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Site selection for stock replenishment using a hydrodynamic model: example of the Pacific oyster *Crassostrea gigas* culture in the Pertuis Charentais (France)

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Abstract

The critical issue for oyster-farmers in the Pertuis Charentais region in France is to obtain a significant spat supply on a yearly basis in areas dedicated to spat collecting to sustain oyster production. To address this practical question, we search for main hydrodynamic driving factors that modify larval yield using a hydrodynamic model. Larval yield is defined here as the number of larvae in spat collecting area coming from one particular bed divided by the total number of larvae generated by this bed. Five hydrodynamic factors have been included into the simulation: spawning time in relation to tide, pelagic larval durations, realistic wind conditions, location of oyster beds and location of spat collecting areas. The main result is that "the location of oyster beds" is the most important factor that impacts larval yield. In Pertuis Charentais region, northern beds supply spat collecting located in the southern areas. Since these beds are constituted of wild oysters, it implies that wild oysters, for which stocks are unknown, may

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sustain most important spat collecting areas in the mouth of the Charente River. The key-role of oyster beds location, highlighted in this study, implies an improved coordination between policies of eradication of wild oyster beds (aimed to increase productivity) and policy of replenishment to improve spatfall level. Based upon those results, wild oyster stock assessment is a complementary step to determine where the replenishment should be carried out. Nevertheless, this first study shows that large variability of contribution of oyster beds indicates that replenishment in well-chosen areas may be successful to improve spat supply.

1 Introduction

Figure 1: Location of the Pertuis Charentais in France.

Oyster farming has developed in France with the popularization of spat collecting technique by Coste (1855) in the mid nineteenth century (Levasseur, 2008). With the control of this technique, oyster fisheries transformed into oyster farming industry at the end of the nineteenth century. More than a century later, natural spat supply was still an important practice for oyster industry. To counteract the high variability of spat collecting, hatcheries slowly develop in France since 1970. Nowadays a severe crisis threatened oyster farming to its roots: since 2007 between 50 to 90 % of spat died every year in what seems to be a massive epizootic (Pernet et al., 2010). This context of massive mortalities has greatly strengthened spat demand and thus the need to improve the reliability of natural spat collecting. This study initiated in the Pertuis Charentais (Fig. 1), one of the main areas for spat collecting in France, aims to (1) give some answers to oyster-farmers on the hydrodynamic system that impacts spat collecting in the bay and (2) provide scientific basis to potential replenishment of broodstock.

As summarized by Pineda et al. (2007), pelagic larval life leads to the displacement from an area (X_0, Y_0) to another area (X_e, Y_e). In the context of oyster farming, we named the first area "the bed of origin" and the last one "the spat collecting area". Pelagic larval stage lasts more or less depending on bioclimatic driving factors. It is noted $t_e - t_0$ and called "pelagic larval duration". During this time, the quantity of larvae generated by the bed of origin, N_0, decreases to a final quantity in the spat collecting area, N_e. The ratio between the quantity produced by the bed and the quantity present in the spat collecting area, $\frac{N_e}{N_0}$, is called the yield of the bed. The aim of this work is to find oyster beds and conditions that maximize this yield. A hydrodynamic model has thus been used to test the effect of many potential driving factors.

2 Method: how to analyse hydroclimatic variability?

Pelagic larval stage of *Crassostrea gigas* oyster, depends on the tight interaction between factors linked to hydrodynamic and factors linked to biology. Among factors linked to hydrodynamic, we can distinguish: (1) the beginning and (2) ending location of pelagic larval stage, (3) the wind and (4) the tide conditions during this period. Among factors linked to the biology, we can distinguish: (1) oyster stock size and (2) larval mortality that modulate the quantity of larvae remaining after the pelagic larval duration whereas (3) temperature and (4) food availability modulate this duration; (5) larval behaviour that can restrict or increase larval dispersal. Temperature and food availability are also linked to larval mortality in an unknown way.

All hydrodynamic linked factors can easily be included in the hydrodynamic model and they were thus all included. In contrast, biological factors have in common to be difficult to measure in spatio-temporal dimensions, especially at the resolution needed for our study. The choice of factors included in the hydrodynamic model depends on several assumptions. As data for stock evaluation are scarce or outdated, we choose to carry out the study with homogenous density on spatial scale. Larval mortality is assumed to be homogenous spatially and can then be disregarded since it does not quantitatively impact larval dispersal. Larval behaviour was not considered in the present study due to lack of accurate information. Pelagic larval duration was accordingly choosen as an indirect evaluation of temperature and food availability effects.

Figure 2: Location of oyster beds of broodstock considered and spat collecting areas identified by circles with number. Colors of oyster beds are only used for their differentiation.

The hydrodynamic of the Pertuis Charentais is simulated, here, using the Model for Applications at Regional Scale (MARS) in its 2D version. A detailed technical description of this model can be found in Lazure and Dumas (2008) and an application case to Arcachon bay in Plus et al. (2009).

Twenty-five beds of origin have been chosen in order to cover all the potential habitats of oysters in the Pertuis Charentais (Fig. 2) (factor name: Bed). Due to computing power limits, only seven spat collecting areas have been chosen in relation to traditional practices by oyster-farmers (factor name: Spat). These areas are empirically known to be optimised. Tide effect has been included through tidal phase at the beginning of the larval stage (factor name: Tide). Beginnings of simulations have been applied in growing tide, spring tide, decreasing tide and neap tide at two different moments in the day: ebb or flood tide. It results in 8 different timings of larval stage. During larval development, larvae can encounter various conditions of wind (factor name: Wind). Six realistic sequences have been chosen among 13 years of summer wind data as representative of frequent summer atmospheric conditions. Three realistic pelagic larval durations are tested in the model: 17, 20 and 23 days (factor name: PLD).

We thus obtained a fully factorial design in which we "emitted" larvae in 25 locations and tested what remained in 7 locations with 8 different beginnings of larval release in relation to the tide and 6 different wind conditions. Finally, larvae in spat collecting areas were sum up according to 3 different pelagic larval durations.

Using this method we tried to put all available information on larval dispersal into the model but discarded unknown or imprecise information. The factorial design allow us to determine the main factor impacting spat collecting. The practical aim is thus to test if replenishment could be potentially efficient but without stock estimation data we definitely cannot be completely realistic.

3 Results

3.1 Which factor is the most important?

Due to the amount of combinations, it was impossible to calculate the percentage of variability attributed to each factor at once. The percentage of variability explained for each modality of Tide factor was first calculated and then the mean was computed (Tab. 1). The results show that the main effect on variability comes from the interaction between oyster bed of origin and spat collecting area. It thus seems that specific beds supply specific spat collecting areas. This variability is less impacted by the bed of origin or spat collecting area as single factors. The yield exhibits large variations according to the bed and spat collecting area chosen. In contrast, pelagic larval duration has a small interplay in the yield of the bed and surprisingly, wind conditions have no effect in comparison to other factors.

Factor	Degree of freedom	Percentage of variance explained
Wind	5	0.04
Bed	24	34.58
PLD	2	1.57
Spat	6	17.14
Wind:Bed	120	0.60
Wind:PLD	10	0.02
Bed:PLD	48	1.67
Wind:Spat	30	0.11
Bed:Spat	144	38.07
PLD:Spat	12	0.53
Wind:Bed:PLD	240	0.05
Wind:Bed:Spat	720	1.43
Wind:PLD:Spat	60	0.04
Bed:PLD:Spat	288	3.92
Wind:Bed:PLD:Spat	1440	0.23

Table 1: Partitioning of the variability in the data set obtained from hydrodynamic simulations for every combinations of factors. "Wind" stand for wind conditions, "Bed" for beds of origin, "PLD" for pelagic larval duration and "Spat" for spat collecting area.

Spatial dimension, for the beginning and end of larval stage, sum up an important part of the variability, highly above pelagic larval duration, wind or tide (Tab. 1). It thus seems that replenishment operated in well-chosen area can reliably increase the amount of spat yearly collected whatever the other conditions.

3.2 Where do the larvae come from?

An important amount of the variability of the yield is linked to the interaction of spat collecting areas and beds of origin. To study this interaction, maps of yield of beds for each spat collecting areas have been drawn (Fig. 3). They might be useful for determining the origin of larvae and giving better insight on the best area to replenish oysters.

These maps show the number of larvae that diffuse in each spat collecting area for ten thousand larvae released. Low yields are represented in blue and high ones in red (Fig. 3). For each map, a black circle recalls the location of the spat collecting area considered. The same scale is used to allow comparison between the different spat collecting areas. For spat collecting in the mouth of Seudre River, lots of beds lead to good mean yield although the most important beds are located on the north east. For spat collected in the mouth of the Charente River (spat collecting areas 2 to 4), oyster beds that actively contributed are situated norther. Similarly, the eastern part of the Pertuis Charentais is the one that potentially contributes the most. The fifth spat collecting area seems to be isolated from others: few beds contribute to supply this area. The latest spat collecting areas exhibit the lowest yield. Only some oyster beds norther seems to contribute to a low spatfall.

A good place to replenish is one with a good yield but also with a low variability of this yield. Coefficients of variability of the yield for each oyster bed and spat collecting area have been accordingly determined (Fig. 4). For the four first spat collecting areas, southern beds exhibit high coefficients of variability, whereas eastern beds in the inlet of Antioche have low coefficients of variability. Northern beds show moderate coefficients of variability. For spat collecting areas situated near Ré Island, number 5 and 7, only northern beds exhibit small coefficients of variability. The sixth spat collecting area displays a similar pattern to the four first ones, but oyster beds with small coefficients of variation are located a bit norther compared to other cases.

If we superpose results issued from both maps, we can see that the most favourable area for stock replenishment for the four main spat collecting areas (1 to 4) is situated in the eastern part of the region at the North of the mouth of the Charente River. Since these four spat collecting areas concentrate an important part of the spat collecting activity, replenishment can potentially improve the number of spat collected. An additional place in the North of Ré Island can be chosen to improve spat collecting for the three remaining areas.

4 Discussion

We previously show areas where the yield of replenishment will be the best to supply spat collecting areas currently used by oyster-farmers. But due to the lack of reliable data, the current situation of oyster stock size in each area was not considered. Oyster beds with high potential yield in the East of the studied region correspond mainly to disused concessions covered by wild oysters. In these areas, stocks are unknown but the variations of density of oysters may have important implications for spat collecting. If stocks in this place are high, it will be difficult to improve spat collecting through replenishment, but if stocks are presently low, room is available for a sucessful

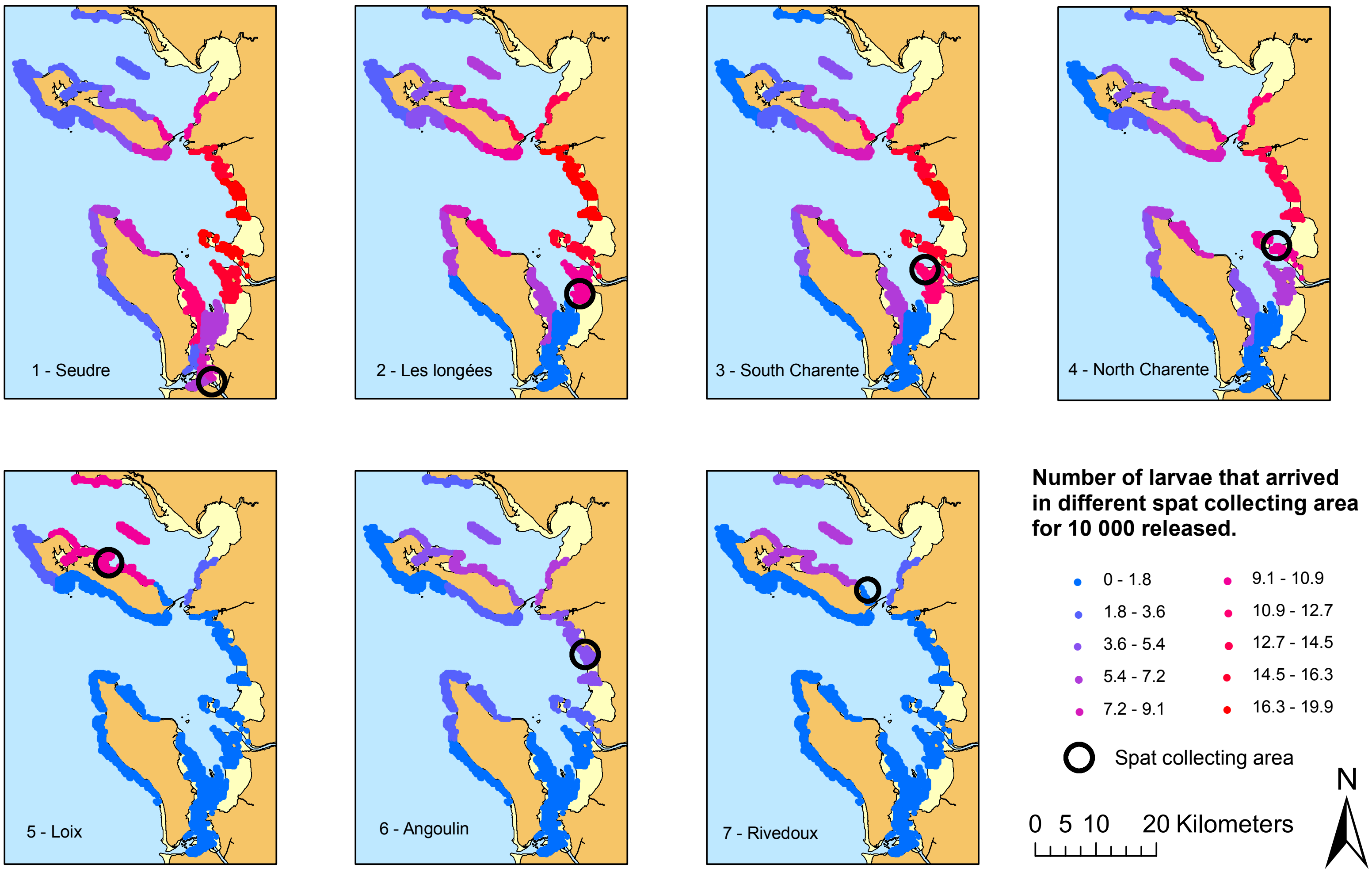

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Figure 3: Mean yield of each oyster bed for the 7 spat collecting areas.

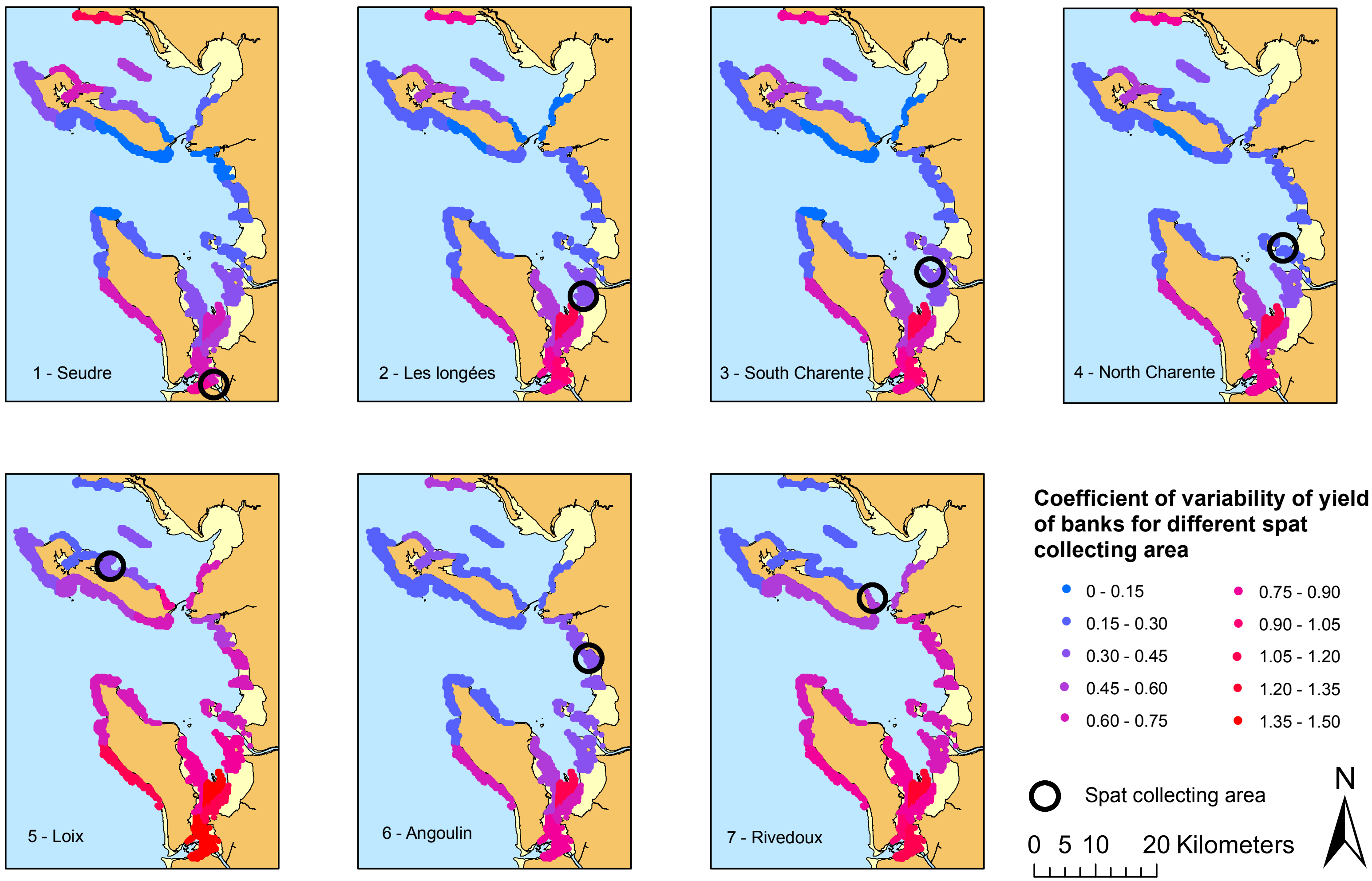

Figure 4: Coefficient of variability of the yield of each oyster bed for each spat collecting area.

replenishment in these areas.

In a previous study on the restoration of *Crassostrea virginica* oysters in Chesapeake Bay, Schulte et al. (2009) insists on the necessity to identify source and sink populations before to initiate a replenishment policy. Here we just made another adaptation of this recommendation to a more specific problem since we based our choice for spat collecting areas on traditional ecological knowledge of oyster-farmers. This may be important if others factors, not tested here, *e.g.* food availability, have a positive effect on larval settlement in these areas.

In the context of massive oyster mortalities in France, identification of the best potential replenishment places can be important to accelerate the interplay between population dynamic and resistance acquisition as it has been described by Hofmann et al. (2009) for *Crassostrea virginica*. If resistance can be transmitted from one generation to another, replenishment of resistant oyster in regions that supply spat collecting areas may help to improve the survival of the spat, and to sustain French oysters industry.

5 Conclusion

By taking the Pertuis Charentais region as an exemple for demonstration, one of the main conclusions of this work states that the analysis of the variability of the system let enough room for replenishment in well chosen areas to increase the yearly reliability of spat collecting. By analysing the mean of the yield for each bed and each spat collecting area, we shows that two subsystems exist in the Pertuis Charentais: the northern inlet supports itself and supplies southern areas whereas the southern oyster beds tend to export their larvae outside (Fig. 5). Oyster beds around the inlet of Antioche also supply spat collecting areas in the mouth of the Charente River. Finally, spat collecting areas in the mouth of Seudre River are supplied by the same beds but with the input of cultivated beds from the South. Southern beds export their larvae through the inlet of Maumusson.

Beyond the replenishment problematic, this study also shows how hydrodynamic models can help decision makers by providing information on the link between beds that must be included into decision process. This study also highlights the need for complementary data on up-to-date stock density for oyster beds with high yields. With such data, it will then be possible to compare larval quantities obtained in the model with field data of settlement densities.

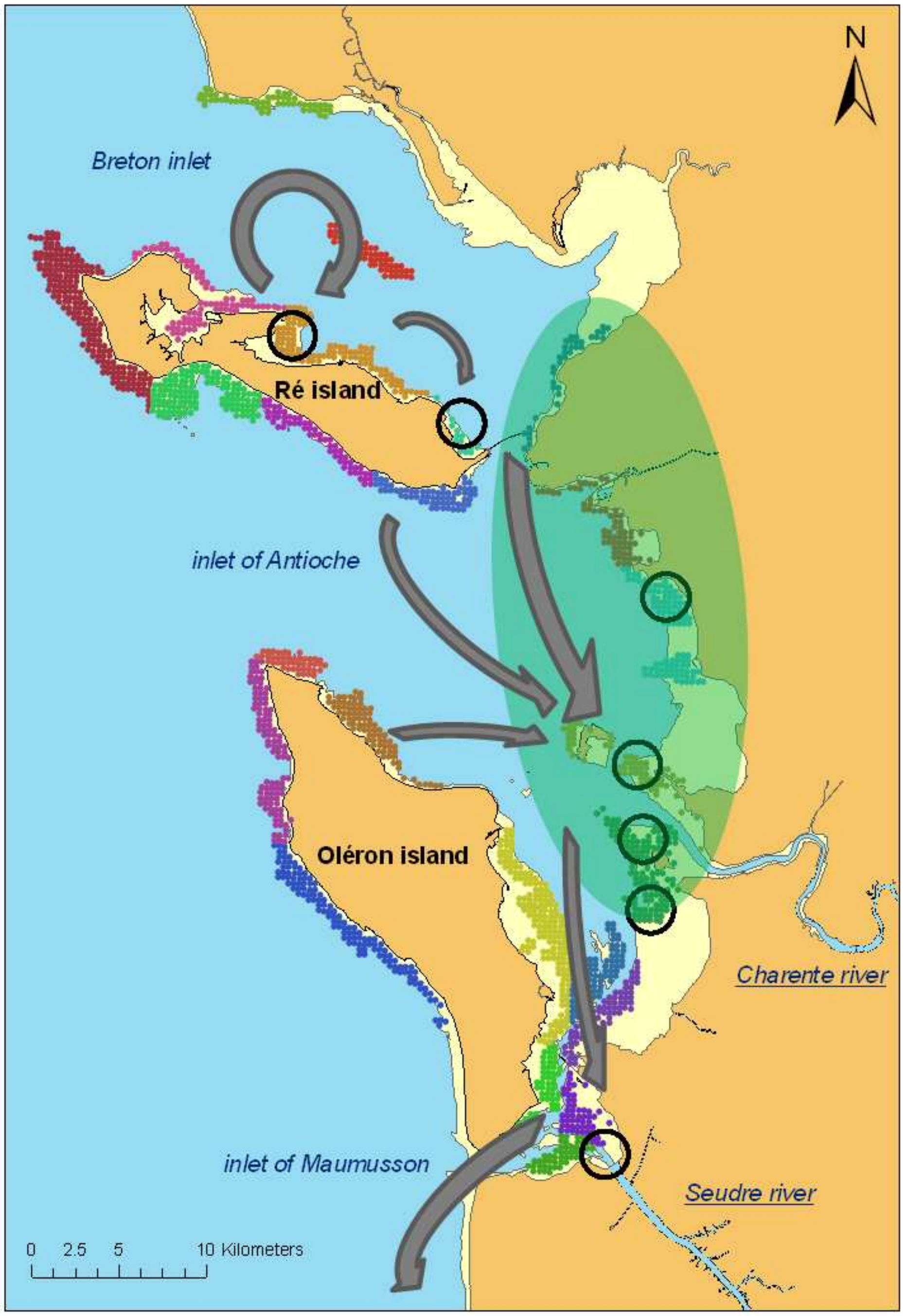

Figure 5: Relations between broodstock oyster beds and spat collecting areas in the Pertuis Charentais. The green zone is the potential zone for replenishment.

Acknowledgements

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