



Assessment method of the sea turtle-nesting habitat of small reef islands

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Abstract

The coral islets in the lagoon of New Caledonia are a major breeding and nesting site for various species. Many species reproduce and nest there, whether they are Chelonians (green turtles and loggerhead turtles), offshore seabirds (Procellariidae: shearwaters, petrels ...) or more coastal (Laridae: terns, ospreys ...) or sqamata (sea krait: *Laticauda saintgironsi* and *Laticauda laticaudata*). These species are dependent on the persistence of the islets in which they find the necessary conditions for nesting. Previous research has shown that these islets can evolve very rapidly at a yearly to decadal timescale. These geomorphological evolutions lead to surface area variations as well as geomorphological, topographical and land cover changes. These changes may lead to an evolution of the sea turtle nesting habitat: reduction of suitable areas for nesting and changes of the accessibility to the nesting sites. The goal of our work is to propose a method that allows to determine, map and quantify the more or less favourable character of the islets coasts to the nesting of sea turtles. Using several parameters, an indicator of the nesting attractiveness of coast is constructed and mapped. This method was applied to 13 coral islets in the southern lagoon of New Caledonia. Comparison of the results with the location of sea turtle nests acquired during the 2020 campaign attest the relevance of the method.

Keywords Sea turtle · Nesting habitat · Coral islet · Geomorphology · Sedimentology · indicator · South Pacific · New Caledonia

Introduction

Problematic

Preferred sea turtles nesting sites are sandy backshores, which are very sensitive to environmental changes and hydrometeorological events such as storms and cyclones. Evolution of the environmental conditions (geodynamics, wave climate, short and long term sea level rise, intensity and frequency of storms and cyclones, tidal and wave induced currents) lead to morphological changes of the fore-beach, erosion of the beaches and the backshore (Ballu et al. 2011; Dickinson 1999; Faure et al. 2010; Ford and Kench 2014; Ford 2012, 2013; Ouillon et al. 2010; Ramsay 2011; Stoddard 1990; Testut et al. 2015; Woodroffe 2008; Xue 1997; Yates et al. 2013).

In the context of sea level rise induced by climate change, coastline retreat and coastal erosion are expected consequences Nicholls and Cazenave 2010; Nunn 2013; Nurse

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et al. 2014; Roy and Connel, 1991; Webb and Kench, 2010; Woodroffe et al., 2008). It is in this perspective that some work has been carried out, to determine the impact of the latter on turtle nesting habitats (e.g. Fish et al. 2005, Long et al. 2011).

New Caledonia is firstly of interest in terms of biodiversity Bozcedon et al. 2005; Brischoux and Bonnet 2009; Debenay and Fernandez 2009; Jimenez et al. 2011; Pandolfi and Bretagnolle, 2002) and is also a major breeding and nesting area for sea turtles in the South Pacific (Read et al. 2015). Turtles come to nest on the beaches of the Grande-Terre of New Caledonia (Read et al. 2013) and the Loyalty Islands (Read et al. 2015) but also on coral islets beaches (Mounier 2007; Oremus and Mattei 2017). The islets of Entrecasteaux and Chesterfields are nesting sites for green turtles (*Chelonia mydas*) while those of the lagoon of Grande-Terre are frequented by loggerhead turtles (*Caretta caretta*).

However, these islets are fragile, threatened and their morphological evolution and surface areas decrease over time (Garcin et al., 2016). These morphological evolutions have an impact on the beaches' topography as well as on the land cover (herbaceous, shrubby or wooded), the beachrock outcropping, the backshore granulometry and accessibility. All these factors contribute to the modification of the aptitude of each islet to accommodate nesting sites for numerous species, such as chelonians or offshore birds.

Sea turtles do not nest on all available islets and seem to favour specific areas of each islets used (Oremus and Mattei 2017). This study will focus on identifying how the morphological characteristics of the islets influence the nests' repartition.

Sites

The Grande-Terre is New Caledonia's main island (South Pacific, between 18° and 23°S and 164° and 167° E, inset Fig. 1). It is a long, narrow island 400 km in length and 50 km in width (about 16,000 km² in area) located on the margin of the Coral Sea's margin, halfway between Australia and Fiji. The Grande-Terre island is surrounded by a barrier reef (linear extent of about 1,600 km) enclosing a large lagoon covering about 24,000 km² (Bonnet et al. 2014). Fifteen thousand square kilometres of New Caledonia's lagoon have been listed as UNESCO World Heritage Site since 2008 and New Caledonia's entire maritime area (1,300,000 km²) became the Coral Sea Nature Park in April 2014. The Western barrier reef is sub-continuous with few passes, while the Eastern barrier is irregular with numerous passes. The lagoon is relatively deep on the Eastern side with depths greater than 30 m, while the Western lagoon is shallow with depths under 15 m (Coutures, 2000; Flamand

2006; IFRECOR.NC¹, SHOM² data). The Southern and Northern parts of the lagoon are very wide, with distances between the barrier reef and Grande-Terre ranging from 20 to 31 km. In the middle part of the island, the lagoon narrows to just 1.7 km.

There are two types of islands in the lagoon: (i) elevated islands with rock outcrops basement; (ii) low-lying islets (cayes; Garcin et al., 2016) made up of bioclastic sands associated with coral reef patches. The rocky islands vary in size and generally have a relatively abrupt landform, while the low-lying islets are smaller in area and very low in altitude (generally up to 2 m). Sea turtles' nests are mainly observed on beaches of the second type.

Method

Determining the turtles' nesting habitat requirements

The loggerhead and green turtles, although of different sizes, have comparable requirements in terms of nesting criteria. The first phase of study focuses on the analysis of islets' characteristics in relation with turtles' nesting habitat. This concerns the geomorphology, sedimentology, land cover and the general context of the islet. Once the inventory of these factors is made, it is a matter of determining how to qualify them from direct observations (field data) and from indirect sources such as satellite images, aerial photographs or any other useful sources (geo-referenced databases). The objective is to provide an indicator value for each factor and then to carry out a multi-criteria analysis to determine a unique indicator of nesting conditions. Relevant indicators defining their favourable, unfavourable or critical characteristics are selected. Methods for evaluating and mapping these indicators are proposed.

For each homogeneous islets' coastline segment, a simple multicriteria analysis of indicators is realized. This is comprised of five possible values from "very favourable" to "very unfavourable". The annual turtle nest inventories made by biologists are put into perspective using the turtle nesting indicator maps for each islet in order to validate the correlations and causality links.

¹ French Coral Reef Preservation Initiative.

² Service Hydrographique et Océanographique de la Marine: the French Navy's hydrographic and oceanographic service.

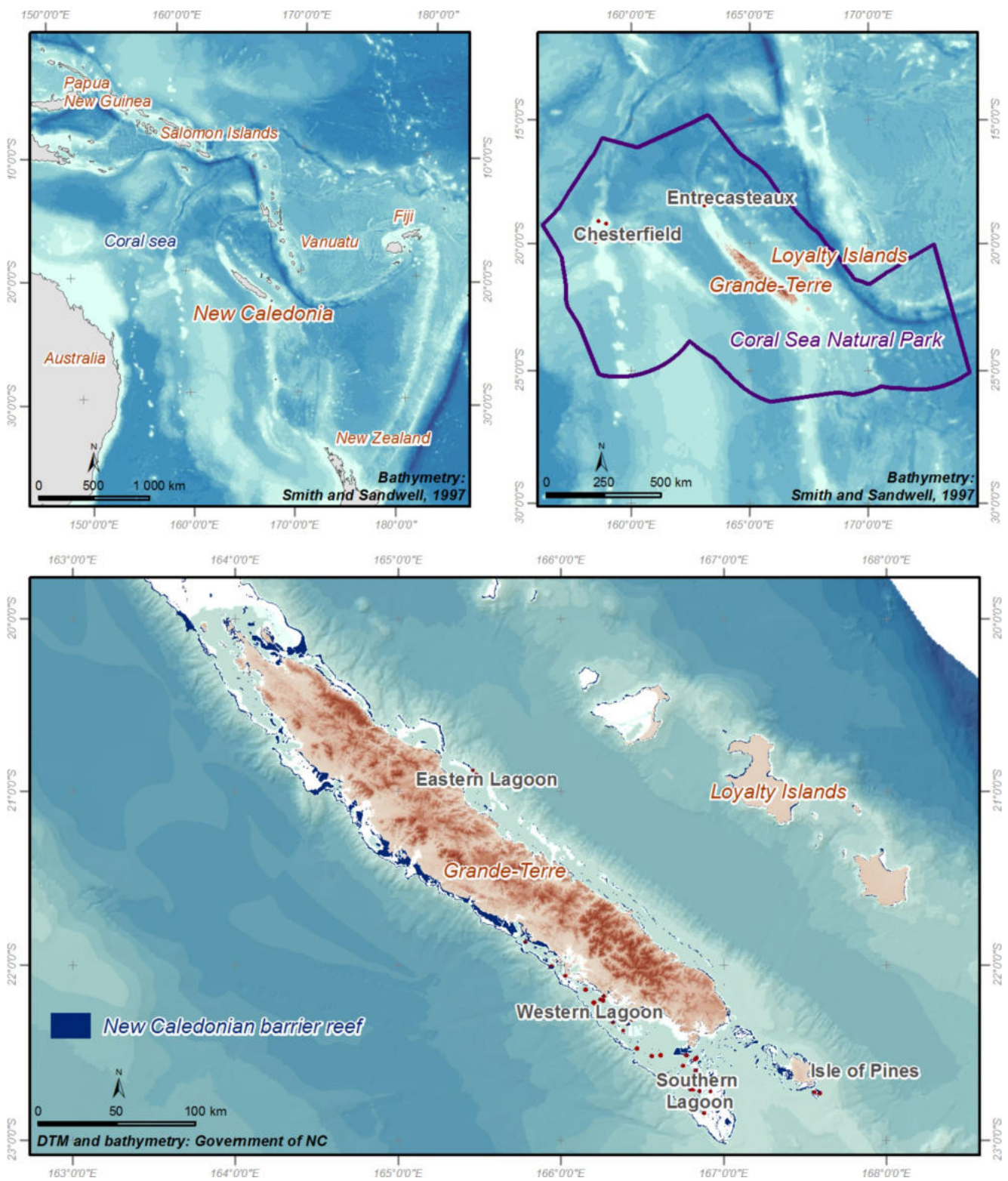


Fig. 1 Location map

Identification and characteristics of turtles’ nesting criteria

Introduction

Turtles nest in areas above high tide level in areas covered

by thin sands, without vegetation or with low-density herbaceous vegetation (Hays et al. 1995; Wood & Bjorndal, 2000; Kamel and Mrosovsky 2004; Read et al. 2020). Sometimes some nests are observed behind shrubby vegetation's limit when its density is low. Nests are marked by an elliptical shaped surface that was first dug and then covered and stirred. Failed nesting attempts are indicated by a bowl or funnel morphology. This shape corresponds to the beginning of nest excavation, which did not succeed and was therefore not plugged.

The stopping of digging by the turtle can be linked to: (i) the sediment's granulometry if the sediment is too coarse in depth to be favourable for nesting; (ii) the presence of roots in depth; (iii) an exogenous disturbance at the time of digging.

In the event of failure, the turtle will try to return quickly to lay eggs near or on another site of the same island or even on other islet (Beyneto & Delcroix, 2005; Murphy and Hopkins-Murphy 1990).

Thus, criteria can be grouped into two families:

- Criteria defining the nesting site's availability and quality,
- Criteria defining the nesting site's accessibility.

A suitable surface area for turtle nesting

Description.

To establish their nests, turtles need an available surface area on the backshore of either bare sand or sand with a low vegetation cover. The greater the area available, the greater the number of nests may be. If the surface area is too limited and the number of turtles is high, there is a risk that the nest digging will be done at the expense of a pre-existing one, resulting in the destruction of the latter. In this case, the rate of hatchlings reaching maturity per number of nests will be reduced dramatically.

The upper beach and backshore areas may decrease if they are affected by erosion. On the coastal segments affected by erosion, one notes their disappearance and the appearance and development of an erosion scarp (Garcin et al., 2016). When the erosion affects the entire islet coast, these areas can be completely destroyed. In contrast, some islets have stable or accretionary segments. A gently sloping beach develops while the backshore area increases over one or more years. These new areas are favourable for nesting. Finally, it should be pointed out that certain islet segments are affected, over several years or even decades, by alternating phases of erosion and accretion. In this case, the attractiveness in terms of nesting will vary according to these phases.

Beachrocks

Description.

Numerous beachrocks are present around New Caledonian islets. According to their morphology and intrinsic characteristics, beachrocks can constitute a constraint or an obstacle to turtle nesting. Based on our knowledge of New Caledonian islets (Garcin et al., 2016) we have identified eight beachrock types/characteristics useful to determine their influence on turtle nesting (Table 1, Online Resource 1):

- Slope in line with that of the beach and at the same topographic level than the beach. In this case the beachrock does not constitute an obstacle to nesting;
- Slope in line with that of the beach but with a higher elevation than the beach level; the beach rock constitutes an obstacle to nesting depending on the difference in elevation between the two;
- Beachrock beds highly oblique relative to the actual beach orientation. If this latter is not in relief it doesn't constitute a constraint for nesting;
- The beachrock slope is inverted in relation to the beach slope: beachrock can constitute an obstacle for nesting;
- The beachrock is multi-beds and stair-like: this case is not necessarily an insurmountable obstacle for adults beaching for nesting at high tide. Conversely, it constitutes a trap for juveniles going to sea after hatching. This obstacle highly increases their mortality rate. In this specific case, the beachrock does not prevent nesting but drastically lowers its reproductive success ;
- Raised beachrock (relative to actual sea level): in this case, the beachrock is an insurmountable obstacle,
- Chaotic dismantled beachrock constituting an obstacle for turtle nesting ;
- Highly weathered and/or holed: is unfavourable for turtle nesting.

Table 1 Assessment of the impact of beachrock types on turtle nesting site accessibility

Beachrock characteristics	Nesting site accessibility	Indicator Value
No beachrock	Very favourable	2
Very oblique in relation to the shore	Very favourable	2
Inline slope without protruding	Favourable	1
Inline slope with protruding	Unfavourable	-1
Inverted slope	Unfavourable	-1
Stair-like multi-beds	Unfavourable	-1
Weathered and holed	Unfavourable	-1
Dismantled	Highly unfavourable	-2
Raised	Highly unfavourable (inaccessible)	-2

The beachrocks have various ages from millennia to several centuries. Due to the islets shape's changes in relation to erosion and accretion processes, beachrocks can appear during erosion phases, and conversely, they can be covered by sand during accretion phases. These changes can occur rapidly (few hours to few days) during a single energetic hydro-meteorological event (storm, cyclone, southern swell...).

Erosion scarps

Some islets are affected by significant erosion of their shorelines. This erosion creates an erosion scarp whose height is variable and linked to the topography and morphology of the islet (Online Resource 1). The scarp height at which it becomes an obstacle for turtle nesting depends on the species concerned. Green turtles (average size of adult around 115 cm) have higher overcoming capacities than loggerhead turtles (average size of adult around 70–95 cm). Green turtles have an overcoming capacity around 0.8 to 1 m, while loggerhead turtles have an overcoming capacity around 0.6 to 0.8 m. The islets within the Grande-Terre's lagoon are mainly frequented by loggerhead turtles, while the islets of Entrecasteaux and Chesterfield archipelagos are mainly frequented by green turtles (Read et al. 2015). The erosion scarp height to be taken into account is therefore dependant on the species breeding on the islet (Read et al. 2015). In any case, the presence of an erosion scarp has an impact on the hatchlings mortality rate during their journey towards the sea.

Erosion scarps evolve according to the phases of erosion, stability or sedimentation that affect the islet. If erosion is chronic and almost continuous, the scarp will persist over time while moving towards the centre of the island (Garcin et al., 2016). The scarp's height depends on the islet's topography. If the erosion affects a relatively low-lying island, the height will remain moderate to low (decimetre to few decimetres). Conversely, if the island is older (i.e. established during the higher Holocene sea level; Yamano et al. 2014; Garcin et al., 2016) or if there are some sandy ridges or small dunes in the backshore, its height will be higher. If a period of coastline stability occurs after the erosion phase, a beach profile regularization will occur. The profile then becomes less steep and therefore can be more easily overcome by turtles. If a phase of accretion succeeds to the erosion phase, the sand deposition at scarp's foot will reduce its height (thus making it easier to overcome). In some cases, the sedimentation could be sufficient to bury the scarp morphology.

Table 2 Assessment of the impact of erosion scarp on turtle nesting site accessibility

Erosion scarp height (m)	Nesting site accessibility		Indicator value	
	Green turtle	Logger-head turtle	Green turtle	Logger-head turtle
No erosion scarp	Easily accessible	Easily accessible	2	2
Erosion scarp up to 0.4 m	Accessible	Accessible	1	0
Erosion scarp up to 0.8 m	Poorly accessible	Hardly accessible	0	-1
Erosion scarp up to 1 m	Hardly accessible	Not crossable	-1	-2
Erosion scarp higher than 1 m	Not crossable	Not crossable	-2	-2

Tree stumps, roots and plant debris

In eroded areas, seaward and on the scarp, it is quite common to observe roots, tree stumps and other woody debris (Online Resource 1). These constitute an unfavourable factor to turtle nesting for two reasons.

First, the wood stumps, roots and woody debris constitute some obstacles preventing turtles from accessing the nesting sites. The second is, if the turtle finally accesses the site, presence of woody-debris can prevent them from creating the nest. In this case, unsuccessful nesting attempts are observed. The presence of roots and woody debris in the sand (surface and in depth) are unfavourable factors that are often the cause of abandoned nesting attempts.

If a significant accretion/deposition phase occurs after the erosional phase (and consecutive apparition of woody debris, roots etc.), previous debris are buried and accessibility to nesting area becomes easier. Nevertheless, these new sandy areas hide, in depth, numerous debris that constitute

Table 3 Assessment of the impact of tree stumps, roots and plant debris on turtle nesting site accessibility

Vegetal debris	Nesting site accessibility, Nesting excavation	Indicator Value
Lack of vegetal and wood debris	Good accessibility, herbaceous cover of the backshore or lack of vegetation	2
Rare vegetal debris, some isolated tree branches	Fairly good accessibility, disruptions during nest excavation, herbaceous backshore with scarce bushes	1
Backshore with bushes or low density stumps and roots	Accessibility sometimes difficult, difficulties to excavate	-1
Numerous wood tree roots exposed	Difficult to impossible access, excavation sometimes impossible	-2
Numerous wood or bushes stumps	Difficult to impossible access, excavation sometimes impossible	-2

an unfavourable context for nest digging and egg survival (Read et al., 2019).

Sediment granulometry

Sediments of islets beaches have various granulometry: from very fine sand to blocks and pebbles (Online Resource 1). A sediment with a fine granulometry is a favourable factor for turtles' nesting. The zones where sediments are homogeneous and fine are preferred to those with a heterometric grain size or those constituted of coarser element (gravels and pebbles, coralline debris etc.). If the sediment is a fine sand but with a low proportion of coarse elements (coral debris), nesting is still observed. On the other hand, during the digging of the nest, if the turtle finds in depth coarser beds (pebbles, coral debris, bioclastic debris, etc.) it will give up.

The beach and backshore sediment granulometry is differs from one islet to another and is variable at the islet scale. The granulometry variability is related to each local context (exposure to waves, currents, distance to reef passes, existence/non-existence of a seaward barrier reef ...). Moreover,

Table 4 Assessment of the sites attractiveness for turtle in relation with the sediment granulometry (unpublished data)

Sediment granulometry at turtle nesting site	Nesting site attractiveness	Value assign to indicator
Fine sand	Very attractive	2
Medium sand	Attractive	1
Sand (fine to medium) with rare debris	Attractive	1
Coarse sand	Moderately attractive	0
Sand (fine to medium) with numerous debris (coral, bioclasts, ...)	Low attractive	-1
Coarse coral debris	Not adapted	-2
Beachrock bed or blocks	Not adapted	-2

the granulometry of a given beach (or of backshore) can change quickly (few hours to few days) during periods of erosion or accretion. A very rapid change of the granulometry of the surficial sediments can occur due to the supply of coarse debris during storms or high-energy events (e.g. southern swells, cyclone, tsunami...). Access to the nesting site will not be as easy and if the backshore is also covered by coarse sediments, the site will be inappropriate for turtle nesting. Conversely, new fine sand layer can be deposited during accretion or recovery phase; in this case, the beach becomes friendlier for turtles. Not all the islets are affected by these granulometry changes but a good part of them are; it mainly depends on each islet's dynamics of changes, in relation with the forcing factors acting upon it.

Reef-flat wideness

A narrow reef-flat (small distance between the reef front and the nesting area) is a favourable factor because it makes access to the nesting area easier, less risky and faster than in the case of a wider shelf.

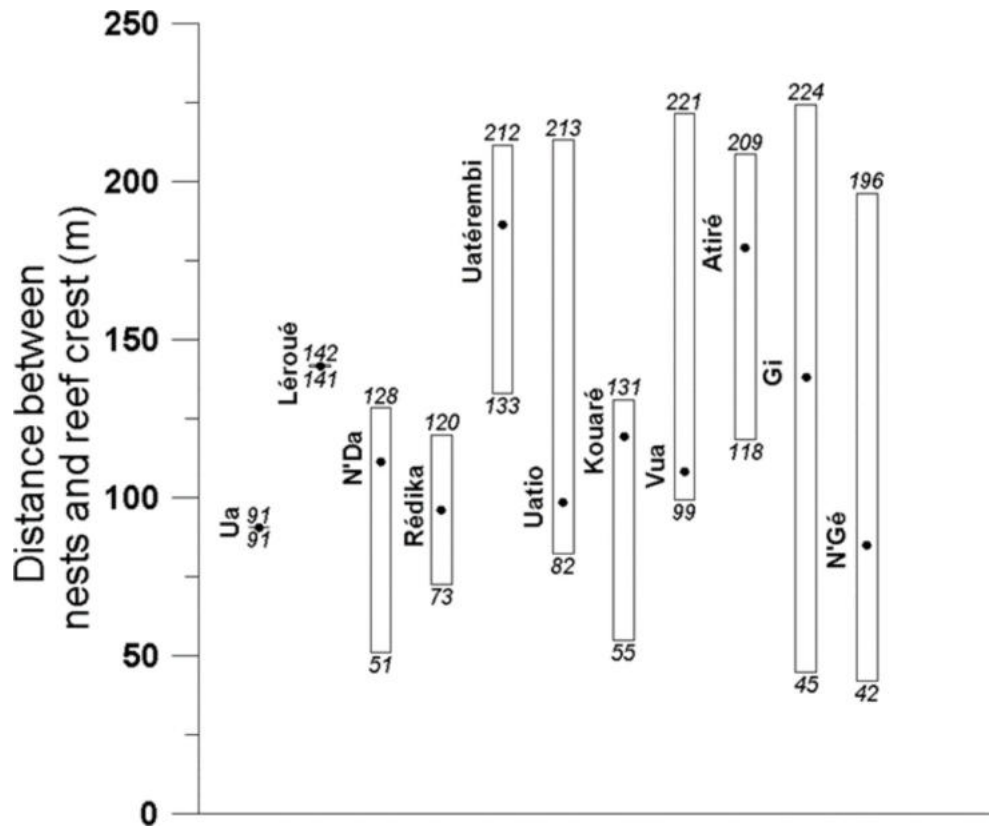
The reef-flat widths surrounding the islets of the Caledonian lagoon are highly variable (Online Resource 1). The values range from a few metres to several hundred metres. Moreover, for some islets, the reef-flat width is also highly variable depending on the segment of shoreline considered. Moreover, for a given width of reef-flat, the presence of a pass leads to a local decrease in the width of the reef-flat and thus allows turtles to access the beach more easily (Online Resource 1).

Based on the location of 140 nests (data acquired by WWF during 2018–2019 campaign) observed on eleven islets spread across Southern Lagoon we have analysed the reef-flat width in front of these nests. The reef-flat widths crossed by turtle have an average value of 129 m, a median of 126 m with a 45 m standard deviation. For each islet, an analysis of nest locations in relation to reef-flat width

Table 5 Distance from nests to the reef-crest and reef-flat wideness for some islets of the Southern lagoon

Islet name	Nest number	Median of reef-crest to nest distance (m)	Minimum reef-crest to nest distance (m)	Maximum reef-crest to nest distance (m)	Minimum reef-flat wideness (m)	Maximum reef-flat wideness (m)
<i>Ua</i>	1	91	91	91	50	317
<i>Lérroué</i>	2	142	141	142	140	413
<i>N'Da</i>	4	111	51	128	41	202
<i>Rédika</i>	8	96	73	120	90	220
<i>Uaterembi</i>	8	186	133	212	130	227
<i>Uatio</i>	12	99	82	213	82	274
<i>Kouaré</i>	13	119	55	131	55	172
<i>Vua</i>	13	108	99	221	99	257
<i>Atiré</i>	25	179	118	209	118	221
<i>Gi</i>	26	138	45	224	45	260
<i>N'Gé</i>	28	85	42	196	42	326

Fig. 2 Distance between the turtle nests (2018–2019 campaign) and the reef crest for eleven islets. For each islet: the bottom of the bar is the lower distance, the top of the bar is the higher distance, the black dot represents the median of the distance nest to reef crest for each islet



crossed by turtles was realized. Table 5 shows: (i) the very great variability of the number of nests per islet (1 to 28) in the Southern Lagoon; (ii) the strong variability of reef-flat’s widths crossed by turtles to make their nests (from 42 to 224 m, Fig. 2).

The very wide dispersion of the lengths crossed on the most nested islands also demonstrates that the number of nests on an island is not only controlled by the width of the platform to be crossed (Fig. 2).

For example, on islands Gi and N’Gé where respectively 26 and 28 nests were observed, the reef-flat widths crossed by turtles are very variable (from about 42 to 224 m). Similarly, the median crossed is 179 m at Atiré and 85 m at N’Gé, while the number of nests recorded is very close (25 and 28 respectively). That implies that the reef-flat width to cross is not the primary island choice criterion for nesting

but that once the island is chosen, the turtles will tend to show preference to the sectors with the narrowest reef-flat (Online resource 1).

Consequently, the reef-flat wideness indicator must be evaluated at the scale of each islet. The value assigned to this indicator is completely dependant of the reef-flat characteristics of each islet. Then, the reef-flat wideness range is computed (maximum wideness – minimum wideness) and split into five classes of equal interval (Delta). The indicator value decrease from the smaller reef-flat wideness classes (value + 2) to the larger ones (value – 2; Table 6).

The reef-flat width can be evolutionary even in the short term (one year to few years) by the islet migration on the reef-flat over time. The distance can also change locally for a particular shoreline segment due to erosion (in this case the distance between the reef front and the islet coastline increase and consequently also the reef-flat) or after an accretion phase (in this case the width lower). At multi-yearly and multi-decadal time scales, this variation of the reef-flat width can become significant.

Table 6 Assessment of the impact of reef-flat wideness on turtle nesting site accessibility for a given islet (MinW = Minimum Reef-flat wideness)

Reef-flat wideness	Value assigned to indicator	
Lower bound	Upper bound	
MinW	MinW + Delta	2
MinW + Delta	MinW + (2*Delta)	1
MinW + (2*Delta)	MinW + (3*Delta)	0
MinW + (3*Delta)	MinW + (4*Delta)	-1
MinW + (4*Delta)	MinW + (5*Delta)	-2

The selected indicators

Five geomorphological indicators were considered as the most relevant and were selected. They are namely beachrock, Erosion scarp, reef-flat width (which integrates the distance to reef-passes if present), granulometry, stumps

Table 7 Indicators used for the assessment of turtle nesting potential for a coastal segment with their characteristics

Indicator	Nesting Site Accessibility	Nesting Site Quality	Data sources	Evolvability	Retrospective analysis	Link with processes
Beachrock (presence & typology)	x		Remote sensing, field	High	Partially possible	Erosion / accretion
Erosion scarp height	x		Field	High	Partially possible	Erosion / accretion
Stumps and woody debris	x	x	Field, partially remote sensing	High	Partially	Erosion / accretion
Sediment granulometry	x	x	Field	Medium	Impossible	Erosion / accretion, exposure to waves energy, extreme events
Reef-flat width	x		Remote sensing, field	Medium	Possible	Erosion / accretion

and woody debris. A large majority of the parameters can evolve at short term during morphogenetic events (storms, cyclones, Southern or cyclonic swells). The parameters' evolutions are related to erosion and accretion processes acting on the islets (Table 7). These processes constitute the principal forcing factor leading to an evolution in the turtle nesting habitats.

The indicators can be grouped into three categories:

- i) one dealing with the **accessibility** of the nesting site,
- ii) one dealing with the **quality** of the nesting sites,
- iii) one dealing with the **accessibility and quality** of the sites.

Indicators related to the accessibility of nesting sites are the most important. Indeed, if turtles have difficulty or cannot reach the top of the beach nor the backshore, there will be few or no nests even if the sectors behind hold very favourable characteristics. The analysis of the parameters (Table 7) shows that, in detail, those that affect the nesting site quality criterion always affect the accessibility criterion as well (e.g. Stumps and wood debris). Consequently, no parameters are only related to the quality of the nesting site. On the other hand, some parameters only affect accessibility (e.g. beachrock, reef-flat width).

Each homogeneous shoreline's segment is assigned a representative value of the state of each geomorphological parameter. Five values can be assigned according to the characteristics' favourability to turtles' nesting: *Very favourable*, *Favourable*, *Moderately favourable*, *Unfavourable* and *Very unfavourable*.

It is then possible to map the favourability value of the segment for each parameter.

Assessment method of the turtle-nesting potential index

For each homogeneous coastal segment, the five indicators are aggregated in a unique and mappable single turtle nesting potential index.

The turtle nesting potential index assessment is a three-step process:

- (i) the average value of the five single indicators is computed (real number). Result range from -2 to $+2$ (i.e. from Very unfavourable to Very favourable) as for single indicators.
- (ii) if one (or more) of the following single indicators ("Beachrock", "Erosion scarp", "Sediment Granulometry", "Stumps and wood debris") is -2 , this value is assigned to the segment, whatever the average obtains. This is justified by the fact that even if all other indicators are favourable, the "Very unfavourable" value of these is critical. For the specific case of the "Reef-flat wideness" indicator, we consider that the "Very unfavourable" value is not critical because even though the nesting site is harder to reach, it remains possible.
- (iii) The numeric value obtained is then converted into one of five classes giving the value of the turtle nesting potential index (Table 8).

Table 8 Correspondance between numerical value and the turtle nesting potential index

Numerical value		Turtle nesting Index	
<i>Min (>)</i>	<i>Max (<=)</i>	<i>Value</i>	<i>Label</i>
1.5	2	2	Very favourable
0.5	1.5	1	Favourable
-0.5	0.5	0	Moderately favourable
-1.5	-0.5	-1	Unfavourable
-2	-1.5	-2	Very unfavourable

This integrate index permits an inter-comparison of the nesting potential of the shoreline segments of one islet and an inter-comparison of the nesting potential of several islets. Due to the geomorphological evolutivity of the islets, the value of this indicator is only representative at a given date. This justifies the fact that the geomorphological analysis of the islets must be done synchronously with the nests' counting campaigns.

Results and discussion: application of the method to 13 islets of the southern lagoon

Our study focuses on the breeding ground of the Great South Lagoon, in the south part of the Grande Terre of New Caledonia (Fig. 1, Online Ressource 2). It is an extensive shallow reef area of about 2,600 km², accounting more than 30 islets widely spread, all of them possibly hosting marine turtle nesting activities. The first step in assessing the conservation status of a given marine turtle population is determining how many reproductive females exist in the population (SWOT 2011). For a long-lived and late mature species like the loggerhead turtle, population monitoring must persist for several years or decades to detect a significant population trend (Chaloupka et al. 2008). It is relatively easy to identify a marine turtle nest, because females leave wide, deep tracks on the open sandy beaches they come to nest on (Girondot 2017). We therefore chose to conduct a count of the number of clutches detected (110 nests) in 13 of the islets (Fig. 3) during the nesting season (from late November to late March, 2019–2020), with a two to three weeks delay between each count for a total of six counts per season. This count can be considered a proxy for total

female population abundance. Although it is not as accurate as the count of uniquely identified females, it requires less effort and presence to adapt to the logistical constraints of the nesting site (SWOT 2011). All tracks of nesting activities more recent than the previous survey are counted, assessed, geolocated and erased to prevent recounting on the next patrol.

Geomorphological and sedimentological descriptors and indicators were recorded directly in the field using the method presented previously. Field observations were supplemented by a GIS analysis (coastline mapping, computation of the "Reef-flat wideness" indicator). Islets coastlines were then segmented according to their characteristics and the indicators aggregated and associated with each coastal segment. Islands' nesting potential were mapped according



Fig. 4 Example of coast segmentation using the turtle nesting potential index and location of turtle nests (Feb. 2020) of the N'Gé islet (Southern Lagoon, New-Caledonia)

Fig. 3 Location map of the 13 studied islets

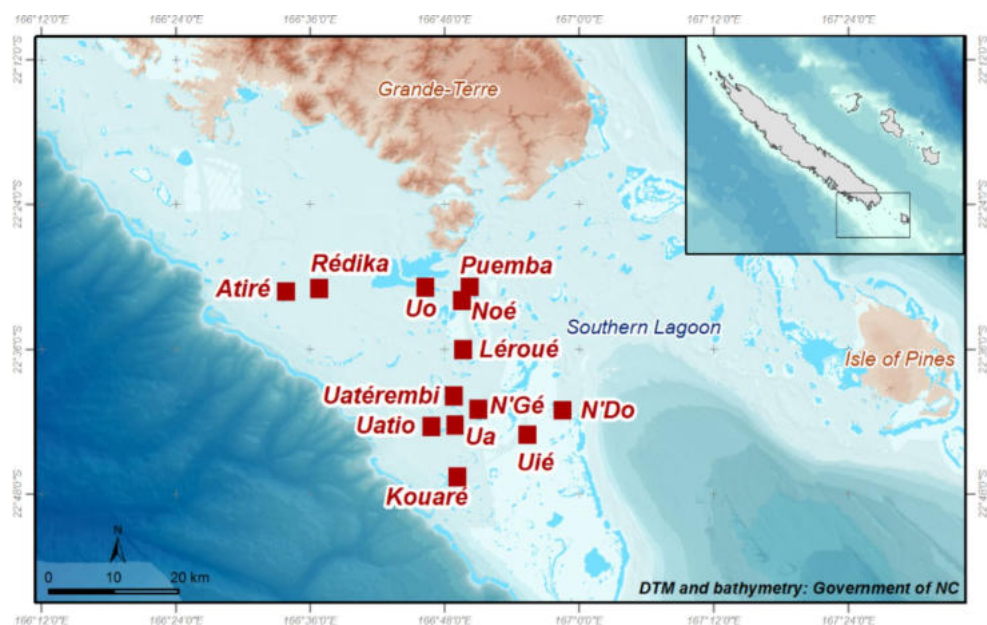
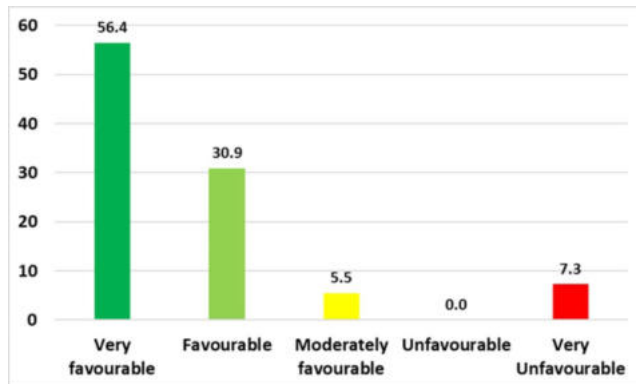


Table 9 The turtle nesting potential index of the coastlines of the 13 islets

Turtle nesting potential	Cumulative length (m)	Length percentage (%)	Turtle nests number	Turtle nests percentage (%)
Very favourable	2 833	24.3	62	56.4
Favourable	2 934	25.2	34	30.9
Moderately favourable	1 025	8.8	6	5.5
Unfavourable	0	0.0	0	0.0
Very Unfavourable	4 874	41.8	8	7.3

**Fig. 5** Percentage of observed turtle nests relative to the turtle nesting potential index

to the five categories (from most to least favourable) in order to evaluate their attractiveness (Fig. 4). The number of nests is associated with each coastal segment. The detailed results obtained (maps) are presented in detail in the supplementary materials.

The cumulative coastline length investigated (sum of coastline of the 13 islets) is 11,665 m. 41.8% of the cumulative coastline length are “*Very unfavourable*” (cumulative length 4,874 m), 8.8% are “*Moderately favourable*” (cumulative length 1 025 m), 25.2% are “*Favourable*”

(cumulative length 3 162 m) and 24.3% are “*Very favourable*” (2,604 m). The “*Unfavourable*” category is not represented in this islets set.

The analysis of the nests’ locations in relation with our coastline classification shows that in (Table 9; Fig. 5):

- 56.4% of the observed turtle nests concern coastal segments characterized as “*Very favourable*”,
- 30.9% concern sectors characterized as “*Favourable*”,
- 5.5% concern sectors characterized as “*moderately favourable*”,
- 7.3% of the observed turtle are located in segments characterized as “*Very unfavourable*”.

This cross analysis between the index value and the number of nests observed in the field indicates that our index is discriminant enough to identify the nesting habitat attractiveness of coastal segments for sea-turtle nesting. Nevertheless, few nests have been observed in *Very unfavourable* coastal segments for unknown reasons. This could be linked to the fact that turtles try to nest in the same place as previous years even if the nesting conditions have become unfavourable due to the geomorphological evolution of the islets.

The average number of nests by coast length (km) by nesting potential index is computed (Table 11). Even if these preliminary results are obtained on a still limited set of data, the “*Very Favourable*” coasts have a sea turtle nest number per km around 13.7 fold higher than the less favourable coasts. The “*Favourable*” coasts have a ratio of around 7.25 and “*Moderately favourable*” of around 3.7.

In order to sort out the attractiveness of each islet towards others, we have computed for each islet the number of nests using the average nest-by-kilometre ratio for each types of coasts. We obtain a theoretical number of nests for each islet as a function of their coastal characteristics. For a given islet, if the number of computed nests is higher than the observed number, we conclude that the islet is under-nested compared

Table 10 Sorting of islets as a function of their cumulative length of favourable coastline for turtle nesting

Length of coastline (m) / Nesting potential	1) Very favourable	2) Favourable	More attractive coast length (1+2)	3) Moderately favourable	4) Unfavourable	5) Very Unfavourable	Less attractive coast length (3+4+5)	# Nests
Uatérémbi	0	778	778	0	0	259	259	5
Leroué	118	482	600	0	0	334	334	1
N’Do	575	0	575	0	0	723	723	11
Ua	429	105	534	0	0	489	489	8
Kouaré	81	378	459	281	0	334	334	4
Noé	301	134	435	0	0	275	275	3
Rédika	125	309	434	258	0	479	479	14
Uié	226	169	395	0	0	248	248	8
N’Gé	289	97	386	31	0	456	456	18
Petit Mato	117	215	332	0	0	127	127	2
Uatio	331	0	331	455	0	131	131	12
Atiré	0	267	267	0	0	243	243	18
Puamba	241	0	241	0	0	776	776	6

Fig. 6 Left : difference between the number of observed turtle nests and theoretical number of nests; right : percentage of the difference between the number of turtle nests observed and the theoretical number of nests; over nested islets in green, under nested islets in red

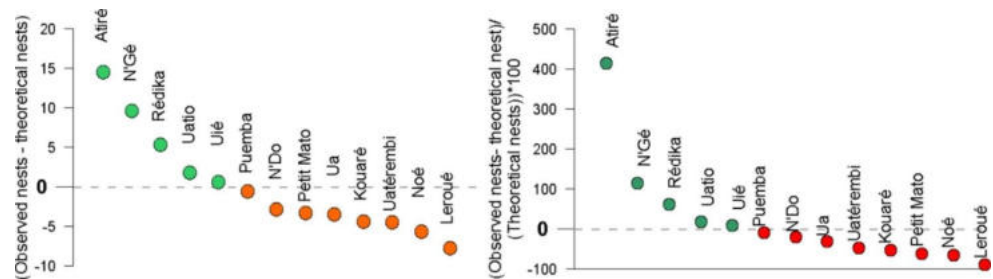


Table 11 Average number of sea-turtle nest by km of each category of coast attractiveness for all the islets investigated

Coast attractiveness	Number of sea turtle nest/ km
“Very Favourable”	21.9
“Favourable”	11.6
“Moderately Favourable”	5.9
“Unfavourable”	-
“Very Unfavourable”	1.6

to its potential (e.g. Kouaré, Leroué, Noé). Conversely, if computed nests number is lower than the observed number, we conclude that the islet is over-nested compared to its potential (e.g. Atiré, N’Gé, Rédika; Fig. 6).

There are probably several factors leading the over-nesting or under nesting of an islet. These factors may include the distance of the islet from the barrier-reef passes and the ease of access from the open ocean to the islet, channels and currents in the lagoon, and human frequentation. Human frequentation is a particularly important factor for turtle nesting. On the New Caledonian islets, this frequentation is very variable from one islet to another according to its accessibility and its distance from either ports or launching docks. Human frequentation of the islets is mainly recreational (fishing, swimming, camping, kite surfing...). The most critical point is night light pollution around the campsites (Witherington and Martin 2000). This can make turtles give up on accessing the nesting sites. However, despite the importance of this factor, human frequentation is not taken into account in our approach because it is not a parameter directly assignable to the characterization of the nesting habitat. It can be considered as an additional exogenous factor that will have to be taken into account once the nesting habitat’s qualification has been carried out.

Conclusions

This method makes it possible to define and map the level of attractiveness of coral islands coasts for turtle nesting. It uses several easily accessible geomorphological and

sedimentological parameters. Comparison of the classification of the coastal segments with the turtle nest counts shows a good agreement between the classification obtained and the nests density. This method will be useful to biologists monitoring turtle nesting sites and to decision-makers in charge of marine area management.

Assessing the influence of morphological and environmental parameters (and their evolution) on turtle nesting is useful to (1) identify the most sensitive areas for turtles in the Southern Lagoon (at the islet scale), (2) provide elements for prioritising turtle conservation and management measures, (3) identify priority conservation areas at the island level (restricted areas), but also at the southern lagoon level (island closure during the nesting period).

It enables a relationship to be established between morphological and sedimentological states (and changes) of beaches and backshore and the nesting potential of marine turtles. This method is easily transposable and applicable to all nesting sites on coral islands around the world but also transposable to others sea turtle nesting contexts. Future morphological changes in coral islets due to climate change and sea level rise will affect sea turtle nesting habitats. The impact of future changes can be assessed using this method.

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