooded or permanent or temporary filled with fresh, salted or brackish water*", and where "*vegetation when exists, is mainly composed by hygrophilous plants for an undetermined period within a year*". Further, a 2007 enforcement order followed by a 2008 ministerial decree (June 24 2008) presents in a more detailed way wetlands definition's elements. To be defined as a wetland, any area has to check at least at one of two major criteria: 1) its soil should fit some precise soil properties, and/or 2) the vegetation found at a certain level in the area should belong to a list of species of habitats (defined or understood as species communities).

A more functional classification of wetlands may be drawn from the study of Pearce and Turner (1990) which distinguish four basic types of wetland (according to their localisation): floodplains, coastal wetlands, wet meadows and peatlands.

Wetland functions can be analysed through the core features of an environmental system that we have emphasized in section (2.1): characteristics, structures and process.
In the case of wetlands, characteristics refer to the number and the types of species, water depth, the size and the shape of the wetlands, the soil properties and hydrological conditions. The structure refers to the communities of plants and animals of which the wetland is composed. In this respect, the focus may be put on the existence of biotic and abiotic webs such as trophic system and to the existence of biological communities (interactions between vegetation, soil types, living species, biomass...). Lastly, concerning the different processes involved, those concern the transformation of energy and matter at different levels such as the photosynthesis, biogeochemical cycling, transpiration, decomposition...

As for any environmental system, characteristics, structure and processes and their interactions determine how the various ecological functions will then be fulfilled (Mitsch et al., 2007). As Turner et al (2000) note (p.11), "*the interaction among wetland hydrology and geomorphology, saturated soil and vegetation more or less determine the general characteristics and the significance of the processes that occur in any given wetland. These processes also enable the development and maintenance of the wetland structure which in turn is key to the continuing provision of goods and services. Ecosystem functions are the results of interactions among characteristics, structure and processes*.". On this basis, wetlands perform many ecological functions (water and climate regulation, wildlife habitat, nutrient cycles...) and provide also a large set of services and goods to the society such as recreational services, fishing, buffer zone against flood risk, water provision...) while they are under heavy economic pressures (urban, industrial and agricultural sprawl).

As we have seen, the Pearce and Turner (1990) typology "source/sink/life support functions" is widely used to characterise the functioning of ecosystems. It may be noted however that each of the main functionalities associated with wetlands (pedological, hydrologic, geochemical, biodiversity or climatic functions) can be related to life support functions. For example, peatland can play a role in climatic regulation by carbon storage and oxygen production (life support function) as well constituting a buffer zone smothering climatic change. In this respect, and based on De Groot's classification, Van der Perk *et al.* (2000) suggested the following important functions for coastal wetlands: regulation functions (climate regulation, water regulation, protection against erosion, waste treatment by purification and filtering, biological control), habitat functions (nursery function, refuge function), production functions (food production and production of raw materials -fish, worms, shellfish, shrimp-), information functions (aesthetic information, recreation/tourism...).

4.2- Drawing up wetlands criticality indicators from a local management tool: "SAGE" (Water development and management scheme) "Gironde Estuary and Associated environment"

4.2.1- SAGE management tools and indicators

Among European estuarine areas, the Gironde estuary is probably the most ecologically unspoiled while being at the same time the less economically exploited zone of estuarine wetlands. But this large area experienced since years some decreases in its global environmental quality. Important factors of degradation are coming from industrial, agricultural, fishing and urban pressures.

In this respect, policy tools have been carried by the water agencies to prevent further or heavier environmental damage on estuarine wetlands. As an example, guideline water development and management scheme (SDAGE) has been put in place: it represents the reference point for all decisions related to territorial development at a large catchment level. At a local level, e.g. for smaller hydrographical area (around 3000 km²), water management may be organized around a local planning tool: water development and management scheme called 'SAGE' which gives guidelines about quality goals, protection rules, usage regulation etc… The SAGE is also meant to improve collective management of water resource imply at different levels all the stakeholders.

The "Gironde estuary and associated environment" SAGE has been built up to improve the global estuarine environmental quality and sustains economic activity in its perimeter (SAGE, 2010). To fulfil this stake, ten major goals have been voted by stakeholders after 4 years of studies and consultations among which seven are directly related to ecological preservation.

These goals concerns: global environment, turbidity dynamics, chemical pollution management, benthic habitat preservation, surface water quality and ecological quality of river catchment, halieutic resources preservation, and wetlands preservation. Within this SAGE perimeter, the major types of wetlands are estuary (10% of total surface), floodplains and marshes. These three estuarine ecosystem components carry out the following functions: groundwater recharge and runoffs, flood control, shoreline stability and erosion control, toxic deposits storage, local climate regulation, and deliver a large amount of services such as: navigability, recreation, wild species resources and biodiversity richness, halieutic resources, agricultural resources, water supply.

To achieve the major goal of "wetland preservation" within the SAGE, ten actions are planned and a multi-criteria assessment of their direct/ indirect, short/mid/long term effects on five subjects has been made (SAGE, 2010).

Those items can be related to the Pearce and Turner typology (1990) of functions (source/sink/life-support functions) as well more general services provided by ecosystems : for instance, biodiversity may be matched with life support function, resources with source function, pollutions with sink function, landscape with cultural service and risk with human health and well being services.

From a general viewpoint, the set of actions aims to improve life support functions and should have a positive impact on the source function. Moreover, short term and indirect effects actions are essentially characterized by knowledge improvement ranging from wetlands location to their insertion in local land planning schemes in order to build up some optimal management rules and reduce anthropic impact on wetlands. In addition, indirect and midterm effects actions consist in a yearly policy assessment, a comprehensive wetlands inventory elaboration and the definition of the strategic wetland areas regarding optimal water management goals. Direct effects should be raised from two actions that aim to identify protection or restoration areas for specific wetlands. Finally, to monitor and assess the various effects on wetlands, lists of indicators have been set up (for instance, the number of urban documents including the wetlands areas or their protection) and are close to state indicators although the reference state is missing due to the lack of initial information on the wetlands types, numbers and locations.

It may be noted however that this local management policy does refer only to a functional approach of natural capital involved in the functioning of the wetlands considered in the "Gironde Estuary" SAGE. No mention is made to criticality conditions or to the ecological resilience properties of those ecosystems within this local tool.

In this respect, a first step for identifying those criticality conditions would be to go through the study of Van der Perk et al. (2000). Indeed these authors have identified a set of criticality criteria for a coastal wetland. According to the latter, it may be possible to assess whether the functioning of the wetland is sustainable (that is whether the provision of services may be sustained without threatening the availability of the related environmental functions). Those criteria are summarized in table1.

Table 1 :
Examples of criteria and measurement units to identify critical natural capital

Criteria	Short description	Measurement unit
Naturalness/Integrity	Degree of human presence in terms of physical, chemical or biological disturbance	Air, water, soil quality ; % key species ; Minimum critical ecosystem size
Uniqueness/rarity	Local or global rarity of ecosystems and species	Endemism ; % surface area remaining
Fragility/vulnerability	Sensitivity of ecosystems for human disturbance	Resilience ; carrying capacity
Life support value	Importance to maintenance of essential ecological processes and life support systems	Critical functions that maintain ozone layer, climate regulation, genetic diversity
Threat	External pressures on remaining natural capital	Critical thresholds (qualitative/quantitative) ; minimum critical ecosystem size

Source : From Van der Perk et al. (2000).

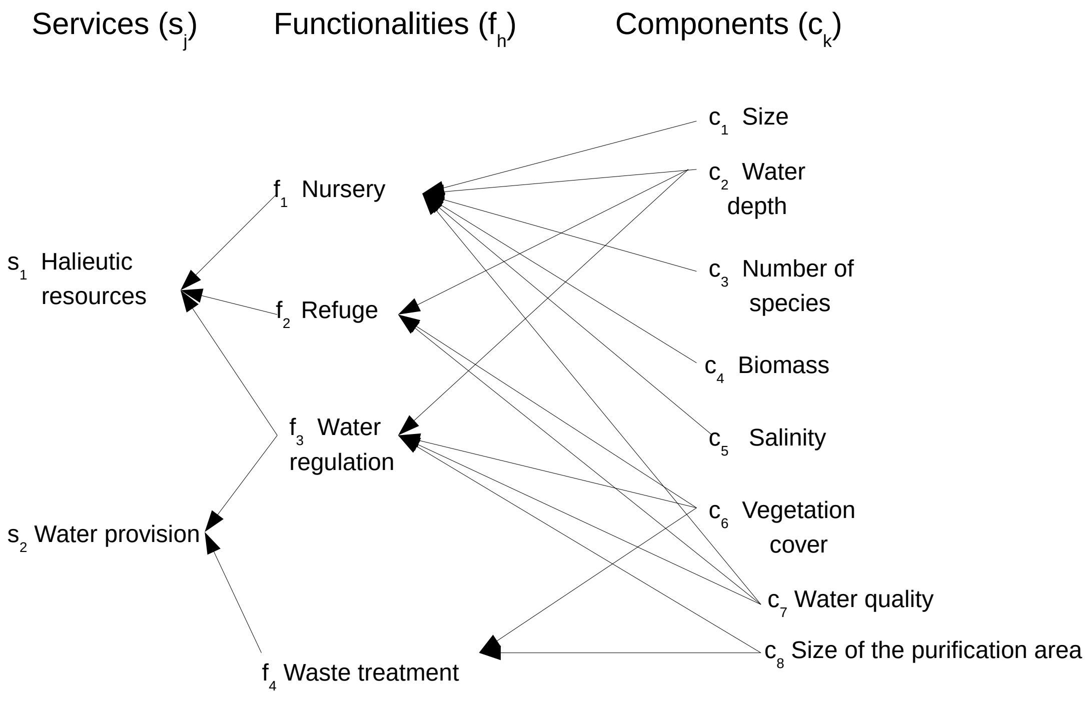
With respect to the resilience property, the challenge is probably more acute. Indeed addressing the resilience of wetlands would require to identify the slow controlling variables that make up ecosystem configuration (types of habitats, biophysical features - soil structure, geomorphology..., relationships between components, diversity -biological and functional-), and the faster variables which are operating at small spatial and temporal scales (Plummer et al. 2007). For instance, and in the particular case of wetlands (See the Everglades case study), the slower variable could be saw grass while the fastest could be periphyton (Holling et al, 2002). In addition, it may be noted that, in most cases, it is not the number of species per se that can sustain an ecosystem in a particular state but rather the existence of species groupings or functional groups (predators, pollinators, herbivores, nutrient transporters, water flow modifiers... with overlapping characteristics anchored in physical processes) (Folke, 2006). This point underlines the fact that species that may be redundant for ensuring the ecosystem functioning during particular stages of the ecosystem development may become of a great importance when the systems needs to regenerate after a disturbance.

4.2.2- Building the criticality and resilience potential indicators for Gironde estuarine wetlands

As mentioned earlier three kind of wetlands are encompassed within the SAGE frontiers: estuary, salty marshes and inland meadows. We focus on two core functionalities, namely regulation and habitat functions. In turn, the first one deals with the nursery and refuge functions whereas the second one rests upon water regulation and waste treatment, those functions can found in the SAGE classification mentioned below.

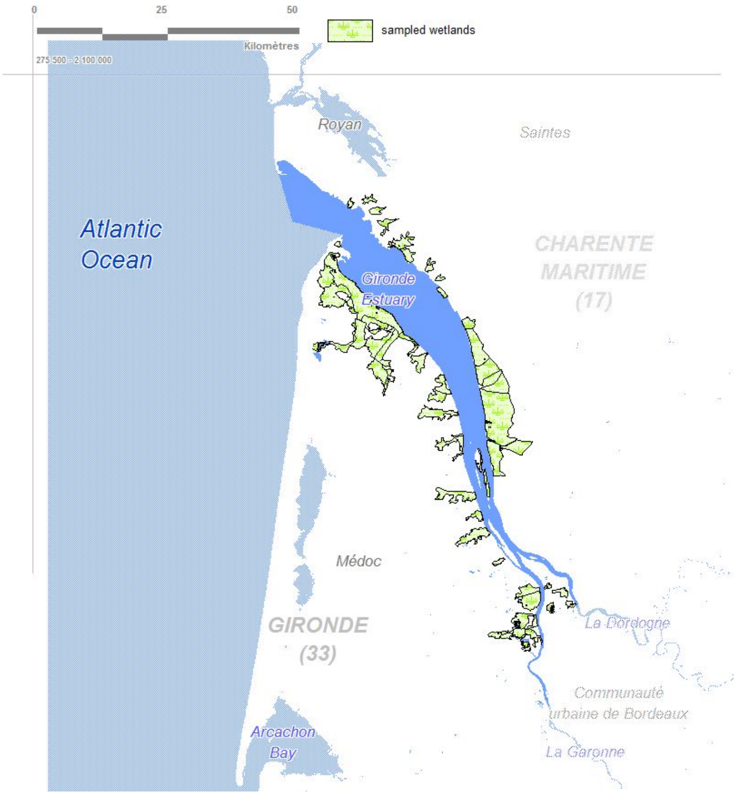
Figure 4

An operational framework to adress the functioning of Gironde estuary wetlands.



In this preliminary work, it has been decided to widen our investigations to two cores services: halieutic resources (s_1) and water provision (s_2), based on further comprehensive data. The chosen unit is the area of wetlands managed at a local level that encompassed different actors: mainly ASA (local landowners association), local (town council, Gironde department, port authority, environmental association) and national (Conservatoire du Littoral) authorities.

Map 1: *Distribution of the studied wetlands along the Gironde Estuary*



Source: Lavaud, GRETHA 2011

Data collection derived from several sources, from scientists or local manager interviews to SOMLIT network river sampling stations.

The following table summarized the data and their sources:

Table2: Data description

Component	**Description**	**Unit / class**	**Data sources**
c_1: Size	Area of the studied unit	Km^2	GRETHA
c_2: Water Depth	Proportion of area under the 6 meter tidal range	%	GRETHA, GIS simulation
c_3: Number of species	Fish density,	fish/m², 3 classes	Thesis D. Nicolas 2010
c_4: Biomass	Macrobenthos density	unit/m²	Livre Blanc Estuaire de la Gironde , 1992 AEAG
c_5: Salinity	3 salinity classes: oligohaline, mesohaline, polyhaline	3 classes	Literature
c_6: Vegetation cover	Main vegetation type based on a 15 classes vegetation cover typology	1: Bushes... to 15: man-made landscape	SIMETHIS-SYMBIOSE, GRETHA & GEREA
c_7: Water Quality	TSS concentration	3 classes of average values in mg/l (low and high tide, surface and depth sampling): $[89_{surface},204_{depth}]$; $[292_{surface},835_{depth}]$; $[398_{surface},1151_{depth}]$	SOMLIT
c_8: Size of the purification area	Proportion of available purification area	%	GREThA, GIS

Concerning the choice of the components, we used proxies to get a comprehensive data set for 54 wetlands managed by local landowners .

The first component (c_1) is the area of the wetland ranging from less than 1km² to 60 km² with an average area of 7,2 km².

Assessing the water depth (c_2) of each wetland unit within the study perimeter is an arduous task without any thorough knowledge on every drainage basin hydrology. GIS simulations have been required to determine the wetland proportion that lies under a six meters tidal range as the Gironde estuary is macrotidal. This raw assessment focuses on topographic variables (altitude, distance to the shore), regardless of any other elements as tidal cycle, flow or climatic conditions. In estuarine mesohaline parts, few fish species are able to live in this highly changing environment (McLusky and Elliott, 2006, cited by D. Nicolas 2010) leading to high abundances. Consequently, the choice of an abundance index (fish density) has been chosen for the third natural component (c_3) rather than the number of fish species.

Macrobenthos -component (c_4)- mainly found on riparian mudflats, is a component of the estuarine biomass strongly related to the salinity gradient - component (c_5)-. Data come from four sampling stations based on the left bank of the Garonne river and Gironde estuary and are expressed in density (unit/m²). The role of vegetation (c_6) as natural component is encompassed by a 15 classes typology adopted by the SAGE authority, ranging from bushes (class 1) to man-made landscape (class 15). The dominant type of each wetland area has been chosen to characterize each unit.

Among indicators of water quality (c_7), the total suspended solids (TSS) concentration is a relevant indicator for our study as TSS result from both antropic and natural actions and contribute to biological water quality degradation. We define three classes of average value based on thirty five data from three different sampling. High TSS concentration can increase sediment production, and therefore the constitution of a pollution stock. This can lower the photosynthesis impacting oxygen availability for living organisms. However, TSS can contribute to the refuge functionality (f_2) as high TSS concentration implies high turbidity which reduces the predation risk.

To assess the available purification area (c_8) for each unit we removed any forms of man-made landscape (for instance roads, buildings, embankments, leisure ground…) by crossing Corine Land Cover and our vegetation cover layers to obtain the part of unspoiled or natural purification potential stating that farmed land can activate the purification functionality called here "waste treatment".

4.3.3 Results and discussion

Our approach consists in the identification of existing services and activated functionality, the design of a set of conditions on natural capital components and the assessment of threshold values of the actual components that could allow to qualify the resilience potential, assessed by the amount of fulfilled conditions.

Our operational framework leads to the determination of 2 solution sets for each service delivery. Based on figure 4 it appears that service 1 requires 3 functionalities, $F_1=(f_1, f_2, f_3)$, while service 2 requires $F_2=(f_3, f_4)$. In terms of required components, the activation of f_1 involves $C_1=\{c_{1,1}, c_{1,2}, c_{1,3}, c_{1,4}, c_{1,5}, c_{1,7}\}$, of f_2 involves $C_2=(c_{2,2}, c_{2,6}, c_{2,7})$, of f_3 involves $C_3 =(c_{3,2}, c_{3,6}, c_{3,7}, c_{3,8})$ and f_4 requires $C_4=(c_{4,6},c_{4,8})$. Hence service 1 needs $C_1 \cup C_2 \cup C_3$ and service 2 needs $C_3 \cup C_4$. For all the components, we have been able to determine some critical values, thus s_1 rests on 8 critical conditions while 4 critical conditions are required for s_2.

The whole set of services (s_1, s_2) requires the fulfilment of every critically conditions of all components. The resilience potential is defined from the two solution sets that are provided for each service.

We start our analysis with the service s_2 which requires less natural components then the service (s_1) for which all the components have to be activated.

The waste treatment functionality (f_4) requires the consumption of two natural components: the vegetation cover (c_6) and the size of the purification area (c_8)[3]. The main assumption rests upon the vegetation cover which is defined by only three dominant vegetation types (forests; wet meadows and tall herb; wet meadows and short grass). The average available purification area of our sample rises to 98%. We consider this value as the minimal proportion needed to achieve the waste treatment functionality. Facing those restrictions on natural components levels, 61% of the wetland areas are still able to activate this functionality.

Wetland is a transitional area where water can be both stored and released. Focusing on water regulation (f_3) implies the use of the following components: the water depth (c_2), the vegetation cover (c_6), the size of the purification area (c_8) and the water quality (c_7). This last component, measured by TSS, can also be taken into account through accumulated sediments and organic matter that can interrupt water flows and eventually decrease the duration of flooding. In addition, some assumptions have been made on the minimal level of the following natural components:

- (c_2): at least 50% of the area is below the 6 meters tidal range to ensure a minimal flooding capacity,
- (c_6): farmland as dominant vegetation type is included as we suppose that farmers seek for water proximity to improve their irrigation scheme,
- (c_7): a 850 mg/l maximum value for TSS concentration to lessen sedimentation. This last assumption shows that natural component (c_7) implies different critical values $(\underline{c}_{2,7})$ and $(\underline{c}_{3,7})$ that are needed to activate functionality (f_2) and (f_3) respectively.

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[3] We omit the first subscript referring to the functionality when it is not necessary.

In our study, only 46% of wetlands are able to provide some water regulation functionality. This preliminary result may need some further investigation by including another component expressing the hydraulic connectivity which can be assessed by the canals maintenance cost[4].

Water provision service (s_2) can be provided by 29% of the wetlands, which means that those ecosystems are able to sustain conjointly water regulation (f_3) and waste treatment (f_4) functionalities.

The latter part of the analysis concerns the halieutic resource core service (s_1) whose solution set requires the activation of all the components.

Refuge functionality (f_2) is activated when the water turbidity is relatively high. The level of permanent or temporary water can allow fish movement and can prevent any predation from limicolous bird. The role of vegetation cover is less direct but is relevant as it seems that long stemmed vegetation can contribute to shelter some fishes species. Water depth - component (c_2)- cannot embody precisely the optimal water level required for the refuge functionality (30 to 50 cm according to experts).

The same restriction have been retained about the level of water depth (c_2) (at least 50% of the area under the 6 meters level of tidal flow), the concentration level of SST is greater than $[398_{\text{surface}};1151_{\text{depth}}]$ mg/l and the dominant vegetation cover is restricted to wet meadows and tall herbs. Therefore, only two observations in our study fulfil the required conditions to activate the refuge functionality (f_2). The decrease of the level of the water turbidity, including a $[292_{\text{surface}};835_{\text{depth}}]$ mg/l concentration level allows only one candidate to emerge. The stringent restriction is about the vegetation cover type: loosening it implies a larger amount of candidates (17 wet meadows with tall herbs or short grass, e.g. 31% of the wetlands under concern).

According to our operational framework, nursery functionality (f_1) seems to be the more challenging in terms of components consumption. Salinity class can affect the species richness but, as mentioned earlier, it has been decided to chose an abundance index stating that a high fish density regardless fish species would have a positive impact on nursery functionality. As a keystone, salinity gradient influences strongly the availability of some

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[4] Assessing canals maintenance costs requires a comprehensive set of monetary data by gathering data from local managers account books. The use of such a partial set of monetary data could have probably restrain the scope of our wetlands sample.

others components data such as classes of fish density, biomass and water quality. Thus, focusing on a single salinity class (mesohaline part of the estuary for example) entails implicit levels concerning the number of species (c_3), the biomass (c_4) and the water quality (c_7). Others "control variables" are the size of each wetland (c_1) and the part of the area that is under the 6 meters tidal range (c_2). Regarding the size, every area of wetland smaller than 1km² has been excluded.
The set of Those conditions restricts the solution set to 33% of the total.

The functionality (f_3) -water regulation- is commonly needed for the 2 services but the most severe limitation on TSS concentration [$398_{surface}$; 1151_{depth}] needed to activate refuge functionality (f_2) only permits the achievement of one service namely (s_2). Loosening the condition on TSS concentration and supposing that it could stand in a blurry area ranging around 800 and 1200 mg/l (for the highest concentration level) would allow 15% of our sample to provide the halieutic resource service.

Table 3: Thresholds values and fulfilment of each functionality.

	$\underline{c}_{h,1}$	$\underline{c}_{h,2}$	$\underline{c}_{h,3}$	$\underline{c}_{h,4}$	$\underline{c}_{h,5}$	$\underline{c}_{h,6}$	$\underline{c}_{h,7}$	$\underline{c}_{h,8}$
f_1	>1 km²	> 50%	64 ind/m²	27000 ind/m²	mesohaline		from $89_{surface}$ to 835_{depth} mg/l	
f_2		> 50%				Wet meadows (high herb or short grass)	from $292_{surface}$ to 1151_{depth} mg/l	
f_3		>50%				Wet meadows and high herb, Wet meadows and short grass, Farmland	From $89_{surface}$ to 835_{depth} mg/l	≥98%
f_4						Forest, Wet meadows and high herb, Wet meadows and short grass		≥98%

Considering the empirical threshold values or the minimum values needed to activate the four functionalities, the conjoint achievement of the two services concerns only one specific wetland which vegetation type is mainly wet meadows with tall herbs. Widening the vegetation cover (c_6) threshold value to wet meadows and short grass would allow 16% of the studied area to fulfil conjointly the two services regardless of the respective amount of service delivered.

5. Conclusion

From a functional approach of natural capital which leads linking capital components, functionalities and ecological services, we have built a methodological framework of the functioning of an ecosystem able to account for its ecological resilience property (role of economic pressures). Then, we have linked the ecological resilience and the sustainability of an ecosystem: the latter depends on the way the criticality conditions associated with natural components are satisfied, which involves the activation of one or more ecological functionalities. The application to the case of a specific ecosystem such as Gironde estuarine wetlands has brought some useful insights for the connection between services and components of natural capital, and for the regulation of ecological services facing economic pressures.

First, after a typology of wetlands being identified, some indicators for the criticality and the resilience potential have been discussed. For all the components involved in our study, we have been able to determine empirically the critical values. Then, we have established the link between the provision of services and those critical conditions: for instance, the halieutic resources service rests on 8 critical conditions while 4 critical condition are required for the water provision service. The resilience potential has been assessed through the delimitation of two solution sets for each ecological service. We have shown that 29% of the wetlands under study can implement the water provision service while the halieutic resources service is provided by 15% of those ecosystems. Lastly, the two services are only jointly provided in the case of a specific wetland that is wet meadows (16% of the area under study). A first extension of our work could be to leave the static approach and build a dynamic framework for analysing feedback effects and links between the components for a better and more complex understanding of the relationships between components, functionalities and services. Viability methods could be a relevant framework to deal with such an issue (Delara and Doyen, 2008; Baumgärtner and Quaas, 2009).

Second, these preliminary results suggest that the design of public policies could be different according the solution set of services that has to be satisfied. Until now, no use conflicts have been considered between the different functionalities or services, so that both the water provision service and the halieutic resources service could be satisfied jointly. But, if it is not the case, then the services provided by wetlands are no longer complement but substitutes. Then some questions arise: how can we choose between the two services? On which decision criteria can a public regulator proceed? Another aspect of this problem can be identified when several functionalities are interacting with each other. Our methodological framework could be extented to the analysis of a set of wetlands in order to define the resilience potential at a broader local scale. In such a situation, it could be interesting to study how various wetlands could be complement or substitute for the provision of a given service depending on whether their functionalities and/or their natural components are matching or not. Another point of interest could be to determine if the spatial closeness of several wetlands of small size is a limiting factor for the resilience of the set of wetlands and in that case to define the design of a public policy which aims to maintain embankments for economic activities.

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