Estuarine, Coastal and Shelf Science 178 (2016) 86–91

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Short communication

Pattern and intensity of human impact on coral reefs depend on depth along the reef profile and on the descriptor adopted

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A R T I C L E I N F O

Article history:
Received 20 July 2015
Received in revised form
21 April 2016
Accepted 30 May 2016
Available online 31 May 2016

Keywords:
Local disturbances
Coral reefs
Non-taxonomic descriptors
Depth gradient
Underwater visual survey
ACI design
Maldives

A B S T R A C T

Coral reefs are threatened by multiple global and local disturbances. The Maldives, already heavily hit by the 1998 mass bleaching event, are currently affected also by growing tourism and coastal development that may add to global impacts. Most of the studies investigating effects of local disturbances on coral reefs assessed the response of communities along a horizontal distance from the impact source. This study investigated the status of a Maldivian coral reef around an island where an international touristic airport has been recently (2009–2011) built, at different depths along the reef profile (5–20 m depth) and considering the change in the percentage of cover of five different non-taxonomic descriptors assessed through underwater visual surveys: hard corals, soft corals, other invertebrates, macroalgae and abiotic attributes. Eight reefs in areas not affected by any coastal development were used as controls and showed a reduction of hard coral cover and an increase of abiotic attributes (i.e. sand, rock, coral rubble) at the impacted reef. However, hard coral cover, the most widely used descriptor of coral reef health, was not sufficient on its own to detect subtle indirect effects that occurred down the reef profile. Selecting an array of descriptors and considering different depths, where corals may find a refuge from climate impacts, could guide the efforts of minimising local human pressures on coral reefs.

1. Introduction

Multiple global and local disturbances represent serious threats to coral reefs worldwide (Carpenter et al., 2008). The severe bleaching event of 1998, for instance, caused mass coral mortality in most tropical regions, implying drastic reduction in hard coral cover (Baker et al., 2008), high spatial variability in the recovery trend, and shift in taxonomic composition (van Woesik et al., 2011; Johns et al., 2014). Local disturbances, such as overfishing, mass tourism and coastal development, may interact with and add to global impacts (Ban et al., 2014).

The greatest threats that tourism and growing human population pose on coastal ecosystems consist in the infrastructure and transport systems required to support development (Davenport and Davenport, 2006). In particular, urbanization, construction of touristic resorts, aquaculture facilities and other coastal services contribute to substantial, often irreversible, environmental degradation (Burt et al., 2015). Dredging, filling, and other constructions in areas characterized by coral reefs and related ecosystems are expected to continue at a high rate (Maragos, 1993). These activities have resulted in major adverse ecological impacts, mainly due to land reclamation and to the consequent flow of sediments into the water. Water turbidity, consequent to increased sediment load, reduces light penetration and deteriorates environmental conditions for zooxanthellate corals (Fabricius, 2005).

Furthermore, sediments interfere with the reproductive success and the recruitment of corals, as well as with the survival and settlement of coral larvae (Erftemeijer et al., 2012). As a consequence, any local disturbance deriving from land reclamation and coastal construction is supposed to have a direct effect on the health state of shallow corals, but indirect effects along the reef profile due to the sliding of sediments at greater depths are more than likely (Rogers, 1990). In an era of global change, extending downward the assessment of local impacts is important, as depth may represent a refuge from climate impacts (Smith et al., 2014; Thomas et al., 2015). Yet, most of the studies investigating effects of local disturbances on coral reefs considered the response of communities only along a horizontal distance from the impact

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http://dx.doi.org/10.1016/j.ecss.2016.05.021
0272-7714/

source, without considering the influence of depth (Graham et al., 2011; Erftemeijer et al., 2012).

This paper aims at assessing the effects of the recent construction of an international touristic airport in an island of the Maldives (Indian Ocean) on the health state of its surrounding coral reef. The status of this impacted reef was compared with that of other nearby Maldivian reefs unaffected by any coastal construction. Underwater visual surveys were conducted at different depths along the reef profile, from the outer flat to the slope until 20 m depth. Different depths were considered because an evident zonation in coral reef communities exists, being influenced by light and exposure to wave energy (Done, 1983; Graham et al., 2014). Furthermore, corals growing at different depths may display distinct vulnerability to human disturbances (Bak et al., 2005), and the effects of the interaction between natural factors and human disturbance are still poorly understood (Done, 1982; Graham et al., 2014).

2. Material and methods

2.1. Study area

In May 2012 we investigated 9 reefs located in Ari and South Malé Atolls (Fig. 1). We chose as impact site the rear reef of the island of Maamigili (Ari), where the Maamigili Villa International Airport (Fig. 2) has been recently built (2009: beginning of the construction; the 1st of October 2011: day of opening). The construction of this airport and of other infrastructures (such as a new harbour) required the realization of an artificial embankment directly over the reef flat along most of the south and east sides of the island (Fig. 2b and c). We compared the status of this reef at different depths with that of other 8 randomly selected reefs, used as control sites (Table 1). Control sites were selected among the two major reef types that occur in the Maldivian atolls (Lasagna et al., 2010b): 4 were outer reefs (ocean-facing sides of the atoll rim, and therefore exposed to wave action), and 4 inner reefs (lagoon patch-reefs or lagoon-facing sides of the atoll rim), the impact site belonging to the latter type. Coral reefs are characterized by a large variability, also at small spatial scale (Lasagna et al., 2010b; Jimenez et al., 2012) and especially the outer reefs; thus, the selection of the sampling sites was done among reefs sharing similar environmental features, such as morphological profile and exposure to wave motion, to avoid the problem of pseudo-replicates (Table 1). As also natural factors, such as waves and currents, may represent serious stressors for coral reefs causing hard coral cover to decrease (Erftemeijer et al., 2012; Graham et al., 2014), especially for the branching corals of the genus *Acropora* (Done, 1982; Madin and Connolly, 2006; Lasagna et al., 2010a), outer reefs were included among controls in order to compare the effects of these natural factors with the mechanical impact due to coastal constructions (Erftemeijer et al., 2012).

2.2. Field activities

In the 9 sites selected, data were collected by SCUBA diving through underwater visual surveys conducted at three different depths along the reef profile: i) outer flat, at around 5 m depth; ii) upper slope, at approx. 10 m depth; and iii) 'ten-fathom terrace' at about 20 m (Bianchi et al., 1997). At each depth, 6 replicate cover estimations (separated at least 10 m from each other) were performed using the plan view technique of Wilson et al. (2007), over a 5 m × 5 m area.

Taxonomic composition is often considered as the best

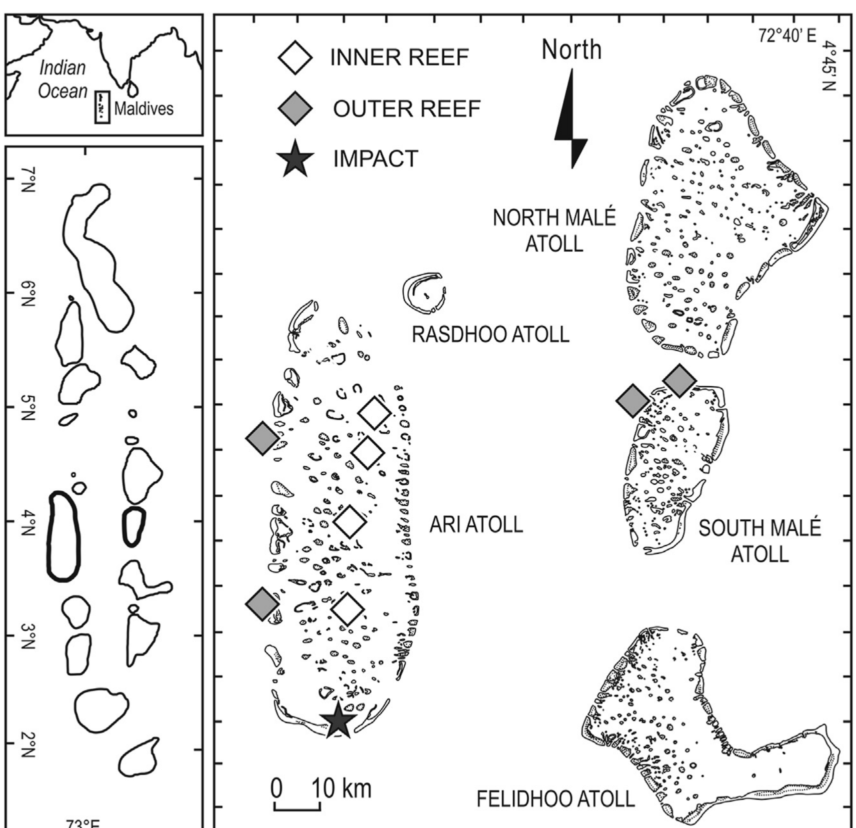

Fig. 1. Geographic setting of the 9 reefs investigated in the Maldivian atolls of Ari and South Malé.

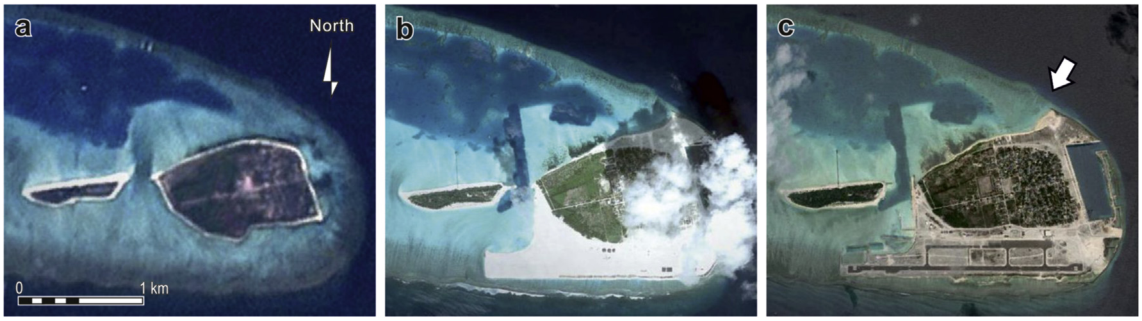

Fig. 2. Changes in the Maamigili Island following the new Maamigili Villa International Airport construction. Arrow indicates the impact site adopted in this study. a) year 2001; b) year 2007; c) year 2011. Images from Google Earth®.

Table 1
Geographic coordinates and main physical and ecological characteristics of the 9 reefs investigated. Position of each reef was recorded using a GPS.

Reef name	Atoll	Coordinates	Typology	Compass bearings (°N)	Depth (m)	Slope (°)	Total hard coral cover (%)	Dominant organisms
Dhonkadhdhahau	Ari	3°29.019′ N; 72°50.350′ E	Impact	220	5	5	10–25	Algae, sponges, corymbose *Acropora*
					10	45	40–50	Algae, sponges, corymbose *Acropora*
					20	30	20–30	Algae, sponges, corymbose *Acropora*
Bodhibinhau	Ari	3°52.572′ N; 72°49.811′ E	Inner	20	5	5	65–80	Tabular *Acropora*
					10	50	45–70	Tabular and corymbose *Acropora*
					20	30	35–45	Corymbose *Acropora*
Kadholhudhoo	Ari	4°00.128′ N 72°52.712′ E	Inner	40	5	30	60–70	Ramose *Acropora*
					10	40	55–60	Ramose *Acropora*
					20	20	50–55	Encrusting corals
Maayafushi W	Ari	4°04.569′ N 72°52.652′ E	Inner	20	5	10	40–50	Massive corals, alcyonaceans
					10	50	30–35	Corymbose *Acropora*, encrusting corals
					20	30	30–45	Corymbose *Acropora*
Thoshiganduhau	Ari	3°43.400′ N; 72°48.124′ E	Inner	20	5	5	70–80	Tabular and ramose *Acropora*
					10	50	35–45	Tabular *Acropora*
					20	30	35–40	Tabular *Acropora*
Boldhuffaru Beyru	South Malé	4°05.565′ N; 73°23.136′ E	Outer	110	5	5	40–65	Tabular *Acropora*
					10	50	50–65	Tabular *Acropora*
					20	20	15–40	Corymbose *Acropora*, alcyonaceans
Mandhoo Beyru	Ari	3°42.478′ N; 72°41.906′ E	Outer	100	5	5	25–40	Bushy corals, algae
					10	40	35–40	Corymbose and tabular *Acropora*, bushy corals
					20	10	15–25	Encrusting corals, algae, sponges
Ran Faru	Ari	4°01.658′ N; 72°42.200′ E	Outer	100	5	5	55–65	Bushy corals, corymbose *Acropora*, algae
					10	40	25–35	Bushy corals, alcyonaceans
					20	5	20–25	Alcyonaceans, algae
Velassaru	South Malé	4°07.553′ N; 73°26.186′ E	Outer	145	5	5	50–60	Encrusting corals, tabular *Acropora*
					10	65	40–55	Massive and bushy corals, alcyonaceans
					20	30	15–30	Massive corals, algae, sponges

descriptor of the overall status of ecosystems (Guidetti et al., 2014); however, the high biodiversity of Maldivian coral reefs (Andréfouët, 2012) led us to adopt non-taxonomic descriptors that assemble species according to their ecological role (Darling et al., 2012; Wilson et al., 2012). In particular, we estimated the percent cover of five broad benthic categories (Lasagna et al., 2008): 1) hard (zooxanthellate) corals; 2) soft (zooxanthellate) corals; 3) other (azooxanthellate, suspension-feeding) invertebrates; 4) macroalgae; 5) abiotic attributes (sand, rock, coral rubble).

2.3. Data analysis

Lack of information on the reef state of health before the construction of the airport prevented the application of a rigorous BACI (Before-After, Control-Impact) design (Underwood, 1992). We therefore adopted an ACI (Azzurro et al., 2010) and asymmetrical design, where the differences between the impact site and the 8 controls were only tested in the "after" condition. Five analyses of variance (ANOVAs) were performed separately for each benthic descriptor in the three depth zones investigated. Prior to the analysis, the homogeneity of variances was tested by Cochran's test and, if necessary, data were transformed appropriately. After subtraction of the variance among controls ($MS_{AmongCtr}$) from the total variance among sites (MS_{site}), impact effect ($MS_{IvsAmongCtr}$) has been tested versus the variance among controls ($MS_{AmongCtr}$) or the variance among residual (MS_{Res}), when the former was not significant.

A multivariate analysis (MDS) for each depth was also performed taking into account the five benthic descriptors altogether. The similarity matrix was based on the Bray-Curtis index on ln(x+1) transformed data. Differences between outer and inner sites (impact site excluded) and between controls and impact were tested with a permutation-based multivariate analysis of variance (PERMANOVA). By this method, we analyzed the variance of our multivariate data explained by the factor "Condition" (which had 3 levels: inner, outer and impact), obtaining the relevant *p*-values using all possible permutations.

3. Results and discussion

The MDS plot for the sites at 5 m depth clearly set apart the impact site from both the inner and the outer controls (Fig. 3a), although the impact site resulted closer to the outer rather than to the inner controls. PERMANOVA indicated that the pairwise difference between the impact site and both the inner and the outer controls was significant ($p < 0.01$); as expected, inner and outer controls were also different ($p < 0.05$). According to the ANOVAs, the difference between impact and controls was mostly due to the significant ($p < 0.001$) decrease of hard coral cover (Fig. 4a) and increase of abiotic attributes (Fig. 4e). Reduction of hard coral cover and increase of abiotic attributes at 5 m depth is an expected consequence of a large coastal construction, and the reef flat is more subjected to resuspension of sediment than deeper water (Maragos, 1993; Larcombe and Prytz, 1995; Price et al., 2014). This mechanical impact caused a stronger disturbance on the inner and more sheltered reef than that exerted by oceanic waves on Maldivian outer reefs. Cover of macroalgae was significantly ($p < 0.05$) higher at the impact site than at the inner controls (Fig. 4d); however, no difference in macroalgae abundance was found with respect to the outer controls. This result can partially explain for the close position of the impact site to the outer controls in the MDS plot (Fig. 3a). According to Goatley and Bellwood (2013), the enhanced flux of sediments due to coastal constructions increases sedimentation on algal matrices, which in turn can prevent algal grazing and possibly lead to an increased abundance of macroalgae. Moreover, high sedimentation due to excavations, landfill and shore protection activities increases dissolved inorganic nutrients in the water column, which are normally immobilised within the sediment deposit (Fabricius, 2005), thus favouring the metabolism of autotrophic organisms.

The impact site at 10 m depth was separated from the controls in the MDS plot (Fig. 3b); according to PERMANOVA, this difference was significant ($p < 0.01$), whereas no difference was found between outer and inner controls. ANOVAs indicated that the difference between the impact site and the inner controls was mostly due to higher cover ($p < 0.001$) of other invertebrates in the former (Fig. 4c). These filter-feeder invertebrates (mostly sponges) may take advantages over algae and corals thanks to the increased turbidity and particulate organic matter content of the water column due to the resuspension and sliding down of sediments operated by the coastal work on the flat (Fabricius, 2005). Similarly, in the outer reefs the comparatively stronger currents flowing down the slope are likely to displace organic nutrients originating from the more productive shallow parts of the reef to the deep ones, where sponges are usually abundant (Wilkinson and Evans, 1989).

The impact site appeared as a tight cluster within inner controls in the MDS plot relative to 20 m depth (Fig. 3c). Consistently, PERMANOVA showed that the impact site was significantly different from the outer controls ($p < 0.05$), but not from the inner controls ($p = 0.06$). Two differences between the impact site and the inner controls were evidenced by ANOVAs: the cover of other invertebrates in the impact site was significantly lower ($p < 0.05$) (Fig. 4c) and the abundance of abiotic attributes was significantly higher ($p < 0.001$) (Fig. 4e). Maldivian reef profiles usually show a steep inclination at 7–15 m depth (Lasagna et al., 2010b), and a terrace at about 20 m depth (Bianchi et al., 1997): this causes heavier sediment deposition on the comparatively levelled substrate at 20 m than on the reef wall at 10 m, and explains both the increased amount of abiotic attributes (mostly sand) and the decreased cover of other invertebrates, whose filter-feeding apparatus may get clogged by sediment (Bell et al., 2015).

4. Conclusions

The Maldives have been among the areas most severely affected by the 1998 bleaching episode (Bianchi et al., 2003). When this study was done (2012), hard coral cover was not returned yet to the pre-bleaching values, the taxonomic composition was different and the reef complexity was not entirely recovered (Morri et al., 2015). The high cover values (up to 30–40% in controls) of abiotic attributes observed at all depths and in all sites were still a visible effect of the widespread coral mortality experienced (Bianchi et al., 2006). The legacy of the 1998 large-scale disturbance represents a serious problem in the face of preventing Maldivian islands from erosion, and the consequences for the local economy may be serious (Cesar, 2000; Sheppard et al., 2005; Graham and Nash, 2013). However, the fact that in all control sites hard corals were often the descriptors exhibiting the highest cover values (from about 15 to 80%, according to the depth) was a positive sign of a slow but continuous recovery (Morri et al., 2010).

Reefs still in the process of recovery may be more vulnerable to further disturbances (Montefalcone et al., 2011): this study is the first attempt to quantify the impact of a local anthropogenic disturbance on the Maldivian reefs still recovering from bleaching. The impact caused by the construction of Maamigili Villa International Airport at 5 m depth was so severe to bring an inner reef into the regressive stage (*sensu* Lasagna et al., 2010b), with amounts of rubble and dead coral even larger than those exhibited by outer reefs exposed to the mechanical damage by oceanic waves (Graham et al., 2014). Resilience depends on reef type (Rowlands et al., 2016), and recovery of reefs showing regressive stage is expectedly slow (Lasagna et al., 2010b). The impact there implied reduction of hard coral cover, increase of algal cover, and dramatic augmentation of non-living substrate. At 10 m and 20 m depth, the impact was less obvious when considering only hard corals and abiotic attributes

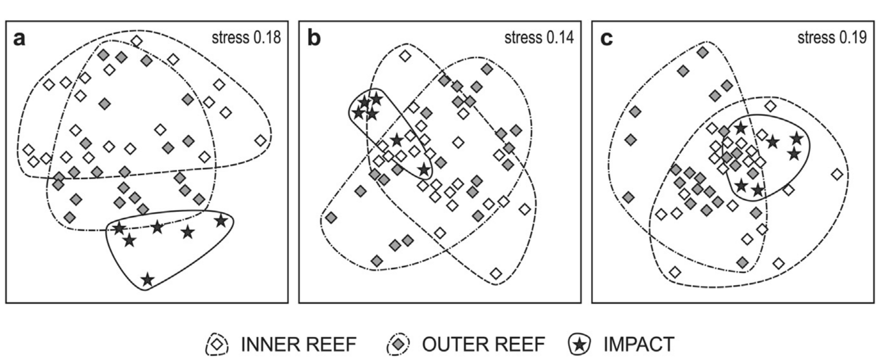

Fig. 3. MDS plots of study sites at different depths. a) 5 m; b) 10 m; c) 20 m. Each individual symbol represents a replicate.

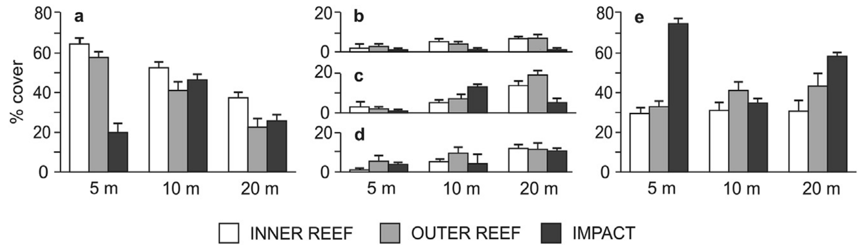

Fig. 4. Mean (+ s.e.) percent cover of hard corals (a), soft corals (b), other invertebrates (c), macroalgae (d) and abiotic attributes (e) in the impact site and in the two control conditions (inner and outer reefs), separately for the three depth zones investigated (5, 10, 20 m).

but still detectable if different descriptors, such as other invertebrates, were considered. Reef profile played a major role in determining pattern and intensity of the impact at different depths. While hard corals are widely used as the main indicators of coral reef state of health (Chabanet et al., 2005; Lasagna et al., 2014), they may not be sufficient to identify indirect and more subtle effects that may occur down the reef profile. Coral cover, when evaluated alone, is a fairly crude measure of coral reef condition (Hughes et al., 2010; McClanahan et al., 2011). Most authors identify taxonomic composition as the most adequate descriptor to be used in monitoring programs. Unfortunately, a taxonomic approach requires specialist expertise and may be very time-consuming for underwater visual surveys on coral reefs. The five comprehensive non-taxonomic descriptors we suggested were easy to use, showed effective in detecting the impact, and allowed reducing the time needed for underwater surveys (Maurer, 2000). The approach we propose can provide pre-survey basic and useful information for planning proper and accurate sampling design. For more detailed analyses, these comprehensive descriptors could be integrated with other non-taxonomic categories of benthic organisms: Morri et al. (2015) used 25 descriptors that included growth forms, trophic guilds and abiotic attributes.

Coral reef recovery dynamics in an era of global change are hardly predictable (Graham et al., 2011). Selecting an array of different descriptors and considering different depth zones (Jokiel et al., 2004) where corals may find refuge from climate impacts (Smith et al., 2014), may serve as guidelines for the efforts of minimising the impact of local human interventions on coral reefs. As the Maldives are experiencing a tumultuous growth of urbanization, coastal development and, especially, tourism (De-Miguel-Molina et al., 2011; Jaleel, 2013), local action is urged to prevent irreversible reef degradation (Kennedy et al., 2013): nonetheless, environmental impact assessment in the Maldives is still inadequate (Zubair et al., 2011). Identifying measures to reduce or avoid adverse impacts on coral reefs requires that improvement in design and construction of coastal projects should be accomplished by early integration of environmental objectives (Maragos, 1993), such as ecological baseline surveys, environmental impact assessments, monitoring, post-construction evaluation and long-time research.

Conflict of interest

The authors have declared that no competing interests exist.

Authors contributions

Conceived and designed the experiments: EN, MM, CM, CNB.
Performed the experiments: EN, MM, CM.
Analyzed the data: EN, MC.
Contributed reagents/materials/analysis tools: MM, MC.
Wrote the paper: EN, MM, CNB.

Acknowledgements

Albatros Top Boat (Verbania and Malè) sponsored and organized our scientific cruise in the Maldives. In particular, we gratefully acknowledge the general manager of Albatros, Donatella 'Dodi' Telli, for her assistance. The sponsor had no role in study design, data analysis, manuscript preparation, or the decision to publish. Giulia Gatti, Alberto Maradini, Alberto Rovellini, Aurora Truccolo participated in field activities and helped collecting data.

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