論文内容の要旨

論文題目 Can marine artificial reefs effectively replace lost natural habitats?

（人工魚礁による消失自然ハビタットの効果的代替の可能性について）

氏名　ブアニエ　エチエヌ

This study consisted of four chapters treating the question whether marine artificial reefs can effectively replace lost natural habitats. The underlying idea is straightforward:　if marine artificial reefs can mimic efficiently natural reefs, they may help replacing lost natural habitats despite such a claim, evidences are lacking. This study aims to assess the conservation potential of artificial reefs with reference to fish assemblages and developed a new distinction method, Habitat Association Index. Using this new distinction method, this study examined the question by applying two different areas. The details are described according to the chapters as follows.

I. Introduction: defining subject and objectives

Despite the commonness of the concept, defining artificial reef remains an open challenge, as there is no widely accepted definition. In this study, the definition proposed by Seaman (2000) is adopted: *"one or more objects of human origin deployed purposefully on the seafloor and which influence physical, biological or socioeconomic processes related to living marine resources"*.

Marine artificial reef studies commonly refer to the distinction between resident and non-resident species (e.g. D'Anna et al., 1994; Johnson et al., 1994; Moreno, 2002; Jan et al., 2003). However, it appears that there is no consensus for the number of subdivisions in artificial reef communities. While not focused on artificial reef communities, a research by Magurran and Henderson (2003) demonstrated that any community can fundamentally be divided into two groups: resident (or core) and transient (or vagrant) species. The suitability of the artificial reef as a replacement habitat may be hard to demonstrate if the

species is transient, as there is no direct link between habitat presence and transient species occurrences. Nevertheless, if the species becomes resident, it indicates that the reef succeeded in providing a habitat, which can replace successfully natural reef habitat. As the concept of residence is essential to demonstrate the suitability of an artificial reef to replace successfully some lost natural habitats, distinguishing resident from transient species is essential.

The exclusive focus of this study on fish assemblages along marine artificial reefs is explained by two reasons. First, literature for marine artificial reef is more important for fish assemblages than for fouling organisms or crustaceans. Second, due to practical reasons, the field data collected in the scope of this study were exclusively related to fish assemblages.

This study has three main goals: 1/ demonstrate the absence of suitable method to distinguish accurately and objectively fish species along marine artificial reefs; 2/ develop suitable theoretical tools to overcome this distinction problem; 3/ apply these newly developed tools to a case study in order to compare fish assemblages along marine artificial reefs and surrounding natural reefs and consequently assess the potential for marine artificial reefs to replace lost natural habitats.

II. Why are available distinction methods not suitable?

As literature shows, artificial reef scientists refer to subjective methods to distinguish resident from transient species (i.e. no theoretical construct to justify their method). For instance, while Relini et al. (1994) requires a species to be present in at least 50 % of the total number of samples to be considered as resident, Costello and Myers (1996) categorise as resident any species which occur in all the samples but two whereas Talbot et al. (1978) define a species as resident if it appears in at least two consecutive samples. Not only do available definitions lack of theoretical construct but also the absence of common distinction method makes any comparison between studies an open challenge.

The core-satellite theory is a general theory in community ecology which aims to distinguish in any ecological region the core (i.e. the resident species) from the satellite species (i.e. the transient species). The distinction method proposed by this theory is based on a spatial approach: several locations within the eco-region are sampled simultaneously. This spatial approach, and its dedicated theoretical tools, is barely suitable for reef scientists who generally adopt a temporal approach (i.e. a single site sampled numerous times over time).

Contrary to the core-satellite theory, Magurran and Henderson (2003) propose a distinction method based on a temporal approach. The authors underline that, fundamentally, plotting species persistence against maximum abundance represents an efficient and objective way to distinguish resident from transient species. The gap, which appears along the persistence axis represents then the boundary between the resident and the transient species. Magurran and Henderson (2003) demonstrate the objectivity of this method by cross-checking results with three other methods: fitting a Poisson process to the species occurrence patterns; referring to the species' biological characteristics; calculating the reciprocal form of the Simpson Index (D) for each persistence level species group and looking at its relation with regard to the number of sample collected. When applied to four different fish assemblage datasets collected along four different artificial reefs, none of the four objective distinction tools successfully used by Magurran and Henderson (2003) is able to provide conclusive results (Boisnier et al., 2010). This lack of efficiency

may be primarily related to the fact that Magurran and Henderson's tools were designed using exceptional datasets (samples collected over decades). As a result, objective theoretical tools capable of identifying accurately resident from transient species in relatively limited datasets have yet to be developed.

III. Developing an objective and accurate method to distinguish resident from transient fish species along marine artificial reefs

In practice, two elements are required to be able to distinguish efficiently and accurately resident from transient species: first, an accurate measurement of the habitat association level of every species present in the dataset; second, the ability to determine from which habitat association level a species passes from being transient status to resident status.

HAI has no unit and is calculated for every species present in the dataset. It is simply interpreted as the level of association between the species and the habitat where it appears. To be calculated, HAI simply requires the collection of presence-absence data. Hence, for any species j, this index is defined mathematically as following:

$$HAI_j = \ln(Alt_j + e) \times \left(\frac{MP_j + MA_j}{AP_j + AA_j}\right) \times \left(\frac{N}{n_j}\right)$$

where:

Alt_j is the number of times presence and absence for species j alternate in the dataset;

e is the Napier's constant;

MP_j is the maximum number of consecutive samples in which species j is present;

MA_j is the maximum number of consecutive samples in which species j is absent;

AP_j is the average presence of species j in consecutive samples;

AA_j is the average absence of species j in consecutive samples;

N_j is the total number of temporal units;

n_j is the number of temporal units where species j appears.

First, one of the interesting properties of this index is to provide a similar output, whatever the temporal unit selected (samples, seasons or years). Second, it is worth pointing out that MA_j and AA_j calculations exclude both the absences occurring prior to the first appearance of the species in the dataset, and the absences occurring after the last occurrence of the species in the dataset, because it is important to remove absences that are not meaningful or misleading. Third, it is necessary to underline the key influence of sampling design on HAI calculation. Two species drawn from different assemblages may be associated to different HAI values if the two fish assemblages are sampled according to different designs. As a result, when sampling design differs, our index should never be used to compare species habitat association levels.

The more present a species is, the lower its HAI tends to be. Besides, the intensity of the relation between HAI and occurrence rate differs between the less present and the most present species. A reference to two logical assumptions enables to justify theoretically a deeper look at this pattern difference: first, the resident and the transient species constitute the two extremes of a continuum; second, the two extremes of

a continuum are expected to display the most distinctive patterns (i.e. to display the maximum level of differences). As a result, amongst all the possible ways to classify species into two groups, looking for the combination offering the maximum difference between groups with reference to the relation HAI-occurrence rate may enable to distinguish resident from transient species. In order to highlight this particular combination, the following method is proposed: first, all the possible combinations to classify the occurring species into two groups are considered (minimum species number per group = one); second, for each combination, a multiple analysis of variance (MANOVA) is performed to test the effect of grouping species (fixed factor) on both occurrence rate and HAI (dependent variables). This effect can be easily assessed through the p value associated with the Pillai's trace. If significance appears (i.e. if the linear model is enhanced by introducing the variable "groups"), it indicates that the assemblage sub-division is meaningful; third, in order to highlight the particular combination which provides the most different groups with reference to the relation between HAI and occurrence rate, this study focuses on the partial η^2 associated to the Pillai's trace and looks for the one closest to 1, as a partial η^2 indicates the weight of this difference in the model beyond its simple statistical significance. The reliability of this three-step method is demonstrated by applying it to two different datasets (collected in Yamagata prefecture and Okayama prefecture respectively) and comparing the result with the result obtained by plotting persistence against maximum abundance (Boisnier et al., 2009).

IV. Can marine artificial reefs effectively replace lost natural marine habitats?

Various artificial reefs were deployed in Funakoshi bay in the 90's. This study focuses on the assemblages associated with small structures (triangle-shaped concrete blocks whose volume equals about 6 m^3) which lie in the Southern part of the bay, at a depth of about 2.5 to 3 meters. Three species (*Sebasticus marmoratus* (Cuvier, 1829), *Pagrus major* (Temminck and Schlegel, 1843) and *Ditrema temminckii* (Bleeker, 1853)) were spotted as resident at both sites. The species similarity level (SSL) observed fluctuated significantly according to the reference. Hence, if the total number of species caught is used as a reference, the number of fish species common to both sites is clearly weak (always inferior to 50 %) and can even drop to levels as low as 20 %. Conversely, if we focus exclusively on the three resident species, the SSL equals 100 % throughout the entire period, indicating a perfect similarity between the two assemblages. This result clearly show that marine artificial reef are able to mimic surrounding natural reefs so efficiently that resident species becomes strictly identical at both site.

Numerous artificial reefs have been deployed off Okayama city in the last decade in order to provide alternative habitat to *S. marmoratus* whose natural habitat has been severely reduced. Different types of reefs have been built: from tiny reefs (the smallest is the "model 1.0" with a volume of 3.125m^3) to huge structures such that the "model 10.0" with a volume of 646.4m^3. It is worth wondering if all these structures are equally suitable for this particular species. Four different designs were compared ("models 1.8, 2.2, 6.0 and 7.0"). While *S. marmoratus* was recorded along the four reefs, it only became resident in a single case, suggesting that the "model 6.0" is closer from the *S. marmoratus*' natural habitat than the three others. This is consistent with previous studies and suggests that if artificial reef may effectively replace lost natural habitats, its efficiency will be related to the degree of structural similarity with the natural habitat.