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Roberto BARBUTI, Stefano CHESSA, Roberto FRESCO, Paolo MILAZZO

PREFACE

The technological innovation in biology and agriculture often leveraging on innovation in computer science and engineering, pushed forward the process of integration among these disciplines. In particular, information technology (IT) provides common methodologies and tools for the automatic acquisition and analysis of the data that concern the management and optimization of the natural and territorial resources.

In agriculture, applications of IT enable the integration of interventions concerning its sustainability and productivity, by offering methods and tools to monitor, control, analyse and optimize the production while keeping it respectful of the environment. Similarly, the best practices for bio sustainability, for the management of bio-diversity and for the bioremediation of the environment (including soil, water etc…) are also progressively adopting IT, which enable more focused (and thus more effective) applications.

In this context, the conference "Technologies and innovation for sustainable management of Agriculture, Environment and Biodiversity" (TI4AAB), was held in July 2016 at the Natural History Museum of the University of Pisa located in the Calci Charterhouse (Calci, province of Pisa) in order to encourage the sharing of emerging knowledge about the above topics.

In fact, the conference was dedicated to fostering innovative cross-disciplinary research and applications and to stimulating the exchange of strategies and experiences, among academic and company experts from different disciplines (agriculture, biology, computer science and engineering and environmental decision making), in order to encourage a common, interdisciplinary discussion about the adoption and perspectives of IT in modern agriculture, environmental management, biodiversity and bio-sustainability in general.

The conference was held under the auspices of the municipality of Calci, the University of Pisa and of the "Ordine dei Dottori Agronomi e Dottori Forestali". It was also attended and supported by some leading national and worlwide industries, like CAEN RFID, OSRAM, STMicroelectronics, EBV Elektronik, Qprel Srl, AEDIT Srl, EMipiace Srl, and Zefiro Ricerca & Innovazione Srl, and by the Italian National Forestry Authority.

This volume constitutes a selection of the contributions presented at the conference and cover the aspects of innovation in agriculture, biology, and applied information technology. In particular, concerning innovation in agriculture, the paper by Nin et al. studies new soilless cultivation systems for wild strawberry growing in the Tuscan Appennine mountains. The paper by Prisa describes experimental research concerning the use of zeolites in combination with effective microorganisms, in order to improve the quality of olive trees. Finally, the paper by Lombardo et al. describes collaborative approaches to innovation in agriculture (co-generation of technology).

Concerning innovation in biology, the paper by Baldacci et al. describes the results of the preliminary phases of the AIS-LIFE project, which aims at developing aerobiological information systems in order to improve pollen-related allergic respiratory disease management. Still concerning the AIS-LIFE project, the paper by Natali et al. aims to describe the strategy used in AIS-LIFE project, to evaluate daily pollen concentration in the atmosphere produced by many allergic plant species. The use of data and GIS system are shown as an approach to assess allergy risk maps.

Concerning innovation in computer science applied to agriculture and biology, two contributions focus on modeling approaches, and two contributions provide a survey of information technology applied to agriculture and biology. Specifically, the paper by Bodei et al. describes the application of the IOT-LYSA formal modelling framework to a possible scenario of grape cultivation, in order to assess water consumption, and the paper by Barbuti et al. proposes a mathematical model of artificial reefs, in order to study the dynamics of algal coverage and of populations of fish in some Italian artificial reefs. Finally, the paper by Fresco et. al. explores the current challenges and IT solutions in order to realize a digital agriculture framework, intended as an evolution from Precision Farming to connected knowledge-based farm production systems, and the paper by Pucci et al. provides a survey on biologging methodologies for the collection of knowledge about animals' behaviour, making a review of some related common data analysis techniques.

All papers have been carefully reviewed by experts in the specific fields. Here is the list of the reviewers, that we thank for the collaboration.

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Roberto BARBUTI [(*)], Paolo BERNI [(**)], Paolo MILAZZO [(***)]

A MATHEMATICAL MODEL FOR THE STUDY OF THE IMPACT OF SMALL COMMERCIAL FISHING ON THE BIODIVERSITY OF ARTIFICIAL REEFS

Abstract: R. Barbuti, P. Berni, P. Milazzo. *A mathematical model for the study of the impact of small commercial fishing on the biodiversity of artificial reefs.*

Artificial reefs are an essential tool for restoring and maintaining biodiversity in degraded marine areas. They make it possible to prevent trawling and, at the same time, create an environment suitable for restocking of several species of fishes. These submerged structures are compatible with small commercial fishing that could have a negative impact on the biodiversity in the artificial reef environment. Fishing policies should be considered in order to make fishing activities sustainable.

We propose a mathematical model of artificial reefs environments. The model can be used to study the impact of small commercial fishing on the biodiversity of an artificial reef and to predict the effects of different fishing policies. The model is developed on the basis of observations made in two protected marine areas located in central Italy where artificial reefs have been realized.

Keywords: Artificial reef, mathematical modelling, ordinary differential equations (ODEs).

Riassunto: R. Barbuti, P. Berni, P. Milazzo. *Un modello matematico per lo studio dell'impatto della piccola pesca commerciale sulla biodiversità delle scogliere artificiali.*

Le scogliere artificiali sono uno strumento essenziale per la ricostituzione e il mantenimento della biodiversità in aree marine degradate. Esse consentono di prevenire la pesca a strascico e, allo stesso tempo, creano un ambiente adatto al ripopolamento di molte varietà di pesci. Tali strutture sommerse sono compatibili con la piccola pesca commerciale, che potrebbe avere un impatto negativo sulla biodiversità nell'ambiente della scogliera artificiale. Al fine di rendere le attività di pesca sostenibili, bisognerebbe considerare adeguate politiche di controllo.

Noi proponiamo un modello matematico degli ambienti delle scogliere artificiali. Il modello può essere usato per studiare l'impatto della piccola pesca commerciale sulla biodiversità di uno scoglio artificiale al fine di predire gli effetti di diverse politiche di controllo. Il modello si basa su osservazioni fatte in due aree marine protette situate nell'Italia centrale dove sono state realizzate scogliere artificiali.

Parole Chiave: scogliera artificiale, modellazione matematica, equazioni differenziali

INTRODUCTION

An artificial reef is a submerged structure placed on the seabed to mimic some characteristics of a natural reef (Jensen, 1998, Seaman and Jensen, 2000). They are used for coastal management in many areas of the world and for many different purposes (Baine, 2001): for increasing fisheries yield in Japan; for recreational diving in the United States; and for the prevention of trawling in Europe.

Artificial reefs are an essential tool for restoring and maintaining biodiversity in degraded marine areas. On the one hand, they can facilitate restocking of marine organisms. On the other hand, they make it possible to prevent trawling and to promote responsible small commercial fishing. As results, artificial reefs can lead to increased natural high-quality production of valuable fish species and can favour the emergence of new activities linked to the sea and fishing, in addition to the traditional touristic activities offered in the coastal areas. An interesting experience is the application of Artificial Reef for IMTA (Integrated Multi-Trophic Aquaculture) in Aquaculture of Zhangzidao Island (Troell M, *et al.*, 2009).

The process of colonization of an artificial reef consists of a well-known sequence of steps. Initially, there is a phase of engraftment of algae on the submerged artificial structures. Algae are very quickly followed by the settlement of sessile animals and other animals that filter plankton or feed on algae directly. Then, the structures are colonized by some urchins, sea stars, crustaceans and by small predators (e.g. Gobies and blennies) which, in turn, promote the establishment of large predators that are often valuable fish species (sea bass, sea bream, snapper, etc.).

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Small commercial fishing can take advantage of the positive effects of artificial reefs on the valuable fish species. However, for such effects to become persistent, for fishing to become sustainable and for biodiversity to be preserved, it is important to implement policies for responsible management of small commercial fishing. In order to maintain biodiversity in equilibrium with the peculiar environmental characteristics where the artificial reef area has been realized, policies should avoid both the excessive marine area exploitation, and the selection in favor of species subject to much less fishing pressure.

Mathematical and computational modelling can contribute significantly to the understanding and management of ecosystems (Barbuti et a. 2009, 2012 and 2015, Bove *et al.* 2014). In the context of marine environments, models have been used, for instance, to study population dynamics and the impact of fishing in the Adriatic sea (Penna *et al.*, 2013, Corea *et al.*, 2014 and Cini *et al.*, 2015).

In this paper we propose a mathematical model for the study of the environment of an artificial reef. The model describes the dynamics of four populations: algae, invertebrates, small predators and large predators. Each population is described by an Ordinary Differential Equation (ODE) that includes a term describing the logistic growth of the population itself as a function of the carrying capacity of the artificial reef environment. For the populations of small and large predators, the carrying capacity is related with the abundance of available pray. The carrying capacity of invertebrates is instead related with the algal coverage of submerged structures. The differential equations describing invertebrates and small predators include also a term describing their predation by small and large predators, respectively. The model also includes parameters that describe the impact of fishing that, with different instruments, can be practiced on small and/or large predators.

The study of the model by means of simulation methods helps to predict the effect of various types of fishing on the biodiversity of the artificial reef environment. This allows the impact of fishing to be assessed and can support management policies formulation such as the enforcement of rules for fishery resource exploitation, limits on catch or periods of suspension.

The paper is organized as follows: we start by describing how artificial reefs work by using as reference example the activities of marine area protection and biodiversity restoration undertaken in central Italy (areas of Sabaudia and Terracina in the Lazio region) in the context of the project "Mare Nostrum". The experience gained with these activities and the collected data guided the development of the mathematical model. Subsequently, we describe the proposed mathematical model, we show simulation results and we reason about possible fishing management policies. Finally, we draw our conclusions and discuss possible directions for future work.

ARTIFICIAL REEF REALIZATION AND IMPACT ON BIODIVERSITY: EXPERIENCE AND DATA FROM TWO AREAS IN CENTRAL ITALY

Project aims and activities

The Lazio region established in 2007 two marine protected areas in coast in front of Sabaudia and Terracina, respectively, in the context of the "Mare Nostrum" project (Regione Lazio SFOP 2000/2006 e Regione Lazio FEP 2007/2013) in order to facilitate restocking. The two areas use artificial reefs, Tecnoreef®, underwater to counter illegal fishing and promote the attraction of marine organisms (Berni P., 2007a; 2007b). To achieve the above objectives, the design of artificial structures guarantees two fundamental factors. The first one is that they do not allow trawling since they are resistant to shock, breakage and drift. The second one is that they encourage the repopulation through the following effects:

1. promoting a local *upwelling* phenomenon (that favours the distribution of nutrients in the environment);
2. facilitating the development of fouling on the surface of the structural elements;
3. producing a high attractiveness for the fish species (migratory and sedentary);
4. playing the role of nursery;
5. creating a suitable habitat for the reproduction and the growing of several species.

Methodology

The underwater barriers realized with modular structures Tecnoreef®, certificated "sea-friendly" according to the UNI EN ISO 14001:2004 standard for the sector of artificial barriers, pre-assembled by means of bolts of stainless low-carbon steel marine. The structures were lowered into the sea and geo-referenced, to form a reef of *atolls*, of about 250,000 square meters at a bathymetry within 15 and 20 meters of depth (shown in Fig. 1). This displacement of the submerged artificial structures prevents vessels from using routes of linear intersection, making it difficult to manoeuvre and preventing the implementation of fishing trips.

The artificial structures have a pyramidal shape and are equipped with holes and irregular spaces that reproduce a natural environment (see Fig. 2). Those pyramids are easily colonized by fouling and provide shelter and a chance for reproduction for many aquatic organisms, particularly for the fish species of high market value.

The structures are designed to induce the formation of the local and circumscribed upwelling phenomenon, by exploiting the sea currents to raise and stir the nutrients present at the bottom, by spraying them upwards in order to draw the fish in search of food and promoting food chain in the area (see Fig. 3).

The submerged artificial structures are able to favour the reproduction of several species. In the two areas of the project, we have observed oviposition of squid, which in turn promote the activity of different predator species. The objective sought in the design was to produce diverse habitats and host niches that could play the role of nursery for

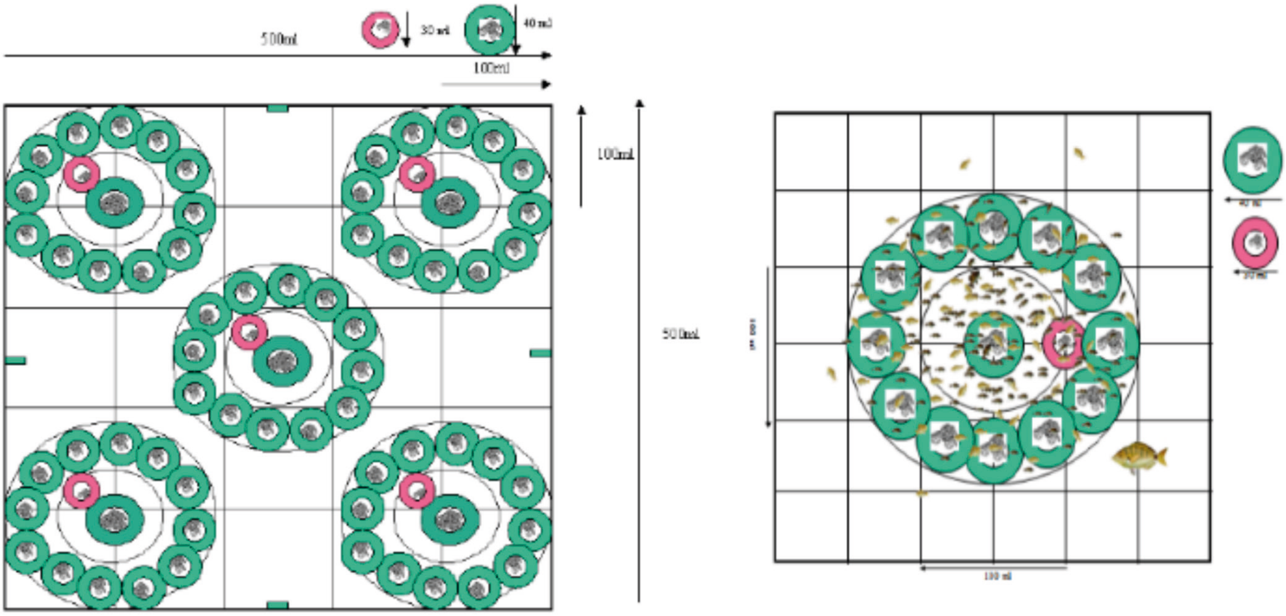

Fig. 1 - General plan of the artificial atolls, implemented in the areas of Sabaudia and Terracina (in collaboration with Eng. Marco Porcelli).

Fig. 2. Basic pyramidal element made with Tecnoreef® sea-friendly modules.

juveniles and, at the same time, favour the reproduction and the settlement of certain species of marine organisms. Among these, categories of marine organisms that have a high responsiveness to the use of artificial reefs are:

- *necto-benthic fishes* (e.g. *Pagellus erythrinus* and *Umbrina cirrosa*): they are in fact the rulers of the artificial barrier. Among them, we have many valuable species of hard substrate;
- *pelagic species* (e.g. *Seriola dumerili*): they are all species that during critical phases of their life cycle (juveniles or coupling) can find a safe haven in the artificial reef, and a point of food supply during migration;
- *crustaceans and molluscs* (e.g. *Octopus vulgaris and Liocarcinus arcuatus*): they are species that interact directly with the surface of the structure. Among them there are species of high commercial value.

Another aspect that contributes to the attraction of many fish species is the *thigmotropism* phenomenon that, in the context of the implementation of the two marine areas, has been emphasized as much as possible (Richard, 1968). This phenomenon (schematized in Fig. 4) is characterized by the interaction of the submerged structure with the sea currents, which cause the structure to vibrate and to emit very low frequency waves. Such waves are perceived from the fishes which, following the perceived vibration, move down to the submerged structure, finding in it a place of shelter and plenty of food (Hawkins, 1986).

RESULTS

The two areas established in Sabaudia and Terracina have been monitored for five years, from 2008 to 2012 (Berni P., 2012a; 2012b). In this period, the artificial structures have been repeatedly examined through underwater photos and videos, and through the sampling of fouling. Moreover, the populations of fishes in the area have been sampled through fishing by using gill nets and trammel nets (Berni *et al.*, 2007).

The overall trend of the considered populations (Sabaudia area) are reported in Fig. 5, 6, 7 and 8. The dynamics of the fouling colonization is shown in Fig. 5. The full coverage of the artificial structures is reached in less than two years. Fig. 6 shows the colonization by invertebrates.

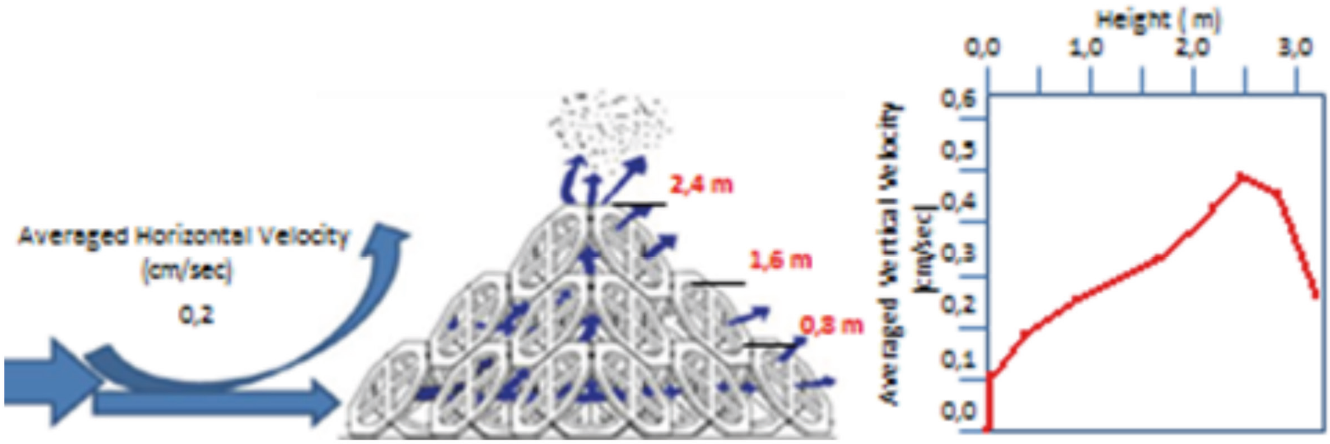

Fig. 3 - Schema of the formation of local patterns of upwelling by interacting with the sea currents (experimental observations in laboratory by P. Berni).

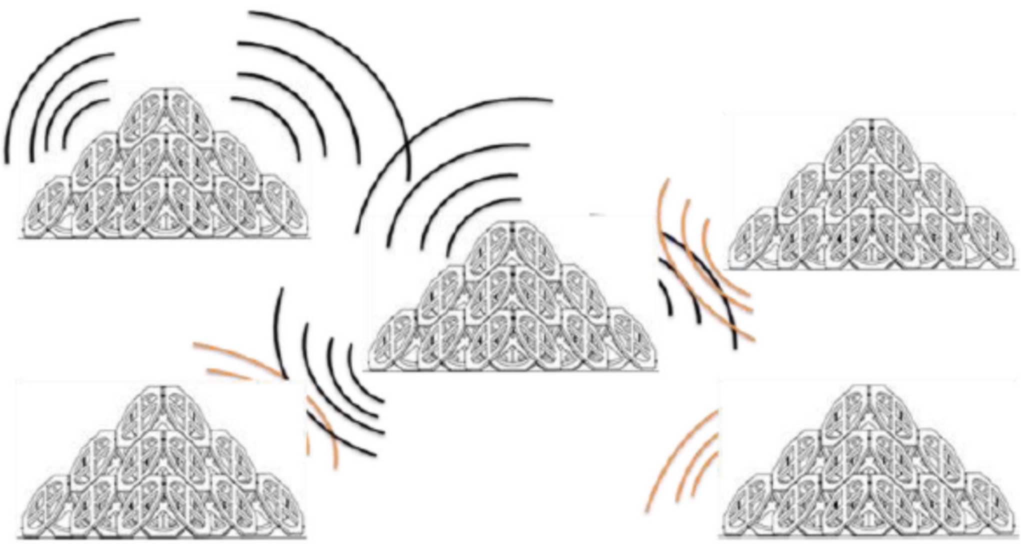

Fig. 4 - Schematic representation of sound effect due to the emission of low frequency waves by the five main atolls that make up the artificial reef system of Terracina and Sabaudia and that increase their attractiveness.

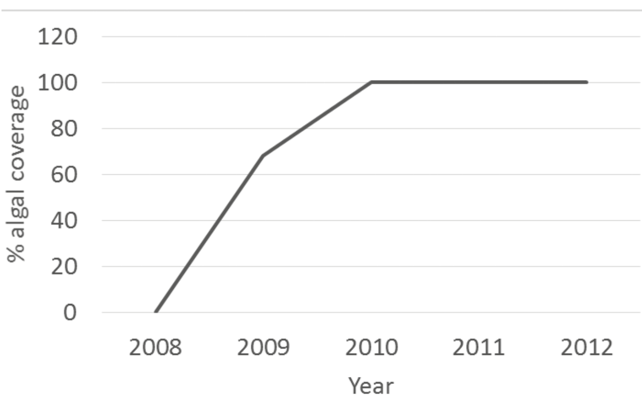

Fig. 5 - Algal coverage of the artificial structures over time (Sabaudia).

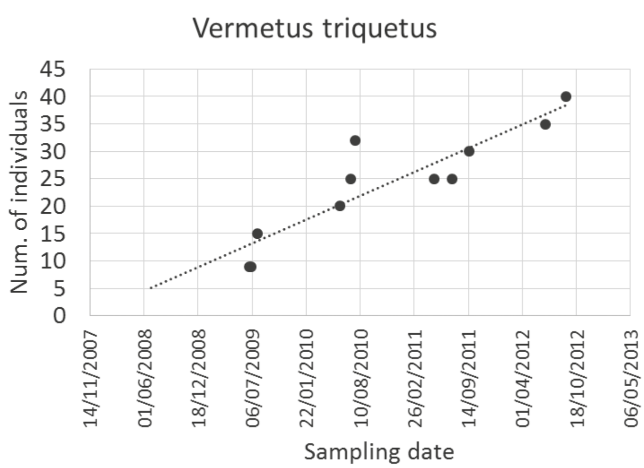

Fig. 6 - Sampling of of *Vermetus triquetus* over time in the cover of the hard surface of the atolls (Sabaudia).

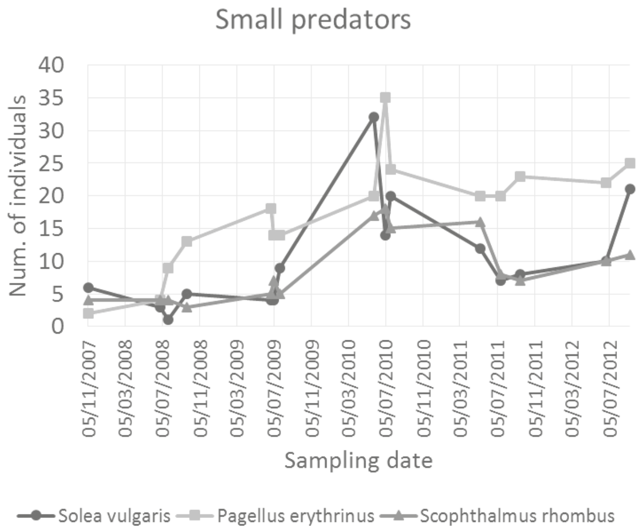

Fig. 7 - Sampling of some species of small predators over time (Sabaudia).

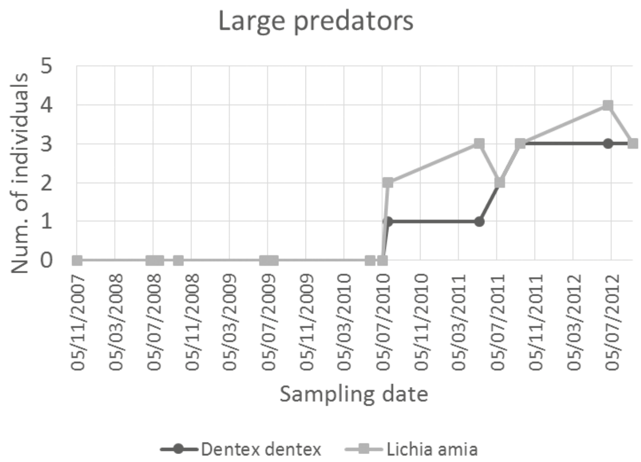

Fig. 8 - Sampling of some species of large predators over time (Sabaudia).

We use *Vermetus triquetus* as an indicator of invertebrate abundance. *Vermetus triquetus* is a marine gastropod mollusc in the family Vermetidae, called the worm shell. It is a sessile gastropod the shell of which is cemented to the substrate. In Fig. 6 we can see that the colonization by *Vermetus triquetus* starts in the second year of the monitoring. The population grows almost constantly in the remaining period of the monitoring. The dynamics of the populations of small predators is depicted in Fig. 7. We use as representatives of small predator fishes the species of *Solea vulgaris*, *Pagellus erythrinus* and *Scophthalmus rhombus.* The consistency of these three species starts to increase after the second year of monitoring, has a peak during the third year, and then decreases to reach an equilibrium in the last two years. The decrease of small predator populations is due to the colonization of the reef by large predators that occurs in the last two years of the monitoring period. Data about the colonization by large predators of species *Lichia amia* and *Dentex dentex* are reported in Fig. 8.

MATHEMATICAL MODELLING OF ARTIFICIAL REEFS

Definition of the model

The mathematical model of artificial reefs describes the dynamics of four populations: algae, invertebrates, small predators and large predators. Each population is described by an ODE. In the equations, variable represents the percentage of algal coverage of the modelled artificial reefs; variable represents the consistency of invertebrates; variable and represent the populations of small and large predators, respectively. The four differential equations are defined as follows.

Eq. 1 - Algae

$$\frac{dA}{dt} = g_A A\left(1 - \frac{A}{cc_A}\right)$$

Eq. 2 - Invertebrates

$$\frac{dI}{dt} = g_I I\left(1 - \frac{I}{cc_I}\right) - p_I IS$$

Eq. 3 - Small Predators

$$\frac{dS}{dt} = g_S S\left(1 - \frac{I}{cc_S}\right) - p_S SL - f_S(t)S$$

Eq. 4 - Large Predators

$$\frac{dL}{dt} = g_L L\left(1 - \frac{I}{cc_L}\right) - f_L(t)L$$

Each differential equation includes a term describing the logistic growth of the modelled population as a function of the carrying capacity of the artificial reef environment. Equations 2 and 3, describing invertebrates and small predators, include also a term describing their predation by small and large predators, respectively. The model also includes terms that describe the impact of fishing on small and on large predators.

Equation 1 describes algae, and it includes only the logistic growth term

$$g_A A\left(1 - \frac{A}{cc_A}\right)$$

where the growth rate is modulated by the ratio of algal coverage .

Equation 2, describing invertebrates, includes a logistic growth term analogous to the one in Equation 1 and a negative term representing the predation by small predators.

Equation 3, describing small predators, includes terms for the logistic growth and the predation by large predators and a negative term representing the fishing pressure. The latter term uses a function on the time variable to describe the considered fishing policy. The function will be varied in different simulations to compare the predicted effect of the different policies on the artificial reef environment.

Finally, Equation 4, describing large predators, includes only the logistic growth and the fishing pressure terms. Also in this case, the fishing pressure depends on a function representing the considered fishing policy. Note that fishing techniques for small and large predators are different. This is the reason for using two different functions form modelling them.

The parameters used in the differential equations have been estimated from the data obtained by the monitoring of the Sabaudia and Terracina areas describes in the previous section. As regards the carrying capacity parameters, in the cases of invertebrates and of small and large predators, they are actually proportional to the corresponding food availability, that is the algal coverage for invertebrates and the consistency of invertebrates for small predators and the consistency of small predators for large ones. The values of these parameters are reported in Table 1.

Table 1 - Model parameters.

Param.	*Description*	*Value*
g_A	Growth factor for algae	3
cc_A	Max. percentage of algal coverage	100
g_I	Growth factor for invertebrates	4
cc_I	Carrying capacity for invertebrates	10 · A
p_I	Predation factor for invertebrates	0.01
g_S	Growth factor for small predators	4
cc_s	Carrying capacity for small predators	0.5 · 1
p_S	Predation factor for small predators	0.01
g_L	Growth factor for large predators	4
cc_L	Carrying capacity for large predators	0.5 · S

Simulation results

We perfomed simulations of the model by considering different fishing policies. Simulation results are shown in Figures 9-15. Note that in these figures the algal coverage is a percentage while the other quantities are population consistencies (number of individuals).

Fig. 9 describes the dynamics of the reef, for a period of 10 years, when no fishing is allowe d (namely, and are constantly equal to zero). We can observe that algal coverage reaches its maximum percentage (100%) in nearly two years as observed in monitored real areas. The populations of invertebrates, small predators and large predators grow one after the other as expected. The populations of

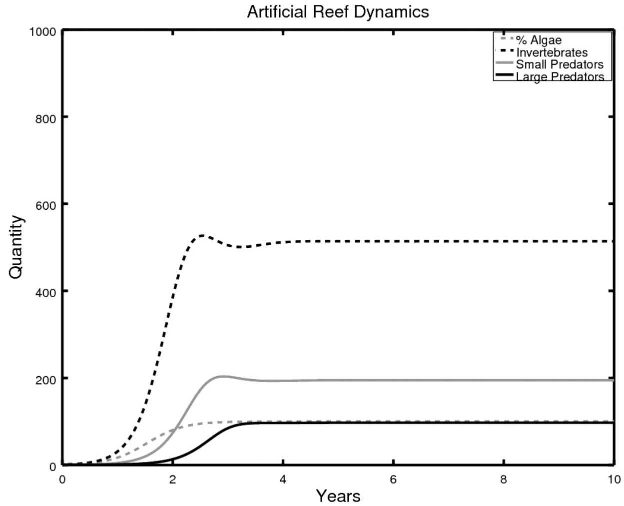

Fig. 9 - Simulation results of the artificial reef when fishing is forbidden.

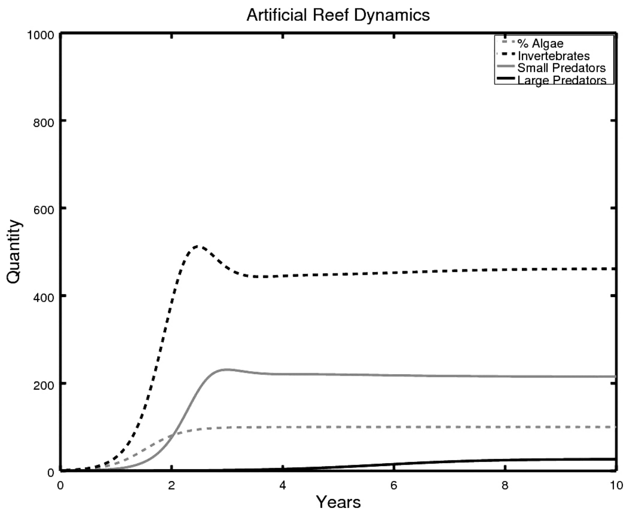

Fig. 10 - Simulation results of the artificial reef when fishing of large predators (only) is allowed.

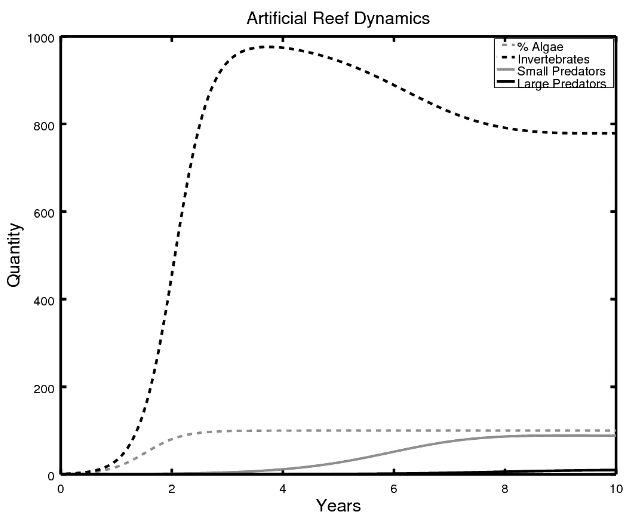

Fig. 11 - Simulation results of the artificial reef when fishing of both small and large predators is allowed.

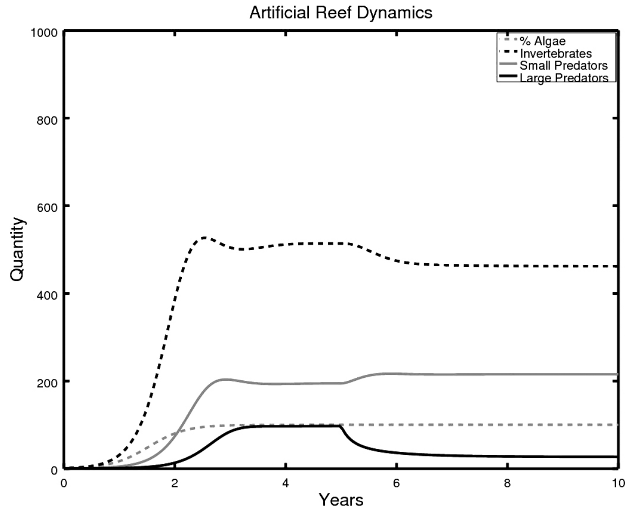

Fig. 12 - Simulation results of the artificial reef when fishing of large predators (only) starts to be allowed from the fifth year.

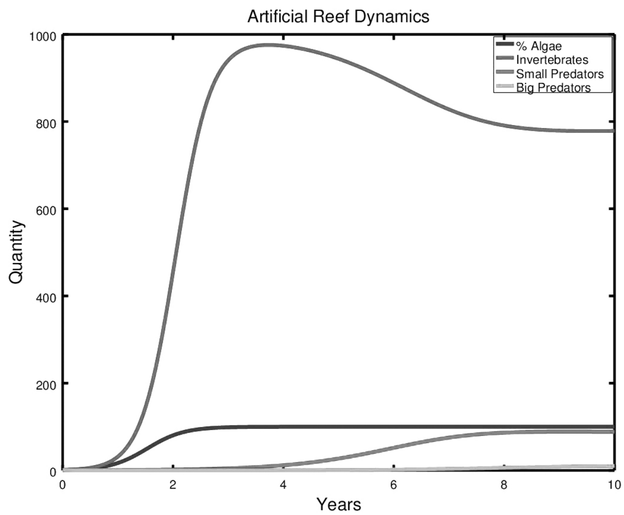

Fig. 13 - Simulation results of the artificial reef when fishing of both small and large predator s starts to be allowed from the fifth year.

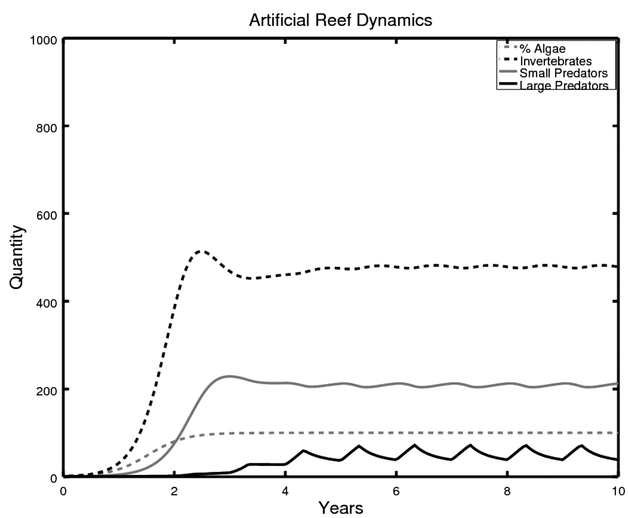

Fig. 14 - Simulation results of the artificial reef when fishing of large predators (only) is forbidden for four month every year.

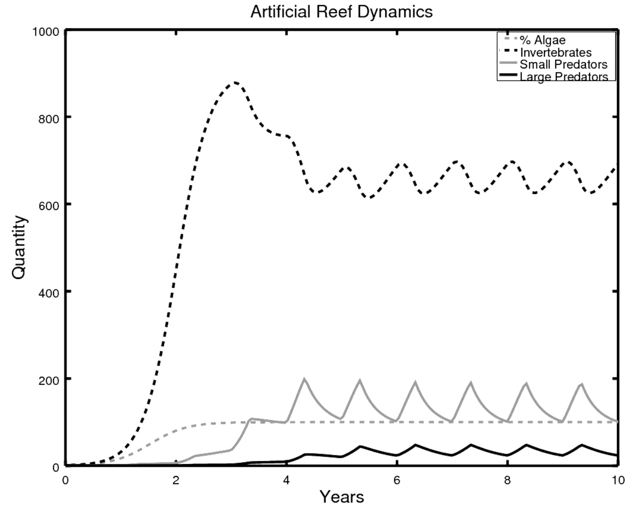

Fig. 15 - Simulation results of the artificial reef when fishing of both small and large predators is forbidden for four month every year.

invertebrates and small predators show an initial peak followed by a small decrease due to the increase of their respective predators. The four populations reach an equilibrium in less than four years.

Figs. 10 and 11 show simulation results when fishing is allowed. In the first case, fishing of only large predators is allowed (is constantly equal to zero, and is constantly equal to three). In the second case, fishing of both small and large predators is allowed (both and are constantly equal to three). Fishing causes the consistency of the corresponding populations to be significantly reduced. On the other hand, fishing causes also the consistency of the prays of the fished populations to increase due to reduced predation. This is the case, for instance, of small predators in Fig. 10 and of invertebrates in Fig. 11.

From the results in Figs. 10 and 11 we can conclude that fishing without limitations leads to an excessive exploitation of fish populations. The same situation is reached at the end of the ten years period also when fishing is forbidden for five years, and then allowed without limitations (this can be represented by functions and defined by cases on). This is shown in Figs. 12 and 13.

Figs. 14 and 15, show the simulation results in which fishing with periods of suspension of four months every year. In Fig. 14 fishing is allowed only for large predators while in Fig. 15 it is allowed for both large and small predators. We can see that in both cases the policy with the suspension periods turns out to be sustainable. This is particularly true when fishing is allowed only for large predators.

CONCLUSIONS

We have proposed a mathematical model for studying the dynamics of population in the environment of an artificial reef. We have shown that the model can be used to compare the effects of alternative fishing policies to be enforced in the artificial reef area. As an example, we have compared a policy that forbids fishing for five years from the establishment of the artificial reef with another that allows fishing to be always performed, but with periods of interruptions every year. Simulation results suggest that latter policy could be more sustainable.

Model parameters have been determined on the basis of observations on the artificial reefs established in two protected areas established in central Italy. Future work may include the study of different environments and species by considering different biological parameters. Moreover, the analysis could be improved by taking stochastic and spatial aspects into account or by applying static analysis techniques (Bodei *et al.*, 2015).

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