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Basic Principles Underlying Research Projects on the Links between the Ecology and the Uses of Coral Reef Fishes in the Pacific

Michel Kulbicki¹, Pierre Labrosse², and Joceline Ferraris¹

Introduction

Pacific island countries cover a very wide geographical area, spanning more than 10,000 kilometres from west to east. This region is the most diverse in the world for shallow water marine life, a characteristic due in large part to the presence of its extensive coral reefs. There are well over five thousand fish species known to date in this area, of which several hundred have not yet been described. This diversity is reflected in the number of coastal organisms of human interest in this area, as well as by the variety of the uses of lagoon and reef fishes or invertebrates (Dalzell et al. 1996). In most Pacific island countries, the catch coming from coastal resources is used mainly for subsistence. This contrasts with offshore fisheries, in particular those for tuna, which are essentially market driven (Gillett and Lightfoot 2001). Because of the low monetary exchange that these coastal resources generate, little attention has so far been given to their management.

Most Pacific island states are facing dramatic increases in their populations. This is resulting in many anthropogenic effects on coastal ecosystems and deep modifications of the socio-economic conditions of human populations, such as a crowding of the metropolitan islands, a decrease in the population of the islands most distant from the major cities, and profound changes in social structure. At the same time, the influence of the market economy is increasing, due in particular to demand for fish products from urban areas and the export of fisheries products to the Asian market or to emerging markets (Dalzell et al. 1996; Sadovy and Vincent 2002). The impact

of the market economy is also felt by the introduction and use of increasingly efficient, and at times destructive, gears (Dalzell et al. 1996) and by the decrease in some places of subsistence fishing. On the other hand, subsistence fishing, as previously mentioned, remains a major source of food for large groups within these populations (Gillett and Lightfoot 2001). Subsistence uses are usually in conflict with monetary uses of coastal resources. As coastal resources are a major source of protein for Pacific island populations, these new monetary uses of resources not only result in increased ecological stress, but threaten food security and change feeding habits. In the coming years, drastic changes in resource levels and their uses are probable and in great part dependent on the population level. Figure 6.1 shows the type of variations one may expect.

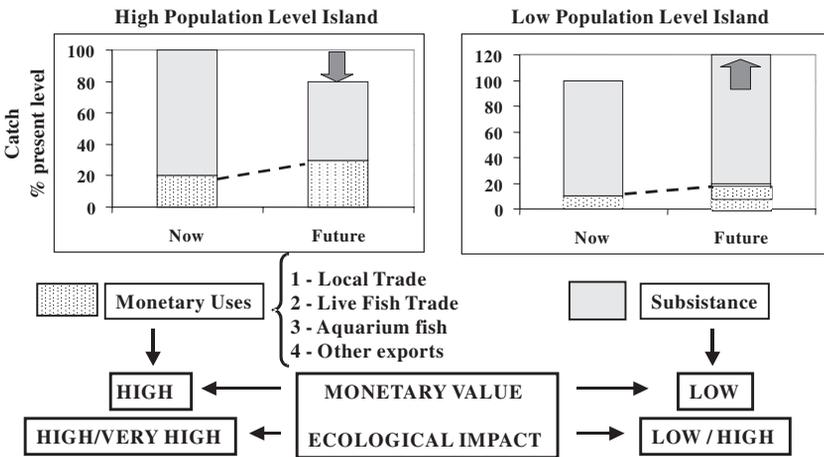


Fig. 6.1. Example of expected evolution of the uses of coastal marine resources in Pacific island countries in the near future.

In this scenario, monetary use of coastal resources would increase most in the populated islands where comparatively larger perturbations of the environment are expected. This could bring lower fish yields in weight even though the monetary value might increase substantially. The decrease in subsistence uses could happen in tandem with changes linked to resource availability, time spent on fishing, new consumption habits, and the availability of non-traditional marine products, like canned and frozen fish. On islands with low popu-

lations or on islands far from the metropolitan areas, it is likely that total catch will increase as a result of an increase in labour and better fishing gear, but the total financial income will remain the same or increase only slightly because of their low connection to the market economy. An increase in catch would only be possible if the resources were not initially exploited at their maximum level. The ability of island populations to sell resources for money will vary widely, depending on factors such as accessibility of the resource, distance to markets, and the availability of local infrastructure such as airports, ports, roads, and storage facilities. The present scenario is of course not unique, but it reflects some of the issues Pacific island states are facing.

This situation necessitates more and better management of coastal ecosystems and their uses (Maragos and Crosby 1996; Crosby et al. 2002). However, Pacific island countries do not usually have the means to conduct sophisticated surveys of their resources and of their uses or to follow intricate management schemes. Even when they do, it is of paramount importance to have solutions which are accepted by local populations (Crosby et al. 2002). Solutions have to be understandable at all levels and easily applicable. Therefore, in order to manage coastal resources, it is necessary to identify solutions that will produce efficient, yet simple, management tools. As the ecosystems supporting these coastal resources are extremely complex and their uses multiple (Dalzell et al. 1996) there is an antagonism between, on the one hand, finding ways to simplify data collection and interpretation and, on the other hand, taking into account the complexity of this environment. The present article investigates the theoretical background underlying potential applications of several current research projects dealing with these coastal resources and their uses. In particular, we will attempt to bridge information coming from ecology with social and economic studies of fisheries. In other words, this is an endeavour to use information on the composition and functioning of whole assemblages with information on the catch (species, level, sizes). It is very important to note that the present article is mainly hypothetical, most of the ideas presented being currently tested by several research programmes but not yet fully assessed.

General Conceptualisation of an Ecological Approach to Pacific Island Fisheries

Pacific countries are archipelagos with a limited number or no large (more than 2,000 km²) islands. From an ecological point of view, these systems are subject to limited outside influences. These include, for instance, the fact that many species have exchanges with nearby islands only through larval colonisation, this phenomenon being itself irregular through time (Doherty 1991). Similarly, most of these islands are isolated socially and economically, as exchanges with other islands are few and often lopsided, with the capital island generally acting as a magnet for people and resources. It is therefore possible to consider, as a first assumption, that these islands are isolated systems from both an ecological and a socio-economic point of view (fig. 6.2). This does not mean that these systems have no exchanges with the outside world, but that these exchanges are limited and in most part measurable with a reasonable accuracy and a limited effort.

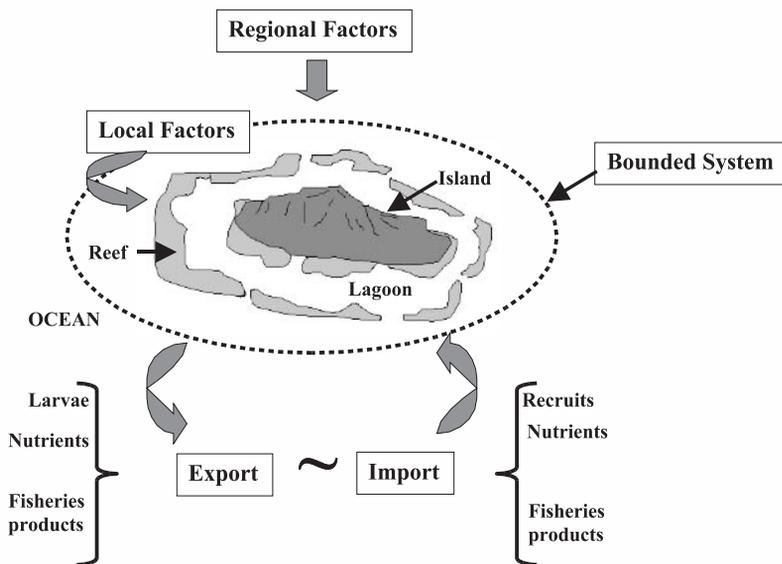


Fig. 6.2. Islands as semi-closed systems from an ecological and socio-economic standpoint.

These basic features make Pacific islands ideal field laboratories to test a number of hypotheses linking resources levels with the ecology of the resources and the uses to which they are put. Indeed, the very large number of islands (thousands, amongst which several hundred are inhabited) makes it possible to look at a range of islands according to criteria such as island size, island type, population level, and distance to the capital island. This potential for an experimental approach based on an analytical design of both ecological and human factors is quite unique in the maritime world.

The status of the resources on a given island is influenced by two major types of factors: regional and local. Regional factors give a general setting to the resources. For instance bio-geographical region, island size, island type, and distance to the nearest island may be considered as regional factors. Local factors will modify, sometimes considerably, the action of the regional ones. One may cite biotope, depth, pollution, fishing level, and climatic events as such local factors. The combination of these local and regional factors determines the nature and the abundance of resources. In order to follow an analytical design, each of the factors one wishes to study will need to have several classes or levels. For instance, island size could be differentiated into small, medium, and large. The number of possible combinations will depend on the number of factors and the number of levels within a factor. In turn, the models subsequently built from this analytical approach will be limited in their precision and predictability level by the number of factors and levels considered as well as by the number of observations per factor and level. In this type of approach there is therefore necessarily a trade-off between the level of precision required from the models and the quantity of fieldwork it is possible to accomplish.

This modelling, or *ecosystem approach*, has several objectives:

- a. To evaluate what can be attributed to uncontrollable *versus* controllable factors in the observed structure of reef fish communities. In particular, to evaluate the impact of fishing on the structure and functioning of reef fish communities;
- b. To give an indication, based on a minimum of easily available information, of the resource potential of a given island or area;
- c. To indicate, within the above resource potential, if one or more group(s) of species is, or are, at risk or, on the contrary, can be further exploited;

- d. To identify habitats or biotopes which may play a particular role in the functioning of these communities.

This approach intends to take into account simultaneously the fish communities, their environment, and the use to which they are put. For the determination of use we will be more interested in exploitation levels and consumption rather than more traditional catch and effort data, as the latter are extremely difficult to assess in artisanal fisheries.

The following overview of our current knowledge of the ecology and fishery of coral reef resources suggests that this ecosystem approach may meet a number of the expected management objectives of Pacific island countries.

Material and Methods

As social and economic studies of fisheries and ecology tend to attribute different meanings to the same word, we wish to give the following definitions for the present article:

Regional diversity: number of fish taxa occurring in a given region;

Regional or Island species pool: list of all the species occurring in a given region or island;

Local Diversity: number on fish taxa on an island, usually restricted to a given biotope (e.g. reefs) and to a particular sampling method (in our case underwater visual censuses – UVC – unless otherwise stated);

Species Density: number of species per unit of observation. All species densities will be expressed in terms of the number of fish species per 50 m transect;

Fish Density: number of fish per unit of area. Here densities will be expressed as fish /m²;

Fish Biomass: weight of fish per unit of area. Here biomasses will be expressed as grams of fish /m²;

Fish stock: cumulated weight of fish over an area. Here stocks will be expressed in tonnes;

Fish meta-community: community represented by all fish species existing in a large area (region, island, or part of an island) encompassing several habitats. Meta-communities will usually be defined for a given biotope as, for example, reef fish meta-community.

Reef fish live in clear and warm waters. Most of the species exploited for subsistence fishing live in relatively shallow waters. These characteristics allow for the survey of these fish communities by underwater visual censuses (UVC). This method has many advantages. In particular, it is non-destructive, which allows for unbiased time replication; it records a large number of species in a limited amount of time; it records habitat characteristics simultaneously (particularly coral and algae cover); and it records size and behaviour easily. UVC sampling allows for the estimation of species density, fish density, and fish biomass as well as the size distribution of the most abundant species. These estimates, combined with information on the diet, size, range, and behaviour of fish species enable us to study the structure of reef fish communities and their variations with a number of factors. In this presentation we will use results from transects that we conducted in several island-states of the Pacific, along with results from transect work found in the literature (Appendix 6.I, Table 6.1).

Ecological Framework

This ecological framework is built on the existence of relationships between parameters of fish communities such as species density, density or biomass at different spatial scales (see Peterson et al. 1998 for the importance of scale). These relationships are then considered with respect to the properties of fish communities such as stability, resistance, and resilience, which are of particular interest for their management.

Relationship between Regional and Local Diversity

Our first hypothesis is that local diversity strongly depends on the number of species found in the region (Hillebrand and Blenckner 2002). The link between regional and local diversity being influenced in particular by factors such as island size, distance between islands, and distance to the centre of biodiversity (Bellwood and Hughes 2001).

The coastal fish fauna found in the Pacific islands has several important characteristics. First it is the most diverse fish fauna in the marine world with more than 5,700 taxa known to date in the 0-100

m depth range. Among these taxa, more than 3,000 are associated with reefs. As a comparative example, the most diverse fish fauna in the Atlantic, the fish fauna of Caribbean reefs, totals less than 500 species. The second characteristic of this fish fauna is the important gradient in regional diversity as one goes from the biodiversity centre of this fauna, located in the Philippines-South China Sea-Indonesia triangle, eastward towards Polynesia (fig. 6.3).

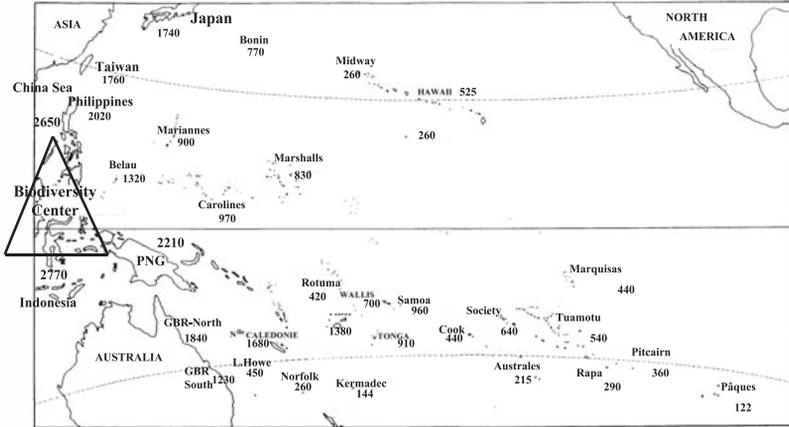


Fig. 6.3. Distribution of coastal species (0-100 m) in the tropical Pacific. References and data available from the first author on request.

This decrease is greatly linked to the increasing distance between islands as one goes eastwards, as well as to the size of the islands which are smaller and smaller on average on this west-east gradient (Kulbicki and Rivaton 1997; Bellwood and Hughes 2001). If both distance and island size are combined it is possible to estimate the potential number of species of an archipelago from these two factors with a reasonable accuracy:

$$\text{Number of Species} = 336 - 0.026 D + 99.9 T \text{ with } r = 0.84 \text{ (} N=54 \text{ and } p < 0.00001)$$

D: Distance to Biodiversity Center in km
T: Island Size on log scale

It is often interesting to classify fish species according to criteria such as their family, genus, size, or trophic status. Grouping by fam-

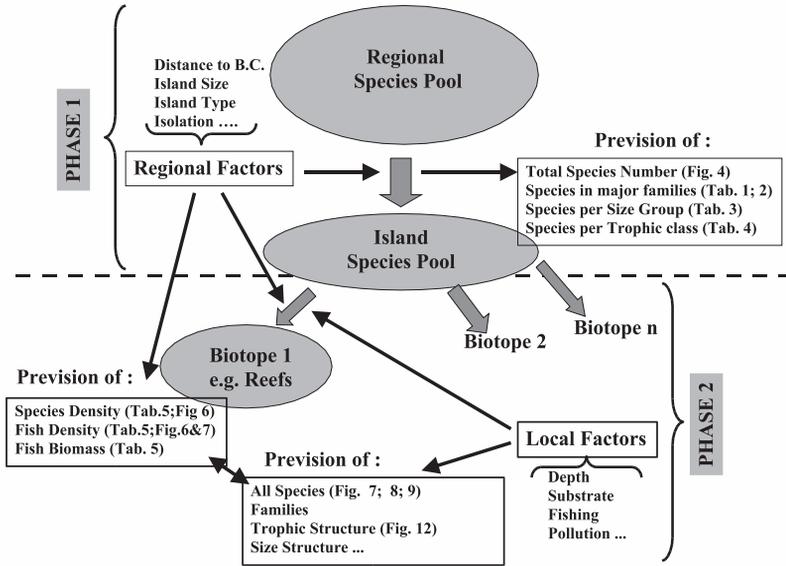


Fig. 6.4. Ecological framework proposed for the analysis of reef fish communities of tropical Pacific islands and the development of management tools.

ily or genus is usually done because within a family, and more so within a genus, species usually share many biological and ecological characteristics, such as size, behaviour, diet, and reproductive strategies. Classifying fish by size may be interesting from an economic point of view as usually the largest species are those which are the first targeted by fishermen and they are often also the most vulnerable. There is also usually a strong relationship between size and abundance, the smallest species being the most abundant. To classify species according to their diet may give important insights into the functioning of fish communities. An analysis of the relationship between regional and local diversity for these various classes shows that for the family level (Appendix 6.II, Table 6.2), the genus level (Appendix 6.II, Table 6.3), the size distribution (Appendix 6.II, Table 6.4), or the trophic structure (Appendix 6.II, Table 6.5) one finds significant correlations with distance to the biodiversity centre and to island size.

In other words, from our current knowledge of the distribution of fish species across the Pacific, from only two regional factors it is possible to make a first evaluation of the characteristics of the species one should find on a given island (fig. 6.4). Of course such a result can be greatly improved by adding to the model other regional factors

such as distance between the islands, the island type, and the reef to land ratio. This modelling corresponds to *phase 1* in our ecological framework (fig. 6.4).

Relationship between Diversity and Other Parameters of the Fish Communities

Once we have established the relationship between the species pool of an island and some regional factors, one may consider the *second phase* of our approach (fig. 6.4). This phase aims at relating the *combined* effects of these regional factors with local factors on specific fish communities. Specific fish communities in this case are defined as belonging to a given biotope within an island. One notices that a restricted number of factors may explain a very high proportion of the variation. This is common to other ecological models (Côté and Reynolds 2002), the usefulness of which depends on how easily the necessary information may be gathered.

A specific fish community may be characterised by a number of parameters, the most frequently used being its species density (species/sampling unit), density (fish/m²) and biomass (g/m³). There are clear relationships between the species pool of an island and these parameters as illustrated for species density (fig. 6.5a) and density (fig. 6.5b).

This means that it is possible to relate these parameters of fish communities directly to a number of regional factors. We are developing a statistical model relating species density, density, or biomass of given types of reef fish communities (barrier reefs in our case) to regional factors. The modelling is in its initial phase as it includes only 4 factors: island size, the distance to the bio-geographical centre, length of the coastline, and island type (Appendix 6.II, Table 6.6). This preliminary model indicates that the species density and density or biomass found on barrier reefs on an island are linked to the general characteristics of this island. Despite the fact that this model yields highly significant results, it still leaves a very high margin of error. The major reason for this is that local factors are not included.

The number of combinations of the various levels of regional and local factors is nearly infinite. Therefore, it is necessary to find which factors are the most important both on a regional and local basis. One way to explore how these factors affect fish communities is to keep constant as many factors as possible and have only one factor

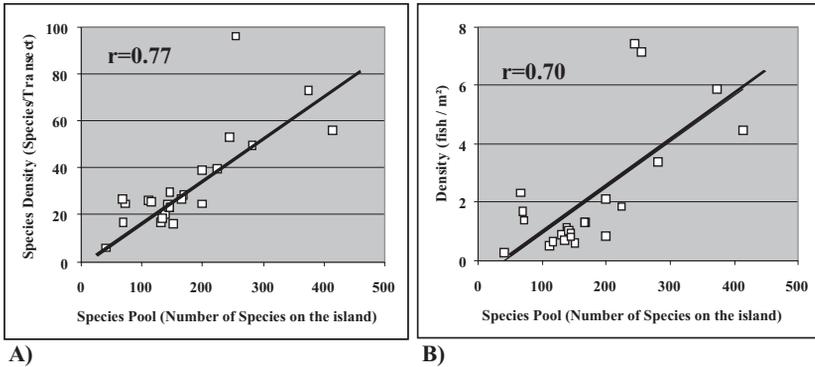


Fig. 6.5. Relationship between local diversity (number of fish species detectable by UVC) and species density (3A) (average number of species per transect) or density (3B) (average fish/m²). Each point represents the average of at least 20 transects on an island. N = 24 islands (references of data Table 1). Results are similar ($r=0.768$) for biomass (g/m²).

fluctuate. This is unfortunately very difficult to achieve, as the number of factors is very high. For instance, fishing pressure is among the most important local factors (Jennings and Kaiser 1998). In order to test its action one would need to compare fish communities from a given reef type on islands from different regions but of similar size, and type. Fortunately the problem is partly reduced by focusing on relationships linking regional and local diversity to species density; and on relationships between species density and other fish community parameters, in particular density and biomass.

Species extinction or extirpation (local extinction) is rather exceptional for coral reef fish (Jennings and Kaiser 1998; Hawkins et al. 2000), affecting only rare species, and it is unlikely that local factors will induce much change in the species pool. In contrast, fishing pressure is well known to decrease local species density (Jennings and Kaiser 1998). As can be observed in figure 6.5a, the local species pool will greatly determine the species density for a given reef type. Such a result is generally acknowledged in ecology (Hillebrand and Blenckner 2002). For a given set of local factors, species density will in turn determine in great part density (fig. 6.6a) and biomass (fig. 6.6b).

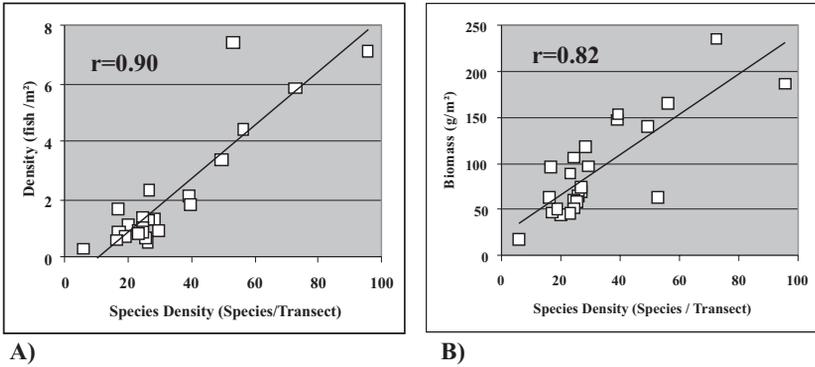
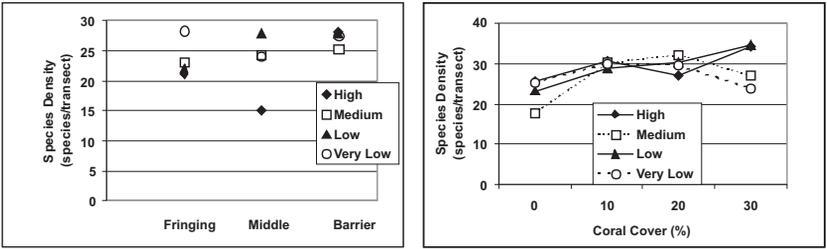


Fig. 6.6. Relationship between species density (average number of species per transect) and observed density (A) (fish/m² on transects) or observed biomass (g/m²)(B). Each point represents the average of at least 20 transects on an island. N = 24 islands (references of data Table 6.1)

The relationships between species density and density or biomass are expected to be influenced by local factors, of which biotope, fishing pressure, and depth are particularly important. We developed the hypotheses that for a given set of regional factors:

1. Species density will vary little with fishing pressure for a given set of local factors.
2. The relationship between species density and density, or biomass, will depend on fishing pressure (Jennings et al. 1998), when all other local factors are set.

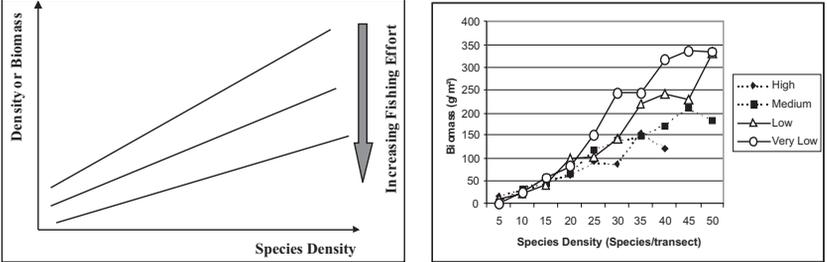
To test the first hypothesis we need to find how species density will vary according to local factors, once regional factors are set. The literature and our own data show that species density will vary with local factors such as coral cover (Bell and Galzin 1984; Roberts and Ormond 1987), algae cover (Rossier and Kulbicki 2000), depth (Luckurst and Luckurst 1978; Friedlander and Parrish 1998), oceanic influence (Grimaud and Kulbicki 1998), type of reef (Williams 1991; Kulbicki 1997) and combinations of these factors (Friedlander and Parrish 1998). However, little is known on how fishing pressure may intervene in these relationships. Fishing pressure is likely to influence local factors such as coral cover or algae cover and therefore indirectly affect species density. Available data from New Caledonia (fig. 6.7) suggest that fishing pressure, within the range available in



A) B)
 Fig. 6.7. Variations of species density with reef type (A) or coral cover (B) according to four levels of fishing pressure (Very Low to High). Data are for commercial reef species in the Northern Province of New Caledonia (Labrosse et al. 1999).

that data set, has little influence on the relationships of species density with other local factors such as reef type or coral cover.

While relationships resulting from the second hypothesis may in general look like figure 6.8, opposite trends can also be expected. In particular, increasing fishing pressure on piscivores may favour higher densities of prey species (even though this is seldom observed – Cury et al. 2002; Pauly et al. 2002).



A) B)
 Fig. 6.8. A) Expected relationship between density or biomass with species density for increasing levels of fishing effort; B) observed relationship between biomass and species density of commercial reef fishes for increasing fishing levels (from Very Low to High) based on data from New Caledonia (Labrosse et al. 1999).

Structure of Fish Communities

The last step in this ecological approach to local fish communities is to look at their structure. Amongst the many traits structuring a community, three are particularly important in regard to the functioning

of the community: diet (Pauly et al. 2002), size (Peterson et al. 1998) and home range (Peterson et al. 1998; Jennings and Kaiser 1998). This type of information is available at a crude level for most species known from Pacific island reefs and lagoons and can thus be included in statistical models, which estimate species diversity according to regional factors (see Appendix 6.II, Tables 6.4, 6.5). One may therefore probably estimate with a reasonable precision the trophic, size, or behavioural structure of a reef fish community from a limited number of regional and local factors. The latter do indeed also play an important role in determining the type of species which will constitute a given community. Consequently, it should be therefore theoretically possible to build a statistical model that shows the structure of a fish community at the species level for a given reef of a given island.

The next question is whether this structure can be linked at the species level to the structure in terms of density, biomass, or even production³ (at present our lack of information on the biology of reef fishes prevents any good estimate of production). This is likely to be a very difficult task since species density is not the only factor driving density, biomass, or production of a fish community. We are presently thinking of testing whether the relationships between species density, density, and biomass, within a given set of regional factors, can be estimated from a limited number of local factors for at least some particular groups, for instance herbivores, large species, or sedentary species. Preliminary results lead us to think that such relationships can be established at least in some cases. We will illustrate this with an example from French Polynesia (fig. 6.9). The reef fish communities from the lagoons of ten atolls were surveyed. The atolls had been chosen according to two gradients: size and degree of opening to the ocean. A statistical model based on General Linear Model (GLM) allowed for the estimation of values of species density (noted as *species* in fig. 6.9), density, and biomass for several trophic categories. This model yielded results for three classes of atoll size (a regional factor) and three levels of hard bottom (a local factor). The figure indicates that there are important trends in the trophic categories according to these two factors. It is not so much the specific results shown in figure 6.9 which are of interest here, but the fact that this type of modelling could be developed for a number of situations. One of the goals of our programmes is to model the trophic structure of fish communities according to the region, the island size, the island type (as regional factors), and according to biotope and fishing level

(as local factors). Graphical representations like figure 6.9 would be generated by this modelling and could assist our understanding of the functioning of these fish communities and how they may be managed.

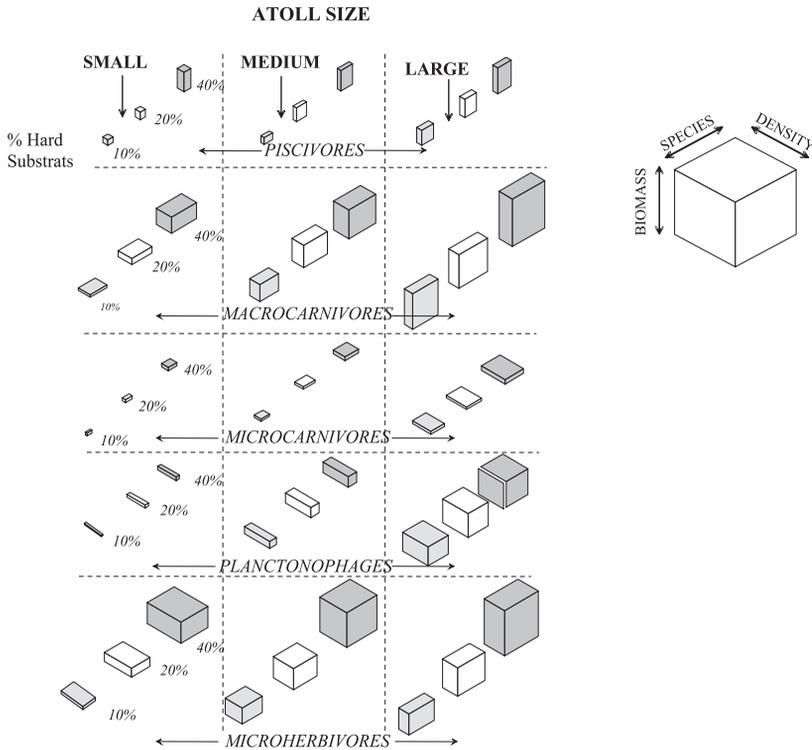


Fig 6.9. Example of a statistical modelling of the trophic structure of reef fish communities. For each 'cube' the vertical dimension represents the biomass (g/m^2), the horizontal dimensions giving the species density (species/transsect) and the density (fish/m^2) as indicated on the separate diagram. The dimensions of the 'cubes' are proportional to the highest value estimated for all situations. Two factors are tested: atoll size (small, medium, and large) and hard substrate cover (10, 20, and 40 percent). Based on data from 10 atolls of the Tuamotu archipelago (French Polynesia) (Kulbicki et al. 2000). Note the importance of herbivores in all cases, the increase of plankton feeders and macrocarnivores with atoll size, and the general increase of species density, density and biomass with hard substrate level.

The Functioning of Fish Communities

Models might yield estimations for species density, density, biomass, or even production, of whole fish communities or for some particular groups within these communities. As demonstrated further, these data can be used in a pragmatic way with a limited theoretical background. However, they could be used even more effectively if they were placed within a framework explaining the possible role of these various parameters in the functioning of the fish community.

At the moment the theoretical background linking these parameters to the functioning of a community is rather tenuous. Most theories are based on diversity and more recently on abundance (Rice 2000; Hubbell 2001; Cury et al. 2002), but very little deals with biomass or production even if these parameters are at times implicit.

From a management point of view, one aim is to harvest as much of a resource as possible without jeopardising it. In such instances it becomes important to consider three parameters of fish communities, stability, resistance, and resilience (see Peterson et al. 1998 for a general review and McClanahan and Polunin 2002 for a review specific to coral reefs). Current theory suggests that these parameters are greatly linked to diversity as indicated hereafter (McCann 2000). Fish communities may be thought of as entities with their own functioning dependent on the properties of each species belonging to this community. However, each species does not have the same importance in the functioning of the community (Cury et al. 2002), some species being more important than others because of specific behavioural, biological, or ecological traits, or because of their density, biomass, or productivity. Species may be gathered into functional groups, a group being defined as all the species having similar biological, behavioural, and ecological traits within a community. For instance in a coral reef fish community one could consider the functional group of small, territorial, and sedentary coral feeders. The diversity of a functional group will change with a number of factors that are not only regional but also local. Another important point is that most functional groups will have a dominant species, often called *driver* species. These driver species will change from place to place and through time within a given place. In other words, the function will be maintained but the rank of the species within a functional group may change with a number of factors (Peterson et al. 1998). A given species will often participate in several functional

groups as it grows. For instance, very small parrotfishes tend to eat small benthic organisms, but as they grow they will switch to herbivory. Therefore they belong first to the category of the small, mobile, schooling microcarnivores, then switch to the category of mobile, schooling herbivores. Some communities are also characterised by *keystone* species or functional groups (Cury et al. 2002). These keystone species or groups may have a tremendous impact on the parameters or the structure of the fish community. For instance, urchin predators can be a keystone group in some tropical fish communities (McClanahan and Shafir 1990). These fish will control the urchin densities which otherwise tend to proliferate and eat most of the algae. In turn the algae level will control the herbivorous fish level which themselves are preys of the piscivores. However, it is important to notice that the role of drivers and keystone species is likely to decrease with the diversity of a community (Peterson et al. 1998).

There are several definitions of stability for a community (McCann 2000). One of them is to consider that a stable community is one for which the densities do not change much over time. Theoretically, stability will increase with diversity (fig. 6.10).

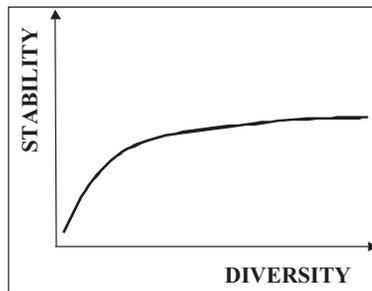


Fig. 6.10. Theoretical relationship between species diversity (e.g. species /transect) and fish community stability (inverse of the variability over time of density or biomass) (Peterson et al. 1998).

This can be illustrated by an example for several lagoon fish communities from New Caledonia (fig. 6.11) for which short-term stability (less than 3-year periods) increases along with diversity (measured by species density). Therefore, factors promoting diversity should also promote stability (see Peterson et al. 1998 for a review on the stability-diversity debate). Stability is an important parameter of fish communities as it plays a major role in the response of these communi-

ties to disturbances. For instance, in a stable system, fishing will usually need to be at a higher level than in an unstable system in order to induce irreversible changes in the fish communities of these systems.

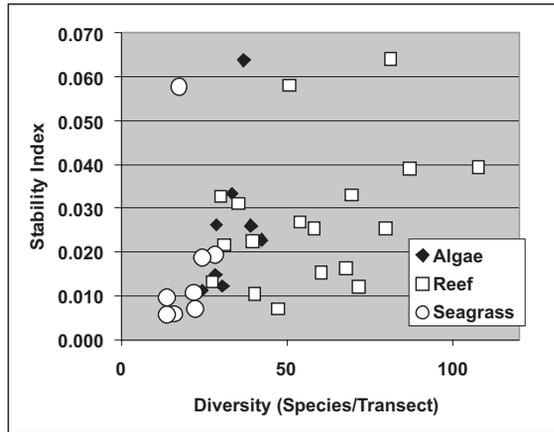


Fig. 6.11. Relationship between fish species diversity and a stability index (inverse of the coefficient of variation of the density over time) for three fish communities of New Caledonia (Labrosse et al. 1999).

Resistance and resilience depend very much on the biological and ecological characteristics of the species involved. Typically, species with short life cycles, high mortality rates and high reproductive efforts are more resilient and less resistant than species with long life cycles, low mortality rates, and late reproductive effort. Therefore, the relative proportion of these species within a community will determine in part the resiliency and resistance of a community to perturbation. In general (Hillebrand and Blenckner 2002), the ratio of long-living (large) species is thought to increase with the number of species (see fig. 6.12). Therefore, one would expect that fish communities with higher species diversity should tend to be more resistant to perturbation, but less resilient. In other words, if for instance a species rich community is submitted to high fishing pressure, it is likely to resist longer than a community with less species, but once this species rich community starts to be affected by fishing it will need a longer time to recover. However, we need to test if this relationship between species diversity and resistant-resilience can be estimated from a limited number of regional and local factors.

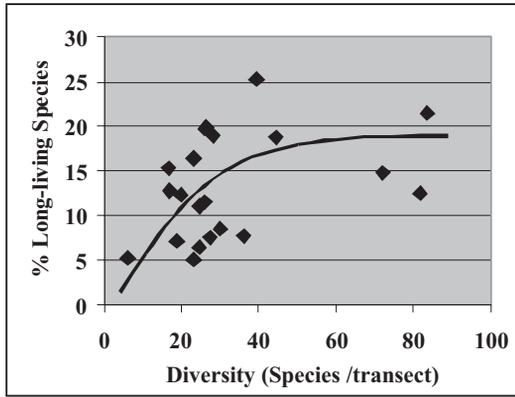


Fig. 6.12. Relationship between diversity and relative importance of long-living species. Each point is the average for an island. N = 20 (references of data Table 6.1)

It is possible to outline the dominance of driver species by using rank-abundance plots (Hubbell 2001). Functional groups with driving species will have steep curves (fig. 6.13a,b), whereas functional groups without such driving species will tend to have flatter curves. This has implications for both the management of these groups and their uses. Groups with steep slopes in their rank-abundance relationships will probably be more resilient and less resistant to exploitation than groups with weak slopes (given that their life-history strategies are similar). On the other hand, from a fisherman's point of view, it could be more interesting to have a steep slope as the number of species entering the catch is limited and consequently easier to target and market.

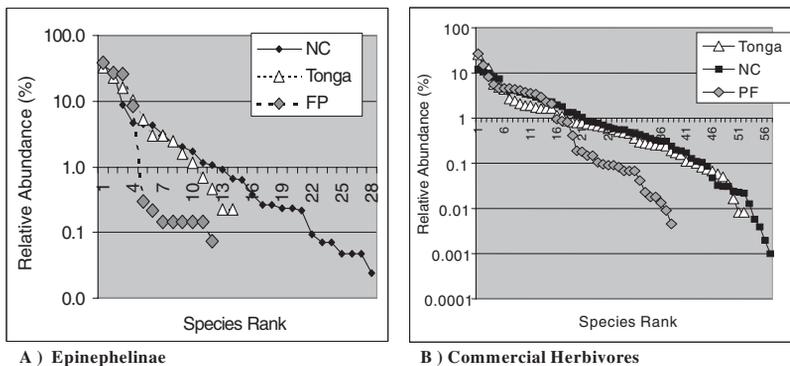


Fig. 6.13. Relationship between relative abundance (percentages on a log scale) and species ranking in abundance (references of data Table 6.1). NC: New Caledonia ; FP: French Polynesia.

One of the main links between density and biomass in theoretical work is the analysis of size-abundance curves (fig. 6.14) (Dickie et al. 1987; Sprules and Stockwell 1995; Rice 2000). The slope of these curves can be compared to some theoretical fit based on the trophic relationship dominating the community. For instance, communities driven by high primary production inputs should have steep initial slopes. A departure from such predicted features can then be interpreted according to local factors (e.g. fishing effort). Recent developments (Raffaelli 2002; Neutel et al. 2002) indicate that the patterns of the food webs and the trophic structure expressed as biomasses can also be good indicators of the stability of communities.

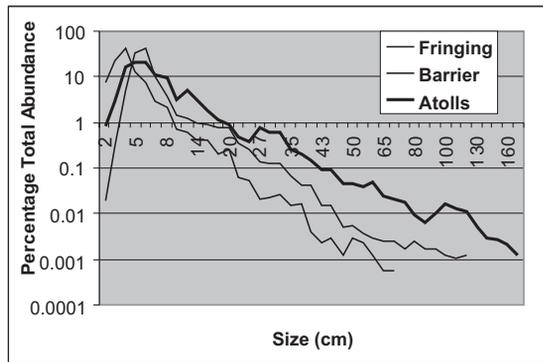


Fig. 6.14. Relationship between relative abundance (percentages on a log scale) and size. Data from New Caledonia (Labrosse et al. 1999).

Fisheries Framework

Reef fisheries in Pacific island countries play a major role in food security and in meeting the need for increased income. In addition to the high species diversity and the wide variety of exploitation types, one of the main characteristics of these fisheries is also represented by the high percentage of subsistence fishing compared to commercial fishing. This situation tends to change slowly as it is linked to the transition from a subsistence economy towards an exchange economy. Thus, Dalzell et al. (1996), considering all Pacific island states together, estimated that around 80 percent of the total catch is represented by subsistence fishing. Subsistence fishing and reef fishing pressure are most often linked to population growth (Russ et al. 1989; Jennings and Kaiser 1998). In recent years, this pressure has

tended to increase in conjunction with the introduction of boats, more efficient fishing gears, and the emergence of new markets. This increase of fishing pressure is often accompanied by a degradation of marine habitat and can lead to overfishing. These disturbances affect both resource characteristics and their users (Johannes 1975; Roberts 1995; Birkeland 1997; Jennings and Kaiser 1998). On a long-term basis, they can threaten the food security of island communities and also affect their sources of income, at the risk of increasing their economic dependence (Anonymous 2000).

Subsistence fishing is at best difficult and most often almost impossible to assess directly, i.e. through monitoring fishing effort and landing surveys. This leads to a general lack of reliable statistics and the impact of this activity is poorly known (Mac Manus 1996). This also makes it difficult to implement relevant reef fisheries management plans (Munro and Fakahau 1993). Despite some attempts (Gillett and Lightfoot 2001), it is also difficult to give a value to subsistence fishing. Indeed, its value lies more in the importance it has for the Pacific islanders themselves, including a cultural value rather than a monetary value. For all of these reasons, obtaining new data on subsistence fishing remains a major concern for managers and decision makers (Adams 1996; Dalzell et al. 1996). Under certain conditions, surveying fish consumption can assist in making indirect estimates of catches due to subsistence fishing (Loubens 1975; Coblenz 1997; Paddon 1997; Labrosse et al. 2000). This can also be used to better understand what the structuring factors of this activity are and then to build indicators of fishing production.

The need for information to better manage reef fisheries is diversely expressed by managers and decision makers. They often still ask for stock estimates and derived parameters, including maximum sustainable yields (MSY). However, these estimates may not be an accurate representation of the real potential, especially in the case of multi-species fisheries (Larkin 1977). MSY values should not be used so much as absolute representations of potential yields but rather as a means to compare areas and then discuss what can be done in terms of management actions and policies. The accuracy of total stock estimates is linked to the accuracy of biotope surface estimates, the latter being often of very heterogeneous quality. MSY estimates are linked to the availability of biological information, but unfortunately current biological knowledge is poor for most reef species and often not easy to access. Therefore, it is difficult to make reliable esti-

mates of MSY and more widely to apply the population dynamics models that are frequently used for mono-specific fisheries. For these reasons, one may wish to favour the use of parameters independent from capture assessments. For instance, species richness, densities, and mainly biomasses estimated from underwater visual censuses can be used for comparisons between different biotopes or locations. These parameters may also be used in conjunction with catches from experimental fishing which are more rigorous and accurate than catch estimates from surveys (Letourneur et al. 2000). Such catch independent parameters may yield useful indications about the status of the resource in regard to fishing activities.

The lack of information for reef fisheries management purposes forces us to look for more global or ecosystemic approaches in order to assess reef fisheries. These combine both socio-economic and resource aspects, including the status of the habitat, and lead to the development of tools, such as indicators, for more ecologically based management of reef fisheries. This should allow us to respond directly to the urgently expressed need of the managers and decision makers of management and monitoring tools as soon as possible. This should be a basis for collection of biological, ecological, and socio-economic information.

Interaction between the Ecological and Fisheries Frameworks

The ecological and fisheries frameworks need now to be related in order to generate information which can be of direct use to management. To illustrate this we will examine two possible scenarios based on data currently under study. The first scenario is based on the first phase of the ecological framework and the second on the second phase of this framework (see fig. 6.4), each scenario uses ecological and fishery data.

Information at the regional level may be difficult to collect, but it can be very powerful when it comes to making management decisions. In our example (fig. 6.15) we wish to show that depending on where one is in the Pacific, decisions taken regarding the use of resources should be different because fishing potential is different. We know from figure 6.4 and Tables 6.2-6.5 that the number of species available in Polynesia is much lower than in Melanesia. Therefore, if one compares an island of similar characteristics (size, type, popula-

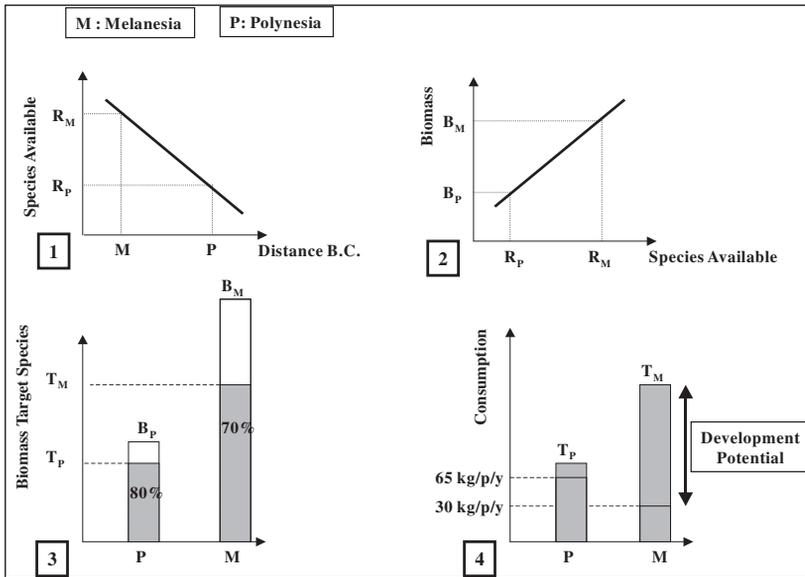


Fig. 6.15. Scenario of comparison between two similar islands from Melanesia and Polynesia.

R_m : number of species on the Melanesian island; R_p : same for the Polynesian island.

B_m : biomass of these species on the Melasian island; B_p : same for the Polynesian island.

T_m : biomass of target species on the Melanesian island; T_p : same for the Polynesian island.

tion level) from Polynesia and Melanesia, the number of species should be much higher in Melanesia (fig. 6.15-1).

Given the relationship between total biomass and species diversity (see fig. 6.6b), one will therefore expect lower biomasses on the Polynesian island (fig. 6.15-2). As fish composition (Randall 1985; Rivaton et al. 1989) and people's feeding habits (Leopold 2000; Poignonec 2002; Yonger 2002) are different in Polynesia and Melanesia, the proportion of the biomass which can be extracted will differ between the two islands (fig. 6.15-3). The fisheries framework indicates that one may consider these islands as more or less isolated systems and that fish consumption is usually a very good indicator of fishing effort. These assessments will indicate the amount of fish consumed in relation to the fish which is available (fig. 6.15-4) and therefore give a good indication of the potential for new develop-

ment. This approach could be very important when considering the potential for the expansion of the live reef-fish trade (Kiribati, Fiji, Tonga), the necessity of increasing lagoon fisheries (Wallis), or the need for coastal resource preservation (Niue).

The second example (fig. 6.16) shows how ecological and fisheries information can be combined to yield useful information for management.

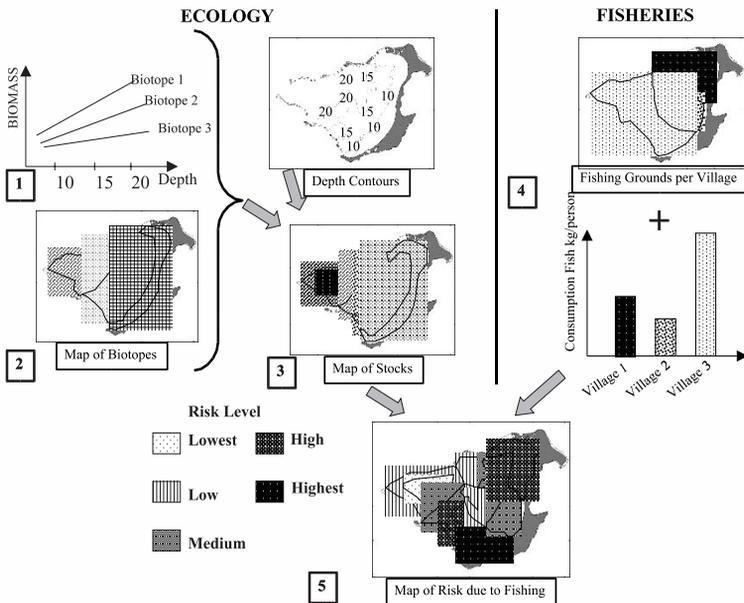


Fig. 6.16. Example of a scenario for the possible interaction between ecology and fishery frameworks to obtain useful information for management purposes.

The atoll of Uvea (New Caledonia) is used here to support the demonstration. On this island (fig. 6.16-1) there is an increase of the biomass with depth (Kulbicki 1995), although this is usually not the case in most atolls. From the analysis of satellite images, aerial pictures and *in situ* verifications (Kulbicki et al. 1993), it is possible to map the major biotopes (fig. 6.16-2). By combining the distribution of biomass with depth with the map of the depth contours it is possible to build a map of the stocks within this lagoon (fig. 6.16-3). Fisheries and fish consumption surveys (Leopold 2000) with the local people may yield crude information on the fishing grounds and the level of

fish consumption (fig. 6.16-4). Combined with the map of the biomasses, this allows the drawing of a map that indicates the level of risk for the resource (fig. 6.16-5). Such maps are not very precise, but they may assist considerably in local management.

These two examples are intended to show that ecological information can be very useful even at a low level of analysis, especially when combined with fisheries information. In order to optimise these ecological and fisheries interactions we need to have solid theoretical foundations (Cury and Cayré 2001; Cury et al. 2002). However, at the moment this is lacking, especially because we know very little about the normal evolution of complex communities exposed to perturbations (Jackson et al. 2001). This lack of theoretical background is expressed by Cury et al. (2002): 'no general theory can be ascribed to the functioning of marine ecosystems, except in the light of the evolutionary theory, which results in poor predictive power for fisheries management'.

Discussion

In the past most fisheries were managed on the basis of single species dynamics or at best on the dynamics of a restricted number of species. Such an approach has proven to be inappropriate in most cases and new approaches are needed (Cury and Cayré 2001). As stated by Pauly et al. (2002), management will 'move towards ecosystem-based management. What this will consist of is not clearly established'. In tropical areas like the Pacific islands the number of exploited species is very important, often more than a hundred in a single fishery, and the variety of the gears used is also high, which requires new strategies to manage fisheries (Crosby et al. 2002). The ecosystems in which these resources evolve are very complex, with in particular a very high spatial heterogeneity. Therefore an innovative approach is needed. This paper indicates two useful directions to pursue by taking into account simultaneously regional and local scales, and the need to further develop pluri-disciplinarity (Bowen 1997; Botsford et al. 1997).

The applications of the frameworks proposed in this paper are mainly designed for closed systems such as islands or lakes. In a continuous system, such as a continental coastline, it is likely that the ecological and fishery situations are far more complex. For instance, consumption is no longer a good indicator of fishing effort, except

maybe in very isolated areas. Similarly, the fish communities are no longer independent from one another.

But even for the type of fisheries where this approach may apply, one may question the feasibility of such an approach. In the ecological framework one may have to consider the regional and the local analytical phases separately. The regional phase supposes the gathering of checklists from as many areas as possible. This is a time-consuming task and requires specialists, in particular taxonomists. At the moment, in the Pacific there are approximately fifty large islands for which such lists exist. The major problems are for the smallest archipelagos in the centre of the Pacific: Gilbert, Phoenix, Line Islands, Tokelau, Tuvalu and also two archipelagos of large islands: Solomon and Vanuatu. Such species lists are not readily available for these areas, even if 'FISHBASE',⁴ an international database created by ICLARM, has lists of species for most countries. In addition, in places like the Pacific, many species are still unknown. These undescribed or unknown species are usually of little economic importance, but in an ecological approach their contribution needs to be evaluated. Nevertheless, the information currently available at the regional level is already sufficient to estimate a number of features of meta-communities. Therefore, for many regions of the Pacific, this regional phase can be considered as already accessible. The connection between the regional and local phases is perhaps where data are the most wanted. There have been numerous surveys of reef fishes across the Pacific in the last thirty years. Unfortunately, much of the initial data has been lost or is very difficult to access. In addition, most surveys have been undertaken using widely varying methods and it is not always possible to compare results between surveys and to use data from different surveys in the same analytical context. This points to the great need for standardised methods. There have been numerous attempts in the past to do so (English et al. 1997; Cappo and Brown 1996), but with little success on a regional basis, mainly because there was no global scheme to use as a frame for these methods. With these problems in mind, SPC (an international organisation working for the development of Pacific island States) is currently trying to standardise such methods in South Pacific countries (Labrosse et al. 2001). In order to connect the regional and the local scales we also need more information on the geography of the islands. Basic information such as island size, population density, and area covered by reefs and lagoons is not readily available and often contains many errors. Satellite images may in part answer these

requirements, but they are not a panacea. They are in fact rather poor tools for marine mapping beyond depths of ten metres, at least with the type of images available at the moment.

Despite this situation there are already a number of island-states for which it is possible to make this regional to local connection. These include in particular New Caledonia, Fiji, some areas of French Polynesia, and, soon, Tonga. The research phase at the local level requires recent data which is hard to obtain in most places for two reasons. Firstly there is usually no plan to gather the proper information and, secondly, the staff and finances required are not always available. In this regard, SPC is currently implementing a work plan in collaboration with the fisheries and/or environment departments of most Pacific island states. For the local level one needs data on the biotopes and on the distribution of the species. Together with this field information, ecological and biological data are also needed, but the models which are currently being developed by SPC only require a broad classification of species. One may be interested for instance to know if a species is carnivorous, has a slow or fast growth rate, or forms schools. More detailed information is at this stage not necessary (e.g. seasonal growth variations, changes of diet with biotope). The proposed framework is in some sense the opposite of classical population dynamics because detailed information on the biology and ecology is not the key issue. The important point is to relate the information from various levels from the regional down to the local (Peterson et al. 1998; Langton and Auster 1999) and to stratify the factors that influence the abundance and quality of the resources. The approach we are promoting matches some of the criteria defined by Murawski (2000) in predicting overfishing. In particular, evaluation of biomass and diversity at different levels of organisation and the evaluation of spatial variability are part of our framework. We know that in such a complex environment it is not possible to properly assess the absolute abundance of even a single species. Instead, a comparison of the relative abundance of a species or group of species with what could be expected from the analysis of the regional and local factors is feasible. This level of information is probably sufficient for present management purposes in many islands of the Pacific. However, this does not imply that basic research on the biology and ecology of fish species should not be given priority. For instance, at the moment we do not have the proper data on mortality, growth, and reproduction needed to evaluate production or productivity of

fish communities, but in the distant future this could be the most pertinent parameter required to evaluate the status of fisheries and other human uses of marine resources. Of course any relationship between production and diversity would greatly ease predictive studies since diversity is far easier to measure than production.

Conclusion

As any initial framework, the approach proposed in this paper will need to be refined. Yet, to our knowledge this is the first attempt to connect ecology, fisheries sciences, and economics in order to provide scientific input for the management of insular fisheries. Quite possibly the barrier to management represented by the complexity of coral reef environments can be overcome by this approach. Meanwhile we need to be careful not to re-introduce this complexity by using intricate models, but neither should we oversimplify these ecosystems. There is a particular need in this type of approach to develop tools which can be used by managers in conditions where there is a minimum of appropriate data. The approach should also be based on concepts that local people can understand. Of special interest in areas like the Pacific is the potential to apply such a framework for local community management.

Notes

1. IRD- B.P. A5 – 98848 Noumea – NEW CALEDONIA e-mail: kulbicki@noumea.ird.nc ; ferraris@noumea.ird.nc.
2. SPC – B.P. D5 – 98848 Nouméa – NEW CALEDONIA e-mail: PierreL@spc.int.
3. Production: amount of matter (e.g. fish) produced over a time period, expressed for instance as g/m /year.
4. The FISHBASE data base is available at: www.fishbase.com.

Appendix 6.I

Table 6.1. References to the data sources of transect work used

<i>Countries</i>	<i>Method</i>	<i>Number of islands</i>	<i>Reference</i>
New Caledonia			
Main Island	UVC – rot.	1	Labrosse et al. 1998
Uvea Atoll	UVC	1	
Chesterfields	UVC – rot.	1	
French Polynesia			
Moorea	UVC	1	Galzin 1985
Tuamotu	UVC	10	Kulbicki et al. 2000
Society Is.	UVC	4	Galzin et al. 1994
Tonga			
Tongatapu	UVC	1	Unpublished:
Hapai	UVC	2	SPC- Noumea
Vavau	UVC	2	New-Caledonia
Fiji	UVC	6	Jennings and Polunin 1996
Samoa	UVC	6	Green 1996
Hawaii			
Midway	UVC	1	Schroeder, 1989
Hawaii	UVC	1	Hayes et al. 1982; Brock et al. 1979; Walsh 1983; Wass 1967; Friedlander 1996
Marianas	UVC	4	Molina, 1982; Dobbelaer 2001
Flores	UVC	1	Kulbicki 1997
GBR	Explosives	1	Williams and Hatcher 1983
Wallis and Futuna	UVC	2	Wantiez 2000

UVC: underwater visual census (transect) rot.: rotenone poisoning

Appendix 6.II

Table 6.2. Multiple regression of species diversity versus distance to the biodiversity centre (km) and island size (log scale) (N=50)

	<i>r</i>	<i>Intercept</i>	<i>D</i>	<i>IS</i>
Acanthuridae	0.83***	16.77	-0.000539	3.38
Apogonidae	0.87***	19.15	-0.002529	9.87
Balistidae	0.91***	14.26	-0.001120	4.03
Blenniidae	0.83***	11.97	-0.001288	7.67
Carangidae	0.84***	11.09	-0.001080	5.29
Chaetodontidae	0.90***	24.10	-0.001311	3.46
Gobiidae	0.83***	21.07	-0.004598	23.33
Labridae	0.91***	39.48	-0.002862	12.82
Lethrinidae	0.88***	9.36	-0.000913	2.33
Pomacentridae	0.91***	31.90	-0.003167	11.83
Scaridae	0.85***	13.30	-0.000829	2.92
Serranidae	0.89***	26.23	-0.002545	8.41
Siganidae	0.90***	6.82	-0.000754	1.25
Tetraodontidae	0.84***	7.21	-0.000667	2.68

*** $p < 0.001$. For each family there is:

Number Species = Intercept + Distance (in km) x D + Island Size (log 10 scale) x IS

Table 6.3. Correlation between the relative importance of genera (within the families Labridae, Pomacentridae and Serranidae) and total diversity; multiple regression of the relative importance of genera with distance to the biodiversity centre and land mass. The data are from 18 regions in the Pacific

	<i>Diversity</i>	<i>Distance</i>	<i>Land mass</i>
Labridae	-0.33		
<i>Anampses</i>	-0.056*	0.58*	-0.59*
<i>Bodianus</i>	-0.20	0.33	0.001
<i>Cheilinus</i>	-0.49*	0.09	0.26
<i>Choerodon</i>	0.83***	-0.56*	0.76***
<i>Cirrilabrus</i>	0.77***	-0.38	0.67**
<i>Coris</i>	-0.54*	0.55*	-0.41
<i>Halichoeres</i>	0.81***	-0.72**	0.65**
<i>Thalassoma</i>	-0.92***	0.66**	-0.82***
Pomacentridae	0.64**		
<i>Abudefduf</i>	-0.62**	0.25	-0.75***
<i>Amblyglyphidodon</i>	0.60*	-0.66**	0.48
<i>Amphiprion</i>	0.55*	-0.74***	0.34
<i>Chromis</i>	-0.32	0.53*	-0.24
<i>Chrysiptera</i>	0.66**	-0.45	0.50*
<i>Neopomacentrus</i>	0.90***	-0.61*	0.82***
<i>Pomacentrus</i>	0.85***	-0.60*	0.66**
<i>Stegastes</i>	-0.41	0.57*	-0.39
Serranidae	0.53*		
<i>Cephalopholis</i>	0.18	-0.24	-0.11
<i>Epinephelus</i>	0.19	-0.39	-0.15
<i>Plectropomus</i>	0.61*	-0.51*	0.47
<i>Pseudanthias</i>	0.58*	-0.54*	0.49*

Diversity: Pearson correlation between relative genus importance and total diversity
Distance: Partial Pearson correlation between relative genus importance and distance to the China Sea
Land mass: Partial Pearson correlation between relative genus importance and land mass on a log10 scale
r significant at: * p<0.05; ** p<0.01; *** p <0.001

Table 6.4. Multiple regression of species diversity (grouped by size classes) versus distance to the biodiversity centre (km) and island size (log scale)

	r^2	Intercept	Distance (D)	Island Size (IS)
>10 cm	0.50;***	27.7;***	-0.000032;*	1.17;***
10-20 cm	0.65;***	31.7;***	0.00036;***	-0.77;***
20-50 cm	0.03;NS	28.7;***	-0.00012;NS	-0.031;NS
>50 cm	0.31;***	11.9;***	0.000090;NS	-0.38;***

For each size class there is:

Number Species = Intercept + Distance (in km) x D + Island Size (log 10 scale) x IS

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 6.5. Multiple regression of species diversity (grouped by diet category) versus distance to the biodiversity centre (km) and island size (log scale).

	r^2	Intercept	Distance (D)	Island Size (IS)
Carnivores				
Piscivores	0.36;***	9.76;***	0.00024;***	-0.18;NS
Macro-carnivores	0.21;***	17.1;***	0.00020;*	-0.22;NS
Micro-carnivores	0.16;*	22.8;***	-0.00027;***	-0.21;NS
Herbivores				
Macro-herbivores	0.10;NS	2.95;***	-7.3 10 ⁻⁶ ;NS	-0.11;*
Micro-herbivores	0.33;***	13.1;***	0.00014;NS	-0.55;***
Plankton Feeders				
Plankton only	0.31;***	11.4;***	-6.8 10 ⁻⁵ ;NS	0.46;***
Plankton + invertebrates	0.66;***	7.00;***	-0.00036;***	0.49;***
Plankton + algae	0.54;***	2.73;***	-0.00011;***	0.21;***

For each trophic group there is:

Number Species = Intercept + Distance (in km) x D + Island Size (log 10 scale) x IS

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 6.6. Factors significant in linking diversity, density or biomass of reef fishes to diversity of the species pool in a multilinear regression model

	<i>Diversity</i>	<i>Density</i>	<i>Biomass</i>
Intercept	65.8; <10 ⁻⁶	4.49; 0.0025	105;0.039
Island Size	NS	NS	NS
Island Size (log)	NS	NS	10.4;0.0078
Coast length	0.11; 0.00014	0.013; 0.0012	NS
Island type	NS	NS	NS
Distance to Biodiversity Centre	-0.0044; 0.0015	-0.00037; 0.0031	-0.0063;NS
Total r ²	0.80***	0.74***	0.52***

Island size is expressed either in km², log (km²) or coast length (km), the model keeping the best out of these three expressions. Island type is a qualitative factor (atoll or high island).

Number of Islands: 25. All data for barrier reefs

The first number indicates the coefficient in the regression, the second the p level

NS: not significant; *** p <0.0001

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