Evaluation of coastal and marine ecosystem services of Mayotte: Indirect use values of coral reefs and associated ecosystems

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ABSTRACT
Coral reefs of Mayotte (342 km\textsuperscript{2}), seagrass beds (7.6 km\textsuperscript{2}) and mangroves (8.5 km\textsuperscript{2}) provide important ecosystem services of which the most important are the coastal protection, fish biomass production, carbon sequestration and water purification. The quantity and quality of these services have been decreasing steadily for several years and should continue to do so if no action is taken to contain anthropogenic pressures. The coral cover of the fringing reefs and the barrier reef has thus declined, respectively, by 60\% in 15 years and 15\% in 8 years. The pioneer front of \textit{Sonneratia} for mangroves has declined by 13\% in 6 years, and for seagrass beds, the water quality suggests a degraded state. The estimated annual value of these services amounts to EUR 124 million. It would be EUR 162 million if the ecosystems were in pristine conditions. The article shows that the preservation of coastal ecosystems is essential from an economic point of view.

Introduction
Coral reefs are among the most productive marine ecosystems, especially in terms of biodiversity (Wilkinson 2008). On a global scale, a fifth has been destroyed and half of the remaining reefs are endangered (Wilkinson 2008; Burke et al. 2011; Bridge et al. 2013; Hoegh-Guldberg 2014). Beyond their ecological importance (habitats, spawning areas, etc.) and coastal protection dimension, coral reefs and associated ecosystems (seagrass beds, mangroves and mudflats) have important economic and social scopes in the French overseas territories, particularly for fishing, tourism and recreation.

Since 2006, the French Government has implemented a programme to evaluate the total economic value (TEV) of coral reefs and associated ecosystems (CRAE) of all French overseas territories, through the French Coral Reef Initiative (IFRECOR). A methodology was developed and approved by the ministry of the environment. These guidelines have been included in the terms of reference for the Mayotte assessment. Assessment is done following the methodology detailed in the guidelines produced by Maréchal et al. (2014) as a part of IFRECOR. The TEV expressed in euro/year, sums up the use values (UV), the indirect use values (IUV) and the non-use values (NUV). Use values are related to leisure activities such as bathing and diving or commercial uses such as commercial fishing. Indirect use values concern regulating ecological functions. Non-use values refer to the spiritual dimension and existence of the nature (Corvalan et al. 2005).

Fieldwork was carried out in 2014 and 2015 in Mayotte. The territory acquired the status of French overseas department and region in 2011. The last census counted 235,132 inhabitants (INSEE 1975–2017) for an area of 376 km\textsuperscript{2}, making Mayotte the overseas department with the highest population density (625 people per km\textsuperscript{2}).

The aim of the article is to present the monetary value of IUV relative to the ecological services provided by CRAE of Mayotte. These services such as coastal protection, production of fish biomass, water purification and carbon sequestration are not subjected to market exchanges.

Schröter et al. (2005) stated: ‘an increase in the habitats vulnerability is likely to decrease the supply of ecosystems’. The assessment of marine habitats vulnerability has become important to point out anthropogenic threats (Halpern et al. 2007) and evaluate marine habitats ecosystem services potential based on vulnerability approaches (Bouahim et al. 2015, Cabral et al. 2015). The article relates an aspect rarely considered in the evaluation of coastal ecosystem services, namely the integration of ecosystem health status in the weighting of production functions. A healthy ecosystem provides a full range of services, the capacity of which decreases as and when it is disturbed, polluted, weakened, etc. In other words, a healthy ecosystem produces ecological services that are quantitatively and qualitatively higher than the same ecosystem in poor condition.

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Marine science institute of Martinique (Observatoire du Milieu Marin Martiniquais – OMMM) has developed, as part of the ecological monitoring of the coastline (Legrand et al. 2008), a method calibrating the health status of coastal marine ecosystems for Martinique, which is applied here. The article casts additional light on how to take into account this key environmental variable in assessing coastal ecological services.

The article is structured in four parts. In the first part materials and methods for the valuation of ecosystem services of coastal protection, carbon sequestration, water purification and biomass production are presented. In the second part, the results show the health status of Mayotte coastal ecosystems then, selected production functions are described before addressing the weighting factors to refine the level of services provided. From these elements, a monetary valuation of IUV is proposed taking into account the weighting factors of ecosystem health status. In the third part, a discussion is offered on the most important aspects to remember, especially those that contribute to the development of public policy. A conclusion summarises the determining elements.

Materials and methods

The valuation of ecosystem services was conducted in Mayotte using the method developed by Maréchal et al. (2014) under the IFRECOR framework on 'Socio-economic valuation'. It follows five stages: (1) identification of ecological ecosystem services linked to indirect uses, (2) ecosystem mapping and health status assessment, (3) definition of production functions and assessment of produced services, (4) application of a weighting coefficient and (5) determination of indirect use (monetary) values.

Identification of ecological ecosystem services

The identification of ecological services linked to indirect uses follows the Millennium Ecosystem Assessment classification (Corvalan et al. 2005). A review of Mayotte marine and coastal biodiversity literature was conducted to collect information on coastal habitat maps prior to fieldwork (Wickel and Thomassin 2005; Jeanson 2009; Herteman 2010; Jamon et al. 2010; PARETO 2013). The ecosystem services selected for Mayotte are regulation services: coastal protection against erosion, coastal water purification, atmospheric carbon sequestration and fish biomass production (of which a portion also forms a provisioning service for fisheries).

It is considered that for coastal protection (given the juxtaposition of natural barrier reefs in Mayotte):

- The outer barrier reef (208 km – Thomassin et al. 1989) ensures global coastal protection,
- The inner reefs (inner barrier and fringing reef), seagrass beds and mangroves have ‘optional’ coastal protection value most of the time, but are not negligible in case of exceptional weather events.

Carbon sequestration is not taken into account for coral reefs because of lack of data. Indeed, coral calcification as a carbon storage process is tangible because one must consider organisms’ respiration and coral dissolution for which CO₂ is thus recycled into the atmosphere (Shaw et al. 2015). Table 1 summarises the production functions selected for the CRAE of Mayotte.

Table 1. Selected ecosystem services for marine coastal ecosystems of Mayotte (Indian Ocean).

| Services                  | Coral reefs |
|---------------------------|-------------|
|                           | Outer barrier | Inner barrier | Fringing reef | Mangroves | Seagrass |
| Coastal protection        | ✓            |               |               |          |         |
| Water treatment           |              | Option        |               |          |         |
| Carbon sequestration      |              |               |               | ✓        | ✓       |
| Biomass production        |              |               |               | ✓        | ✓       |
| NA: non-applicable production function; Option: indicates an optional production function.
water bodies assessment under the EU Water Framework Directive (PARETO, ASCONIT 2013).

**Definition of production functions and assessment of produced services**

Ecosystem services estimation relies on ecosystems surface data, assessment of their health status and maximum production level for each service (Table 2).

While coastal protection, carbon sequestration and biomass production services benefit from extended references, water purification valuation is based only on Costanza et al. (1997) monetary reference despite the absence of reference work to validate this result.

**Coastal protection**

The coastal protection service mitigates extreme weather events such as tsunami or hurricane swells (Kunkel et al. 2006). The reef structures absorb up to 90% of the waves energy (Ferrario et al. 2014). If extreme natural conditions threaten the coastline of Mayotte, the inner barrier reef, the fringing reef, seagrass beds and mangroves would absorb most of the waves’ energy left. Only two sectors in Mayotte are more sensible to cyclonic swell given the direction of waves that may enter the lagoon through reef pass: Pointe Kani in the south and Tsingoni bay on the west coast where waves’ height can remain greater than 1 m while for the rest of Mayotte coast, waves’ height is less than 50 cm (Lecacheux et al. 2007). Seagrass beds stabilise the sediment and reduce waves’ energy by about 40% (Fonseca and Cahalan 1992; Christianen et al. 2013). The last physical barriers, composed of mangrove forests, dissipate wave energy and significantly diminish wave height over very short distances (Jéanson 2009). Mangrove trees Sonneratia sp. characterise the pioneer front of mangroves and absorb about 50% of wave energy over a distance of 100 m (Mazda et al. 2006).

**Carbon sequestration**

Mangroves and seagrasses ecosystems form significant carbon sinks and each contribute, respectively, to 14 and 15% of the carbon storage capacity of the oceans (Laffoley and Grimsditch 2009; Waycott et al. 2009; Donato et al. 2011). The respective net productivities of Sonneratia/Avicennia and Rhizophora mangrove communities are 9.54 tC/ha/year and 10.5 tC/ha/year (Poungparn and Komiyama 2013). These values are applied to Mayotte mangroves.

The estimated net productivity of seagrass beds is 1.19 tC/ha/year (Duarte et al. 2010), equivalent to 435 tCO$_2$e/km$^2$/year on average. This later value is applied to Mayotte case study.

**Water purification**

Water purification is the absorption capacity of nutrients by ecosystems in relation to their surface and health status. Coral reefs have very low capacity of water purification, but the coral – algal shift in coral reefs increases the water purification function according the intensification of algae cover.

The capabilities of bio-remediation of mangrove forests were assessed at Malamani (Herteman 2010) and studies are still under progress. This study shows that wastewaters are partly absorbed by the vegetation.

Seagrass meadows can trap nutriment-loaded sediments, acting as coastal water filters (Duarte 2000). Besides, seagrass plants absorb dissolved minerals and nutrients for their own growth directly from water.

**Biomass production**

Coral reefs provide habitat and nursery grounds for many fish species and represent very important fishing areas for the local population. The pioneer fronts of Sonneratia alba communities are submerged by seawater and house fifty-eight species of fish (Ponton et al. 2013). Seagrass areas also form nursery grounds for juvenile fish that use the dense canopy as a shelter during early life stages (Pogoreutz et al. 2012). Other larger species use seagrass beds as transition area to feed and hunt (Unsworth et al. 2008), and are targeted by fisheries.

| Table 2. Production functions and services estimation. |
|-----------------------------------------------|
| Indirect use service | Definition | Data used for services estimation |
|---------------------|------------|----------------------------------|
| Coastal protection  | Ecosystem’s ability to reduce wave power/energy | Coastline/surface area of ecosystems playing a protection role |
| Water treatment     | Ecosystem’s ability to absorb nutrients | Coefficient of wave power attenuation provided by ecosystem |
| Carbon storage      | Ecosystem’s ability to absorb atmospheric or dissolved carbon | Health status of ecosystems |
| Biomass production  | Ecosystem’s ability to produce exploitable fish biomass | Area of ecosystem playing a water treatment role |

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The fish biomass production (of which a portion forms also a provisioning service as part of the biomass is subject to fishing) represents the ecosystem ability to produce exploitable fish biomass.

Application of a weighting coefficient

Production functions are weighted according to the estimated amount of service provided by the ecosystem. Health status indexes and levels of vulnerability of marine environments are elaborated from published references. They are applied to a production function that would provide 100% of the service.

The coastal protection service provided by coral reefs is weighted by their health conditions (Wickel and Thomassin 2005; PARETO 2013) and the methods from Sheppard et al. (2005) and Ferrario et al. (2014), considering that:

- A 100% mortality of live corals in coral reefs leads to an average 10% decrease of the waves attenuation effect;
- The outer barrier absorbs up to 91% of the wave power;
- A linear model correlates coral reef health status and wave attenuation;
- The width of the reef flat influences the attenuation of the remaining wave power.

The width of the reef flat is 1150 m for the outer barrier (between 800 and 1500 m) and 425 m for the fringing reef (between 50 and 800 m) (Jeanson 2009). The average width of the inner barrier reef flat, measured from 18 measurements of aerial images (Google Earth) is 360 m.

Ecosystem vulnerability categories established by the UICN (2015) for mangroves were used to weight mangrove services of Mayotte: 20, 40, 60, 80 and 100%, respectively, for habitat critically endangered (CR), endangered (EN), vulnerable (VU), near threatened (NT) and of least concern (LC).

The European Water Framework Directive (WFD) recommendation on seagrass beds classification was used for the weighting of ecosystem services. Five health status categories are used to assess ecosystem (bad, poor, moderate, good and high) to which will be associated the respective weighting coefficients 20, 40, 60, 80 and 100%.

Weighting of ecosystem services of CRAE by health status is poorly developed in the literature and few indicators are available to estimate the health status of coral reefs, mangroves and seagrass beds. WFD indicators have been created or are under development (Le Moal and Aish 2013; Dirberg 2015). For coral reefs ecosystems, coral and macroalgae covers are the major variables (Le Moal and Aish 2013), while for mangroves and seagrass beds, canopy height and density of plants/trees are often used (Dirberg 2015; Taureau et al. 2015).

Determination of indirect use monetary values

Determining indirect use monetary value is specific to each service and ecosystem. Carbon sequestration and production of fish biomass valuation use, respectively, the price market of a tonne of CO2 and kilogram for fish. Water purification and coastal protection functions are evaluated according to replacement cost and value transfer methods. The value transfer method was used to provide economic value of ecosystem services through a simple approach usable in different contexts and for comparison. This methodology, although questionable, was retained in the IFRECOR terms of reference for this study, essentially because it can be easily adjustable to any case study. Coastal linear length ecosystem and gross domestic product (GDP) are basically the only data necessary to obtain a gross estimate. This article provides guidance for conducting and refining such value transfers to facilitate its application despite the various constraints that make primary data collection impractical.

The coastal protection service value is calculated using the method of costs replacement by artificial breakwater-like structures such as:

\[ PC_i = \left( C_i \times E_i \times PIB_m \times T_i \right) / PIB_r \]  
(1)

with:

- \( PC_i \) = value of coastal protection for ecosystem i (€/year),
- \( C_i \) = cost of producing a man-made structure providing the same service of coastal protection as ecosystem i (€/km/year or €/km²/year),
- \( E_i \) = coastline or surface of ecosystem i (km or km²),
- \( PIB_m \) = GDP/capita of Mayotte (€),
- \( PIB_r \) = GDP/capita of reference study area (€) and
- \( T_i \) = type of protection provided by ecosystem (between 0 and 1 for service provided, respectively, between 0 and 100%).

The water treatment value is obtained from the estimated replacement cost of coastal waters natural purification functions by technological artefacts such as:

\[ TE_i = \left( C_i \times E_i \times PIB_m \right) / PIB_r \]  
(2)

with:

- \( TE_i \) = value of water treatment provided by ecosystem i in Mayotte (€/year),
- \( C_i \) = water treatment reference value per unit of area of ecosystem i (€/km²/year),
- \( E_i \) = total surface area of ecosystem i providing a type of water treatment (km²),
- \( PIB_m \) = GDP/capita of Mayotte (€) and
The value of carbon sequestration services is obtained by estimating the amount of carbon assimilated by the ecosystem multiplied by the average price of a tonne of CO₂ according to the following equation:

$$\text{SQ}_i = A_i \times E_i \times \text{PCO}_2$$  \hspace{1cm} (3)

with:
- **SQ**ₐᵢ = value of carbon sequestration for ecosystem i (€/year),
- \( A_i \) = \( \text{CO}_2 \) absorption rate for ecosystem i (t\text{CO}_2/km²/year),
- \( E_i \) = total area of ecosystem i (km²) and
- \( \text{PCO}_2 \) = average price of a tonne of \( \text{CO}_2 \) (€).

The production of fish biomass is calculated from the estimated value of catchable (and marketable) biomass using the following equation:

$$\text{PB}_i = B_i \times T_i \times E_i \times \text{VA}$$  \hspace{1cm} (4)

with:
- **PB**ᵢ = biomass production value for ecosystem i (€/year),
- \( B_i \) = average biomass production per unit area for ecosystem i,
- \( T_i \) = portion of marketable and exploitable species (between 0 and 1),
- \( E_i \) = total area of ecosystem i and
- \( \text{VA} \) = average value added per kilo of fish for the considered region.

**Results**

**Marine ecosystems mapping**

Coastal ecosystems of Mayotte consist of coral reefs, mangroves and seagrass beds with respective areas of 342 km² (Andréfouët et al. 2008), 8.5 km² (UICN 2015) and 7.6 km² (Loricourt 2005 – see Figure 1). Coral reefs comprise barrier reefs (266 km² – 208 km), fringing reefs (47 km² – 195 km) and internal lagoon reefs (30 km² – 18 km) forming a double barrier in the southwest of the island (Guilcher et al. 1965; Thomassin et al. 1989; Wickel and Thomassin 2005; Andréfouët et al. 2008). The large area of coral reefs of Mayotte comes from the geological history of the

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**Figure 1.** Geographical distribution of CRAE of Mayotte – Modified from Gigou et al. (2009). Copyright 2017 by Agence des Aires Marines Protégées. Adapted with permission.
island and the subsidence effect (sinking of the island under its own weight), causing the formation of the lagoon and the barrier reef. The lagoon area is four times the land surface (Thomassin et al. 1989; Mirault and David 2009). The relief is the result of an intense past volcanic activity. Sixty-three per cent of the surface of Grande-Terre is characterised by slopes greater than 15% and/or located at more than 300 m altitude.

Mangroves spread over a linear strip of 76 km and an area of 8.5 km², covering 30% of Mayotte coast (UICN 2013). They are only located in bays and the few flat areas of the coastal zone. The nomenclature of mangrove of Mayotte comes in four ecological assemblages, from land to the sea: salty marshes (6%), rear mangroves (22%), central and internal foreshore mangroves (55%) and the pioneer fronts of *Sonneratia alba* (17%).

Eleven seagrass species have been found in Mayotte. Generally multi-specific, 56% of seagrass beds are located near the barrier reef on the eastern part of Mayotte, 39% close to the fringing reefs of Grande-Terre and 5% around Mtsamboro and Karoni islets (Loricourt 2005). They thrive on sandy substrates outside reef flats areas but the depth of the lagoon (30 to 45 m) does not offer optimal light conditions for the development of the Indian Ocean seagrass species.

**Health status of coral reef and associated ecosystems**

The health status of coral reef varies according to geographical sectors related to the 1998 and 2010 bleaching events (Nicet et al. 2012; Eriksson et al. 2013). Beside, the crown-of-thorn starfish (*Acanthaster planci*) that feed on corals destroy large surfaces during proliferation outbreaks (Gérard et al. 2008; Gigou 2011). Beyond the pressures of natural origin, coral reefs (particularly, fringing reefs) are affected by demographic pressures, such as the deterioration of coastal water quality, hyper-sedimentation, trampling upon reefs (shore fishing) and destructive fishing techniques. The health status of coral reefs (Wickel and Thomassin 2005; PARETO 2013) of Mayotte (Figures 2 and 3) is generally cited as degraded, but some areas show high coral cover.

Urban development and expansion of human activities along the coastline are the main factors of degradation of mangroves, including the accumulation of macro waste and wastewater discharge of all watersheds (Herteman 2010; Thongo 2016). According to the assessment criteria of the Red List of French ecosystems (UICN 2015), the salt marshes (50 ha) and the rear mangrove (190 ha) are the most threatened habitats, ranked ‘Critically Endangered’ (CR). The central and internal foreshore mangroves (465 ha) are classified as ‘Least Concerned’ (LC). The pioneer fronts of *Sonneratia alba* (141 ha) are listed ‘Vulnerable’. Jeanson (2009) evaluates the regression of mangrove surfaces by 5.5% between 1950 and 2003 (Figure 4).

Finally, the seagrass ecosystems, poorly studied in Mayotte, with the exception of specific feeding grounds for the green turtle populations, *Chelonia mydas* (Ballorain et al. 2010), show signs of deterioration that cannot yet be specified. The deterioration of water quality, hyper-sedimentation and trampling, are, in this respect, the main threats from human activities. The crossover study between the distribution of seagrass beds and the quality of water bodies highlighted that 7.6 ha and 296.4 hectares of seagrass beds are subjected...
to water bodies of, respectively, poor and moderate quality (between Mamoudzou and Bandrélé), and 456 ha are located in a water body presenting ‘good’ ecological environmental conditions, as is the case of the lagoon and offshore water masses (Figure 5).

Surface data and health status from each ecosystem is synthesised in Table 3.

**Production functions and weighting factors**

The level of ecosystem services varies according to the health status and/or the vulnerability of ecosystems.

**Coral reefs**

The weighting calculations for coral reefs are complex. Indeed, as long as the physical structure of the reef remains, coastal protection function is poorly affected by the health status of the ecosystem and weighting factors are never below 90%, despite low coral cover. The average outer barrier reef width is 1150 m, what influences also coastal protection. Efficiency varies between 95.5 and 98.5% depending on the coral cover. For the inner barrier, the average width of the reef is 360 m and wave energy attenuation rate ranges between 92.7 and 97%.

Finally for the fringing reef, the average width is 425 m, and the coastal protection function is fulfilled at 93.4% to 97.4% depending on the coral cover (Table 4).

The biomass production service is not weighed in the case of coral reefs as the fish biomass assessment is based on actual fish assemblage data in the current state of the ecosystem. This is a direct measurement.

**Mangroves**

Weighting factors for mangroves follow the vulnerability criteria from UICN (2015). Each vulnerability class is assigned a weight that is used in the monetisation of the coastal protection, water purification and carbon sequestration services (Table 5). The fish biomass is a direct estimate from aerial visual census (Guezel et al. 2009) and Djarifa fishing statistics in Mayotte (Jamon et al. 2010).

**Seagrass**

The weighting factors for seagrass beds are based on the ecological state of the water bodies presented in Figure 5. For instance, a seagrass patch located within

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**Figure 3.** Health status of the fringing reefs of Mayotte – Modified from Wickel and Thomassin (2005, p. 12). Copyright 2017 by Wickel J. and Thomassin BA. Adapted with permission.
a water body of moderate quality will be assigned a weighting factor of 0.6 (Table 5), used in the monetisation of production functions.

Monetary value of ecosystem services

Coastal protection service

The cost of installation of a breakwater system is approximately € 4000/m (France 2014 – GDP/cap.: € 25846) with an annual maintenance cost equivalent to 4% of the installation cost (Balouin et al. 2012). Taking into account the import taxes of 30% and the amortization over 10 years of the structure, the annual cost is € 728/m or € 728,000/km. The transfer of value based on the GDP per capita (€ 7900 in 2014) and taking into account of the weighting factors (Table 5) results in an annual cost of € 222,518/km. Overall, monetary values of coastal protection by coral reefs reach about € 45.1 million/year for the outer barrier, € 3.8 million/year and € 40.9 million/year, respectively, for inner and fringing reefs where these values are considered optional (Table 6).

Seagrass beds reduce waves’ energy by 40% (Fonseca and Cahalan 1992; Christianen et al. 2013). Using the same value transfer mode than the one used for reefs, the annual value of coastal protection reaches € 63907/km according to the weight factors described in Table 5.

Spurgeon et al. (2004) and Cooper et al. (2009) put forward replacement values of mangroves by respective artificial structures of € 254,559/km²/year in Samoa (GDP/hab: € 2126) and € 239,204/km²/year in Belize (GDP/hab: € 4219). Considering an average value of € 88.2 per GDP unit, the value of coastal protection service of mangroves in Mayotte reaches annually € 491,077/km², taking into account the GDP per capita during the transfer of value and health status of mangroves (Table 5, supra).

The ‘optional’ values of coastal protection provided by mangroves and seagrass reach, respectively, € 4.2 million/year and € 2.7 million/year. Reported to the km² of each ecosystem, fringing reef has the highest value (869 K€/year), while barrier reef and inner barrier reef have respective values of 169 K€/year and 127 K€/year. Finally, mangroves and seagrass have

Figure 4. Evolution of mangrove surfaces (ha) over the 1950–2003 period. The seaward arrows illustrate growth of mangroves; the landward arrows represent a regression of mangroves areas – Modified from Jeanson (2009, p. 146). Copyright 2017 by M. Jeanson. Adapted with permission.
Figure 5. Distribution of seagrass areas in Mayotte and environmental status of coastal water bodies – Modified from Loricourt (2005, p. 43), and PARETO, ASCONIT (2013, p. 143). Copyright 2017 by Loricourt A., PARETO and ASCONIT. Adapted with permission.

Table 3. Summary of surface data and health status of coastal ecosystems in Mayotte (Indian Ocean).

| Coral reef | Coral cover % | 0–5 | 6–10 | 21–50 | 51–80 | >80 |
|------------|---------------|-----|------|-------|-------|-----|
| Area (km²) | 96            | 84  | 51   | 47    | 21    |     |

| Mangroves  | Vulnerability | Area (km²) | CR | EN  | VU | NT | LC |
|------------|---------------|-------------|----|-----|----|----|----|
|            | Area (km²)    |             | 2.40| -   | 1.41| -  | 4.65|

| Seagrass   | Ecological state | Area (km²) |
|------------|------------------|-------------|
|            | Bad              | -           |
|            | Poor             | 0.076       |
|            | Moderate          | 2.96        |
|            | Good              | 4.56        |
|            | High              | -           |

Table 4. Weighting of coastal protection service associated to coral reefs of Mayotte (Indian Ocean).

| Type of reef | Outer barrier | Inner barrier | Fringing reef |
|--------------|---------------|---------------|---------------|
| Reef flat width (m) | 1150 | 360 | 425 |
| Coral cover (%) | Linear (km) | Weighting factors (%) | Linear (km) | Weighting factors (%) | Linear (km) | Weighting factors (%) |
| 0–5          | 45            | 95.5          | 0.8           | 92.7          | 71.2           | 93.4          |
| 6–20         | 36            | 96.0          | 4.2           | 93.3          | 70.6           | 94.0          |
| 21–50        | 22            | 96.8          | 3.1           | 94.4          | 41.9           | 95.1          |
| 51–80        | 27            | 97.8          | 3.1           | 95.9          | 11.1           | 96.4          |
| >80          | 11            | 98.5          | 6.8           | 97.0          | 0.2            | 97.4          |

* Coral cover on the barrier and the reef flat are considered equal.
values per km² of 491 K€/year and 353 K€/year, respectively.

**Water purification service**

Coral reef organisms have limited ‘water purification’ capabilities, evaluated by De Groot et al. (2012) to US $ 8500/km²/year, or € 7752/km²/year (Table 6).

As reported by Lal (2003), the value of treatment of inland waters by mangroves in Fiji represents € 174,200/km²/year for a GDP/capita of € 5078 in 2003. According to the transfer of values for Mayotte, and the health status of mangroves, the value of water treatment by mangroves reaches annually € 191,435/km².

According to Costanza et al. (1997), the value of the water purification service produced by seagrass beds is US$ 19002/ha/year or € 1,732,255/km²/year (Table 6). This result is to be interpreted with caution because it is the only existing value from the literature without clarification on the monetary valuation of this service (Barbier et al. 2011). If we consider the weighting factors (Table 5), the value of water purification for seagrass beds is € 1,243,759/km²/year.

The values of water purification services vary greatly according to ecosystems. Coral reefs have a total value of € 2.7 billion/year, but in the absence of data on the water purification by algae, it is difficult to quantify the weighted value. It is likely that the real value of water purification by coral reefs with nearly 60% algal cover is substantially higher.

Mangroves water purification represents up to € 1.6 million/year, with a value per unit area of 191 K€/km²/year, well below that of seagrass beds which is € 1.2 million/km²/year. The monetary value of the water purification service provided by seagrass beds in Mayotte reaches almost € 9.5 million/year.

**Carbon sequestration**

Considering the stock market value of a tonne of CO₂ equal to € 6.12 (2015) and the values of net productivity of mangroves (3667 tCO₂eq/km²/year) and seagrass (435 tCO₂eq/km²/year), monetary values of carbon sequestration for these two ecosystems are, respectively, 134 KE/year and 15 KE/year. The value of carbon sequestration per km² for mangroves is 8.3 times that of seagrasses (€ 15853 against € 1911). This difference is explained by the size of the plants structuring each ecosystem.

**Fish biomass production**

The average biomass of commercial fish species of Mayotte coral reefs is estimated at 95.8 g/m² (Wickel

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**Table 5. Weighting of ecosystem services of mangroves and seagrass of Mayotte (Indian Ocean).**

| Ecosystem services | Mangroves | Seagrass |
|--------------------|-----------|----------|
|                     | Health status | Vulnerability | Area (ha) | Ecological state | Area (ha) | Weighting factors (%) |
| CR                 | Bad        | 240       | 134,113   | > 2,651,184     | > 7,612 (2015) | 20 |
| EN                 | Poor       | -         | 3,816,249 | 1,619,544      | 491,077     | 40 |
| VU                 | Moderate   | 141       | 1,619,544 | 296,4          | 45,089,035  | 60 |
| NT                 | Good       | -         | 45,089,035| 45,089,035     | 89,007      | 80 |
| LC                 | High       | 465       | 353,170   | 353,170        | 22,442      | 100 |

* CR: Critically endangered; EN: Endangered; VU: Vulnerable; NT: Near Threatened; LC: Least Concerned (IUCN 2015).

**Table 6. Monetary values of ecosystem services provided by CRAE of Mayotte (Indian Ocean).**

| Ecosystem services | Length (km) | Area (km²) | Max Unit value | Monetary value (€/year) | Value per km² (€/year) |
|--------------------|-------------|------------|----------------|-------------------------|------------------------|
| Coastal Protection |             |            |                |                         |                        |
| Outer barrier reef | 210         | 222,518    | 45,089,035     | 169,508                 |                        |
| Inner barrier      | 18          | 222,518    | 3,816,249      | 127,208                 |                        |
| Fringing reefs     | 195         | 222,518    | 40,861,390     | 869,391                 |                        |
| Mangroves          | 47          | 695,200    | 4,154,515      | 491,077                 |                        |
| Seagrass           | 42          | 89,007     | 2,684,095      | 353,170                 |                        |
| Water treatment    |             |            |                |                         |                        |
| Coral reefs        | 342         | 7752       | > 2,651,184    | 7752                    |                        |
| Mangroves          | 8.46        | 271,008    | 1,619,544      | 191,435                 |                        |
| Seagrass           | 7.6         | 1,732,255  | 9,452,569      | 1,243,759               |                        |
| Carbon sequestration* |         |            |                |                         |                        |
| Coral reefs        | 342         | -          | -              | -                       | -                      |
| Mangroves          | 8.46        | 22,442     | 134,113        | 15,853                  |                        |
| Seagrass           | 7.6         | 2662       | 14,527         | 1911                    |                        |
| Fish Biomass Productionb | |            |                |                         |                        |
| Coral reefs        | 342         | 120 t/km²/year | 92,340,000 | 270,000                |                        |
| Mangroves          | 1.41        | 25 t/year  | 75,000         | 53,191                  |                        |
| Seagrass           | 7.6         | 1 t/km²/year| 16,370        | 2154                    |                        |

*Value of a tonne of CO₂ in the stock market: 6.12 € (September 2015).

The value added per kilo of fish is € 3 (Own survey 2015).
et al. 2005) and 82.8 g/m² for the stations of the Coral Reefs Observatory (Chabanet 2002). The average value is either 90 g/m² or 90 t/km² for all the reefs of Mayotte.

The evaluation of fish biomass in mangroves is based on traditional fishery: djari fishing, exclusively women practice. The fishing gear, the 'lamba', is similar to a beach senne with a much smaller mesh. The fishing practice gathers a team of three to nine women for one to three djariñas. They target small pelagic and juvenile fish out of mangroves, within protected bays and on the reef flat at low tide (Jamon et al. 2010). The average number of djariña fishing trips in Mayotte was estimated at 1092 per year in 2009, of which 70% in mangroves (Guezel et al. 2009) or 764 djariña fishing/year. According to Jamon et al. (2010), the average weight of the catches of one fishing trip in mangroves is 32.8 ± 10.4 kg, or an annual total of approximately 25 ± 8 t/year (Table 6).

(Gullström et al. 2002) found that the exploited biomass of seagrass fish in Mozambique is approximately 1 t/km²/year. When transposed to Mayotte and by applying weighting factors (Table 5), the exploitable biomass accounts 0.72 t/km²/year.

The total biomass production value for coral reefs reaches 92 M€/year, much higher than the values for mangroves and seagrass beds, respectively, 75 K€/year and 16 K€/year.

The value per unit area (km²) helps to show the real marketable fishery potential of each ecosystem, reefs having the highest value (270 K€/year) compared to mangroves (53 K€/year) and seagrass beds (2 K€/year).

The economic value of indirect uses is estimated at € 151 million/year, of which € 140 million originates from coral reefs only, € 1.8 million from mangroves and € 9.5 million for seagrass (Table 7).

Coastal protection and biomass production are the two major ecological services, followed by the seagrass water purification capacity. Optional values associated with coastal protection from inner and fringing reefs, mangroves and seagrass add € 52 million. By reporting the IUV per km² of ecosystem, seagrass rank first with the highest value (€ 1.2 million/km²/year), followed by coral reefs (€ 0.4 million/km²/year) and mangroves (€ 0.2 million/km²/year). These values reflect ecosystems in various health statuses. The total VUI would be € 188 million if ecosystems were in pristine conditions, which represents € 37 million more. Considering the optional coastal protection values, the total economic value would be € 245 million for ecosystems in very good condition, that is, € 42 million more than the current value of € 203 million.

**Discussion**

The deterioration of ecosystem health status changes the amount of services produced. However, services are not affected in the same way, as a specific function can increase in degraded ecosystems. This paradox is especially true for water purification and carbon sequestration services provided by coral reefs. When coral reefs are degrading along with algal overgrowth, the production functions increase due to the macroalgae capacities for water purification and carbon absorption. However, the coastal protection and biomass production functions are, respectively, hardly and moderately impacted by coral coverage as long as the physical structure of the reef remains. Indeed, coral reef organisms have limited or negligible ‘water purification’ abilities compared to seagrass beds (Costanza et al. 1997; De Groot et al. 2012). However, algae overgrowth, usually leads to the reduction of live coral cover (Hughes 1994; McManus et al. 2000; Mumby 2009), but contributes positively to water purification by absorbing part of the nutrients (Lapointe 1997). Considering the steep growth of macroalgae induced by the enrichment of coastal waters with nutrients and their ability to absorb excess nitrates and phosphates, the water purification service provided by degraded reef ecosystems will increase. A high economic value, not quantifiable in the present state of knowledge, is then allocated to a service provided by a degraded state of the original ecosystem. This production function would be minimal in a healthy reef ecosystem. It exists thereupon only because of the degradation of the ecosystem under pressures of anthropic origins. Carbon absorption by algae through photosynthesis is unequivocally proven and even comparable to that of seagrasses (Beer and Koch 1996; Hanelt et al. 2003) while it is questioned on healthy reef formations (Shaw et al. 2015). Eutrophic conditions in coastal waters of Mayotte promote algal

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**Table 7.** Overview of maximum IUVs and monetary IUVs gathered for the CRAE or Mayotte (Indian Ocean).

|                | CR       | M       | S       | Total      | Options    | Total + options |
|----------------|----------|---------|---------|------------|------------|-----------------|
| IUV max        | 172.5 M€ | 2.6 M€  | 13.2 M€ | 188.3 M€   | 57.0 M€    | 245.3 M€        |
| IUV calculated | 140.1 M€ | 1.8 M€  | 9.5 M€  | 151.4 M€   | 51.5 M€    | 202.9 M€        |
| %              | 81%      | 71%     | 72%     | 80%        | 90%        | 83%             |
| Total loss     | 32.4 M€  | 0.7 M€  | 3.7 M€  | 36.9 M€    | 5.5 M€     | 42.4 M€         |
| IUV/km²        | 0.4 M€   | 0.2 M€  | 1.2 M€  | 0.4 M€     | 0.6 M€     | 0.6 M€          |
growth; the function of carbon sequestration increases accordingly, as does the monetary value of this service.

Pascal et al. (2014) evaluated the carbon sequestration service for Mayotte at €2,380,000. In this article, the evaluation is based solely on the absorption of carbon dioxide, not taking into account the amount of carbon that has been stored for hundreds of years in the soil. Consequently, the value in this paper is 16 times lower than the previous stated value: €148,640. Valuation of carbon sequestration service varies greatly in the literature. The reason is the number of compartments to valued (soil and/or living biomass) and the number of processes (carbon storage and/or carbon absorption) included in the evaluation. Also, one of the major factors is to determine the value of one ton of carbon dioxide. According to Canu et al. (2015), the value of one ton of CO₂ is €19, which appears to be very conservative compared to the value of €97/tCO₂ reported by Van Den Bergh and Botzen (2014). In this article, the current market price is the reference (€6.12 in 2015).

Degradation of coral substrate and erosion of reefs are rather slow mechanisms: the changes occurring in ecosystems neither affect entirely the coastal protection service (Sheppard et al. 2005), nor the biomass production (Ainsworth and Mumby 2015). Other parameters influence the production of the service such as the presence of a barrier reef and the extent of the reef flat (Ferrario et al. 2014). Degraded coral reef communities hardly affect wave energy attenuation, reducing it by 10% maximum (Sheppard et al. 2005). The weighting by the health status is therefore not significant; the associated value remains high accordingly. Services of coastal protection and carbon sequestration are discussed in Pascal et al. (2014). Although very interesting, they used a detailed experimental approach based on the evaluation of avoided cost. As a result, coral reefs that would protect highly urbanized areas are worth much more than coral reef protecting pristine coastal habitats without any human infrastructures. In other words, if there is no infrastructure to protect, coral reef is worth nothing in terms of coastal protection, which is a very limiting approach. As a result, Pascal et al. (2014) evaluated the coastal protection in Mayotte at €10.5 million while in our article the value reaches €45.1 million.

The progressive and rapid shifts between coral dominant communities and dense algal populations affect the structure of fish communities in coral reefs (Wilson et al. 2006), but not necessarily the biomass. The complex three-dimensional structure of the reef is determining for the presence of dense fish populations. The proportion of herbivorous fish is increasing in algae dominated environments. According to Ainsworth and Mumby (2015), it appears that the total loss of coral cover leads to a reduction of 39% of reef fishery landings in Eastern Indonesia. McClanahan et al. (2016) found that natural fish biomass in pristine coral reefs in the Western Indian Ocean can reach 120 t/km². Using this later value, the maximum monetary value of fish biomass production in Mayotte reaches €123 million, that is, €31 million more than the monetary value of €92 million obtained. Pascal et al. (2014) evaluated the commercial biomass production service for both commercial and self-consumption fisheries related to CRAE such as coastal fisheries, deep-sea fishing and supervised sport fishing and reached an annual value of €9,180,500. Our results refer to the fish biomass production (of which a portion forms also a provisioning service as part of the biomass subjected to fishing) and represent the ecosystem ability to produce exploitable fish biomass worth €92,340,000 per year, which significantly differs from the previous cited report value.

Mangroves and seagrass beds of Mayotte actively contribute to the purification of coastal waters and nutrient absorption. This ecosystem service generates the highest monetary value (respectively, €1.6 million and €9.5 million, representing 89 and 99% of the total value of indirect use services provided by these ecosystems). However, even if these ecosystems absorb excess nutrients, the fact remains that poor water quality negatively impacts their functioning. According to Herteman (2010), the wastewater effect on mangrove crabs population in Mayotte translates into a modification of the nitrification/denitrification process (bioturbation) and over time significantly perturbs the mangrove ecosystem. For seagrass beds, excess nutrients favours algae growth at the cost of seagrass plants (Duarte 2002).

Besides the need to maintain production functions by implementing specific measures to mitigate or even annihilate the effects of human activities, coastal ecosystem preservation also requires conservation of iconic species, some of which are listed on the red list of UICN. Seagrass beds are important feeding areas for dugongs (Dugong dugong – Vulnerable), less than 10 individuals remain in the lagoon of Mayotte (Pusineri et al. 2013), green turtles (Chelonia mydas – Endangered) and, to a lesser extent, hawksbills turtles (Eretmochelys imbricata – Critically Endangered). In this context, the preservation of dense and healthy seagrass beds is a key issue, associated to strong regulations to limit poaching and risks of collision with boats. The decline of seagrass beds has much more serious and durable consequences than the sole disappearance of this ecosystem (Waycott et al. 2009), given the close relationship with associated ecosystems.

The marine and coastal environments of Mayotte have been deteriorating for several decades. Between
1989 and 2004 (15 years), the coral cover of fringing reefs has decreased by 60% (Wickel and Thomassin 2005), while between 2005 and 2013 (8 years) that of barrier reef has shrunk by 15% (PARETO 2013). Degradation also occurs in mangroves where Sonneratia pioneer fronts have diminished by 43 ha in 30 years (Jeanson 2009). Such changes affect the production functions of ecosystems. For pristine coastal environments, the maximum value of these services would reach € 188 million/year (up to € 245 million with optional values of coastal protection). Given the actual state of degradation of ecosystems, the IUV calculated (€ 151 millions) is € 37 million lower than the optimal value. If we consider the optional values, the IUV calculated reaches € 203 million (€ 42 million lower than the optimal value). The gradual degradation of ecosystem health in recent years is the principal reason. Natural events such as increased water temperature leading to coral bleaching, hurricanes and proliferation of crown-of-thorn starfish Acanthaster had major contribution to the changes observed. However another factor, much more significant, is imputable to public inaction, that is, the lack of political consideration, laissez-faire attitudes and the deficient interest in understanding the ecological and economic functions of marine coastal environments. Thus, overall the lacking € 37 million/year in services may be interpreted as the cost of public non-intervention in Mayotte CRAE management.

The results of the Mayotte study have been presented to the Environment, Planning and Housing Directorate. The economic development of Mayotte is a priority, which relegates environmental imperatives in the background. The same observation can be made currently to all French Overseas Collectivities where IFRECOR works. The lack of understanding and additional mechanisms to integrate economic evaluations in the decision-making process makes unlikely the use of the results of such work, and constitutes a very critical issue for the marine park of Mayotte.

It is expected that the IUV will continue to decrease in the near future because too little is done to counter pollution by sewage releases. In 2015, only the Mamoudzou municipality was equipped with a functional water treatment plant which can process discharges of 10000 inhabitants, while the total population of the island exceeds 235,132 inhabitants. The shortage of water treatment therefore degrades the coastal water quality, meaning the presence of heavy metals, polyaromatic hydrocarbons and polychlorobiphenyls (Thomassin et al. 2010). According to Duprey et al. (2016), eutrophication of coastal waters causes a decrease in coral cover and a decrease in species richness. Therefore, nutrient loading is a key parameter to control, prior to protect coastal marine ecosystems.

Protection of CRAE is a major challenge for the island of Mayotte in the current context of uncontrolled urbanisation of the coast (PADD 2008).

**Conclusion**

The total value of indirect uses provided by CRAE of Mayotte reaches € 176 million/year. This amount is significant to the local economy of Mayotte since it is higher than the added value generated by the agriculture: 95 M€, the industrial: 57 M€ or the construction sector: 135 M€ (INSEE 1975–2017). The estimated values of coastal protection (€ 30 million) and biomass production (€ 81 million) by coral reefs and those of water purification services provided by mangroves (€ 1.6 million) and seagrass beds (€ 9.5 million) emphasise the economic interest in conservation efforts for the preservation and restoration of ecosystems. Coral reefs contribute to 91% of the economic value derived from the four ecosystem services presented in this article. However, the ecosystem with the highest monetary value, relative to one square kilometre, is seagrass beds (€ 1.2 million), followed by reefs (€ 0.4 million) and mangroves (€ 0.2 million).

Human activities contribute to the degradation of Mayotte CRAE including remote reefs, located more than 10 km away from the coast. One third of these reefs have a coral cover between 0 and 20%. This assessment is worrying in a context of economic development and increasing risks of degradation. Consequently, the economic loss from indirect use values reaches € 32 million.

This study highlights the close link between environmental conservation and economic valuation challenges, and should provide support for future policy decisions on coastal management and marine environmental protection. The paradox highlighted that a higher monetary value is assigned to a deteriorating ecosystem, however, shows the limits of the economic evaluation. It is therefore necessary to accompany the results with interpretation elements, essential to public decisions.

Several lines of study can be sketched in this regard. This involves, for example, quantifying the water purification function by seagrass beds, but also by algae that are becoming particularly important among reef communities. In order to monetise this service, it is necessary to estimate (1) the absorption rate of nutrients by an ecosystem or organism and (2) the replacement cost of a technological artefact (water treatment plant) for an equivalent water treatment level.
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