Des systèmes vidéo rotatifs pour étudier l'ichtyofaune : Applications à l'analyse des variations spatiales et temporelles dans le lagon de Nouvelle-Calédonie

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DES SYSTEMES VIDEO ROTATIFS POUR ETUDIER L'ICHTYOFAUNE

Applications à l'analyse des variations spatiales et temporelles dans le lagon de Nouvelle-Calédonie

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Soutenue le 24 Avril 2014, devant le jury composé de :

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DES SYSTEMES VIDEO ROTATIFS POUR ETUDIER L'ICHTYOFAUNE :
Applications à l'analyse des variations spatiales et temporelles dans le lagon de Nouvelle-Calédonie

Résumé- L'estimation de la diversité et de l'abondance des espèces de poissons est fondamentale pour comprendre la structure des communautés et la dynamique des récifs coralliens. Les observations sont généralement obtenues par des recensements visuels en scaphandre autonome (UVC). Ces informations peuvent également être obtenues de manière originale grâce aux observations issues des techniques vidéo sous-marines modernes sans plongeur qui permettent des couvertures spatiales et temporelles accrues. La première phase de ce travail de thèse synthétise l'ensemble des travaux ayant été effectués avec des techniques vidéo entre 1952 et 2012. La seconde phase, présente deux systèmes vidéo rotatifs complémentaires, utilisés pour étudier la diversité de l'ichtyofaune et des habitats marins dans le lagon de Nouvelle-Calédonie : le STAVIRO (pour « STAtion VIdéo ROtative ») et le MICADO (pour « Module d'Imagerie Côtier, Autonome pour le Développement de l'Observation sous-marine »). La troisième phase de ce travail consiste à comparer ces systèmes vidéo aux UVC puis à examiner l'effet « observateur » inhérent aux techniques vidéo rotatives. Il résulte de cette étude que : (i) les observations des communautés de poissons par UVC et STAVIRO différaient significativement, (ii) la richesse spécifique et la densité des espèces de grande taille n'étaient pas significativement différentes entre les techniques, (iii) la diversité et la densité des espèces de petite taille étaient plus élevés avec les UVC; (iv) la densité des espèces pêchées était plus élevée avec les STAVIRO et (v) seuls les UVC ont détecté des différences de structure des assemblages en fonction du type de récif. L'étude de l'effet « observateur » a montré que sur une liste d'espèces définie, les dénombrements et les identifications des individus peuvent être considérées comme similaires entre observateurs ayant une expérience suffisante (> 6 mois). La dernière phase de ce travail a permis d'appliquer la technique MICADO à l'étude des variations temporelles de l'ichtyofaune d'un site corallien à l'échelle de la journée. Elle a permis de mettre en évidence des variations cycliques journalières en fonction de l'heure et de la marée et des « profils type » de variations ont pu être identifiés pour certains groupes d'espèces. Ce travail de thèse permet ainsi de participer au développement de nouvelles techniques d'observations complémentaires des techniques traditionnelles afin d'enrichir les connaissances du fonctionnement et de la dynamique des écosystèmes coralliens.

Mots clés: vidéo sous-marine; systèmes d'observation; poissons coralliens; Nouvelle-Calédonie

UNDERWATER ROTATING VIDEO SYSTEM TO STUDY THE ICHTHYOFAUNA:
Applications to spatial and temporal variations in the lagoon of New Caledonia

Abstract - Estimating diversity and abundance of fish is fundamental for the understanding of community structure and dynamics of coral reefs. Observations are generally gathered using Underwater Visual Census (UVC). These informations can also be collected by underwater video techniques involving no diver and allowing a high spatial and temporal coverage. The first part of this PhD thesis is a review of publications using underwater video techniques between 1952 and 2012. The second part present two rotating video systems used to study the diversity of ichthyofauna and habitats in the lagoon of New Caledonia: the STAVIRO (for "STAtion VIdeo ROtative") and the MICADO (for "Module d'Imagerie Côtier, Autonome pour le Développement de l'Observation sous-marine"). The third part of this work is a comparison of these techniques with UVCs and an analysis of the "observer effect" for the rotating video techniques. The comparison between rotating video systems and UVC showed that: (i) fish community data collected by UVC and by STAVIRO differed significantly; (ii) species richness and density of large species were not significantly different between techniques; (iii) species richness and density of small species were higher for UVC; (iv) density of fished species was higher for STAVIRO; and (v) only UVC detected significant differences in fish assemblages structure across reef type. The comparison of fish counts obtained from the same videos by different observers showed that for a defined list of species, estimates of species richness and total abundance can be considered as similar between observers with sufficient experiences (> 6 months). The last part of this PhD is an application of rotating video techniques to the study of daily temporal variations of the ichthyofauna. Daily variations were observed depending on the time of day and the tidal state and typical patterns of variations have been described for some species groups. The outcomes of this work bring original insights of new techniques complementary to traditional techniques in order to enhance our understanding of the functioning and dynamic of coral reef.

Keywords: underwater video; observation systems; coral reef fish; New Caledonia

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CHAPITRE 1

Introduction générale

Les récifs coralliens, leurs définitions, compositions, répartitions et utilités ont été présentés dans de nombreux ouvrages (e.g. Spalding et al., 2001 ; Sheppard et al., 2009 ; Dubinsky et Stambler, 2010 ; Hopley, 2011) et sont étudiés par de nombreux programmes (e.g. Initiative Française pour les Récifs Coralliens[2] et du NOAA Coral Reef Conservation Program[3]). Ce chapitre a pour objectifs de rappeler les grands principes concernant les récifs coralliens, l'ichtyofaune associée, le contexte calédonien ainsi que les différentes techniques d'observation de la biodiversité marine afin de définir le contexte de la problématique de ce travail de thèse.

1. L'écosystème corallien, un des écosystèmes les plus diversifiés de la planète

1.1. Caractéristiques générales

Les récifs coralliens sont des structures sous-marines construites par les coraux. Les coraux sont des animaux marins, vivant en symbiose avec des algues, les zooxanthelles, qui constituent leur propre squelette calcaire formant les structures récifales. Ils couvraient 284300 km^2 en 2001 (Figure 1.1 ; Spalding et al., 2001). La grande majorité des formations coralliennes se développent entre la surface et une trentaine de mètres de profondeur, pour peu que la température de l'eau ne descende jamais en dessous de 20°C, que la salinité soit constante et que l'intensité lumineuse soit suffisante (Veron, 2000). Internationalement reconnus comme l'un des milieux les plus riches au monde, les récifs coralliens et les écosystèmes qui leurs sont associés (herbiers de phanérogames et mangroves) sont de gigantesques réservoirs de biodiversité. Leur richesse, en termes de biodiversité, est incontestable et est souvent comparée à celles des forêts tropicales humides (Connell, 1978). Les récifs coralliens abritent des dizaines de milliers d'espèces animales appartenant à tous les groupes zoologiques, invertébrés marins (mollusques, crustacés, éponges, coraux, vers, ...), poissons et mammifères. Les récifs coralliens jouent également un rôle très important dans la protection naturelle des côtes en constituant une barrière physique contre la houle et les courants. De ce fait, ils

[2] IFRECOR : http://www.ifrecor.org/r%C3%A9cifs-coralliens
[3] http://coralreef.noaa.gov/

atténuent l'amplitude des catastrophes naturelles, tempêtes, cyclones et tsunamis pouvant impacter le littoral.

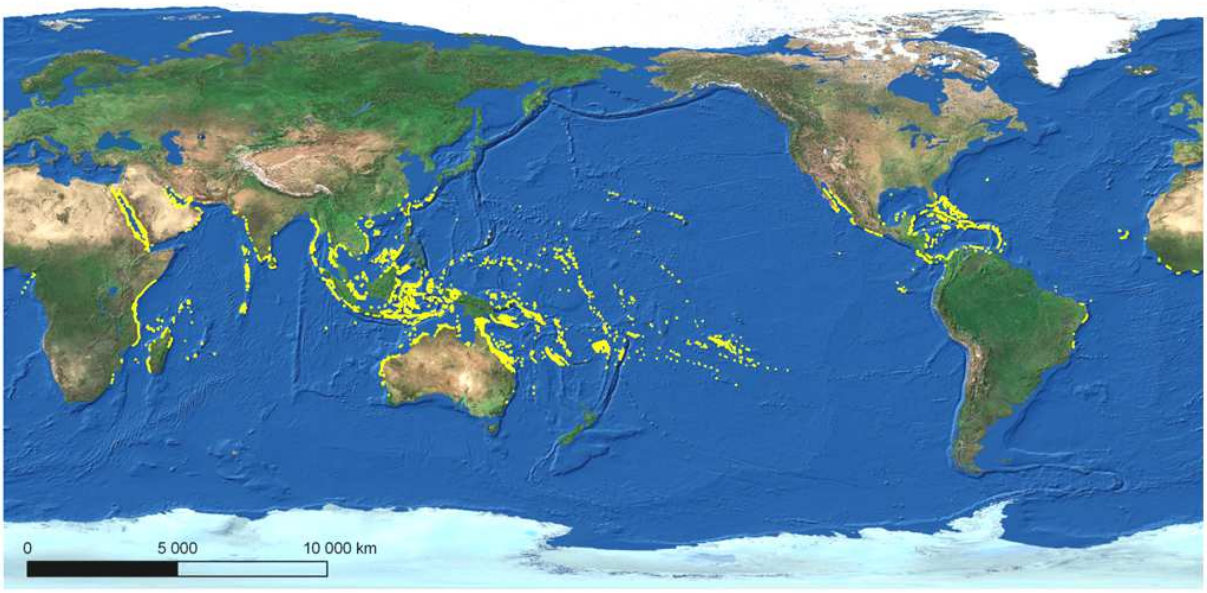

Figure 1.1. Répartition des récifs coralliens dans le monde. Les récifs coralliens sont représentés en jaune (fond de carte ESRI, position des récifs : Spalding et al., 2001).

Outre ces intérêts écologiques, les récifs coralliens jouent un rôle économique et alimentaire d'une importance capitale pour des millions de personnes vivant dans les régions côtières (la pêche, l'aquaculture, la perliculture, la médecine, l'exploitation minière, la construction et le tourisme) (Moberg & Folke, 1999 ; Williams & Polunin, 2000 ; Davenport & Davenport, 2006). En effet, un demi-milliard de personnes, soit 8% de la population mondiale, vit à moins de 100 km d'un récif corallien. Ce chiffre inclut les 30 millions de personnes dont l'habitat et le mode de vie dépendent exclusivement des récifs coralliens (Wilkinson, 2008).

1.2. Pressions et perturbations

Malgré leur incontestable intérêt, les récifs coralliens ont perdu près de 20% de leur superficie à cause de l'activité humaine, notamment dans les zones littorales très urbanisées (Wilkinson, 2008). Selon le bilan planétaire 2011 réalisé par Burke et al. (2011), 75% des récifs mondiaux actuels sont menacés et plus de 60% sont sous une

menace directe immédiate. Les principales causes de cette détérioration sont la pression démographique croissante dans les zones côtières et les activités associées: remblaiement, extraction, pêche et pollution littorale (Lecaillon et al., 2000 ; Hughes et al., 2003 ; Burke et al., 2011). L'augmentation de la fréquence des cyclones, la hausse des températures et l'acidification des océans, toutes liées aux changements climatiques globaux, concourent également à la disparition progressive des récifs coralliens via notamment le blanchissement. Ce phénomène a gagné en fréquence, en distribution géographique et en intensité au cours des 40 dernières années et rien ne prouve actuellement que les coraux pourront s'adapter et survivre au blanchissement sur le long terme (Graham et al., 2011a,b ; Pratchett et al., 2011). Cette disparition programmée est amplifiée par d'autres dérèglements, notamment l'explosion démographique d'Acanthaster planci, l'étoile de mer prédatrice de coraux (Wilkinson, 2008).

La conservation des écosystèmes coralliens est devenue un enjeu majeur, autant à l'échelle de la planète que localement. Il s'agit de préserver non seulement les habitats et les espèces, mais aussi les fonctions de l'écosystème afin de conserver cet équilibre naturel fragile. Les Aires Protégées sont un instrument privilégié des stratégies de conservation, promues par la Convention sur la Diversité Biologique (CDB[4]). Initialement définis en 2002, les objectifs quantitatifs et qualitatifs de création d'un réseau mondial d'Aires Marines Protégées (AMP) ont été actualisés en octobre 2010 lors de la conférence de Nagoya (COP, 2010). L'obligation de s'appuyer sur les meilleures connaissances scientifiques disponibles pour la conception d'AMP a été réaffirmée, avec pour objectif de créer un ensemble global de réseaux d'AMP couvrant 20 à 30% de chaque habitat d'ici 2020. Le nombre d'AMP se situe maintenant à environ 5880 (dont 143 AMP en France ; Agence des Aires Marines Protégées, 2011), couvrant plus de 4,2 millions de kilomètres carrés. Ce chiffre équivaut seulement à 1,17% de la zone maritime mondiale (Toropova et al., 2010).

Définir de nouvelles AMP nécessite dans un premier temps de définir *où* protéger et *quoi* protéger (Dudley & Parrish, 2006). Leur mise en œuvre soulève par ailleurs la question de l'évaluation et du suivi de leur efficacité. À cet effet, fournir des méthodes standards, des critères et des indicateurs de ces effets devient obligatoire dans la plupart des conventions et textes visant à protéger l'environnement marin (la CDB, La Stratégie

[4] http://www.cbd.int/

Cadre pour le Milieu Marin, l'European Union 2008, le Great Barrier Reef Strategic Assessment, le NOAA's Coral Reef Conservation Program et l'Hawaï Coral Reef Strategy par exemple).

2. Contexte calédonien

La France est le seul pays à posséder des récifs coralliens dans les trois océans de la planète. Les récifs français et leurs lagons couvrent 57557 km^2 dont 90% se situent dans l'océan Pacifique (Andréfouët et al., 2008)[5]. Les 8 collectivités françaises d'outre-mer abritent ainsi près de 10% des récifs et 20% des atolls du monde. La France dispose de la deuxième plus vaste Zone Economique Exclusive (ZEE) du monde avec plus de 11 millions de km^2 et les collectivités de l'outre-mer représentent plus de 90% de l'espace maritime français.

La Nouvelle-Calédonie est une collectivité française située dans la région mélanésienne de l'océan Pacifique Sud. Elle se situe dans la mer de Corail par 21°30' Sud et 165°30' Est à environ 1500 km à l'est de l'Australie et à 1700 km au nord de la Nouvelle-Zélande. Ses plus proches voisins sont le Vanuatu et les îles Fidji. La Grande Terre de l'archipel de Nouvelle-Calédonie est la troisième île du Pacifique Sud en superficie (18575 km^2 au total et environ 3400 km de côtes). L'archipel calédonien regroupe l'île principale (la Grande-Terre), l'île des Pins au sud, les îles Belep au nord, les îles Loyautés à l'est (Ouvéa, Lifou, Tiga et Maré) ainsi que de nombreux récifs et îlots éparses (notamment les récifs d'Entrecasteaux au nord et l'archipel des Chesterfield et Bellona à l'ouest). Cet ensemble constitue une Zone Economique Exclusive de 1,4 millions de km^2 (Figure 1.2). Le lagon néo-calédonien a une surface de plus de 20000 km^2 (englobant la Grande-Terre et l'île des Pins; Andréfouët et al., 2009), ce qui en fait le plus grand lagon du monde, d'une profondeur moyenne de 25 mètres. Enfin, la Nouvelle-Calédonie possède également la plus longue barrière continue de corail (1600 km de long) et la seconde plus longue barrière discontinue du monde après la Grande Barrière de Corail en Australie (2600 km).

[5] Les récifs coralliens représentent près de 9000 km^2 dont 4570 Km^2 sont compris en Nouvelle-Calédonie (Andréfouët et al., 2008)

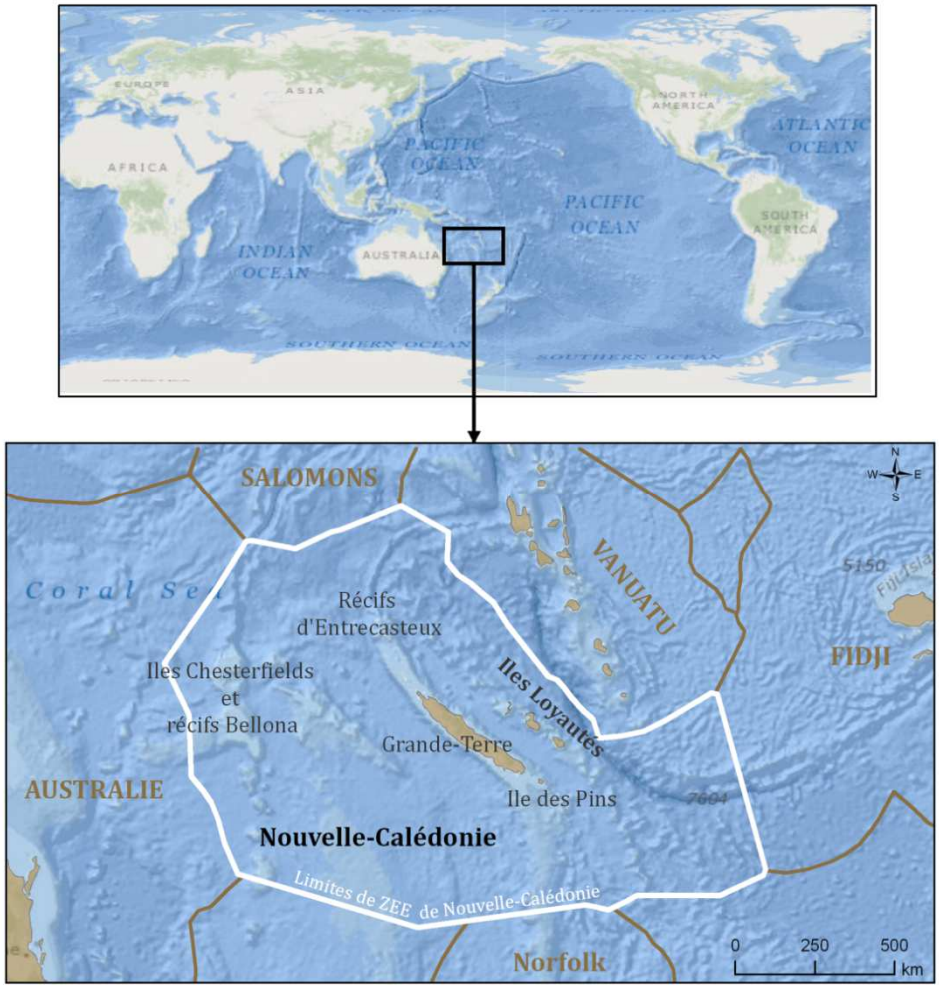

Figure 1.2. Représentation graphique de la Nouvelle-Calédonie et de sa Zone Economique Exclusive (Auteur : D.Mallet, fond de carte : ESRI (the Ocean Basemap service and the World Physical Map service), limites des ZEE : tirées du programme ZoNeCo).

La proximité géographique de la Nouvelle-Calédonie du centre de diversité maximum de l'Indo-Pacifique[6], la variété des biotopes, la diversité géomorphologique des formations coralliennes et des caractéristiques environnementales (gradient de température nord/sud et gradient de température et de salinité est/ouest) induisent une biodiversité marine remarquable. Cette région possède, en effet, une grande diversité d'écosystèmes et d'habitats (lagons, récifs barrières, intermédiaires et frangeants, herbiers, mangroves, îlots, estuaires, etc.) et est caractérisée par une faune marine d'une richesse exceptionnelle (Payri & Richer de Forges, 2006). Un total de 2328 espèces de poissons (Fricke et al., 2011 ; Kulbicki et al., 2011), 5000 espèces de

[6] Indonésie, Phillipines, Papouasie Nouvelle-Guinée ; défini comme le « Coral triangle » en anglais ; Allen 2008 ; Veron et al. 2011

crustacés, 5500 espèces de mollusques, 350 variétés de coraux, et un taux d'endémisme de près de 5 %, y ont été dénombrés (Payri & Richer de Forges, 2006). L'ensemble des poissons recensés en Nouvelle-Calédonie (dont 107 espèces sont endémiques) appartiennent à 246 familles (Fricke et al., 2011). L'annexe A présente le nombre d'espèces recensées par famille selon Fricke et al. (2011). Les familles comportant le plus d'espèces sont les Gobiidae (190 espèces), Labridae (129 espèces), Pomacentridae (112 espèces), Serranidae (95 espèces), Apogonidae (81 espèces), Blennidae (64 espèces), Macrouridae (52 espèces), Myctophidae (52 espèces) et Scorpaenidae (52 espèces) ; alors que 74 familles ne sont composées que d'une unique espèce. De plus, selon Kulbicki (1997), les récifs et les fonds durs lagonaires ont une richesse spécifique, densité et biomasse supérieures à celles des fonds meubles du lagon. Les familles composant les communautés diffèrent d'un biotope à l'autre puisque les récifs se caractérisent par l'abondance d'herbivores alors que les fonds meubles sont dominés par les planctonophages (Kulbicki, 1997).

3. Méthodes d'échantillonnage de l'ichtyofaune

La faune sous-marine en général, et l'ichtyofaune en particulier, peuvent être échantillonnées par diverses méthodes. Il n'existe pas de méthode parfaite et le choix d'une méthode représente un compromis entre ce qui est idéal et ce qui est réalisable. Ce choix est toujours dicté par la question que l'on souhaite traiter et par la précision nécessaire pour y répondre. Les méthodes d'échantillonnage peuvent être divisées en deux groupes : les méthodes de « capture » nécessitant de prélever les individus hors de leur environnement et les méthodes « d'observation » qui ne nécessitent pas de prélever les individus. Les méthodes basées sur des captures comme l'utilisation de pièges (Crossland, 1976 ; Miller & Hunte, 1987), de chaluts ou de filets (Wallace et al., 1984 ; Winhold & Kurta, 2008), d'hameçons ou de lignes (Sigler, 2000 ; Zeller et al., 2003) ainsi que l'utilisation d'explosifs ou d'ichtyocides (Williams & Hatcher, 1983 ; Kulbicki, 1990) nécessitent de prélever (et dans de nombreux cas de tuer) les individus recensés. Ces méthodes sont souvent destructrices et interdites à l'intérieur des AMP et ne seront pas développées dans la présente thèse.

Les méthodes d'observation visuelles permettent, quant à elles, d'estimer l'abondance et la diversité des organismes marins présents dans un milieu donné sans perturber physiquement l'assemblage des populations (Sale & Douglas, 1981). Dans les récifs coralliens, ces dernières regroupent principalement les échantillonnages visuels en plongée (ou UVC[7]) et les méthodes utilisant la vidéo sous-marine ou la photographie (Johnston et al., 1969 ; Dumas et al., 2009). La synthèse bibliographique de Murphy & Jenkins (2010) regroupe l'ensemble des méthodes d'observation utilisées pour étudier les poissons et leurs habitats associés. Cette étude synthétise les applications, les avantages et les inconvénients de toutes les méthodes utilisées, notamment les UVC, la télédétection, l'acoustique, la photo et la vidéo sous-marine.

Les comptages visuels en plongée (ou UVC) sont les méthodes d'observation les plus utilisées depuis 1/2 siècle (première publication sur les UVC : Brock, 1954). Ces méthodes permettent, entre autres, d'évaluer les populations de poissons en relation avec le changement climatique, l'exploitations des ressources ou les actions de gestions (e.g. Edgar & Barrett., 1997; Harborne et al., 2008; Jackson et al., 2001; McClanahan et al., 2007; Masuda, 2008 ; Ward-Paige et al., 2010). Le terme « UVC » regroupe en réalité plusieurs familles de méthodes différentes : 2 basées sur des transects, 1 s'effectuant en nageant librement dans une zone définie et 2 s'effectuant en point fixe. Le tableau 1.1 synthétise les principes, les données calculées ainsi que des publications associées à ces différentes familles de méthodes. Une version de la méthode dite de « transect en bande »[8] a été utilisée pour la première fois en 1954 par Brock (1954), avec deux plongeurs identifiant, dénombrant et estimant la taille de chaque individu observé dans un rectangle (ou transect) de 6 mètres de large sur 50 mètres de long. Cette méthode a donné naissance à une famille de méthodes devenue la plus utilisée pour étudier la distribution des poissons récifaux tropicaux et tempérés, avec des variations dans les dimensions de ce transect en fonction des études (Kulbicki, 1998). Elle permet d'estimer la richesse spécifique, la densité, la taille des individus par espèce et la biomasse quand les relations taille-poids sont connues. La seconde famille de méthodes UVC utilisant des transects est la méthode de « transect en ligne »[9] (e.g. Burnham et al., 1980 ; Buckland et al., 2001) qui nécessite au moins 1 plongeur identifiant, dénombrant et estimant la taille

[7] UVC : « Underwater Visual Census » en anglais
[8] « strip transect » en anglais
[9] « line transect » ou « distance sampling » en anglais

des poissons observés le long d'un transect de longueur variable. Le plongeur estime l'espèce, le nombre d'individus, leur taille et la distance perpendiculaire au transect à laquelle chaque individu est observé. Cette famille de méthode a été utilisée pour étudier certaines communautés de poissons, notamment dans le Pacifique où les densités sont importantes (e.g. Kulbicki & Sarramegna, 1999 ; Bozec et al., 2011). La méthode « des parcours aléatoires »[10] permet de recenser toutes les espèces présentes pendant un temps défini par un plongeur nageant librement dans la zone à échantillonner (e.g. Jones & Thompson, 1978). La seule restriction spatiale de cette méthode consiste à rester dans les limites physiques du récif étudié. Cette méthode est plus utilisée pour étudier les communautés de poissons dans de larges zones d'habitats éparses (e.g. Jones & Thompson, 1978). Elle est particulièrement adaptée pour recenser les petites espèces puisque le plongeur peut librement s'approcher de ces dernières. Enfin, la famille des méthodes de « comptage en point fixe » (e.g. Bohnsack & Bannerot, 1986) requiert au moins un plongeur, stationnaire, qui dénombre, identifie et estime la taille des poissons de la zone à échantillonner qu'il observe face à lui ou bien au cours de rotations sur lui-même. Cette famille de méthodes peut s'effectuer pendant un temps contrôlé où toutes les espèces observées sont recensées dans un cylindre virtuel s'étendant de la surface au fond dans le cas où le plongeur tourne sur lui-même. Elle est adaptée à l'étude des espèces mobiles quand l'effort d'échantillonnage est important par rapport à la zone étudiée, car elle permet d'augmenter la réplication des sites échantillonnés par sa durée d'observation limitée dans le temps (e.g. Chateau & Wantiez, 2005 ; Wantiez et al., 2006).

[10] « rapid visual census » en anglais

Tableau 1.1. Description, données calculées et bibliographie associée aux quatre méthodes d'échantillonnage UVC

Méthode	Méthode	Données calculées	Bibliographie associée
Transect en bande	Au moins 1 plongeur identifie et estime le nombre et la taille des poissons observés dans un rectangle prédéfini Largeur = 2,5 à 10 m Longueur = 20 à 100 m	- fréquence d'occurrence - liste d'espèces - richesse spécifique - densité et biomasse - structure de taille - caractérisation de l'habitat	Brock, 1954 ; Sale, 1980 ; Sale & Sharp, 1983 ; John et al., 1990 ; Kulbicki, 1990 ; Halford & Thompson, 1994 ; Kulbicki, 1998 ; Thompson & Mapstone, 2002
Transect en ligne	Au moins 1 plongeur identifie et estime le nombre et la taille des poissons le long d'un transect de largeur variable. Les estimations de distances des individus se font perpendiculairement au transect Largeur = maximum de visibilité Longueur = 20 à 50 m	- fréquence d'occurrence - liste d'espèces - richesse spécifique - densité et biomasse - structure de taille - caractérisation de l'habitat	Burnham et al., 1980 ; Kulbicki ,1988 ; Kulbicki et al., 1994 ; Wantiez et al., 1997, Kulbicki & Sarramégna, 1999 ; Letourneur et al., 2000 ; Labrosse et al., 2002 ; Lipej et al., 2003 ; Bozec, 2006
Parcours aléatoires	Recensement de toutes les espèces présentes pendant un temps défini par un plongeur nageant librement.	- fréquence d'occurrence - liste d'espèces - richesse spécifique - abondance relative - structure de taille	Jones & Thompson, 1978 ; Brock, 1982 ; De Martini & Roberts, 1982 ; Kimmel, 1985 ; Sanderson & Solonsky, 1986
Comptage par point fixe	Au moins 1 plongeur identifie et estime le nombre et la taille des poissons face à lui ou au cours de rotations sur lui-même le long d'un transect de largeur variable. Rayon = maximum de visibilité	- fréquence d'occurrence - liste d'espèces - richesse spécifique - densité et biomasse - structure de taille - caractérisation de l'habitat	Bohnsak & Bannerot, 1986 ; Watson & Quinn, 1997 ; Francour et al., 1999 ; Chateau & Wantiez, 2005 ; Wantiez et al., 2006

Toutes ces méthodes requièrent des plongeurs expérimentés en identification des espèces et de l'habitat marin (le niveau d'expertise dépend de l'étude et des données à collecter). La nature des résultats obtenus dépendent en grande partie de l'observateur et de son expérience (Bell et al., 1985 ; Thompson & Mapstone, 1997 ; Williams et al., 2006 ; Bernard et al., 2013). Les biais inhérents aux observations effectuées par des plongeurs ont été largement étudiés et sont maintenant bien connus de la communauté

scientifique. La liste ci-dessous recense la plupart des variabilités d'observation reconnues des méthodes UVC:

- Identification des espèces (Brock, 1982 ; Thompson & Mapstone, 1997)
- Difficulté à détecter certaines espèces cryptiques (Willis, 2001)
- Estimation de la taille et de la distance des individus (Thresher & Gunn, 1986 ; Edgar et al., 2004 ; Harvey et al., 2004)
- Changement de comportement des poissons dû à la présence de l'observateur (Chapman et al., 1974 ; Dickens et al., 2011)
- Vitesse de nage de l'observateur (Lincoln-Smith, 1988)
- Taille des transects pour la méthode des transects en bande (longeur : Kulbicki et al., 2010 ; largeur : Cheal & Thompson, 1997)

De plus, les caractéristiques environnementales telles que la clarté de l'eau (ou visibilité, Brock, 1982 ; MacNeil et al., 2008a,b) et la complexité de l'habitat (Edgar & Barrett, 1999) affectent souvent les observations effectuées ; tandis que l'abondance des espèces, leurs tailles, leurs apparences physiques et leurs comportements influencent leur détectabilité (Kulbicki, 1998, Willis, 2001 ; Edgar et al., 2004 ; MacNeil et al., 2008a,b ; Bozec et al., 2011 ; Bernard et al. 2013).

La plupart des contraintes des UVC sont générales à l'ensemble des méthodes d'observation visuelles, comme les méthodes basées sur les observations vidéo. Par exemple, les problèmes d'identification des espèces, des espèces cryptiques, d'estimation de taille et distance (ou de calibration), de surface échantillonnées sont également vrais en vidéo. Néanmoins, les techniques vidéo pourraient s'affranchir de certaines contraintes, comme par exemple les biais liés à la présence d'un observateur sous l'eau. Les méthodes d'observation en plongée et en vidéo n'observent probablement pas les mêmes composantes des assemblages et ont des capacités différentes en termes de précision et de fréquence d'observation. Ainsi, la vidéo pourrait apporter des informations différentes, complémentaires et très utiles à la connaissance du milieu marin. Définir les avantages et inconvénients des techniques de vidéo sous-marine et utiliser ces techniques sur des problèmes actuels d'écologie marine est au cœur de ce travail de doctorat.

4. Objectifs de la thèse

La biodiversité des écosystèmes coralliens est loin d'être complètement connue, décrite et caractérisée, notamment en ce qui concerne ses structures spatio-temporelles. Le fonctionnement et la dynamique de ces écosystèmes sont également insuffisamment compris. L'enjeu est de compléter ces connaissances pour pouvoir répondre aux questions soulevées par la mise en œuvre urgente de stratégies de conservation de la biodiversité et de gestion des ressources associées.

La biodiversité des écosystèmes coralliens calédoniens fait et a déjà fait l'objet de projets de recherche au travers desquels un ensemble de données et de connaissances ont été acquises (e.g. Wantiez, 1994a,b ; Kulbicki & Rivaton, 1997 ; Letourneur et al., 1998a,b ; Labrosse et al., 2000 ; Wantiez & Chauvet, 2003 ; Bozec et al., 2005 ; Kulbicki et al., 2005a,b ; Kulbicki, 2006 ; Dumas et al., 2007 ; Mellin, 2007 ; Carassou et al., 2008 ; Mattio,, 2008 ; Chateau & Wantiez, 2009 ; Guillemot, 2009 ; Andréfouët & Wantiez, 2010 ; Preuss, 2012). Les méthodes d'observation traditionnellement utilisées pour ces études reposent principalement sur des techniques visuelles et sur des pêches expérimentales (voir § 3). Malgré la somme de connaissances acquises, il apparaît nécessaire de mieux appréhender les facteurs de variation de la biodiversité dans leurs dimensions spatiales et temporelles. Les relations entre les différentes composantes de la biodiversité doivent également être approfondies, afin de progresser dans la compréhension du fonctionnement des communautés coralliennes. Prendre en compte ces diverses composantes inscrit ce questionnement dans une approche écosystémique, qui pourra contribuer *in fine* à une gestion durable des usages côtiers dont la pêche.

Si les problèmes liés à l'expertise, l'identité et l'expérience des observateurs sont communes à toutes les méthodes d'observation, la vidéo constitue probablement un complément intéressant aux UVC pour approfondir nos connaissances des zones récifo-lagonaires puisqu'elle permet certainement l'exploration d'habitats inaccessibles aux plongeurs avec une capacité de réplication spatio-temporelle incomparable. Actuellement, la principale technique vidéo utilisée est la vidéo appâtée qui permet d'attirer les prédateurs sans diminuer l'abondance des autres groupes (Harvey et al., 2007). En Nouvelle-Calédonie, un système vidéo rotatif utilisant une caméra en haute définition pour observer l'ichtyofaune et ses habitats, a été développé en 2007 (STAVIRO ; Pelletier et al., 2012). Ce système vidéo a été développé afin de permettre l'acquisition de données sur plusieurs plans d'observation tout autour d'un point central

(on parlera de vision à 360° dans la suite de cette thèse pour qualifier ce type d'observation), en influençant le moins possible l'ichtyofaune environnante (sans appât), tout en conservant un système relativement léger, facilement transportable et utilisable. Aucun des systèmes vidéo existants ne répondaient à l'ensemble de ces exigences lors de la conception de ces systèmes. Le système a été perfectionné en 2008 et depuis cette date un grand nombre de vidéos ont pu être enregistrées dans des zones protégées ou non du lagon de Nouvelle-Calédonie[11]. En 2009, des systèmes programmés pour filmer quelques minutes toutes les heures pendant la période de jour (MICADO) ont été testés sur des périodes de 24 h et plus, dans des AMP et des zones non-protégées ainsi que dans différents habitats. Les images obtenues montrent les variations journalières de l'ichtyofaune.

Caractériser les variations de l'ichtyofaune requiert de pouvoir s'appuyer sur des observations qui renseignent sur l'état et la dynamique des communautés. Les principales questions soulevées par ce besoin sont :

- Quelles sont les variations de l'ichtyofaune connues et quelles sont celles qu'il faudrait approfondir ?
- Quelle est l'influence des facteurs environnementaux sur ces variations ?
- Peut-on expliquer les variations observées par des facteurs extrinsèques tels que les pressions d'origine anthropique et comment les actions de protection telles que les AMP les influencent-elles ?

Ces questions peuvent être abordées de manière originale grâce aux observations issues des techniques vidéo sous-marines, qui ne requièrent pas de plongeurs et qui permettent une couverture spatiale et temporelle accrue au regard d'autres techniques d'observation.

Afin d'apporter des éléments de réponse à ces questions, ce mémoire de thèse est composé de 5 chapitres s'articulant de la façon suivante :

Le **chapitre 2** fera la synthèse des travaux utilisant des techniques vidéo et un bilan en termes d'avantages et inconvénients.

Le **chapitre 3** présentera les deux techniques vidéo sous-marines rotatives complémentaires, développées et utilisée en Nouvelle-Calédonie (STAVIRO et MICADO).

Le **chapitre 4** permettra d'évaluer les atouts et les limites des techniques vidéo rotatives présentées dans le chapitre 3 en répondant aux questions suivantes :

[11] Ainsi qu'en Méditerranée française depuis 2010

1) Quelle est l'image de l'ichtyofaune obtenue en utilisant les systèmes vidéo rotatifs par rapport à l'image obtenue à partir d'observations UVC ?
2) Y-a-t-il une différence entre observateurs lors de l'analyse des images vidéo ?

Nous répondrons à la première question en nous appuyant sur une comparaison appariée d'observations effectuées en UVC et en STAVIRO utilisant la même méthodologie (point fixe rotatif). La seconde question sera traitée en comparant les observations obtenues par quatre observateurs analysant les mêmes vidéos indépendamment.

Dans le **chapitre 5** nous utiliserons le système temporel MICADO pour analyser les variations temporelles diurnes des communautés de poissons dans un habitat corallien. L'objectif de ce chapitre est de traiter la question suivante : Est-ce que l'heure de la journée et l'état de la marée influencent l'abondance, la fréquence d'occurrence ou la diversité des poissons récifaux d'une même station ? Si oui, quelles espèces présentent des profils de comportement particulier et quels sont-ils ? Cette étude sera effectuée à partir de vidéos enregistrées sur une même station à haute fréquence (10 enregistrements vidéo par jour, avec une vidéo par heure du lever au coucher du soleil pendant 34 jours consécutifs).

Enfin dans le **chapitre 6**, l'ensemble des informations obtenues sera synthétisé afin de mener une réflexion sur les potentialités innovantes des techniques vidéo rotatives présentées dans cette thèse. Ce dernier chapitre permettra de traiter les questions suivantes :

1) Quels sont les atouts et les limites des techniques vidéo rotatives ?

2) Quelles sont les améliorations possibles à apporter aux différents systèmes afin de combler certaines de leurs limites ? Cette réflexion s'appuiera sur les connaissances et expériences acquises (chapitre 2) ainsi que sur les limites des systèmes existants identifiées dans le chapitre 3.

3) Quels sont les éléments de réponses apportés par l'étude des variations temporelles de l'ichtyofaune grâce au système MICADO ? Quelles sont les perspectives et recommandations d'utilisation des techniques vidéo rotatives présentées dans cette thèse ?

CHAPITRE 2

Les techniques vidéo sous-marines utilisées pour observer la biodiversité marine côtière

Les techniques vidéo sous-marines sont de plus en plus utilisées pour étudier la faune marine en parallèle des comptages visuels en plongée ainsi que des captures expérimentales. A moins d'être un spécialiste des techniques vidéo, il est difficile de faire la distinction entre ces différentes techniques, d'identifier leurs atouts et leurs limites ainsi que la portée de leurs applications. L'objectif de ce chapitre est donc de synthétiser l'ensemble des travaux publiés concernant les techniques vidéo sous-marines conçues et utilisées pour étudier la biodiversité côtière des environnements peu profonds (moins de 100 m de profondeur). La recherche et la synthèse de ces travaux ainsi que les nombreux échanges avec les spécialistes de ces techniques, m'ont permis d'une part, de faire un point précis sur l'ensemble des techniques existantes et d'autre part, de mieux appréhender ce que les systèmes vidéo rotatifs peuvent apporter en terme de données innovantes. L'article présenté dans ce chapitre est le résultat de ce travail effectué au cours de mes deux premières années de thèse et a été accepté pour publication dans le journal Fisheries Research (Janvier 2014).

1. Article 1. Synthèse bibliographique de 60 ans de publications sur les techniques vidéo sous-marines utilisées pour observer la biodiversité marine côtière: (1952 – 2012)

Résumé de l'article 1 :

Les techniques vidéo sous-marines sont de plus en plus utilisées dans les études d'écologie marine. Les progrès technologiques concernant les caméras, les capteurs (comme les sondeurs), l'énergie et le stockage de l'information rendent ces techniques maintenant accessibles à la majorité des utilisateurs potentiels. Cependant, les techniques de comptages sous-marins opérés par des plongeurs, ainsi que les données issues de la pêche demeurent les moyens les plus utilisés pour observer la biodiversité côtière.

Dans cet article, nous synthétisons l'ensemble des études publiées utilisant des techniques vidéo sous-marines développées depuis les années 1950 pour suivre et étudier la biodiversité côtière (182 articles). Des techniques comme la vidéo sous-marine autonome, appâtée ou non, la vidéo opérée par des plongeurs et la vidéo tractée sont décrites, ainsi que les applications correspondantes. Nous analysons ensuite la complémentarité des techniques, d'abord à partir d'études comparant des techniques vidéo avec d'autres techniques, basées ou pas sur la vidéo ; puis nous considérons leurs apports au regard de leurs coûts respectifs.

Ces résultats sont discutés vis-à-vis des défis actuels en matière de suivi et d'étude de la biodiversité côtière. La vidéo devrait plus souvent être considérée et utilisée, soit en complément ou comme alternative aux techniques basées sur la plongée, la pêche et l'acoustique. Elle pourrait en particulier être utilisée lors de suivis de la biodiversité côtière dans des zones et habitats variés, et à de plus grandes échelles que les suivis actuels, en vue d'une approche de gestion et de conservation basée sur les écosystèmes.

Article 1

Fisheries Research (accepté le 31 Janvier 2014)

Underwater video techniques for observing coastal marine biodiversity: a review of sixty years of publications (1952-2012)

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Abstract

Underwater video techniques are increasingly used in marine ecology studies. Technological progress regarding video cameras, sensors (such as sounders), battery life and information storage make these techniques now accessible to a majority of users. However, diver-based underwater visual censuses, and catch and effort data, remain the most commonly used for observing coastal biodiversity and species. In this paper, we review the underwater video techniques that have been developed since the 1950s to investigate and/or monitor coastal biodiversity. Techniques such as remote underwater video, whether baited or not, diver-operated video and towed video are described, along with corresponding applications in the field. We then analyse the complementary of techniques, first from studies comparing video techniques with other observation techniques, whether video-based or not, and second by documenting their respective cost efficiencies. These findings are discussed with respect to current challenges in monitoring and investigating coastal biodiversity. Video should be more often considered and used, either in addition to or as an alternative to diver-based, fishing and acoustic techniques, as it may be particularly suited for monitoring coastal biodiversity in a variety of areas and on larger scales than hitherto and within an ecosystem-based approach to management and conservation.

Keywords: Underwater Video, monitoring, coastal biodiversity, fish, habitat

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1. Introduction

The conservation of marine and coastal biodiversity and associated ecosystem services through ecosystem-based management (Christensen et al., 1996) requires appraising a wide array of biodiversity components on large spatial scales. Biodiversity here encompasses mostly fish and macroinvertebrate species, whether or not exploited, and corresponding assemblages and habitats. Biodiversity is rarely observed and assessed on such scales due to observation costs. The main techniques used to study and monitor biodiversity are either extractive (e.g. fishing, dredging), based on acoustics, or based on Underwater Visual Censuses (UVC).

Extractive techniques have been used mostly for fish, macrobenthic organisms and endogenous fauna, primarily for the assessment of fished populations. Fishing-based surveys (see e.g. Petitgas et al., 2009) focus on catchable species, whether or not exploited. The potential of catch-based surveys for an ecosystem approach to fisheries management has been addressed by Trenkel and Cotter (2009) and Jouffre et al. (2010), among others. Catch-based monitoring provides information about catchable species, but not on other species, nor on habitat. Catchability may vary across species and as a function of weather conditions (Trenkel and Cotter, 2009) and vessels (Pelletier, 1991). Sampling effort by fisheries is considerable, but data interpretation may be tricky due to the uncontrolled sampling design. Scientific catch surveys circumvent this problem, but provide small sample sizes compared to fisheries catch (Trenkel and Cotter, 2009). In addition, extractive techniques have an impact on biodiversity, which may not be desirable in the context of monitoring conservation strategies. Rotenone sampling is similar to fishing, in that it is extractive, focuses on fish species, and selects only part of the fish assemblage (Robertson and Smith-Vaniz, 2008). It is thus used more for inventories and small-scale observations than for monitoring. Underwater acoustics is currently effective for pelagic and semi-demersal species, and for zooplankton (Trenkel et al., 2011). However, species present in the acoustic data have to be identified through complementary techniques, and benthic species are not well-observed. For instance, Jones et al. (2012) combined acoustics and video to estimate rockfish biomass in untrawlable areas.

In shallow areas, UVC techniques have been used for over sixty years to monitor fish, macrobenthic organisms and habitats (Brock, 1954). They are considered to be reliable

and cost effective (Thresher and Gunn, 1986). Advantages and disadvantages of UVC for estimating fish abundance and diversity have been reported and discussed in several papers (Chapman et al., 1974; Sale, 1980; Brock, 1982; Harmelin-Vivien et al., 1985; Watson et al., 1995; Thompson and Mapstone, 1997; Willis, 2001; Kulbicki et al., 2010; Dickens et al., 2011). The main limitation of UVC lies in the need for divers' presence underwater, which influences the observation of vagile macrofauna, restricts the number of observations that can be carried out, and constrains depth observation.

In recent years, underwater video techniques have been increasingly used for observing macrofauna and habitat in marine ecosystems (see e.g. Sarradin et al., 2007 for a review concerning deep ecosystems). Technological progress regarding video cameras, sensors (such as sounders), battery life and information storage now make these techniques accessible to the majority of users. The term "underwater video" encompasses an array of techniques developed around the world, and used in a variety of contexts and for different purposes. Murphy and Jenkins (2010) reviewed the observation methods used for spatial monitoring of fish and associated habitats. They summarized the applications, advantages and shortcomings of all methods used, including UVC, remote sensing, acoustics, experimental catch and effort data, and underwater video. Because of this broad scope, the paper did not document the various video techniques and their applications. To our knowledge, there are no published papers describing underwater video techniques and their applications, and discussing their respective relevance for observing shallow water marine biodiversity. Yet many papers have been published using video techniques in this context, and video-based techniques have considerably evolved over time. The present review focuses on the video techniques developed and used for this purpose, from the first published papers through to 2012. Section 2 describes the main techniques, along with technological issues. Applications of each technique are summarized in section 3. In section 4, studies comparing video techniques with other observation techniques are listed, and their conclusions are summarized. The last section discusses the potential of video techniques for monitoring and investigating biodiversity issues in coastal environments, in order to provide guidance in choosing among techniques.

2. State of the art regarding underwater video techniques

Literature searches were conducted using the ISIS Web of KnowledgeSM and Google Scholar for relevant keywords, including “underwater video”, “underwater television”, “remote underwater video”, “baited video”, “BRUV”, “towed video”, “video transect” and “stereo-video”. In addition to database searches, we also hand-checked the reference lists of all studies retrieved to identify all relevant primary research published in peer-reviewed journals, books and proceedings of international conferences. Thus a substantial amount of grey literature was not taken into account in this review.

We restricted the literature search to environments shallower than 100 m. At greater depths, observations are more constrained by technological issues, scuba diving is not routinely feasible, and artificial light is needed. Papers pertaining to freshwater ecosystems were not included in the review either. Studies using photography, photogrammetry, underwater video for evaluating fishing gear catchability or acoustic techniques, and video tracking (Delcourt et al., 2012) fell outside the scope of the paper. The search resulted in a list of 182 peer-reviewed papers, taking into account the majority of peer-reviewed papers within the scope of the present review. As video systems are increasingly used around the world, the number of published studies has greatly increased over the last decade (67% of the papers were published from 2002 onwards). Papers were sorted according to four main techniques: remote underwater video, baited remote underwater video, towed video and diver-operated video. Note that the term “remote” is used here to designate a technique which does not require human presence underwater, while the term “autonomous” indicates a system that is not linked to a vessel or a platform. Baited Remote Underwater Video will be denoted BRUV following most studies using this technique, while unbaited Remote Underwater Video will be simply termed RUV for the sake of concision. RUV thus includes here all remote video systems that are not baited, whether dropped from the boat or set by divers. Note that trademarks on “BRUVS” and “RUVS” of the Australian Institute of Marine Science were not used as they are too specific and do not encompass all the techniques discussed in this review.

2.1. Remote Underwater Video (RUV)

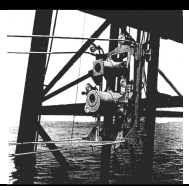
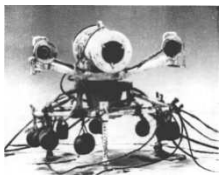
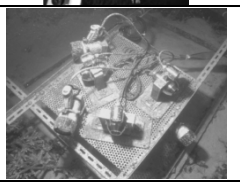
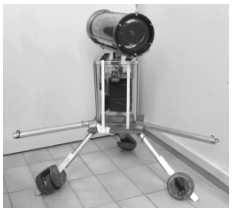
The first published work reporting the use of underwater video systems in the coastal environment dates back to the 1950s.The Scottish Marine Biological Association of Millport developed an underwater video program in 1948, and tested it in the Aquarium of the Zoological Society of London in 1949 (Barnes, 1952, 1953). In 1951, the Royal Navy constructed a system which was successfully used to identify a Royal Navy submarine lost at sea in 1951. It then served for other projects on bottom fauna (Barnes, 1955) as suspended in a mid-water environment (Backus and Barnes, 1957) and for other Navy applications (Barnes, 1963). RUV has used more frequently in marine sciences since the 1960s (Table 1). It provided the first data on fish movement and behaviour in daytime and at night, which had not been previously studied without human disturbance (Barnes, 1952; Kumpf and Lowenstein, 1962; Booda, 1966; LaFond, 1968). RUV systems exhibit different designs and technical features, including additional sensors, and can be distinguished in terms of their autonomy (linked or autonomous).

Linked systems

The system developed by LaFond et al. (1961) filmed from the surface to the bottom (20 m depth) while moving up and down a vertical-rail track placed under a platform (Table 1). It was used to study diurnal and nocturnal fish movements along with plankton dispersion (see section 3). Over the same period of time, an experimental RUV equipped with hydrophones and lights for night vision (AC-RUV, “AC” for acoustic) was developed by Kumpf and Lowenstein (1962) and Kronengold et al. (1964). The system was permanently set on sea bottom in the Bahamas (Steinberg and Koczy, 1964), in order to (i) identify the sounds present in a supposedly silent environment; (ii) learn about wildlife behavioural response to sound disturbance; (iii) describe the temporal patterns of sounds, and (iv) evaluate the advantages and limitations of systems coupling video and acoustics. Initial problems resulting from a large system size and from fouling on the camera housing led to an improved smaller AC-RUV system (Holt, 1967; Stevenson, 1967; Table 1).

More recently, Stokesbury et al. (2004) developed a vertical RUV system (Table 1) to study scallop distribution off the northeastern coast of the United States. Tyne et al. (2010) used the same system to record benthic habitats in Western Australia. The camera filmed a 1 m^2 bottom quadrat area at depths ranging between 2 and 16 m.

Table 1. Technical specifications of unbaited RUV systems. Horizontal (H) and vertical (V) in the second column refer to the direction of image recording.

Source	Type	Technical details	Illustration
LaFond et al. (1961)	H-RUV	Mounted on a vertical rail Linked to mobile platform Additional equipment: six floodlights	
Kumpf and Lowenstein (1962); Kronengold et al. (1964)	AC-H-RUV	Linked to laboratory control panel by a multi-conductor cable. Observation duration: 24 h Lens view angle: wide 2 spotlights, hydrophones, sound projector	
Stevenson (1967); Holt (1967)	AC-HV-RUV	Linked to laboratory control panel Energy supplied through a submarine cable Observation duration: 24 h Pan tilt mechanism (360° horizontally and 50° vertically), lens view angle: wide Remotely controlled windshield-wiper, releasing a toxic material, hydrophones, sound projector	
Fedra and Machan (1979)	H-RUV	Autonomous Observation duration: 1 week Lens view angle: wide Side flash reflectors (12 V battery in separate housing), Electronic timer (6V batteries)	
Dunbrack and Zielinski (2003)	V-RUV	Autonomous Observation duration: 240h (20 days) Black & white camera, electronic timer Additional time-lapse video recorder	NA
Stokesbury et al. (2004) and Tyne et al. (2010)	V-RUV	Downward-oriented video camera, attached to the apex of a stainless steel pyramid Linked to boat Black & white camera linked to a laptop computer Additional infrared illumination	
Jan et al. (2007)	H-RUV	Linked to laboratory, internet video streaming Continuous recording: Colour camera Additional illumination for night time	
Aguzzi et al. (2011); Condal et al. (2012)	H-RUV	Linked to laboratory, transmission of audio and video for internet streaming Pan tilt mechanism (360° horizontally and 210° vertically)	NA
Pelletier et al. (2012)	ROT-H-RUV	2 waterproof housings connected by an axis. Engine lower housing sets in motion the upper housing Programmed rotations of 60°every 30 seconds Autonomous Observation duration: 9 min (i.e. 3 rotations) Colour HD camera, Lens view angle: 60°	

Autonomous systems

Fedra and Machan (1979) used the first autonomous RUV in the North Adriatic Sea (Mediterranean) (Table 1). The system was set on the seabed by a diver and then left for a week, in order to study the behaviour and distribution of benthic and demersal species, their feeding activities and movement patterns, along with species interactions and the influence of environmental conditions (see section 3). Chabanet et al. (2012) recently introduced a similar system to investigate the temporal variability of undisturbed fish populations over a twenty day time period. Dunbrack and Zielinski (2003) devised a system with a camera mounted on a tripod. It was placed at the edge of the reef slope to film down the reef and study the ecology, behaviour and population status of the bluntnose sixgill shark (Hexanchus griseus) in the Georgia Strait, British Columbia (see also Dunbrack, 2006, 2008).

The rotating RUV system (ROT-RUV: "ROT" for rotation, termed "STAVIRO" by the authors) of Pelletier et al. (2012) (Table 1) is fixed on a tripod, dropped from the boat onto the seabed, and retrieved using buoys and rigging. It has been used in the New Caledonian lagoon (South Pacific) since 2007 and in the Western Mediterranean since 2010 to study and monitor the spatio-temporal distribution of marine macrofauna and habitat (Pelletier et al., 2012; D. Mallet, M. Bouchoucha, D. Pelletier, unpublished data). Unlike other RUV systems, the 360° view afforded by rotation provides panoramic images and a much larger surveyed area than fixed systems, while avoiding the image distortion characteristic of fisheye lenses. Potential double counting is minimized by paying particular attention to the direction of fish movement with respect to rotation, and by calculating the mean abundance over rotations, to average out the variability between rotations (Pelletier et al., 2012).

Most of the above techniques were implemented with the help of divers, except for Stokesbury et al. (2004), Tyne et al. (2010) and Pelletier et al. (2012). Only four RUV techniques identified in this review did not use artificial light (Stevenson, 1967; Petrell et al., 1997; Dunbrack and Zielinski, 2003; Pelletier et al., 2012).

Video systems remaining underwater for several days inevitably face the problem of fouling, i.e. the accumulation of organisms, impairing the quality of images. Yet in the literature examined, this problem was raised and addressed only by Stevenson (1967) and Chabanet et al. (2012), who used automatic windshield wipers to clean the lens surface regularly.

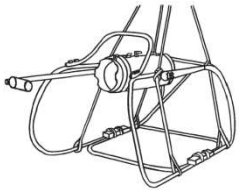
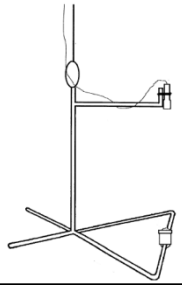
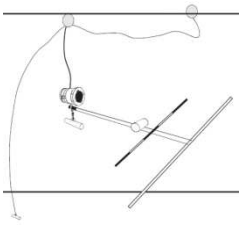
2.2. Baited Remote Underwater Video (BRUV)

A BRUV system uses either a single camera or two cameras (see subsection 2.5) filming the area surrounding a bait used to attract fish. The bait bag is placed close to the camera, at a distance ranging between 0.5 m and 1.5 m (Ellis and DeMartini, 1995; Willis and Babcock, 2000; Heagney et al., 2007). The species attracted and the bait range of action depend on the bait used (Harvey et al., 2007; Stobart et al., 2007; Wraith, 2007). Pilchards (Sardinops sp.) are currently used in most studies (Mclean et al., 2010, 2011; Watson et al., 2010; Bassett and Montgomery, 2011; Goetze et al., 2011; Harvey et al., 2012a; Langlois et al., 2012a, 2012b). BRUV systems are directly deployed from the boat (Watson et al., 2005, Cappo et al., 2007a, Bassett and Montgomery, 2011). Willis and Babcock (2000) and Watson et al. (2005) showed that a soak time of 25 to 40 minutes underwater was required to obtain representative observations for the majority of fish species, but they recommended a duration of 50 to 60 minutes for observing most target fish species in the census. The main differences among BRUV systems concern the orientation of the system in relation to the sea bottom (horizontal or vertical, Table 2), which result in distinct observed abundances and species compositions (Langlois et al., 2006; Wraith, 2007). BRUV has also been used with infrared light to study nocturnal fish; for example Bassett and Montgomery (2011) studied the olfactory capabilities of nocturnal fish species and their influence on response to bait using this system.

Horizontally oriented BRUV

Horizontal BRUV (H-BRUV) (Ellis and DeMartini, 1995) provides a wide viewing angle for observing the area surrounding the bait. An array of species can be observed, in particular those not approaching the bait bag because of fish behaviour or competition for the bait (Cappo et al., 2004; Harvey et al., 2007). H-BRUV systems have been mainly used to study spatio-temporal variations in reef fish assemblages, the influence of depth and location upon fish and species distribution, and the effect of MPAs on biodiversity (Cappo et al., 2007b and section 3). H-BRUVs are generally set on the seafloor, though Heagney et al. (2007) used mid-water BRUV to study pelagic fish.

Table 2. Technical specifications of Baited RUV systems. Horizontal (H) and vertical (V) in the second column refer to the direction of image recording.

Source	Type	Technical details	illustration
Ellis and DeMartini (1995)	H-BRUV	Autonomous Set on bottom Observation duration: 10 to 60 min Colour camera (red filter for underwater vision) Lens view angle: wide No additional sensors	
Willis and Babcock (2000)	V-BRUV	Linked to boat Observation duration: 30 or 60 min Colour camera	
Heagney et al. (2007)	Mid-water H-BRUV	Autonomous Mid-water device Observation duration: 45 min Lens view angle: wide Depth sounder	

Vertically oriented BRUV

Vertical BRUV (V-BRUV) has been used for studying the size and abundance of carnivorous fish (Babcock et al., 1999; Willis and Babcock, 2000) and the effect of protection by MPAs (Willis et al., 2000, 2003; Denny and Babcock, 2004; Denny et al., 2004; Willis and Millar, 2005). The restricted field of vision due to the camera pointing downwards ensures a constant field of view and a constant focal length, particularly where water clarity or topography varies between observations (T. Willis, personal communication). Langlois et al. (2006) suggested that some species would rarely approach the system when the camera was positioned above the bait. Other authors suggested that recent V-BRUV does not affect blue cod and various other species (T. Willis, personal communication). Lightweight stands have been shown to provide precise relative density estimates of carnivorous fishes (Willis et al., 2000).

2.3. TOWed Video (TOWV)

Machan and Fedra (1975) introduced the first TOWed Video technique (TOWV) in shallow waters. The system was towed by a vessel at low speed (0.1 to 1 $m.s^{-1}$). TOWV films along a transect of predefined size and trajectory (30 m to 20 km). The various systems developed (Table 3) were linked to the vessel by a coaxial cable and a rope. The main difference among them lies in the position at which the system operates in the water column, i.e. seabed or mid-water.

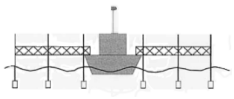
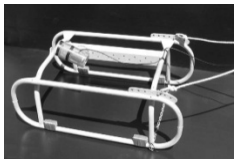
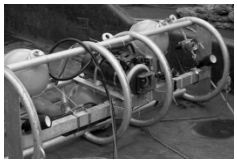
Seabed TOWV

In the coastal domain, the first TOWV systems were towed on the seabed using a sledge (seabed-TOWV, Table 3). These were used in the Mediterranean Sea (Machan and Fedra, 1975), in South-West England (Holme and Barrett, 1977) and in Alaska (Spencer et al., 2005, Rooper and Zimmermann, 2007). The video camera is slightly angled downwards on the sledge, which carries additional equipment (Table 3). Seabed-TOWVs have been used to study sea floor and epifaunal species (mostly crustaceans and flat fish) (see section 3). It should be noted that in shallow waters such as lagoon areas, vagile species were found to be sensitive to the boat noise (D. Pelletier and G. Hervé, unpublished data).

Mid-water-TOWV

Mid-water-TOWV systems are more recent than seabed-TOWVs in shallow waters (Norris et al., 1997). These systems are towed at a constant elevation in the water column, thus providing a wider view of the seafloor compared to seabed-TOWVs. The system of Riegl et al. (2001) is set on each side of the boat with vertical tubes that can be lowered or raised between 0.5 and 3.5 m below the sea surface, so as to adjust to varying depth (Table 3). Most mid-water-TOWVs are equipped with a depth sounder (Hayashizaki and Ogawa, 2006; see also Schaner et al., 2009, for a freshwater application). They have mostly been used to characterize, quantify and assess changes in benthic flora (seagrass, macro-algae and coral) and fauna.

Table 3. Technical specifications of Towed video systems (TOWV). Camera orientation is reported in the third column.

Source	Type	Technical details	Illustration
Machan and Fedra (1975)	Seabed TOWV	Angled down (30°) Linked to boat Boat speed: max 1 $m.s^{-1}$ Observation distance: 20 km in 1 day Still camera, spotlight, flash	
Holme and Barrett (1977)	Seabed TOWV	Angled down (45°) Linked to boat Boat speed: ½ - 1 knot (0.257-0.514 $m.s^{-1}$) Transect length: around 3.5 km Observation duration: 2.5 h (max 3h) Still camera, light	
Norris et al. (1997)	Mid-Water TOWV	Angled down Linked to boat Boat speed: max 1 $m.s^{-1}$ Transect length: 174 m Observation duration: 183 s Colour camera Additional light	NA
Riegl et al. (2001)	Mid-Water TOWV	Vertical The video cameras were individually linked to six onboard recorders Transect length: 50 m Colour camera Lens view angle: wide	
Spencer et al. (2005)	Seabed TOWV	Vertical Linked to boat Boat speed: 0.6 $m.s^{-1}$ Transect length: 30, 100, and 200 m Observation duration: 2 h Black & white camera Lens view angle: field of view = 5 m^2 Temperature sensor	
Hayashi-zaki and Ogawa (2006)	Mid-Water TOWV	Vertical Linked to boat Transect length: 50 m GPS, depth sounder	NA
Rooper and Zimmer mann (2007)	Seabed TOWV	Angled down (35°) Linked to boat Boat speed:1.8-2.7 $km.h^{-1}$ Observation duration: 45 to 55 min Colour camera Three lasers, lights	

2.4. Diver-Operated Video (DOV)

The diver-operated video technique (DOV) consists of a diver holding a video system and filming a defined area. Similarly to UVC, the observation area may vary in size (transects from 2 to 500 m, Table 4) and shape (along a predefined line, inside a quadrat, or rotating around a fixed point). The diver is sometimes towed (Carleton and Done, 1995; Vogt et al., 1997; Kenyon et al., 2006), recalling the "Manta tow" technique, where a towed snorkeler implements a transect (Fernandes, 1990). Towed DOV has been used to record benthic habitat along long transects (up to 500 m long).

The DOV technique (Alevizon and Brooks, 1975) involves a diver filming vertically along a transect line. DOV is generally conducted at a constant swimming speed over the entire transect (0.1 to 3 m s-1, Table 4). Elevation above the seafloor ranges from 0.15 to 0.5 m (parameter documented in 16 papers out of 22). But in some cases, transects are conducted at a larger elevation (1 to 3 m) to ensure a wider viewing angle (Table 4). A reference bar attached to the camera housing is sometimes used to control the camera elevation (Leonard and Clark, 1993; Vogt et al., 1997; Rogers and Miller, 2001; Lam et al., 2006; Cruz et al., 2008).

Pelletier et al. (2011) presented the browsing video transect technique, where the diver browses inside the strip transect area, at varying elevation, speed and angle, and zooming when needed. This technique mimics the behaviour of UVC divers in strip transects. These authors demonstrated that more individuals and species were recorded from browsing transects than from straight ones conducted at a constant elevation.

Bortone et al. (1991, 1994) proposed a protocol where the diver simultaneously rotates and records images, mimicking the UVC stationary point count technique (Bohnsack and Bannerot, 1986). DOV was also used to study fish behaviour by Krohn and Boisclair (1994) (energy expenditure of swimming fish) and Hall and Hanlon (2002) (observation of particular individuals for up to 1.5 h).

Table 4. Referenced studies involving DOV, with main protocol features, and study focus. For comparison, Bortone et al. (1991, 1994) presented the stationary rotating point count technique for counting fish, with an observation radius of 5.64 m (see text for details). ST: straight transect; TC: time census; TT: towed transect; BT: browsed transect.

Source	Census type	Length (m)	Distance above the bottom (cm)	Speed ($m.s^{-1}$)	Study Fish / Habitat
Alevizon and Brooks (1975)	ST	50	NA	NA	Fish
Davis and Anderson (1989)	ST	200	100	0.33	Fish
Greene and Alevizon (1989)	ST	NA	NA	constant	Fish
Leonard and Clark (1993)	ST	2	50	0.07	Habitat
Aronson et al. (1994)	ST	25	NA	slowly	Fish & Habitat
Parker et al. (1994)	TC (15 min)	NA	100	with prevailing current	Fish
Carleton and Done (1995)	TT	200	100 – 150	1 - 1.23	Habitat
	ST	200	100 – 150	0.63 - 0.78	Habitat
Vogt et al. (1997)	TT	500	50 – 70	0.11 - 0.25	Habitat
Ninio et al. (2000)	ST	50	25 - 30	NA	Habitat
Rogers and Miller (2001)	ST	20 and 100	40	0.03	Habitat
Ninio et al. (2003)	ST	50	25 to 30	NA	Fish & Habitat
Tessier (2005); Tessier et al. (2005)	ST	24	300	0.3	Fish
Watson et al. (2005)	ST	25	NA	NA	Fish & Habitat
Houk and Van Woesik (2006)	ST	15, 35 and 50	NA	0.15	Habitat
Kenyon et al. (2006)	TT	19.2 to 38.6	100	0.69 – 0.97	Habitat
Lam et al. (2006)	ST	50	40	0.10	Habitat
Leujak and Ormond (2007)	ST	50	30 – 35	0.12	Habitat
Cruz et al. (2008)	ST	20	40	0.05	Habitat
Langlois et al. (2010)	ST	25	30	3	Fish & Habitat
Watson et al. (2010)	ST	50 and 100	30	0.34	Fish & Habitat
Pelletier et al. (2011)	ST	50	150	0.2 - 0.3	Fish
	BT	50 x 4	varying elevation	speed	Fish

2.5. Stereo-video technique

The stereo-video technique is not additional to those described above, but it involves a particular recording that produces a 3-dimensional (3D) image. It was developed by Harvey and Shortis (1995) to improve fish size estimation by divers. The technique simultaneously uses two cameras to record the same scene. Left and right images are synchronized on the computer based on a light-emitting diode (LED) placed at 2.5 m from the cameras and seen on both images. Images are then cross-checked from ad hoc software to obtain a 3D image allowing individual size measurement. A 1.4 m distance between the two cameras was found to provide a trade-off between the precision afforded by a greater distance and diver's ability to manoeuvre the system (Harvey and Shortis, 1995). This system recorded and measured individuals in a distance range of 2 to 10 m, depending on underwater visibility. Length measurements were found to be more accurate and repeatable when the orientation of the subjects to the stereo-cameras was less than 50° (Harvey and Shortis, 1995, 1998). Stereo-video has been shown to provide more accurate estimates of both fish length and distance than visual estimation by divers (Harvey et al., 2001a, 2001b, 2002a, 2004) or single video (Harvey et al., 2002b). As such, it also helps distinguishing individuals (Harvey et al., 2007).

The stereo system has been adapted to all underwater video techniques (RUV and BRUV, TOWV, and DOV), but it has been mostly implemented on H-BRUV systems (Watson et al., 2007, 2009; Chatfield.et al., 2010; McLean et al., 2010, 2011; Goetze et al., 2011; Birt et al., 2012; Dorman et al., 2012; Fitzpatrick et al., 2012; Harvey et al., 2012a, 2012b, 2012c; Langlois et al., 2012a, 2012b). Several comparisons of underwater observation techniques used stereo-video (Watson et al., 2005, 2010; Langlois et al., 2010). Shortis et al. (2009) provide a detailed review of the status of underwater stereo-video measurement and marine and ecology applications. With the same objective of measuring fish, Heppell et al. (2012) used two lasers fixed on each side of a single camera, rather than stereo-video.

2.6. Technological progress

The first video systems used (Barnes, 1952, 1953, 1955; Backus and Barnes, 1957, Myrberg et al., 1969, 1973) suffered from (i) difficulties in setting and retrieving systems; (ii) malfunctioning of electronically driven systems; and (iii) the limitations of video sensors which severely impaired image quality.

Various systems have been developed and used over time (Figure 1). The emergence and evolution of such systems was primarily driven by technological progress, enabling considerable improvements in performance, while making these tools more robust, smaller and cheaper. The digital revolution led to increased sensor resolution, with a dramatically improved image quality, in particular with the advent of High Definition (HD). Regarding energy supply, batteries have become smaller and more powerful. Data storage devices now make it possible to record and archive more images, since camera internal memory or Secure Digital (SD) cards can now store up to 120 Gigabytes (GB), while the capacity of standard external hard drives is 1 or 2 Terabyte (TB). The increasing volume of observation files is therefore matched by a corresponding increase in information storage capacities.

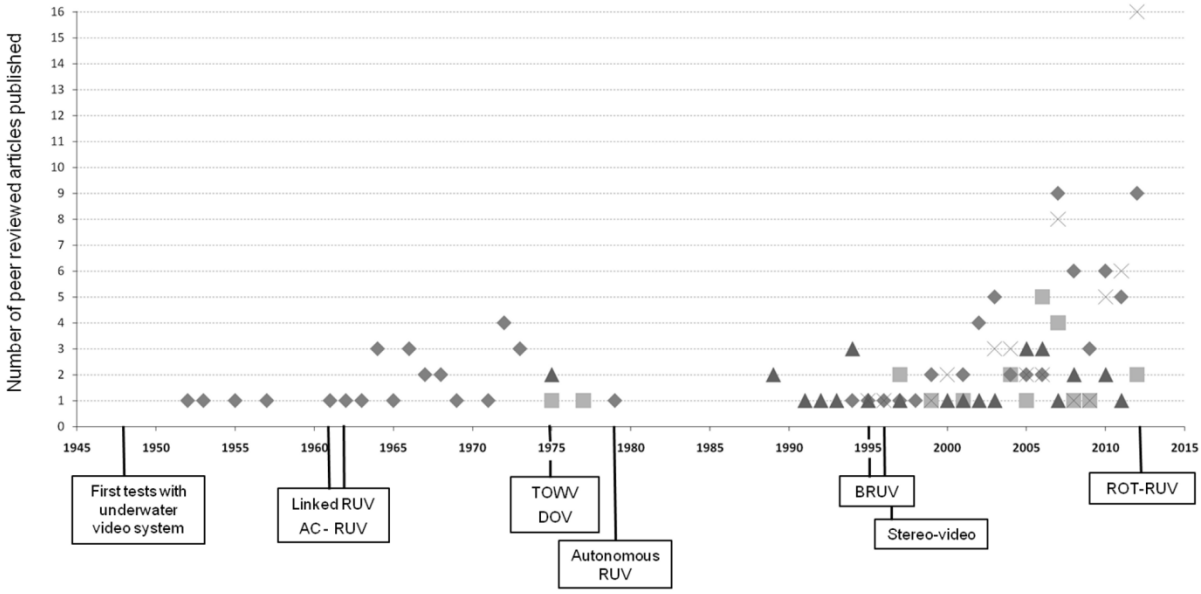


Figure 1. Historical perspective on the development of underwater video systems, with associated papers (◆RUV; ■ TOWV; ▲DOV; X BRUV).

3. Underwater video: Where is it used and what is it used for?

Video systems are increasingly used around the world, particularly over the last decade (Figure 1). Nevertheless, there are not many teams using these techniques. Numerous studies have been published in Australia (63 papers from 1995 to 2012), the USA (24 papers from 1957 to 2012) and New Zealand (24 papers from 1995 to 2011), and in comparison, relatively few papers from other countries (Figure 2 and Supplementary Material A). The first publications on RUV systems originated in Europe (United Kingdom in 1952) and North America (USA in 1957), and then extended to all continents (Oceania in 1995, Asia in 1997 and Africa in 2008). Twenty papers were published from the Bahamas AC-RUV between 1962 and 1973. BRUV has mainly been used in Australia since 2003 (32 of the 52 BRUV-based papers), and in New Zealand since 1999 (11 papers). In Australia only H-BRUV has been used, whereas in New Zealand V-BRUV has mostly been used (9 of the 11 BRUV-based papers). Studies involving TOWV and DOV are both more widespread and less numerous, with respectively 23 and 28 papers published since 1975. Note that the grey literature and studies outside the scope of this review (deep environment and freshwater) contain a large amount of work which has not been cited here (including some of the authors' work).

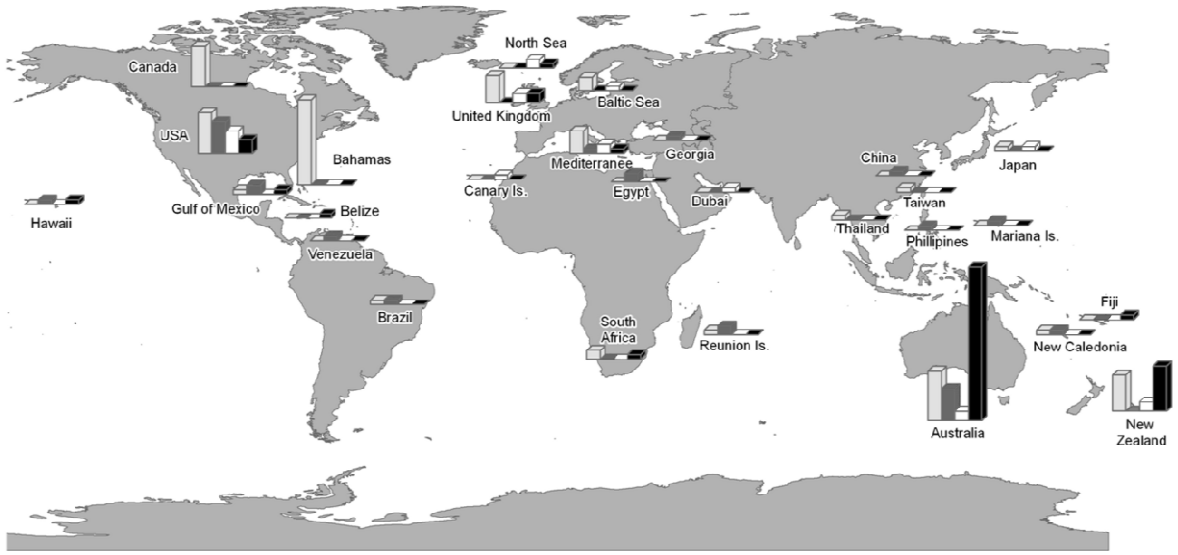


Figure 2. Geographical distribution of published studies. Each bar is proportional to the number of papers published for each technique: RUV; DOV; TOWV and BRUV. The number of papers published by year and country per technique are given in Supplementary Material 4.

The techniques described in the previous section have been used for a variety of purposes in the context of coastal biodiversity. Applications were classified according to five main subjects (Table 5) to provide an overview. Studies of animal behaviour and activity are a major field of application (52 references published between 1952 and 2012). Six papers used video to investigate the effect of human-induced disturbances upon species behaviour. Forty-eight papers investigate spatial and temporal patterns of fish abundance, size and of fish assemblage composition, in particular to appraise the effects of habitat, anthropogenic pressures and MPAs. Thirty-two references dealt with habitat mapping and benthic cover monitoring, but benthos monitoring at species level was addressed by only four references. Not surprisingly, video techniques have been specialized, depending on these areas of application. RUV has been preferably used for behaviour-related studies (45 references), and only recently become of interest for assessing species response to environmental conditions and habitat through spatially-replicated designs (8 references from 2008). In contrast, BRUV has been extensively used for this latter purpose (25 references), with an emphasis on size estimation through stereo-video, whereas it has been hardly used for behavioural studies. TOWV has been almost exclusively used for habitat mapping and monitoring purposes (15 references); studies mostly focused on benthic macrofauna (e.g. coral cover and scallops) and macroflora (e.g. sea grass and algae), though some examined demersal fish species. DOV has also been used for assessing fish abundance and assemblages (13 references), habitat mapping and monitoring (15 references), and investigating fish behaviour (2 references). It is important to note that each technique was tested in both temperate and tropical ecosystems. It should also be underlined that Table 5 provides an average picture over the review period. Technological progress entails new observation capacities, and therefore new fields of investigation, such as exemplified by recent applications of RUV to fish and habitat monitoring. In addition to these applications, the great potential of video for addressing specific biodiversity-related topics was also illustrated by unusual applications, e.g. seals in underwater caves (Dendrinos et al., 2007).

Table 5. Applications of underwater video techniques according to five main topics. NR indicates that No reference was found in the literature search.

	RUV	BRUV	TOWV	DOV
Natural behaviour and activity patterns (e.g. circadian)	Kumpf (1964); Steinberg and Koczy (1964); Steinberg et al. (1965); Cummings et al. (1966); Stevenson and Myrberg (1966); Stevenson (1967); LaFond (1968); Richard (1968); Myrberg et al. (1969); Colin (1971,1972,1973); Myrberg (1972a, 1972b); Myrberg and Spires (1972); Smith and Tyler (1973); Fedra and Machan (1979); Dunlap and Pawlik (1996); Barans et al. (2002, 2005); Bellwood et al. (2003) ; Dunbrack and Zielinski (2003); Jenkins et al. (2004); Bellwood et al. (2006); Dendrinos et al. (2007); Enstipp et al. (2007); Fischer et al. (2007); Fox and Bellwood (2007); Mantyka and Bellwood (2007a, 2007b); Bellwood and Fulton (2008); Fox and Bellwood (2008a); Meynecke et al. (2008); Cvitanovic and Bellwood (2009); Hoey and Bellwood (2009); Hoey (2010); Hoey and Bellwood (2010, 2011); Bennett and Bellwood (2011); Burkepile and Hay (2011); Lefèvre and Bellwood (2011); Burge et al. (2012); Hannah and Blume (2012); Masuda et al. (2012); Vergés et al. (2012) **(45 references)**	Burrows et al. (1999); Bond et al. (2012); Burge et al. (2012)	Bräger et al. (1999) ; Grabowski et al. (2012	Krohn and Boisclair (1994); Hall and Hanlon (2002
Effect of human-induced disturbance on species behaviour (diver, bait, acoustics)	Dearden et al. (2010); Watson and Harvey (2007); Picciulin et al. (2010)	Watson and Harvey (2007); Dorman et al. (2012); Langlois et al. (2012b); Young and Bellwood (2012)	NR	NR

Table 5 (suite)

	RUV	BRUV	TOWV	DOV
Spatial and temporal patterns of abundance, size and fish assemblage composition (including effects of habitat, anthropogenic pressures and protection)	Dunbrack (2008) ; Becker et al. (2010); Aguzzi et al. (2011); Bloomfield et al. (2012); Burge et al. (2012); Chabanet et al. (2012); Condal et al. (2012); Pelletier et al. (2012) **(8 references)**	Willis and Babcock (2000); Willis et al. (2000, 2003); Denny and Babcock (2004); Denny et al. (2004); Cappo et al. (2007a); Malcolm et al. (2007); Stobart et al. (2007); Wraith (2007); Stoner et al. (2008); Gomelyuk (2009); Watson et al. (2009); Chatfield et al. (2010); McLean et al. (2010, 2011); Cappo et al. (2011); Goetze et al .(2011); Lowry et al. (2011) ;Martinez et al. (2011) ; Birt et al. (2012); Fitzpatrick et al. (2012) ; Gladstone et al. (2012) ; Harvey et al. (2012a,b); Schultz et al. (2012) **(25 references)**	Shucksmith et al. (2006); Carbines and Cole (2009)	Alevizon and Brooks (1975); Davis and Anderson (1989); Greene and Alevizon (1989); Aronson et al. (1994); Bortone et al. (1991, 1994); Parker et al. (1994); Ninio et al. (2000); Tessier et al. (2005) ; Watson et al. (2005, 2010); Langlois et al. (2010); Pelletier et al. (2011) **(13 references)**
Benthos abundance and size monitoring	Handley et al. (2003); Dunbrack (2006)		Holme and Barrett (1977); Spencer et al. (2005)	
Habitat mapping, Benthic cover monitoring and impact of fishing gears on habitat	Tyne et al. (2010) ; Pelletier et al. (2012)		Machan and Fedra (1975); Holme and Barrett (1977); Norris et al. (1997); Riegl et al. (2001); Rosenkranz and Byersdorfer (2004); Spencer et al. (2005); Hayashizaki and Ogawa (2006); McDonald et al. (2006); Bucas et al. (2007); Rooper and Zimmermann (2007); Smith et al. (2007); Grizzle et al. (2008); Carbines and Cole (2009); Bulh-Mortensen et al. (2012); Grabowski et al. (2012) **(15 references)**	Leonard and Clark (1993); Aronson et al. (1994); Carleton and Done (1995); Vogt et al. (1997); Ninio et al. (2000); Rogers and Miller (2001); Watson et al. (2005, 2010); Houk and Van Woesik (2006); Kenyon et al. (2006); Lam et al. (2006); Leujak and Ormond (2007); Cruz et al. (2008); Tilot et al. (2008); Langlois et al. (2010) **(15 references)**

Lastly, attention was paid to the kind of information collected by each technique. Fish species are most often identified at the lowest possible taxonomic level, notwithstanding a small fraction of individuals, in general small species, identified only at higher levels such as genus or family (see e.g. Pelletier et al., 2011). This must be taken into account when calculating metrics based on species counts. In some instances, metrics may only be calculated at genus or family level. In general, epifauna and epiflora are identified according to broad categories, e.g. sponges (Tyne et al., 2010), macroalgae (Bucas et al., 2007), tunicates and ophiuroids (Carbines and Cole, 2009). Benthos and habitat are generally characterized through percent covers of the sea bottom. In all cases, the species that can be observed in a reliable way must be carefully listed. Cryptic species are poorly observed and the limitations of visual counts due to underwater visibility are also valid for video techniques. Small species may be more difficult to identify from video images than from visual counts, whereas diver-avoiding species are more likely observed from diver-free video systems (Mallet et al., 2014).

A large number of metrics can then be obtained from all the techniques (Table 6). Species are counted over the observation duration to provide presence/absence, occurrences and species richness. In the case of vagile species, abundance is estimated over the whole video sequence or part of it for RUV, DOV and TOWV. In contrast, for BRUV the metric used is the time of first appearance per species (Wraith, 2007), and most often MaxN, the maximum abundance per species seen over the observation period (Ellis and DeMartini, 1995). MaxN is a conservative estimate of abundance (Willis et al., 2000). Bacheler et al. (2013) proposed using the mean number of fish observed in a series of snapshots over a viewing interval (MeanCount). Schobernd et al. (2013) compared MaxN and MeanCount from simulations, laboratory experiment and modelling. They found that MeanCount was generally linearly related to true abundance with a variability similar to MaxN. Fixed species and habitat are quantified either through abundance or percent cover. Estimating the size of individuals is generally done using stereo-video. Counts may also be assigned to size classes to avoid the issue of size estimation. Lastly, depending on the way cameras are set, video may allow other metrics to be considered, such as the number of bites from herbivores, the occurrence of activities, or parameters describing habitat (Table 6).

Table 6. Metrics computed from the main video techniques. The list of metrics may depend on the particular implementation of the technique.

Technique	Fish and Macrofauna-related metrics	Benthos- and Habitat-related metrics
RUV and DOV	Frequency of occurrence, presence/absence per species Species richness Abundance or abundance density per species or per size class of the species : maximum abundance seen during the observation period, or mean abundance over viewing intervals during the observation period Number of bites by herbivores Distance from fish to the camcorder Occurrences of activities per individual	Percent cover of abiotic substrate Habitat topography and complexity Percent cover of epifauna and epiflora
BRUV	Number of species within the field of view during the observation period Maximum fish abundance seen during the observation period Maximum number of individuals per species simultaneously observed during the observation (MaxN) Time to first appearance per species	
TOWV	Abundance and percent cover of some macro-invertebrate species	Abundance of epibenthic species Percent cover of epifauna and epiflora Percent cover of biotic and abiotic substrate and habitat Habitat topography and complexity

4. Complementarity of techniques

4.1. Comparative studies

From our literature search, we identified forty-two papers comparing two or more observation techniques (Table 7). More than 65% (28 out of 42) of papers compared UVC with a video technique: RUV (5 papers), TOWV (3), DOV (8), BRUV (9), and stereo-RUV (5). As video is perceived as a relatively new observation technique, it was often compared to UVC, which is commonly used for observing fish communities and habitats in shallow areas. Other comparisons involved two or more video techniques for (i) testing the effect of using two cameras compared to a mono-camera (stereo-RUV versus

RUV); (ii) testing the effect of baiting (BRUV versus RUV); and (iii) evaluating their respective relevance for studying reef fish assemblages (BRUV versus TOWV, stereo-RUV versus stereo-DOV, stereo-BRUV and stereo-DOV). Finally, several papers compared underwater video with, on the one hand, experimental fishing (two papers dealing with RUV, five with BRUV, two with stereo-BRUV and one with TOWV) and, on the other, acoustic techniques (one paper about BRUV).

Table 7. Studies comparing techniques. NR indicates that No reference was found in the literature search. Only studies with a protocol aimed at comparing data from distinct techniques were quoted.

	RUV	Stereo RUV	BRUV	Stereo BRUV	TOWV	DOV
RUV	NR	Harvey et al. (2002b)	Harvey et al. (2007); Bernard and Götz (2012)	NR	NR	NR
Stereo BRUV	NR	Watson et al. (2005)	NR	NR	NR	NR
TOWV	NR	NR	Morrison and Carbines (2006); Monk et al. (2012)	NR	NR	NR
Stereo DOV	NR	Watson et al. (2005)	NR	Watson et al. (2005); Langlois et al. (2010); Watson et al. (2010)	NR	NR
UVC	Francour et al. (1999); Cooke and Schreer (2002); Fox and Bellwood (2008); Burge et al. (2012); Longo and Floeter (2012)	Harvey et al. (2001a,b, 2002a, 2004); Cappo et al. (2003)	Willis and Babcock (2000); Willis et al. (2000); Westera et al. (2003); Langlois et al. (2006); Morrison and Carbines (2006); Stobart et al. (2007); Colton and Swearer (2010); Burge et al. (2012); Lowry et al. (2012)	NR	Morrison and Carbines (2006); Assis et al. (2007); Leujak and Ormond (2007)	Greene and Alevizon (1989); Michalopoulos et al. (1992); Leonard and Clarck (1993); Rogers and Miller (2001); Tessier et al. (2005); Lam et al. (2006); Pelletier et al. (2011)
Fishing	Cooke and Schreer (2002); Wells et al. (2008)	NR	Ellis and DeMartini (1995); Willis et al. (2000); Cappo et al. (2004); Morrison and Carbines (2006); Bloomfield et al. (2012)	Harvey et al. (2012c); Langlois et al. (2012a)	Morrison and Carbines (2006)	NR
Acoustic	NR	NR	Gledhill et al. (1996)	NR	NR	NR

Comparisons always used metrics based on species counts (species richness, taxonomic diversity, and frequency of occurrence), and on abundance estimates (Table 8). Note that each study presented a number of distinct results, which may vary across taxa and across environmental settings. Hence, although some techniques may have been compared using the same metric in several studies, conclusions might differ from one study to another. For instance, in some studies greater fish diversity was recorded with BRUV than with DOV (Langlois et al., 2010), TOWV and SRUV (Watson et al., 2005), and UVC (Willis and Babcock, 2000), while others show that more fish species were detected with UVC than with BRUV (Tessier et al., 2005; Langlois et al., 2006; Stobart et al., 2007; Colton and Swearer, 2010; Lowry et al., 2012) and DOV (Greene and Alevizon, 1989; Pelletier et al., 2011). In general, differences in observed abundances between techniques also depend on taxa (Watson et al., 2010; Pelletier et al., 2011), thereby determining distinct observed assemblage structures (Table 8).

Directly comparing techniques in the field is rather difficult in that observations may be influenced by many factors, either natural or linked to fine-scale system deployment. Paired observations are needed to control for observation conditions, such as time of the day, weather, and the precise observation location. But since implementation in the field may depend on the technique, the number of observations that can be carried out within a given time period, as well as the habitat and depth constraints, may also differ from one technique to another. Thus, a paired comparison may only address the issue of comparing two observations of the same seascape and species, and not the actual advantages and shortcomings of each technique, and therefore not all facets of their complementarity.

For comparisons involving a diver-based technique, i.e. UVC or DOV vs TOWV, RUV or BRUV, the main differences between techniques were due to the presence of divers. The influence of divers' presence on UVC observations has been widely documented (Chapman et al., 1974; Harmelin-Vivien et al., 1985; Kulbicki, 1998; Dearden et al., 2010). UVC also raise a number of additional issues such as the need for species identification skills, the variability of observations between divers, and the influence of swimming speed (Brock, 1982; Bell et al., 1985; Smith, 1988; Kulbicki et al., 2010; Dickens et al., 2011). In the case of diver-free video observations, the factors inherent in each technique, that may affect observations, have not been evaluated from specifically designed studies. These include, for instance, the bait plume or noise, the use of artificial light, and more generally the behaviour of animals with respect to the video system.

Table 8. Main outcomes of comparative studies involving video techniques (see references and Supplementary material for details). For each topic of interest, symbols ">", "≥", "≠"," ≈" compare the number of items or the assemblage structure detected by the two techniques, which may represent a qualitative summary over several results.

FISH	
Species richness	
UVC > H-BRUV > V-BRUV	Langlois et al. (2006)
UVC > BRUV	Colton and Swearer (2010)
UVC > RUV	Francour et al. (1999)
RUV > UVC & Experimental fishing	Cooke and Schreer (2002)
UVC ≥ DOV	Pelletier et al. (2011)
UVC >DOV	Green and Alevizon (1989)
TOWV > UVC	Assis et al. (2007)
BRUV > RUV & DOV	Watson et al. (2005) ; Bernard and Götz (2012)
RUV > BRUV	Harvey et al. (2007)
BRUV > DOV	Langlois et al. (2010); Watson et al. (2010)
BRUV > Exp. Fishing / Traps	Ellis and DeMartini (1995); Harvey et al. (2012)
Assemblage structure	
UVC ≠ BRUV	Colton and Swearer (2010)
BRUV ≈ UVC	Westera et al. (2003)
BRUV ≠ RUV ≠ DOV	Watson et al. 2005)
BRUV ≠ DOV	Langlois et al. (2010); Watson et al. (2010)
BRUV ≠ TRAWL	Cappo et al. (2004)
BRUV > Traps	Harvey et al. (2012)
Abundance	
UVC > BRUV	Langlois et al. (2006); Colton and Swearer (2010)
UVC ≥ DOV	Pelletier et al. (2011)
TOWV > UVC	Assis et al. (2007)
RUV > UVC & Exp. Fishing	Cooke and Schreer (2002)
BRUV > RUV	Harvey et al. (2007) ; Bernard and Götz (2012)
BRUV ≠ DOV (depends on family)	Watson et al. (2010)
UVC ≠ DOV (depends on family)	Pelletier et al. (2011)
BRUV > Traps	Harvey et al. (2012)
Occurrences	
BRUV > Experimental fishing	Ellis and DeMartini (1995); Harvey et al. (2012)
HABITAT – BENTHOS	
UVC > DOV: Diversity of coralline algae observed	Leonard and Clark (1993)
DOV ≈ UVC: Live coral cover	Rogers and Miller (2001)
DOV > UVC:	
% Coral cover	Lam et al. (2006)
Occurrence of Gorgonians & Macroalgae, % Bleached coral	Rogers and Miller (2001)
TOWV > UVC: % Benthic cover	Leujak and Ormond (2007)

In addition, the area actually surveyed by each technique inevitably affects the number of species and individuals detected.

Hence, many factors can explain differences between observations obtained from distinct techniques. Because not all these factors can be controlled, it is important to bear them in mind when interpreting the outcomes of comparisons.

From the published studies, no single technique clearly appears to outperform the others; although some are more appropriate for particular purposes. Thus RUV appeared as an appropriate diver-free observation technique, as it can be left in place for a long time, at a range of depths, and in low light conditions when using additional lights (see Supplementary material B, C and D for detailed outcomes of the comparisons in Table 8). It can be used to investigate areas, parameters and factors that cannot be observed from techniques relying on divers, and it enables a high level of temporal and spatial replication. RUV was often found appropriate for surveying common and conspicuous species. BRUV was found particularly appropriate for sampling generalist carnivores, large predators and mobile species. Because it relies on attracting species, it may be usefully deployed in areas when fish are scarce, e.g. pelagic areas or sandy substrates in lagoon areas. The main advantage of TOWV lies in its ability to sample a large area in a short period of time, thereby increasing the spatial coverage of habitats, and the probability of observing species, including rare species (although motile species may be sensitive to boat noise). DOV was deemed adequate for studies at smaller scales, e.g. to study changes in corals, gorgonians and macro-algae, and to provide representative observations of fish abundance and species diversity. The various techniques should thus be seen as providing complementary standpoints on shallow biodiversity and species.

4.2. Cost-efficiency considerations

In addition to the information provided by each kind of observation, investment and operating costs are crucial parameters when considering an observation technique. Overall, few papers documented implementation costs for the techniques used, whereas the time required for image analysis is often seen as a shortcoming of underwater video techniques. Francour et al. (1999) found that underwater video was more cost-efficient than UVC in terms of total time spent in the field and in the laboratory. Based on a subset

of papers, Murphy and Jenkins (2010) found that relative costs were AUD$1,000–5,000 for RUV and AUD$5,000–10,000 for BRUV. However, financial costs are difficult to evaluate for a given technique, because of the various ways of manufacturing systems, and because of differences in the characteristics of the camcorders and sensors used. It is thus more relevant to compare required staff time rather than financial costs of equipment. Note also that time spent at sea is always more expensive than laboratory time (Pelletier et al., 2011; Bernard and Götz, 2012). The cost-efficiency of several observation techniques were compared by Leujak and Ormond (2007) (six techniques for surveying coral communities) and by Langlois et al. (2010) (stereo-BRUV versus stereo-DOV transects for observing fish assemblages) (Table 9). Pelletier et al. (2011, 2012) detailed observation costs (including both field and image analysis) for DOV and ROT-RUV, with respect to UVC.

Cost-efficiency considerations must account for the fact that a technique which is better at observing or detecting species, either because of attraction (BRUV) or because of a higher image resolution, will inevitably require increased time for image analysis. For example, Bernard and Götz (2012) found that a BRUV station required 7 hours of staff time versus 3.5 hours for RUV, but this was mostly due to the fact that BRUV detected more species and individuals than RUV (Table 9). Consequently, a larger time for post-field analysis should not be considered as a weakness if higher diagnostic power is the end result (Bernard and Götz, 2012).

Table 9. Cost-related information per technique.

	Reference	Staff time per station (hrs)
RUV	Bernard and Götz (2012) Pelletier et al. (2012)(ROT-RUV)	3.5 0.5-1.6
BRUV	Langlois et al. (2010)(stereo-BRUV) Bernard and Götz (2012) Gladstone et al. (2012)	1.75-3 7.0 1.5 (soaktime only)
DOV	Leujak and Ormond (2007) Langlois et al. (2010)(stereo-DOV) Pelletier et al. (2011)	 0.75-1.8 0.4-2.5
TOWV	See Table 3	depends on tow length
UVC	Pelletier et al. (2011)(strip transect) Bohnsack and Bannerot (1986) (stationary point count) Leujak and Ormond (2007) (Line Intercept Transect)	 0.75-1.5 0.2 1.25

5. Underwater video in the light of current monitoring challenges

As mentioned in the introduction, conservation objectives and sustainable management of coastal biodiversity and resources involve monitoring the status of several biodiversity components in large areas. This is the case for MPA assessment and for regional or global conservation agendas. Present global commitments to reduce biodiversity loss entail setting up MPAs in most regions of the world. MPAs are not only more numerous, but also larger, and how they achieve conservation objectives must be assessed. Consistently with MPA conservation objectives (Pelletier, 2011), monitoring and assessment should include fish and macroinvertebrate resources, but also fixed fauna, essential habitats, and protected or emblematic species. Maintaining the diversity of taxa and the functioning of species assemblage are additional conservation objectives. Yet, biodiversity is rarely observed and assessed on large spatial scales due to observation costs.

Underwater video may help in making good some of these monitoring gaps. Three main questions are generally raised by the use of video techniques for observing and monitoring biodiversity, species and habitat in shallow waters: i) how much does it cost?; ii) is image analysis (i.e. identifying and counting species) an issue?; and iii) what are the observation area and the required duration of observations? Cost-efficiency questions were addressed in subsection 4.2 when comparing video techniques. Issues ii) and iii) are addressed below in subsections 5.1 and 5.2. We will then discuss the two main advantages of most underwater video techniques: their non-obtrusive nature and the potential for high replication (subsections 5.3 and 5.4). Finally, we will compare the advantages and shortcomings of observation techniques in subsection 5.5.

5.1 Is image analysis an issue?

The issue of image analysis is often raised by the use of video, in particular the ability to identify and count species, along with the time required to do this. Underwater visibility is a limitation for all visual techniques, whether UVC, video or photo. However, divers conducting UVC or DOV may compensate for reduced visibility by moving toward the observation target. Moreover, the larger the observation surface area, the more critical the visibility. In this respect, RUV may be more dependent upon visibility than

BRUV which attracts species closer to the camcorder. High Definition was not always used in recent studies, yet we believe it substantially improves the quality of the resulting data at little extra cost. Being able to take time to identify and count, including the possibility of consulting identification books or experts is actually convenient. Because video footage is archived, it may be shared and analysed independently, thereby enabling discussion about identifications and cross-validation of image analyses. In addition, archiving footage ensures data traceability. Identifying species and counting individuals from two-dimensional images may be initially challenging to people trained in other techniques, but most people learn to do so within a month or two.

The second issue concerns the time needed for image analysis. From our experience, the post-treatment of images balances the time gained in the field through diver-based visual techniques (Pelletier et al., 2011, 2012). This required time may vary depending on the kind of information extracted, e.g. the list of taxa studied, and on the experience of the observer. But it is mostly dependent upon the abundance and species richness in the observation area, which should not be seen as a drawback (see end of section 4).

5.2. Observation area and duration

Video techniques exhibit large differences in terms of information provided. First, observed surface areas are not all the same. Horizontal RUV enables observed surfaces and distances to be estimated through horizontal vision, in a similar way to UVC. However, the accuracy and precision of these estimates, whether from RUV or from UVC, should not be neglected. Delineation of the observed surface area (e.g. from strip transects) or mark setting to standardize surveyed areas is possible, but inevitably increases observation duration and may influence observations, because it requires divers. Stereo-video makes it possible to precisely estimate the observation distance and the size of observed individuals, which are otherwise visually estimated either from post-field image analysis (RUV, TOWV, non stereo-BRUV, DOV) or underwater (UVC). For such visual estimations, training from silhouettes has proved useful (Thompson and Mapstone, 1997; N. Guilpart, D. Mallet, D. Pelletier, unpublished data). For vertically-oriented systems (TOWV or RUV), the observed surface may be estimated based on lens and zoom parameters, provided that the camera elevation above the floor is controlled

and known. In the particular case of BRUV, the unknown bait plume prevents the evaluation of the actual surface concerned by the observation.

Regarding observation duration, BRUV is constrained by effective bait attraction, which needs a minimum amount of time, from 25 to 40 minutes (Willis and Babcock, 2000; Watson et al., 2007, Bernard and Götz, 2012). TOWV allows continuous recording of images along the vessel trajectory and footage is often subsampled for image analysis (see references in Table 3). The duration of a single RUV observation varies from a few minutes to an hour (see references in Table 5), depending on the study objective and the system characteristics.

5.3. Non-obtrusive observations of species assemblages?

Underwater video techniques provide direct observations of species in their natural habitat, and they are not extractive. Diver-free video techniques are also less intrusive than UVC (see section 1 for references). Among these, TOWV may disturb the ecosystem through vessel noise, though this can be circumvented by using appropriate engines. BRUV data rely on bait attraction within an unknown distance around the observation system. In this respect, observations resemble fishing data, as they are selective, depending on both species and bait. The effect of bait composition and size on catch was well studied (Saila et al., 2002; Smith, 2002; Lowry et al., 2006; Alos et al., 2009; Dorman et al., 2012), as was the behaviour of species near baited fishing gear (e.g. in deep environment: Craig et al., 2005) or near fishery discards (Hill and Wassenberg, 2000). But the distance and range of attraction of vagile fauna by the bait is difficult to test, and to our knowledge, no such study was published at the time of the review. Regarding (unbaited) RUV, our own experience indicates that while some fish already present nearby may be curious when a system is first set up, they rapidly resume their normal behaviour, and the video system does not seem to attract distant fish (D. Mallet and D. Pelletier, unpublished data).

5.4. Temporal and spatial replication

With the exception of DOV, for which the number of observations that can be carried out per day is limited by diver's presence (although DOV is quicker than UVC in the field), a large amount of data may be collected per day, making it possible to accomplish highly spatially and temporally replicated designs. Most RUV techniques were indeed designed to be set for a long time and to provide information on behaviour, diurnal rhythms and species activity over long periods of undisturbed observation. This enables an array of questions to be addressed that cannot be studied by other observation techniques. The ability of video systems to produce a large number of observations can also be used in a spatial perspective, for instance to investigate changes in macrofauna and population behaviour, and to correlate communities with environmental variables or anthropogenic pressures. Hence, the response of biodiversity to fishing, MPA protection and other impacts of coastal uses may be addressed at relevant scales. Observation designs may be properly replicated with respect to factors influencing the distribution of biodiversity, such as site and habitat on several scales. A high level of replication then enables relationships between biodiversity metrics and environmental variables to be investigated by increasing the statistical power of analyses and diagnostics.

Beyond the replication issue, the consistency between data collected in distinct areas by different teams is reinforced by the use of identical systems. Within an ecosystem-based approach to fisheries management, a better understanding of the temporal variations in spatial patterns of biodiversity and resources is needed. In this respect, diver-free techniques may at the same time enable small-scale studies with an increased resolution and enlarge the spatial coverage of designs up to the ecosystem scale. For DOV, data consistency is also increased, as there are no differences between videos filmed by distinct divers. Moreover, additional sensors can be coupled to video systems and thus collect additional information on biotic and abiotic variables, as recently advocated by Johnson et al. (2012).

5.5. Which technique for observing and monitoring coastal biodiversity?

The choice of a video technique first depends on the object of the study. Reviewed applications of video techniques in shallow waters were listed in Section 3. These are only a sample of the potential use of each technique, as in this area, technological progress is swift (subsection 2.6) and there is room for innovation and alternative types of implementation. General recommendations may thus be made regarding the scope of each technique (Table 10, last column), but these main features should be seen as indicative rather than prescriptive. For instance, none of the references specifically dealt with the observation of juvenile or larval fish. Yet this could be achieved by several existing RUV techniques, by setting them in appropriate locations with adequate camera settings. Likewise, shy species may be monitored using automated systems regularly recording species activity. Indeed a wide spectrum of applications is feasible with the current technologies.

There are still advantages and shortcomings associated with each technique. These were discussed in the previous subsections (5.1 to 5.4) and summarized in Table 10. Choosing a technique must thus stem from both the general features of each technique and their proven outcomes, but technical adaptations and fast technological changes should also be taken into account. The techniques most often used for observing and monitoring coastal biodiversity and resources remain UVC, fishing and, to a lesser extent, acoustics. This situation prevails for both research studies and management-oriented monitoring. Although not recent, the advent of video techniques has not altered this situation. Indeed, many video systems developed in the past only served during a given research project, and were not intended to be transferred to other contexts or users. This situation changed with the development of BRUV, where the same technique is now repeatedly used in many different contexts.

In the process of selecting a technique for a given study, investment and operating costs are two crucial parameters, particularly when replicated designs involving a large number of observations are envisaged. Although these costs were not often documented in the papers, the review showed that compared to UVC, i) video techniques generally involved less time spent on the field at the expense of more time spent in post-treatment, for image analysis; and ii) a lower level of scientific expertise was required during field work. Other features may vary from one technique to another (see Section 2 for description of techniques).

Table 10. Comparison of the main advantages and shortcomings of each observation technique and recommendations for future use. UVC, fishing and acoustics are reported for comparison.

Methods	Advantages	Shortcomings	Recommendations
RUV	Non extractive Least invasive method Constant observation duration Does not require diver Possible observation at large depth Fast implementation Possible participation of non-scientific staff	Duration of image analysis Management of large data sets	Diurnal and seasonal patterns of behaviour, species activity and abundance over long periods/at high frequencies Highly spatially-replicated designs Monitoring of conspicuous and target species
BRUV	Non extractive Increased observed fish abundance through baiting Constant observation duration Does not require diver Opportunity to work in deep water Possible participation of non-scientific staff	Unknown effect of bait plume Relatively long observation duration Duration of image analysis Management of large data sets	Monitoring populations of fishes, and particularly carnivorous species Monitoring in areas where diversity and abundance are low
TOWV	Non extractive Does not require diver Opportunity to work in deep water Fast implementation Large spatial coverage Possible participation of non-scientific staff	May disturb the ecosystem due to vessel noise Management of large data sets Duration of image analysis	Monitoring habitat and fixed benthic species over large areas
DOV	Non extractive Does not require scientific diver	All effects associated with the presence of a diver underwater (see below) Duration of image analysis	Study benthic cover and macrofauna
UVC	*Non extractive* *Widely used* *Possible participation of volunteers for simplified protocols*	*Observer effect* *Diver effect* *Depth limitation* *Requires diver trained to species identification and counting* *Observation duration*	*Studies at species level* *Inventories and species counts* *Small species*
Fishing	*Extractive* *Does not require diver* *Possible observation at large depth* *Possible participation of fishers*	*Unknown observation volume and species catchability*	*Monitoring of resources*
Acoustics	*Non extractive* *Spatial coverage* *Possible observation at large depth*	*High-tech analysis of data* *No species identification*	*Monitoring of resources coupled with another technique, e.g. fishing* *More suitable for pelagic species*

5.6. Future prospects for underwater video monitoring

The technological progress seen in the last decade (see subsection 2.6) will continue, so that system autonomy, storage capacity, and sensor resolution will increase. Human-operated systems will continue to be used, particularly for research and in the context of participative management in coastal areas. But there is a wide scope for automated systems. These can be permanent stations with multiple sensors, either cabled (see e.g. ESONET project: http://www.esonet-noe.org/About-ESONET and Aguzzi et al., 2011, 2012) or mobile systems transmitting information, e.g. programmed gliders (Moline and Schofield, 2009). Such advances will considerably increase the amount of data collected by underwater video systems (among other techniques). It will thus be essential to analyse and manage these large data sets. Automated image analysis will be key for gaining time. Several projects have been set up with this objective, see for instance the Fish4Knowledge project, which aims to analyse undersea fish videos (www.Fish4Knowledge.eu, Phoenis et al., 2013). However, species identification and counting not requiring human intervention still remains a challenge. Properly managed data is the second issue, particularly in view of long-term monitoring. Furthermore, data for biodiversity monitoring and assessment are often collected at the scale of an entire ecosystem, and they are to be shared within collaborative projects. Developing shared protocols and data management utilities for collecting and utilizing the wealth of data that will be made available in the future should be a priority.

Global commitments to conservation also entail research issues at larger scales, particularly regarding spatial patterns of biodiversity and ecosystem approaches to management and conservation (Christensen et al., 1996). Hence, for both research and monitoring purposes, observations with improved spatial coverage and resolution should be carried out in all habitats; they should document exploited and non-exploited species, as well as benthic coverage, including sensitive taxa such as sea grass and coral. These considerable information needs cannot be achieved solely through the techniques used so far, and complementary observation techniques are needed, among which video techniques, either on stand-alone basis or preferably combined with other techniques, are definitely a good candidate.

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1) the Horizontal Remote Underwater Video system of LaFond *et al.* (1961) reproduced with the permission of E.C. LaFond, "Photographic problems in oceanography", Underwater Photo-Optical Instrumentation Applications, Seminar Report, SPIE, pp. 11-18. San Diego, California, (1968).

2) the Acoustic Remote Underwater Video system of Kumpf and Lowenstein (1962) reproduced with the permission from H.E. Kumpf and J.M. Lowenstein, "Undersea Observation Station", Sea Frontiers, volume 8, 198-206, (1962).

3) the Acoustic Remote Underwater Video system of Stevenson (1967) reproduced with the permission of R.A. Stevenson, "Underwater television", Oceanology Intl, volume 2, 30-35, (1967).

4) the Horizontal Remote Underwater Video system of Fedra and Machan (1979) reproduced with the permission from Springer, Marine Biology, K. Fedra and R. Machan, "A Self-Contained Underwater Time-Lapse Camera for in situ Long-Term Observations", Marine Biology, volume 55, 239-246, (1979).

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7) the Horizontal Baited Remote Underwater Video system of Ellis and DeMartini (1995) reproduced with the permission from the U.S government, D. Ellis and E. DeMartini, "Evaluation of a video camera technique for indexing abundances of juvenile pink

snapper, *Pristipomoides filamentosus*, and other Hawaiian insular shelf fishes", Fisheries Bulletin, volume 93, 67-77, (1995).

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10) the Seabed Towed Video system of Machan and Fedra (1975) reproduced with the permission from Springer, Marine Biology, R. Machan and K. Fedra, "A New Towed Underwater Camera System for Wide-Range Benthic Surveys", Marine Biology, volume 33, 75-84, (1975).

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13) the Seabed Towed Video system of Spencer et al. (2005) reproduced with the permission of Mara L. Spencer, A.W. Stoner, C.H. Ruer, J.E. Munk, "A towed camera for estimating abundance of juvenile flatfishes and habitat characteristics: Comparison with beam trawls and divers", Estuarine, Coastal and Shelf Science, volume 64, 497-503, (2005).

14) the Seabed Towed Video system of Rooper and Zimmermann (2007) reproduced with the permission from Karna McKinney, Alaska Fisheries Science Center, NOAA Fisheries.

Supplementary materials

N.B. : L'ensemble de ces documents sont consultables en Annexe B de cette thèse

Supplementary material A. Geographical distribution of reviewed studies. Numbers after each region correspond to references available at the end of this document. They are classified from the oldest to the most recent reference for each region

Supplementary material B. Main outcomes of the studies comparing a video technique with UVC (62% of comparative studies, Table 7). H-BRUV=Horizontal Remote Underwater Video, RUV=Remote Underwater Video, SRUV=stereo remote underwater video, DOV= Diver-Operated Video, TOWV= towed video, UVC=underwater visual census, V-BRUV=Vertical Remote Underwater Video.

Supplementary material C. Main outcomes of comparisons between video techniques (19% of all comparative studies, Table 7)

Supplementary material D. Main outcomes of comparisons between a video technique and fishing or acoustics (14% of all comparative studies about fishing techniques and 5% about acoustics, Table 7)

2. Synthèse

182 travaux traitant de technique vidéo sous-marine publiés entre 1952 et 2012 ont été synthétisés dans ce chapitre. Ces techniques ont été classées en 4 familles de techniques distinctes : les techniques vidéo à distance non appâtées (RUV pour « Remote Underwater Video » en anglais), les techniques vidéo à distance appâtées (BRUV pour « Baited Remote Underwater Video »), les techniques vidéo tractées (TOWV pour « TOWed Video ») et les techniques de transect vidéo (DOV pour « Diver Operated Video »). La technique de « stéréo-vidéo » a été considérée comme une amélioration (utiliser 2 caméras afin de mesurer les individus et les distances à partir des images vidéo) adaptable et adaptée à chacune des 4 familles de techniques. Les techniques vidéo ont été utilisées dans une variété d'applications en milieu côtier : études sur le comportement des poissons (52 publications sur ce sujet, majoritairement des RUV (45)), impact des pressions anthropiques sur la faune marine (8 publications), variations spatio-temporelles de la composition des assemblages de poissons (48 publications), suivis du benthos (4 publications) et des habitats (32 publications)[12]. Les atouts, limites et recommandations d'applications sont synthétisés dans le tableau 10 de l'article 1. Le choix d'une technique provient à la fois de la caractérisation générale de chaque technique et des résultats obtenus par les études précédentes mais les adaptations techniques et les évolutions technologiques rapides doivent également être prises en compte. Les techniques les plus souvent utilisées pour observer et suivre la biodiversité côtière restent les UVC. Bien que n'étant pas récentes (1ère publication en 1952) et malgré les perfectionnements technologiques, les techniques vidéo n'ont pas modifié cette situation. En effet, de nombreux systèmes vidéo développés dans le passé n'ont servis que lors d'un projet de recherche donné, et n'ont pas été utilisés dans d'autres contextes ou par d'autres utilisateurs.

Les techniques vidéo sous-marines sont au cœur de ce travail de thèse. Ce travail sera utilisé tout au long du manuscrit afin de replacer régulièrement les questionnements associés aux systèmes vidéo rotatifs dans un contexte global.

[12] Certaines publications traitant de différents aspects

CHAPITRE 3

Des systèmes vidéo rotatifs en haute définition pour étudier l'ichtyofaune

Le chapitre précédant a montré que la vidéo sous-marine se distinguait des autres techniques d'observation visuelle sur deux caractéristiques majeures : 1) la possibilité de réaliser un grand nombre de réplicas dans l'espace pendant une période temporelle réduite et 2) la possibilité de réaliser un grand nombre de réplicas temporels sur une zone spatialement peu étendue. Ces deux caractéristiques font de la vidéo un outil capable de répondre à un certain nombre de questions qui n'ont que très peu été abordées à ce jour sur la structure et le fonctionnement des assemblages de poissons à échelles spatiales et temporelles contrôlées. Néanmoins, avant d'aborder ces questions, il est nécessaire d'adapter le design des systèmes vidéo à des objectifs de forte réplication spatiale et temporelle. Ceci est l'objectif de ce chapitre qui présente deux systèmes vidéo rotatifs complémentaires, utilisés pour étudier la diversité de l'ichtyofaune et des habitats marins dans les lagons de la Nouvelle-Calédonie : le STAVIRO (pour « STAtion VIdéo ROtative ») et le MICADO (pour « Module d'Imagerie Côtier, Autonome pour le Développement et l'Observation sous-marine »). Le système STAVIRO permet d'étudier l'ichtyofaune et les habitats marins avec une forte réplication spatiale, tandis que le système MICADO permet ces mêmes observations avec une haute fréquence temporelle. Chacun des deux systèmes est programmé pour tourner de 60° toutes les 30 secondes, enregistrant des images vidéo en haute définition (1920×1080 pixels) sur des points préalablement définis selon les études envisagées. L'article 2 présente le système STAVIRO ainsi que sa méthodologie d'utilisation illustrée de résultats obtenus à partir de vidéos enregistrées dans le lagon du Grand Nouméa de la Nouvelle-Calédonie en 2007. L'article 3 présente le système MICADO de la même façon (présentation technique du système, méthodologie d'utilisation et exemples d'applications) montrant les potentialités de ce dernier à forte réplication temporelle.

Ces informations méthodologiques fournissent les éléments indispensables à la compréhension du fonctionnement de ces deux systèmes complémentaires, évalués et appliqués dans les chapitres suivants.

1. Article 2[13]. Etude des variations spatiales à partir d'observations spatialement répliquées : le STAVIRO

Résumé de l'article 2 :

L'observation des variations spatiales et temporelles de la biodiversité marine utilisant des techniques non-destructrices est fondamentale pour la compréhension de la résilience des écosystèmes, ainsi que pour le suivi et l'évaluation des stratégies de conservation (e.g. les Aires Marines Protégées). Les observations sont généralement obtenues par des recensements visuels en scaphandre autonome ou UVC (Underwater Visual Census en anglais) menés par des plongeurs. Les problèmes inhérents à la présence de plongeurs ont été discutés dans de nombreuses publications scientifiques. Les techniques vidéo sont de plus en plus utilisées pour observer l'ichtyofaune sous-marine et leurs habitats. La plupart des techniques vidéo ne nécessitant pas la présence d'un plongeur utilisent des systèmes vidéo appâtés à distance. Dans cet article, nous présentons une technique vidéo originale qui repose sur un système vidéo rotatif à distance et non-appâté comprenant une caméra en haute définition. Le système est posé sur le substrat marin pour enregistrer des images vidéo. Ces dernières sont ensuite analysées au bureau afin de quantifier la couverture biotique et abiotique du fond de mer, mais également pour identifier et dénombrer les poissons et autres espèces marines comme les tortues marines. La technique a été largement testée dans un écosystème corallien très diversifié du lagon Sud de la Nouvelle-Calédonie, sur la base d'un protocole d'échantillonnage couvrant à la fois des zones protégées et non protégées dans les principaux habitats lagonaires. La technique a permis de détecter et d'identifier 170 d'espèces, et en particulier des espèces pêchées qui n'ont pas été perturbées par le système. Une approche paysagère de l'habitat peut facilement être réalisée à travers les images. Un grand nombre d'observations peut être effectué par jour de mer. Cette étude a montré le fort potentiel de cette technique discrète pour observer à la fois l'ichtyofaune et l'habitat. Elle offre une couverture spatiale unique et peut être mise en œuvre en mer à un coût raisonnable par des personnes non-expertes. En tant que telle, cette technique est particulièrement intéressante pour l'étude et le suivi de la biodiversité côtière au regard des défis actuels de conservation et de l'accroissement des besoins de surveillance.

[13] *J'ai contribué à l'analyse des données et à la rédaction de cet article pendant mon doctorat.*

Article 2

OPEN ACCESS Freely available online

PLoS one

Remote High-Definition Rotating Video Enables Fast Spatial Survey of Marine Underwater Macrofauna and Habitats

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Abstract

Observing spatial and temporal variations of marine biodiversity from non-destructive techniques is central for understanding ecosystem resilience, and for monitoring and assessing conservation strategies, e.g. Marine Protected Areas. Observations are generally obtained through Underwater Visual Censuses (UVC) conducted by divers. The problems inherent to the presence of divers have been discussed in several papers. Video techniques are increasingly used for observing underwater macrofauna and habitat. Most video techniques that do not need the presence of a diver use baited remote systems. In this paper, we present an original video technique which relies on a remote unbaited rotating remote system including a high definition camera. The system is set on the sea floor to record images. These are then analysed at the office to quantify biotic and abiotic sea bottom cover, and to identify and count fish species and other species like marine turtles. The technique was extensively tested in a highly diversified coral reef ecosystem in the South Lagoon of New Caledonia, based on a protocol covering both protected and unprotected areas in major lagoon habitats. The technique enabled to detect and identify a large number of species, and in particular fished species, which were not disturbed by the system. Habitat could easily be investigated through the images. A large number of observations could be carried out per day at sea. This study showed the strong potential of this non obtrusive technique for observing both macrofauna and habitat. It offers a unique spatial coverage and can be implemented at sea at a reasonable cost by non-expert staff. As such, this technique is particularly interesting for investigating and monitoring coastal biodiversity in the light of current conservation challenges and increasing monitoring needs.

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Introduction

Conserving marine biodiversity is a global concern exemplified by the programme of work of the Convention on Biological Diversity (CBD) to "promote political actions for addressing biodiversity loss and the degradation of ecosystems and ecosystem services, as well as their implications for human well-being" (www.cbd.int/doc/decisions/cop-10/cop-10-dec-11-en.pdf). Marine Protected Areas (MPAs) are a key instrument for the conservation of marine biodiversity and associated ecosystem services [1]. Within the CDB, the quantitative targets for a global coherent network of MPAs set in 2002 were updated in 2010, with requirements for grounding the design of MPAs in the best available scientific knowledge, and to assess the performance of these MPAs to achieve their conservation objectives. Along with the implementation of conservation and restoration strategies for biodiversity, CDB urges Parties "to promote the generation and use of scientific information, develop methodologies and initiatives to monitor status and trends of biodiversity and ecosystem services, share data, develop indicators and measures, and undertake regular and timely assessments" [2].

However, in many areas around the world, the state and evolution of marine biodiversity remains unknown or poorly evaluated. This is primarily due to the lack of comprehensive and comparable field data, in relation with insufficient human and financial resources. The scarcity of data hampers the study of spatial and temporal patterns and variations in biodiversity facing stressors such as anthropogenic pressures and environmental changes. Appraising and understanding these variations is nevertheless indispensable for the understanding of ecosystem resilience, and such observations are central to the design, monitoring and assessment of biodiversity conservation strategies, including e.g. MPA.

Devising cost-effective and non-destructive observation techniques that permit collecting data with an appropriate spatial and temporal coverage is thus a timely challenge. With respect to

underwater macrofauna and habitat, Underwater Visual Censuses (UVC) realized by divers have been widely used for monitoring coral reefs and temperate coastal ecosystems, and in particular macrofauna and benthic cover, e.g. [3]. Advantages and disadvantages of UVC for estimating fish abundance and diversity have been reported and discussed in many papers, among others [4,5,6]. The presence and abundance of vagile species at the observation location is significantly affected by the presence of a diver underwater [7,8] and some species may not be well observed [9]. Furthermore, the level of experience of the diver is a source of heterogeneity in the data [10], and estimations of both fish size and distance are subject to uncertainties [11,12]. A recent study quantified the consequences of such diver effects upon the abundance of reef fish groups [13].

In terms of capacity, UVC require experienced divers that are able to identify species and estimate individual fish sizes. Other drawbacks of UVC lie in the reduced number of observations that can be achieved within a given day, the limited depth range and the logistics of scuba diving, resulting in rather high field costs. For this reason, UVC are not conducted systematically in every habitat. Most often, the habitats where species are the most abundant, e.g. reef habitats, are preferred, whilst observations in soft-sediment areas are scarce.

Aside from UVC, video techniques have been increasingly used for observing underwater macrofauna and habitat, particularly in the last decade [14,15]. Most video techniques that do not need the presence of a diver use baited remote systems (Baited Remote Underwater Video, BRUV) [16,17]. BRUV attract a range of species beyond the carnivorous ones, and have also been used for studying fish assemblages, particularly using stereo-video [18,19,20]. The latter was developed to improve the estimation of fish size and distance [11]. A drawback of baited video lies in bait attraction which selectively influences species, thereby affecting the assessment of fish community structure [21], and the bait plume is difficult to evaluate [22]. From a technical standpoint, baiting requires to leave the system in place long enough to ensure bait effectiveness, and the vertical recording of images is not suited for observing habitat around the station.

Understanding biodiversity patterns and their evolution within an ecosystem approach to management (http://www.unep.org/ecosystemmanagement/) requires comparable observations in all habitats. This is also indispensable for monitoring the response of biodiversity to conservation strategies. Techniques that can be deployed in all habitats, and do not require divers nor expert staff on the field are preferred by environmental offices and managers.

This paper focuses on the need to devise observation techniques that offer a good spatial coverage and a holistic approach of macrobiodiversity, in the light of current conservation challenges and increasing monitoring needs. We present an original video technique (STAVIRO-***STA****tion* ***VI****deo* ***RO****tative in French*) that was developed and tested in a highly diversified coral reef ecosystem. The technique utilizes a High Definition (HD) camera enclosed in a rotating unbaited system, which was designed to ensure a minimum disturbance of species. Recorded images are analysed at the office to quantify biotic and abiotic sea bottom cover, and to identify and count fish species and some other species such as marine turtles, marine mammals and snakes. The technique was tested in the South Lagoon of New Caledonia in 2007, and then used each year from 2008 to 2010. Video transects using the same camera were carried out in 2007 and directly compared with UVC (Pelletier et al. 2011).

We reported here the findings of the 2007 survey for both macrofauna and habitat. First, we investigated the range of macrofauna species and abundances observed and identified from the images. Secondly, habitat data were analyzed to derive a typology of stations. In a third step, a range of biodiversity metrics pertaining to several components of macrofauna were computed from the data and their spatial variations were analysed in relation with protection status and habitat. Finally we discussed the advantages, shortcomings and complementarity of STAVIRO and UVC techniques for observing coastal biodiversity.

Materials and Methods

Ethics Statement

No specific permits were required for the described field studies. During the field study, only the video systems were immersed in water; no animals were collected or manipulated. This activity did not require any permission in the study area, and fully complied with New Caledonian environmental regulations (Code of the Environment, http://www.province-sud.nc/images/stories/pdf/environnement/Code.pdf).

Study area

The study area (22°22.5°S, 166°14′E) was located in the Southwest Lagoon of New Caledonia, South Pacific. The lagoon is large and encompasses a highly diversified coral reef ecosystem where anthropogenic pressures are heterogeneously distributed, with various recreational uses such as fishing, boating, jet-ski and others. The lagoon comprises a network of MPAs including reefs and islets.

Monitoring biodiversity in this area is challenging due to its size, to species diversity, and to the variety of habitats, anthropogenic pressures and protection status encountered.

The observation design included two protected areas: Signal Islet and Larégnère Islet, where all fishing had been prohibited since 1989, and two adjacent unprotected reefs: Senez Reef and Larégnère Reef, as well as in the lagoon area between the two islets. Observations were conducted in the various habitats around these islets and reefs, including coral reef areas, seagrass beds and soft-bottom areas. Observations were realized at depths ranging between ~1.5 m and 20 m.

The STAVIRO observation system

The system consisted in two waterproof housings related by an axis. The lower housing contained an electric engine powered by 2.4 V rechargeable batteries which sets in motion the axis related to the upper housing enclosing the HD camera (Figure 1). The two housings were tied onto an aluminium support that was dropped from the boat onto the sea bottom. The support was rigged to an intermediate buoy that keeps the rigging tight, this buoy being itself fixed to a rope connected to a larger buoy in surface that was used to retrieve the system at the end of the observation.

The camera was a HD Sony™ camera HDR-SR11 with an integrated 30 Gigabyte hard drive enabling the recording of up to 4 hrs of HD images. The camera recorded a signal following the 1080i standard, i.e. with a full HD resolution of 1920×1080 pixels. Images were saved on the internal hard drive using the AVCHD™ format which is based on the MPEG-4 AVC/H.264 for image compression. The housing and camera resulted in an approximate focal angle of 60°.

The system is set on the sea floor and rotates at predefined time intervals from a fixed angle. Rotations of the housing camera were programmed via a timer enclosed in the engine housing.

Observation protocol

After a number of trials, rotations were programmed so that the camera housing rotates from 60° every 30 seconds. Hence, six

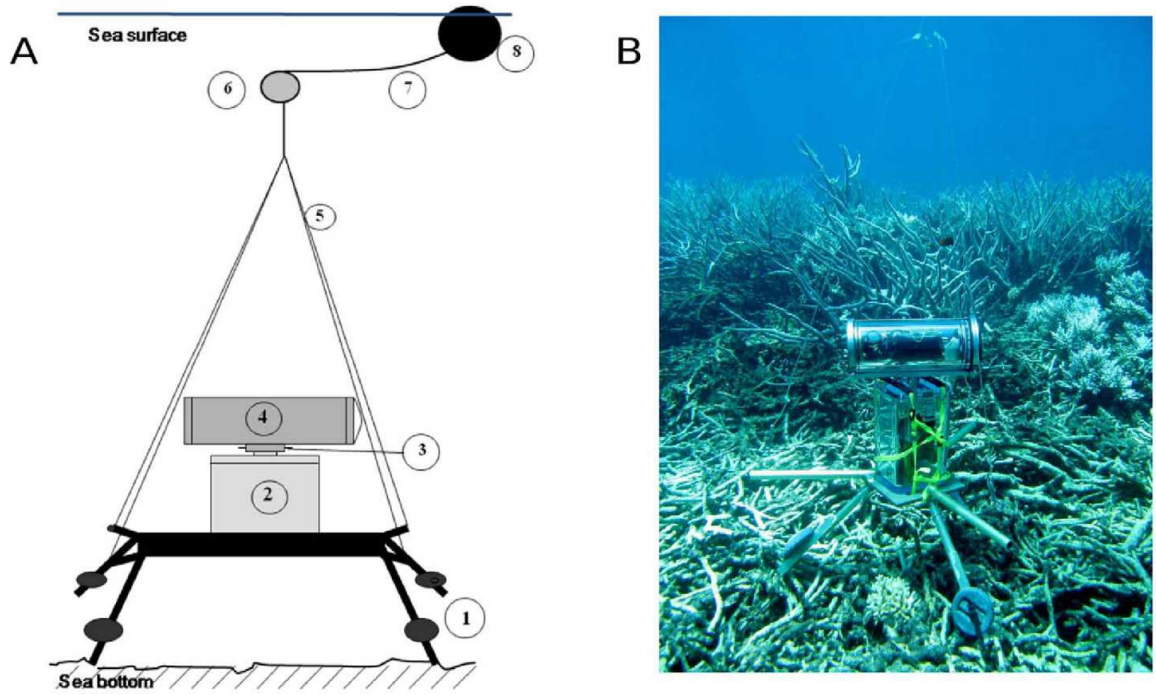

Figure 1. Description of the underwater rotating video system. (A) 1) weighted aluminium support; 2) engine housing; 3) rotating axis; 4) video camera housing; 5) nylon fishing line; 6) intermediate buoy; 7) floating rope; 8) surface buoy. (B) picture of the system in place.
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observation sectors were recorded per 360° rotation, and a rotation takes approximately three minutes. In order to gather information about the variability of fish presence and abundance, the system was left in place long enough to ensure at least three complete 360° rotations. Disturbances due to boat presence, engine noise and setting and retrieval of the system were minimized by leaving the system in place at least one minute before and after the three complete rotations. Overall, the system was left in place for around 12′. No artificial light was used to avoid disturbance and attraction.

Stations were regularly spaced within the study area using ArcGIS (ArcGIS (Version 9.3). ESRI. 2008) to ensure an appropriate spatial coverage. For stations located in rocky substrates, the distance between stations was approximately 200 m, while in soft bottom areas between the islets, stations were ca. 400 m apart. Slight deviations from this planned spacing incurred when the intended location was not fully suitable for setting the system horizontally.

Twenty-two day trips were organized between 18th June and 31th July 2007. Two systems were simultaneously used. After each day, the recorded video sequences were dumped from the camera hard drives on a PC hard drive. Each sequence was previewed and it was validated for analysis when i) at least three rotations could be analysed; and ii) horizontal underwater visibility was at least 5 m. When a station was not valid, it was carried out again the following day.

Image analysis

Images were analysed using a standard viewing software that enabled slow view and zooming, such as PowerDVD (PowerDVD (Version 9.0 Ultra). Cyberlink Corp. 2009) or the Nero Suite (The Nero Suite (Version 9) Nero Ltd. 2009). Images were analysed per 60° observation sector. At all stations, individuals observed within a 5 m distance from the camera were identified and counted per species for a list comprising a large number of species, and commonly used in the UVC monitoring conducted in the region (Table 1). This list of 26 families comprises all fished species, Chaetodontidae, emblematic fish species, turtles, and Dugondidae. Species that live close to or in corals, such as Pomacentridae and Apogonidae, and small pelagic species, like Clupeidae and Engraulidae, were not counted in the present study, although they can be identified from images [23]. In many stations, horizontal underwater visibility was larger than 10 m. Individuals occurring at distances larger than 5 m were counted separately, and the observation distance was recorded, as is usually done during stationary UVC [24]. These individuals were analyzed separately.

Images were analysed with the assistance of expert UVC divers, particularly at the onset of the analysis stage. Individuals were counted per sector, and then summed up for each 360° rotation. To minimize potential double counting, particular attention was given to the direction of fish movement with respect to camera rotation.

For each species and each station, we calculated the maximum abundance observed over the three rotations, and the mean abundance over those rotations, which averaged out the variability between rotations. Maximum abundance observed, also termed MaxN, is widely used for BRUV [25]. Abundances were expressed in densities, i.e. numbers of individuals per m^2 (ind.m^{-2}), which were computed from fish observed within a 5 m radius from the camera, based on the disk surface area. To assist in estimating whether the distance of fish to the camera was lesser or larger than

Table 1. List of families identified and counted during image analysis.

Acanthuridae	Kyphosidae	Mullidae
Balistidae	Labridae:	Myliobatidae
Carangidae	*Bodianus*	Priacanthidae
Carcharhinidae	*Cheilinus*	Scaridae
Chaetodontidae	*Choerodon*	Scombridae
Chanidae	*Coris*	Serranidae
Dasyatidae	*Epibulus*	Siganidae
Ephippidae	*Hemigymnus*	Sphyraenidae
Haemulidae	*Oxycheilinus*	Zanclidae
Hemiramphidae	Lethrinidae	Cheloniidae
Holocentridae	Lutjanidae	Dugongidae

The list includes the fished species and emblematic species that can be observed visually (from UVC) or by video. For Labridae, only the genuses in italics were considered.

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5 m, the person analyzing the images used screenshots of plastic fish silhouettes of several sizes (0.2 m, 0.4 m, 0.6 m, 0.8 m and 1 m) and colours (bright and dark ones), taken at several distances from the same camera (2 m, 5 m, 7 m and 10 m), following [26].

In addition to abundance estimation, fish size was estimated as small, medium or large, and corresponding size bounds were defined by expert UVC divers for each species.

Habitat was characterized using the medium-scale approach [27]. For each station, habitat was described by three sets of variables: i) substrate composition; ii) biotic cover; and iii) depth, bottom topography and complexity (Table 2). Substrate composition accounted for the granularity of abiotic bottom cover. Biotic cover included live coral, macroalgae and seagrass. Complexity quantified the number and variety of potential refuges. Habitat parameters were averaged over sectors at a given station, except for depth, which was recorded from the boat.

Data analysis

Habitat data were analysed in two ways. Firstly, the distributions of percent covers of live coral and seagrass were modelled as a function of protection status using binomial GLM, and the effects of the two factors were statistically tested. Secondly, habitat data were used to construct a typology of stations based on the main habitats encountered in the studied area. In order to account for the three groups of variables describing habitat, the typology was achieved in several steps. A Principal Component Analysis (PCA) was first carried out on substrate composition data, followed by an Hierarchical Ascending Cluster Analysis (HACA) based on Ward's distance [28]. The resulting cluster index was then considered along with the other variables describing habitat (Table 2) in a Multiple Correspondence Analysis followed by an HACA. For this purpose, depth was coded into four categories 0 to 5 m, 5 to 10 m, 10 to 15 m, and 15 to 20 m. Topography and complexity were coded into three categories (1, 1 to 2.5, and 2.5 to 5) based on the distribution of average values per station, while biotic covers of coral, seagrass and macroalgae were coded into four categories using 33% and 66% percentiles as intermediate bounds. The clusters of stations resulting from the typology were subsequently described using the initial habitat variables, by testing the difference in the frequency of each category of a given variable between the cluster and the whole set of stations. Such differences were statistically tested using t-statistics based on a Gaussian assumption [29]. A significant test indicated that the frequency of the category was higher (positive statistic) or lower (negative statistic) in the cluster compared with the whole set of stations. In this case, the category was considered to significantly explain the cluster. The resulting typology assigned a habitat cluster index to each station, which was subsequently used as a habitat factor when analyzing spatial variations in vagile macrofauna.

With respect to the latter, we first investigated the frequency and abundance density of each taxonomic family in the data set. Observed frequencies were qualitatively compared with published studies involving UVC, and conducted in the same area and habitats ([30,31,32]). [30,32] were conducted on the barrier reef in the same lagoon area in 1993, 1995 (and 2001 for [32]), while [31] encompassed five islets in the area, including the site studied in the present paper, and data were collected in 1985, 1990 and 1994.

Secondly, the overall density and species richness per station were computed as synthetic metrics of biodiversity. In a third step, we focused on the abundance of three key fished species and on the abundance of Chaetodontidae. Finally, we analyzed the frequency of emblematic species of the lagoon, such as turtles, sharks, rays and humphead wrasse (*Cheilinus undulatus*).

Each of the above metrics was modeled with respect to protection status and habitat using a two-way General Linear Model. For each metric (except for frequencies), the appropriate statistical distribution was selected as the one minimizing Akaike's criterion ([33]) among the Gaussian, log-normal, Poisson and negative binomial distributions. The frequency of emblematic species was modelled through presence/absence data using a binomial GLM model to test the effects of protection status and habitat. Spatial differences in species richness, abundance density

Table 2. Habitat description.

Parameter	Definition
Depth	Depth measured from boat when setting the system
Topography	If h denotes the largest altitude between troughs and elevations, values from 1 to 5 respectively correspond to h negligible, $h<1$ m, $1<h<2$ m, $2<h<3$ m, $h>3$ m
Complexity	Values from 1 to 5: none, low, medium, strong, outstanding
Substrate composition	Percent cover of mud, silt, sand, rubble, small boulder (<0.3 m), large boulder (0.3 m≪1 m), rock (>1 m), slab
Live coral	Percent cover of live coral
Macroalgae	Percent cover of macroalgae
Seagrass	Percent cover of seagrass

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and presence/absence data were then tested from multiple comparisons [34].

Results

Implementation of the technique

The observations were collected over twenty-two days of field work, by two persons in addition to the pilot, and in some days, only one person with the help of the pilot for hauling the system aboard.

In very shallow waters (less than 1.4 m), it was more appropriate to leave the system without the rigging so that it did not entangle in the camera housing when rotating. As the system was still under validation, no station was set at depths larger than 20 m, but the housings could actually endure larger depths.

Out of the 317 stations realized, 221 (i.e. 70%) of the stations, were validated for image analysis. Non-exploitable stations resulted from defects in rotation, recording or camera autofocus, and sometimes the system fell or was not horizontal. In few cases, only one system was used due to technical problems. On average, 14.4 stations were obtained in a given day, corresponding to 3.7 stations per hour, with a mean observation time per day of ca. four hours. The maximum number of stations obtained during a single day was 31. Station depth ranged between 1.2 and 20 m.

Image analysis

The analysis time per station ranged between 10 minutes and 1 hour and 15 minutes for fish, and ca. 5 minutes for habitat.

Images were analysed for 196 stations out of the 221 valid ones. The rest of the stations were close to other stations and the underwater visibility was less good than at neighboring stations.

Among the 196 stations analysed, no vagile macrofauna was seen in 58 stations. In the 138 other stations, 10357 individuals were counted, corresponding to 149 species and 23 families (Table 3). 148 (i.e. 1.4%) individuals could only be identified at the family level, while 560 (i.e. 5.4%) were identified only at the genus level. These were mainly Lethrinidae (328 ind.), *Scarus* (228 ind.), *Acanthurus* (92 ind.). Overall, 6.8% of individuals were not identified at the species level, in general because they were too far or swam through the field of vision too quickly.

Biotic cover and habitat

The observations encompassed various habitats. Live coral cover was zero in 50.5% of observations, and it was larger than 33% at 7% of observations. Seagrass and macroalgae were absent from 49% and 25% of stations, respectively.

Live coral could be observed on the reef slope around the two islets and the two reefs (Figure 2). It was larger on the leeward side of the islets. Data also showed the presence of live coral patches between the islets and in a few stations further from the islets and reefs. Seagrass was absent from the windward side of Larégnère Islet and Larégnère Reef which were less sheltered than the windward side of Signal Islet (Figure 3). In reverse, it was found in most stations on the leeward sides of the islets and reefs, and in the lagoon area between the two islets. At the eastern tip of Larégnère Islet, seagrass was absent but macroalgae were abundant (see typology on Figure 4).

The typology led to a partition of the stations into 5 clearly separated clusters (Table 4). The larger cluster (lagoon, 105 stations) included stations with an average 87.5% sand cover, depths larger than 10 m at two thirds of the stations. Live coral was absent from 78% of these stations, and seagrass and macroalgae cover were lower than on average over all stations. The second largest cluster (50 stations) mostly comprised stations with a substrate of mixed debris consisting of rubbles (average 30.1%), sand (average 38.6%) and hard coral (average 21.7%), and corresponding to intermediate depths (Table 4). Seagrass and macroalgae were absent from 82% and 60% of the stations respectively. Stations with a large live coral cover constituted a cluster of 18 stations. Coral cover was high (average 46.8%), and seagrass was absent from all stations. Substrate was mixed and rocky, including hard coral cover (average 61.8%), slab (average 9.0%), and stations were shallow (average depth 4.4 m). Complexity was higher than in the rest of the stations. The seagrass cluster comprised 14 stations with a seagrass cover larger than 66% on a sandy substrate, and with a medium complexity. The smallest cluster (9 stations) gathered all stations where macroalgae cover was larger than 66%. Seagrass was absent from 89% of these stations. In clusters 1, 2 and 3, sand cover was higher than 87% on average, while it was clearly lesser in clusters 4 (average 38.6%) and 5 (average 12.4%) (Table 4). The spatial distribution of clusters confirmed that the living coral habitat was located on the leeward side of the islets, while debris dominated

Table 3. Species number, abundance and frequency of the families observed in the 196 stations.

	2007 STAVIRO		[35]	[31]	[32]
Nb. observations	**196**	**196**	**157**	**132**	**212**
Numbers observed	**Individuals**	**Species**	**Species**	**Species**	**Species**
Chaetodontidae	227	20	22	31	Na
Acanthuridae	1444	17	23	24	25
Mullidae	805	12	12	14	13
Scaridae	873	12	24	22	22
Serranidae	179	12	23	25	21
Labridae	301	11	12	10	17
Lutjanidae	3591	11	11	18	13
Lethrinidae	1492	10	17	18	17
Carangidae	173	8	5	11	7
Balistidae	262	7	12	0	6
Siganidae	462	6	7	9	8
Haemulidae	62	4	4	9	5
Carcharhinidae	14	3	3	Na	3
Cheloniidae	13	3	Na	Na	Na
Scombridae	47	3	1	1	1
Dasyatidae	9	2	2	0	2
Kyphosidae	225	2	1	1	1
Chanidae	72	1	Na	1	Na
Ephippidae	44	1	0	0	1
Holocentridae	1	1	1	Na	6
Myliobatidae	3	1	1	0	1
Priacanthidae	39	1	0	1	0
Zanclidae	19	1	1	Na	1

The last three columns contain the number of species per family usually observed in UVC transects realized in the same habitats in the same area [31,32,35]. The number of Labridae species corresponds to the genus listed in Table 1. The number of Holocentridae species corresponds to the only fished species in the family. Na means the family was not observed in the cited reference.

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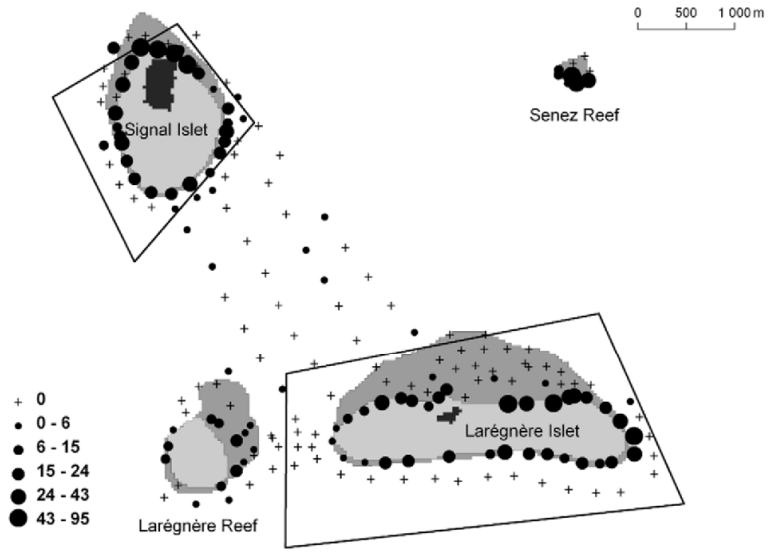

Figure 2. Map of live coral percent cover. Circles are proportional to percent cover (see legend in insert).
doi:10.1371/journal.pone.0030536.g002

stations were found on their windward side (Figure 4). Stations from the largest cluster were situated in the lagoon area between the islets and around the islets at a small distance. Seagrass was mainly encountered close to the islets on the sheltered side.

Species and abundances observed

149 species belonging to 23 families were observed among the list of 26 families (Tables 3 versus Table 1). In order to provide qualitative elements of comparison, we reported the number of species observed from UVC transects conducted with the same or a very similar list of censused species, in the same panel of habitats within the same lagoon area [31,32,35] (Table 3). In each reference cited, a transect corresponded to an approximate surveyed surface of 200 m^2. The area analysed in video stations was limited to ca. 78.5 m2 for density estimates and species richness of fish species (but rays and sharks), because of the observation radius of 5 m (see § 2.4), but it rose up to ~300 m^2 for occurrence counts of large emblematic species (sharks, rays and turtles) when visibility was high. On average, 82% of the species observed in these UVC were also detected from our stations.

In the rotating video, the most often observed families were Chaetodontidae, Acanthuridae, Scaridae, Serranidae, Lutjanidae,

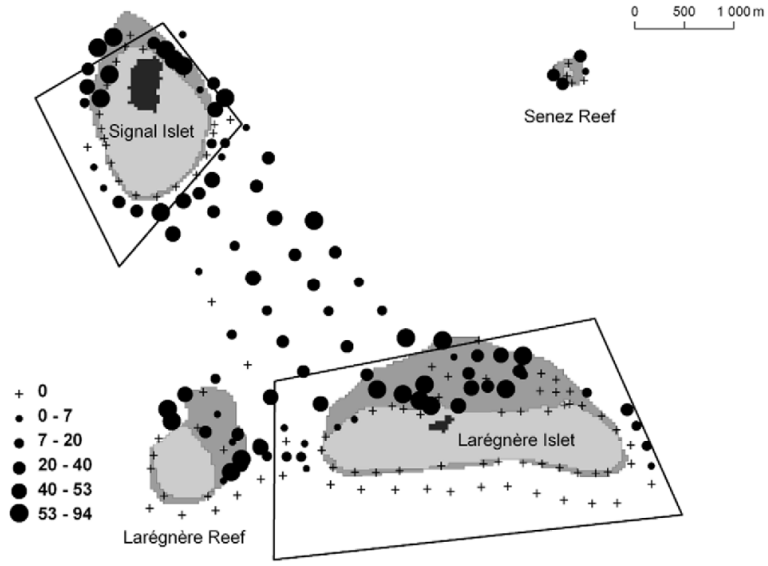

Figure 3. Map of seagrass percent cover. Circles are proportional to percent cover (see legend in insert).
doi:10.1371/journal.pone.0030536.g003

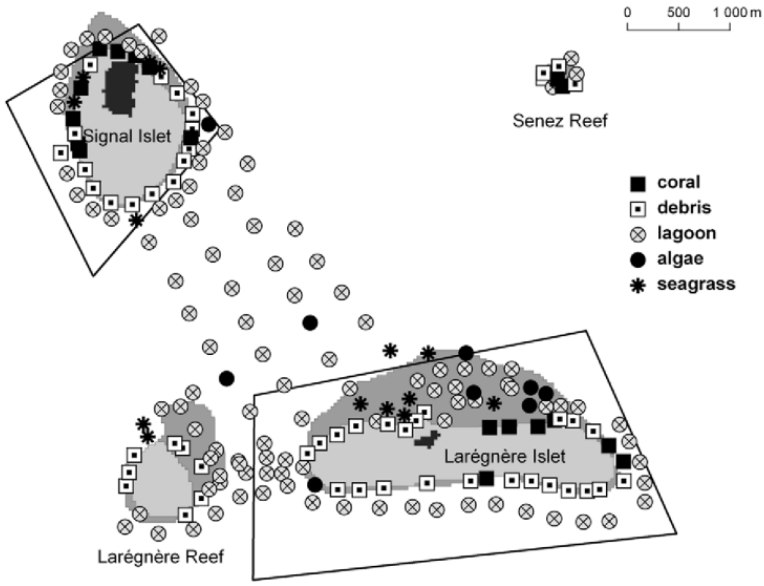

Figure 4. Distribution of habitats resulting from the typology of stations (see legend in insert for symbol definition). Clusters were described in Table 4.
doi:10.1371/journal.pone.0030536.g004

Mullidae, Labridae and Lethrinidae, which also were the most common families observed in UVC (see frequencies per family on Figure 5). Lethrinidae were seen in 52% of the stations, while Mullidae, Scaridae, Acanthuridae and Balistidae were seen in ca. 40% of the stations. Labridae were observed in one third of the stations, and Siganidae, Serranidae, Chaetodontidae were observed in one fourth of the stations.

Maximum abundance densities were observed for Lutjanidae (8.11 ind.m^{-2} and 1.30 ind.m^{-2}) (mostly due to fish schools of *Lutjanus quinquelineatus* and *L. fulviflamma*), Kyphosidae (0.96 ind.m^{-2}). Lethrinidae and Acanthuridae were frequently observed in large abundances, and to a lesser extent Scaridae and Mullidae (Figure 5).

Overall abundance density per station was larger on the reef slopes of the islets and reefs (Figure 6). But non-negligible densities were also observed in the lagoon area between the two islets. Mean and maximum overall densities per station significantly differed according to habitat (GLM with Gamma distribution, $p<2.10^{-16}$ in both cases), but not according to protection status.

Species richness was found to strongly depend upon habitat (Figure 7). Using a GLM model with a Gamma distribution, the effect of protection status was not significant, but the habitat effect was clear ($p<2.10^{-16}$) and interactions were significant ($p<0.04$). Multiple comparisons evidenced that species richness was significantly higher in coral, debris and macroalgae habitats compared to the lagoon and seagrass ones ($p<0.001$). In every habitat, species richness did not significantly differ between protected and unprotected areas.

The abundance densities of three major fish species were then investigated. The leopard coralgrouper *Plectropomus leopardus*, a favorite target species for spearfishers, was observed in the three habitats lagoon, coral, and, in smaller densities, on debris. Density per station differed according to habitat (GLM with Gamma distribution, $p<2.4.10^{-5}$), but not according to protection status.

Table 4. Description of the habitat clusters resulting from the typology.

	Explanatory variable						
Cluster	**Substrate**	**Depth (m)**	**Topo graphy**	**Comple xity**	**Live coral (%)**	**Seagrass (%)**	**Macroalgae (%)**
Lagoon (105)	sand ($p<6.10^{-25}$)	**11.0** ($p<7.10^{-4}$)	1.5 ($p<2.10^{-6}$)	1.9 ($p<3.10^{-6}$)	0.8 ($p<4.10^{-17}$)	**20.1** ($p<3.10^{-6}$)	**24.3** ($p<2.5.10^{-10}$)
Sea grass (14)	sand ($p<5.10^{-3}$)	7.5 (*NS*)	1.5 (*NS*)	2.0 ($p<5.10^{-3}$)	0.9 (*NS*)	**80.0** ($p<2.2.10^{-21}$)	3.0 (*NS*)
Macro algae (9)	sand	7.6 (*NS*)	1.9 (*NS*)	**2.5** (*NS*)	0.5 (*NS*)	1.6 ($p<3.10^{-2}$)	**82.6** ($p<2.10^{-15}$)
Debris (50)	mixed sand and rocky ($p<2.3.10^{-19}$)	**6.7** ($p<7.10^{-6}$)	**2.2** ($p<3.10^{-2}$)	**2.4** ($p<3.10^{-3}$)	**16.0** ($p<9.10^{-22}$)	4.0 ($p<7.10^{-8}$)	2.5 ($p<7.10^{-10}$)
Coral (18)	mixed rocky ($p<5.10^{-21}$)	**4.4** ($p<5.10^{-3}$)	**2.6** ($p<2.10^{-10}$)	**3.3** ($p<6.10^{-12}$)	**46.8** ($p<8.10^{-15}$)	**0.0** ($p<2.10^{-6}$)	0.3 ($p<3.10^{-5}$)
All stations (196)	–	**8.9**	**1.8**	**2.2**	**8.9**	**17.6**	**17.7**

The number of stations belonging to each cluster was reported between parentheses. For a given explanatory variable, the number of stations displaying the characteristic was reported, along with the p-value corresponding to the test of the difference in proportion between the cluster and the whole set of 196 stations.
doi:10.1371/journal.pone.0030536.t004

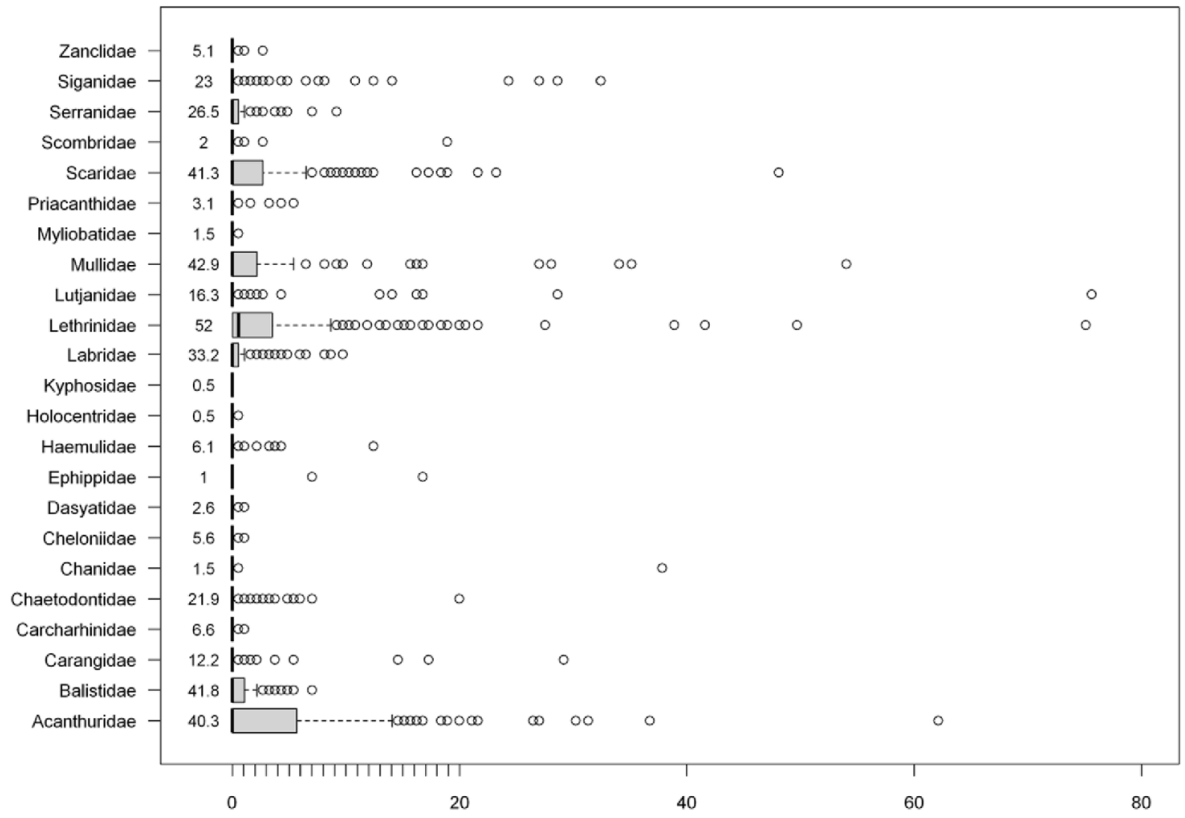

Figure 5. Distribution of abundance density per family. Abundance density was the average over rotations. On each boxplot, boxes showed the interquartile (0.25, 0.75) ranges; whiskers extended to the data point at ≤1.5 times the box length away from the box; values outside this range were represented by dots. Four outlying values were not reported for better readability of the plot : 810.6 ind/100 m^2 (two values) and 129.7 ind/100 m^2 for Lutjanidae, and 95.5 ind/100 m^2 for Kyphosidae. The frequency (in % stations where the family was seen) was reported on the left of the boxplots for each family.
doi:10.1371/journal.pone.0030536.g005

The spangled emperor *Lethrinus nebulosus*, a target species of line fishing was mainly observed in the seagrass habitat, and to a lesser extent in the lagoon habitat. Density per station significantly differed according to habitat (GLM with Gamma distribution, $p<0.0032$), but not according to protection status. The third target species, the bluespin unicornfish *Naso unicornis*, was another important target of spearfishing (Figure 8). The density of *N. unicornis* was also modeled from a GLM with a Gamma distribution considering the two factors habitat and protection status. Main effects and interactions between the two factors were significant (habitat: $p<0.0022$, protection status: $p<0.031$, and interactions: $p<0.0087$). The density of the species was thus larger in the protected areas, and particularly so in the coral and debris habitats which were preferred by the species.

In the next step, we considered the density of Chaetodontidae, which are indicators of coral health status and abundance (see e.g. [36]). The family was absent from the seagrass habitat. A GLM with a Gamma distribution fitted to the density of Chaetodontidae on the other four habitats showed a significant habitat effect ($p<10^{-6}$), but no effect of protection status. Multiple comparisons evidenced significantly higher densities in the coral and debris habitats than in the lagoon habitat (respectively 2.9 ind/100 m^2 and 0.67 ind/100 m^2, versus 0.11 ind/100 m^2). The relationship between Chaetodontidae density and live coral cover was thus clearly detected from the data.

Emblematic and rare species were the final focus of the study. The frequency of occurrence of marine turtles (Chelonidae), sharks (Carcharinidae), rays (Dasyatidae and Myliobatidae) and humphead wrasse (*Cheilinus undulatus*) were computed per habitat and protection status. Three turtle species were encountered in three habitats (coral, debris and lagoon), in relation with their preferenda, but also because these habitats comprised more stations than the other ones (Figure 9). Turtles were systematically observed in protected areas. From a binomial GLM model of presence/absence restricted to the coral, debris and lagoon habitats, both habitat and protection status effects were found to be significant ($p<0.01$ for both effects). Sharks were observed in four habitats, mostly in protected areas (Figure 10). Rays were observed in seven stations mostly in the lagoon habitat and once in the macroalgae habitat (results not reported). *Cheilinus undulatus* was encountered in the coral and debris habitats, only in protected areas (results not reported). Presence/absence GLM modeling did not evidence any significant effect of habitat or protection status for none of these three species groups. Rare species such as turtles, sharks, and rays could thus be observed at a non-negligible number of stations (Table 5).

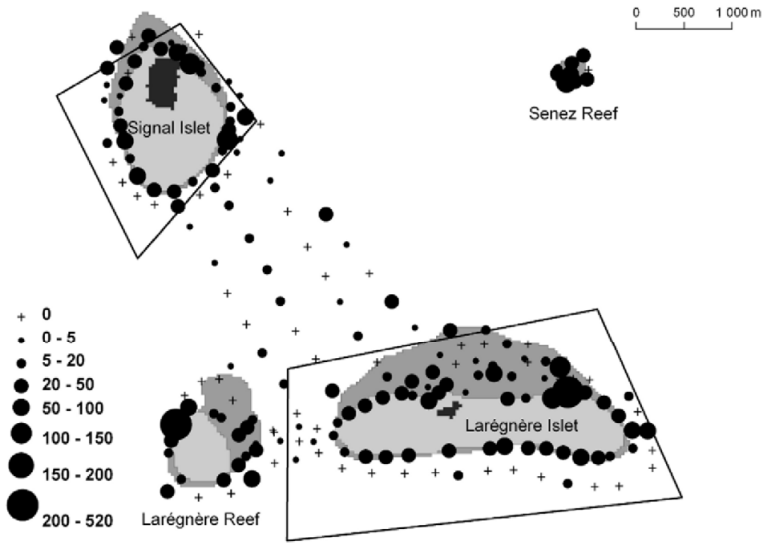

Figure 6. Maximum overall abundance per station. Circles are proportional to the maximum observed abundance density per station (i.e. MaxN) (see legend in insert, densities were plotted in #ind/100 m^2).
doi:10.1371/journal.pone.0030536.g006

Discussion

Observations of biodiversity

In the present study, 149 species from 23 taxonomic families were observed.

A quantitative comparison of UVC transects and HD video transects conducted with the same type of camera also showed that HD video detected reasonably well the species and individuals observed in UVC [23], since 85% of species seen by UVC were also detected by HD video (based on the analysis of all fish species, unlike the present analysis which focused on a list of species, see Table 1). In the latter paper and in the present study, the proportion of species that were not identified up to the species level remained very low. Large abundances of fish species could be observed from the HD rotating video, in particular fished species. Carangidae, Carcharinidae, Dasyatidae, Myliobatidae and Chelonidae were observed at a number of stations. These outcomes were likely explained by i) the absence of a diver, ii) by the larger variety of habitats investigated using this technique, including seagrass and other soft bottoms; and iii) by the large number of stations realized.

Video observations of macrofauna compared in a satisfactory way with those from UVC surveys conducted in the same area and

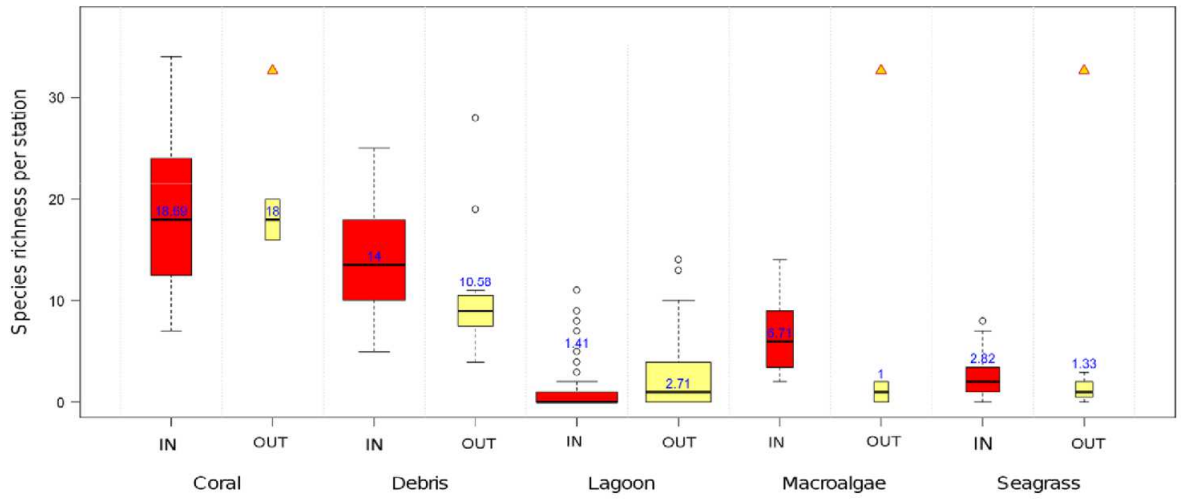

Figure 7. Species richness per station as a function of habitat (see Table 4 for habitat definition) and protection status (IN versus OUT). On each boxplot, boxes showed the interquartile (0.25, 0.75) ranges; whiskers extended to the data point at ≤1.5 times the box length away from the box; values outside this range were represented by dots. Triangles indicated boxplots with less than 5 data.
doi:10.1371/journal.pone.0030536.g007

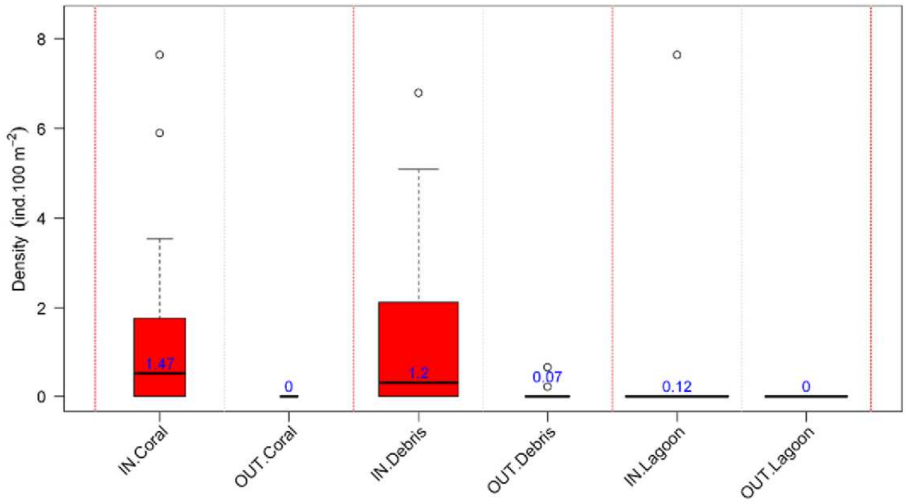

Figure 8. Distribution of *Naso unicornis* abundance density according to habitat (lagoon, debris and coral) and protection status (IN versus OUT of protected area). The species was not found in the other two habitats. Abundance density was the average over rotations. On each boxplot, boxes showed the interquartile (0.25, 0.75) ranges; whiskers extended to the data point at ≤1.5 times the box length away from the box; values outside this range were represented by dots. Triangles indicated boxplots with less than 5 data.
doi:10.1371/journal.pone.0030536.g008

in the same habitats, although quantitative comparisons could not be conducted as the timings of the studies, the number of observations and the observation surface area were very different. Note that the objective of this study being to demonstrate the adequacy of the technique for spatial survey, no formal comparison with UVC was carried out here.

Our results showed that the technique detected well the species and families observed in UVC, even in this highly diversified coral reef ecosystem. A pilot study was conducted in 2010 in rocky and seagrass habitats in a Mediterranean ecosystem, during which 33 species could be observed from 22 STAVIRO stations (Pelletier and Hervé, unpubl. data).

In addition, video provided information about habitat and particularly biotic cover at no extra cost along with fish data. Analysing images for abiotic substrate and biotic cover proved to be easy and quick. Simultaneous information on vagile macrofauna and habitat collected at a large number of stations are a valuable asset for analyzing spatial and temporal patterns of

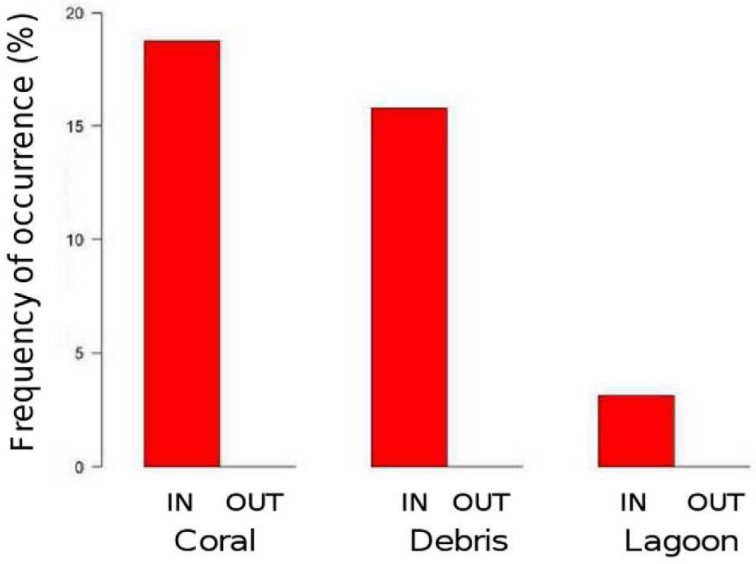

Figure 9. Frequency of occurrence of marine turtles. Frequencies were plotted per habitat (labeled on the X-axis) and per protection status (protected areas in dark grey and unprotected areas in light grey).
doi:10.1371/journal.pone.0030536.g009

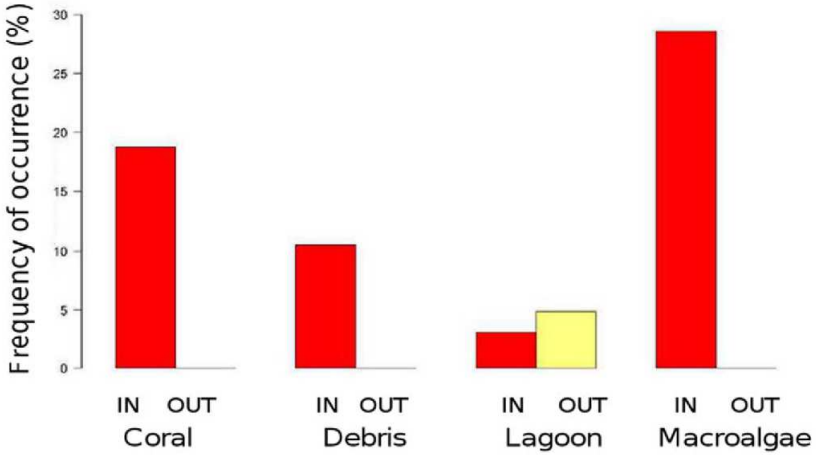

Figure 10. Frequency of occurrence of sharks. Frequencies were plotted per habitat (labeled on the X-axis) and per protection status (protected areas in dark grey and unprotected areas in light grey).
doi:10.1371/journal.pone.0030536.g010

macrofauna in relation with both habitat and anthropogenic pressures.

Implementation of the technique

As far as field work is concerned, 70% of the stations were validated during the 2007 survey, which was high for a first test of the technique in the field. The few technical problems encountered in 2007 were easily solved, since 1246 validated stations (corresponding to a 81% validation rate) could be realized in 2008, 2009 and 2010 in the same area and in similar places in the New Caledonian lagoon (results not reported here, Pelletier and Mallet, unpubl. data). Defective stations only resulted from a poor underwater visibility in relation with weather conditions. In these surveys, the mean number of observations per day obtained from two rotating systems was 30 stations for ca. 6 hrs of field work. Note that as the technique is easy to implement and requires limited logistics, it is possible to target favorable conditions for field work.

Overall, the system proved to be remarkably stable and was used in depths ranging from 1.2 m to 27 m, and in various sea and weather conditions. The number of observations that can be realized in a given period of time depends on the travel distance between two stations; it is thus recommended to realize pairs of stations that are not too far apart.

The main advantages of the technique presented in this paper lie in the fact that i) a large number of observations can be realized on the field within a short period of time; ii) it can be implemented easily on site by technical staff following a repeatable protocol. This enables to cover large areas including many habitats, and to obtain comparable data from several sites. Another major advantage is to avoid on-site observer effects. As for drawbacks, the system needs to be set horizontally and on a steady bottom like most remote systems. Setting the system on outer slopes or in areas fully covered with live coral may thus take a few minutes.

At the laboratory, images were analyzed by two persons, particularly at the onset, to build the capacity for identifying species and counting individuals from images. Analyses for fish assemblages were carried out with the help of an experienced UVC fish expert. Image analysis was greatly enhanced by the use of HD as was also found by [37]. Between 2007 and 2010, several persons were trained to image analysis, and this experience showed that the continuous presence of a fish expert was not needed. Because images can be viewed as many times as needed, image analysis can proceed in a flexible way, using identification guides and building on previous analyses. Training a person to analysis required at most one month.

Cost-effectiveness of observation techniques

Three techniques were quoted in this article: STAVIRO, UVC and BRUV. We herebelow provided a tentative comparison of UVC and STAVIRO in the light of spatial survey of biodiversity (Table 6). BRUV were not included in Table 6 as field work parameters for the technique were not available in the study area. From the literature, BRUV shares with STAVIRO the advantages inherent to the absence of a diver. The use of a bait permits to increase the number of individuals observed by attraction of

Table 5. Frequency of occurrence of emblematic species in the video stations.

Emblematic species	Overall frequency in the 196 stations	Highest frequencies in given habitats
Marine turtles	6.6%	19% in protected coral habitat (16 stations) 16% in protected debris habitat (38 stations)
Sharks	7%	28.5% in protected algae habitat (7 stations)
Rays	6.1%	50% in protected algae habitat (2 stations) 6.7% in lagoon habitat (105 stations)
Humphead wrasse	1.0%	6.3% in protected coral habitat (16 stations)

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Table 6. Cost-effectiveness of UVC and STAVIRO techniques.

Observation technique	Time (observation, image analysis data input)	Staff required Nb of observations per day	Advantage
UVC	• On site: 45′ to 90′ per fish transect & 10′ per habitat transect • At the office :15′ for data input	• 2 divers (1 fish expert, 1 for habitat) • Max. 3 transects per day and per diver	• Widely used • Mostly field work • Little work after data collection
STAVIRO	• On site: 15′ per station • At the office: 10′ to 65′ per station for fish et 10′ for habitat (image analysis+ data input)	• On site: 2 technical staff • 20 stations per day with 1 system, 30 stations per day with 2 systems • At the office: 1 trained person(1), possible validation by fish expert	• Spatial coverage • No diver effect on fish nor on data collection • Simultaneous data on macrofauna and habitat • Single protocol • Reduced time at sea • Larger range of depths • Archiving of data • Several analyses possible

(1)Training period, one month maximum.

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carnivorous (and other) species, but the uncertainty about the bait plume hampers the estimation of density estimates. Baiting also requires that the station be left at least 35′ to 60′ in place to ensure bait effectiveness [38].

The STAVIRO does not rely on a diver or on a bait. Although it cannot be ascertained that the presence of the system underwater does not influence the vagile macrofauna, STAVIRO is certainly less obtrusive than UVC and BRUV.

Unlike UVC, many STAVIRO stations can be realized within a given amount of time. The time spared at sea for each station is utilized at the office to analyse images, and the overall time needed per observation is approximately the same for UVC and STAVIRO (Table 6). But field work can be realized by non-expert staff.

In developing the STAVIRO technique, priority was given to facilitate and speed up implementation in the field, while keeping the system as affordable as possible in order to foster its use. Hence, size estimation was not central, and abundances per size class were deemed precise enough. For the same reason, the system did not include a device for estimating the distance to the fish on the image. Similar to UVC training, observers were trained to estimate distances from underwater images displaying fish silhouettes from different sizes placed at several known distances (Mallet, unpubl. data).

Archiving data is a very important point with video observation. Although filing HD images raises issues of storage, archiving bears several advantages. Firstly, information is fully traceable, which is desirable for monitoring and reporting. Secondly, several independent analyses can be carried out, either for different needs corresponding e.g. to distinct levels of analysis, or to check previous analyses. Thirdly, images may be very useful for communication purposes, as they speak for themselves. This might be invaluable for reporting monitoring results, and also for educational purposes.

HD rotating videos thus appear as a promising observation technique for investigating spatial distributions of biodiversity and their evolution over time. Its advantages make it interesting for research and for monitoring the performance of conservation strategies such as MPAs. The implementation of a monitoring network of STAVIRO to monitor biodiversity in the New Caledonian lagoon is presently under development. This network would support reporting on biodiversity status for World Heritage sites (http://whc.unesco.org/en/). As the technique can be implemented by non-expert staff, it could be relevant in participatory community-based management involving local stakeholders, an approach that is being advocated for an improved governance of coastal areas [39,40].

Being suited for both research and monitoring, this technique might support adaptive management of marine ecosystems [41], in that properly designed observation networks could at the same time inform the monitoring process and provide valuable information for research about biodiversity restoration in protected areas, and more generally about ecosystem resilience. Given the expected trends in marine biodiversity and the global conservation commitments, proactive management strategies would certainly benefit from the development and wide use of such tools.

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Author Contributions

Conceived and designed the experiments: DP GH KL. Performed the experiments: DP GH KL MB NG. Analyzed the data: DP DM KL GMT MB NG. Contributed reagents/materials/analysis tools: DP DM KL GMT GH MB NG. Wrote the paper: DP DM KL GMT GH MB NG.

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2. Article 3. Etude des variations temporelles à partir d'observations répliquées dans le temps: le MICADO

Résumé de l'article 3 :

La distribution de l'ichtyofaune marine est soumise à de fortes variations dans le temps et dans l'espace. Les variations temporelles ont été beaucoup moins étudiées que les variations spatiales. La plupart des études temporelles publiées traitent de variations à grande échelle (annuelle, saisonnière ou mensuelle) et peu d'entre elles ont étudié ces variations à court terme. L'objectif de cet article est de présenter une technique vidéo originale, autonome et rotative pour observer l'ichtyofaune vagile à haute fréquence temporelle : le système MICADO. Ce système permet une vision panoramique et vise à quantifier la présence, l'abondance et la diversité de l'ichtyofaune marine. Il se compose : i) d'un boîtier renfermant une caméra vidéo en haute définition, ii) d'un moteur entraînant la rotation de la caméra, et iii) d'une minuterie permettant de programmer les périodes de temps à enregistrer. Dans la présente étude, le système a été utilisé pendant une semaine complète dans deux habitats de récifs coralliens différents. 119 vidéos ont été enregistrées. 11914 individus appartenant à 88 espèces ont été observés dans un habitat composé majoritairement de coraux branchus, tandis que 1410 individus appartenant à 47 espèces ont été observés dans un habitat moins complexe (composé majoritairement de coraux massifs). La richesse spécifique et la densité globale étaient significativement plus élevées tôt le matin et tard dans l'après-midi dans l'habitat de coraux branchus. Dans l'habitat majoritairement composé de coraux massifs, la richesse spécifique était plus importante tôt le matin, à midi et tard dans l'après-midi, mais la densité globale n'a pas été influencée par l'heure de la journée. Les occurrences et l'abondance varient selon les espèces, l'heure et les habitats. Le système MICADO est discret et peut être laissé en place pendant une longue période, ce qui permet l'observation des populations de poissons à des moments critiques comme le coucher et le lever du soleil, et dans un intervalle de temps qui ne peut être égalé par des techniques nécessitant des plongeurs. En raison de sa petite taille et de son faible poids, le système MICADO peut être utilisé dans une grande variété d'habitats allant des platiers récifaux aux fonds meubles, et fournit des observations de l'ichtyofaune sous-marine non-perturbées à haute fréquence temporelle. Ces informations devraient être prises en compte dans les travaux de recherche traitant, par exemple, de l'effet des AMP et de l'impact de la pression de pêche.

Article 3

(*En préparation*)

The MICADO video system: A programmable Autonomous Remote High-Definition Rotating Video system for High-Frequency observation of underwater macrofauna

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Abstract

The distribution of marine macrofauna is subject to strong variations in time and space. Temporal variations have been much less documented than spatial ones. Most published studies dealt with annual, seasonal or monthly scales and few focused on short-term temporal variations.

The aim of this paper is to present an original autonomous rotating video technique for high temporal sampling frequency of vagile macrofauna: the MICADO. This system ensures panoramic observations aims at quantifying the occurrence, abundance and diversity of species. It consists of i) a housing enclosing a camera; ii) an engine which induces the rotation of the camera; and iii) a timer to program the time periods for switching the system on and off.

In the present paper, the system was used during one week in two coral reef habitats, and recorded 119 videos. 11914 individuals belonging to 88 species were observed in a branched coral habitat, while 1410 individuals belonging to 47 species in a less complex habitat (massive coral). Mean species richness and overall density were higher early in the morning and late in the afternoon in the branched coral habitat. In the massive coral habitat, species richness was higher early in the morning, at midday, and late in the afternoon, but overall density did not depend on hour. Occurrences and abundance varied according to hour, species and habitat.

The MICADO system is inconspicuous and can be left in place for a long time, enabling observation of fish populations at critical times such as sunset and sunrise, and over a time range that cannot be matched by diver-based techniques. Due to its small size and low weight, the MICADO system can be used in a variety of habitats from reef flat to sandy bottoms, and provide high-frequency undisturbed observations.

Keywords: monitoring; remote underwater video; marine biodiversity; temporal survey

1. Introduction

The distribution of marine macrofauna is subject to strong variations in time and space (Sale, 1980). A number of studies on reef fish assemblages have focused on explaining spatial variations in abundance, either through environmental or anthropogenic factors (Milazzo et al., 2005; Sangil et al., 2013; Wantiez et al., 2006). Temporal variations in fish presence and abundance have been much less documented, perhaps in relation to the perception of spatial patchiness being more structuring for reef fish assemblages than temporal heterogeneity (Thompson and Mapstone, 2002).

Temporal variations take place at several scales. They may be cyclic (diel, lunar, seasonal, inter-annual) (Reebs, 2002) or occur in response to disturbances such as cyclonic events, outbreaks of starfish and various anthropogenic pressures (Wantiez et al., 2006). Like spatial variations, temporal variations in macrofauna distribution may arise from: (1) actual changes in abundance, e.g. due to recruitment, mortality or migration from or to the study area; (2) transient changes in distributions, within the area of interest but without net change in population size; and (3) from observation error (Thompson and Mapstone, 2002). Short-term (or high-frequency) movements may be directly related to foraging behaviour, use of refuges for avoiding potential predators.

When the sampled area is smaller than the home range of observed species, and when sampling frequency and timing do not enable to observe these short-term shifts within the habitat occupied, the different sources of temporal variations may be confounded.

For non-sessile species, it is therefore important to investigate short-term variations in addition to spatial variations, in order to account for both in designing and interpreting the outcomes of temporal studies (Thompson and Mapstone, 2002). Yet,

most published studies dealt with annual, seasonal or monthly scales (see among others Condal et al., 2012; Connell and Jones, 1991; Fisk and Harriott, 1990; Galzin, 1987b; Jenkins and Wheatley, 1998; Kingsford, 1992; Winemiller, 1990). Among the few studies considering high-frequency temporal variations of reef fish populations, many focused on day-night variations of fish assemblages (Colton and Alevizon, 1981; Danilowicz and Sale, 1999; Galzin, 1987b; Hobson, 1965; Rooker and Dennis, 1991). Other studies concentrated on changes in behavior, distribution and abundance of reef fish at sunrise and sunset (Danilowicz and Sale, 1999; Galzin, 1987b; Hobson, 1972; Santos et al., 2002). In some instances, continuous or high-frequency observations were collected during daylight over a short period of time to study diurnal patterns of abundance (Birt et al., 2012; Chabanet et al., 2012; Colton and Alevizon, 1981; Spyker and Van Den Berghe, 1995; Willis et al., 2006). No single pattern of variations according to daylight was evidenced by these studies. But in some cases, the abundance of certain species was found to significantly vary according to day time. For instance, fish abundance significantly differed between at least two time periods for 6 of 25 species in Colton and Alevizon (1981) and for 5 species of 18 (mostly Labridae) in Spyker and Van Den Berghe (1995). In Chabanet et al. (2012), average fish abundance remained rather constant between days, but Acanthuridae were more numerous in the morning, whereas Scaridae abundance was higher at sunrise and sunset. Birt et al. (2012) observed a significant variation in the composition of fish assemblage within and between days in relation to rare species.

Most of these studies (but Birt et al. 2012 and Chabanet et al. 2012) were based on direct underwater observations by divers as in many quantitative studies of reef fish assemblages (López-Pérez et al., 2012). Data collected by divers or snorkelers through Underwater Visual Census (UVC) techniques such as transect observations (Brock, 1954) yield invaluable information, but are also recognized to involve a set of drawbacks that affect data quality and quantity (Brock, 1982; Edgar et al., 2004). These include the observer's influence on fish behavior (Chapman et al., 1974) and intra- and inter-observer variability (Bernard et al., 2013). On the logistic side, diver-based visual observations also imply time and depth limitations, restriction to day-time, as well as the need for well-trained divers (Bell et al., 1985; Smith, 1988). In order to study vagile macrofauna without human disturbance, other techniques have been developed such as underwater video techniques. Like UVC, the first Remote Underwater Video (RUV) techniques were developed in the early 50s in shallow marine environments (Barnes,

1952). They are now increasingly used all over the world to study marine biodiversity. Because they do not require divers, the RUV technique overcomes several of the shortcomings mentioned above (Alevizon and Brooks, 1975). Furthermore, in the light of investigating short-term variations, autonomous video techniques enable temporal replication of observations. For instance, Chabanet et al. (2012) presented a system with programmed recording of video sequences of 2 min every 2 hours, enabling continuous operation for up to one month. The system was set facing a coral reef colony (1 m^2 surface area) for observing variations of fish populations; seventy-five species could be observed this way over two periods of 3 weeks.

The aim of this paper is to present an original autonomous high definition video technique for high temporal sampling frequency of fish and other vagile macrofauna. This rotating system enables a panoramic view, and does not require any external intervention during sampling. The recorded footages are fully consistent with those from Pelletier et al. (2012); thereby enabling joint analysis of spatial and temporal data, as suggested by Thompson and Mapstone (2002).

The interest of the technique is illustrated by a survey conducted in 2012 on a highly diversified reef within a no-take zone in New Caledonia. We first investigated the range of species and abundances observed and identified from the images during ten time periods during daylight. We then discussed the advantages and shortcomings of MICADO for observing short-term variations of coastal fish assemblages.

2. Materials and methods

2.1. The MICADO observation system

Like the STAVIRO system of Pelletier et al. (2012), the MICADO system rotates from 60° every 30 seconds and encloses a High-Definition (HD) camcorder with a wide-angle lens. It consists of i) a single waterproof housing enclosing a camera; ii) an engine (powered by 2.4V rechargeable batteries) which induces the rotation of the camera; and iii) a timer to program the time periods for switching the system on and off. The camera used in the present study was a HD Sony™ camera HDR-XR500 with an integrated 120 Gigabyte hard drive enabling the recording of up to 12 hrs of HD images. The camera records a signal following the 1080i standard, i.e. with a full HD resolution of 1920 x

1080 pixels. The housing and camera result in an approximate focal angle of 60°. To ensure a panoramic view, the zooming level is set at minimum and the focus is manually adjusted at the farthest. The housing is fixed onto a weighted tripod (6 kg) to stabilize the system on the sea floor (Figure 1).

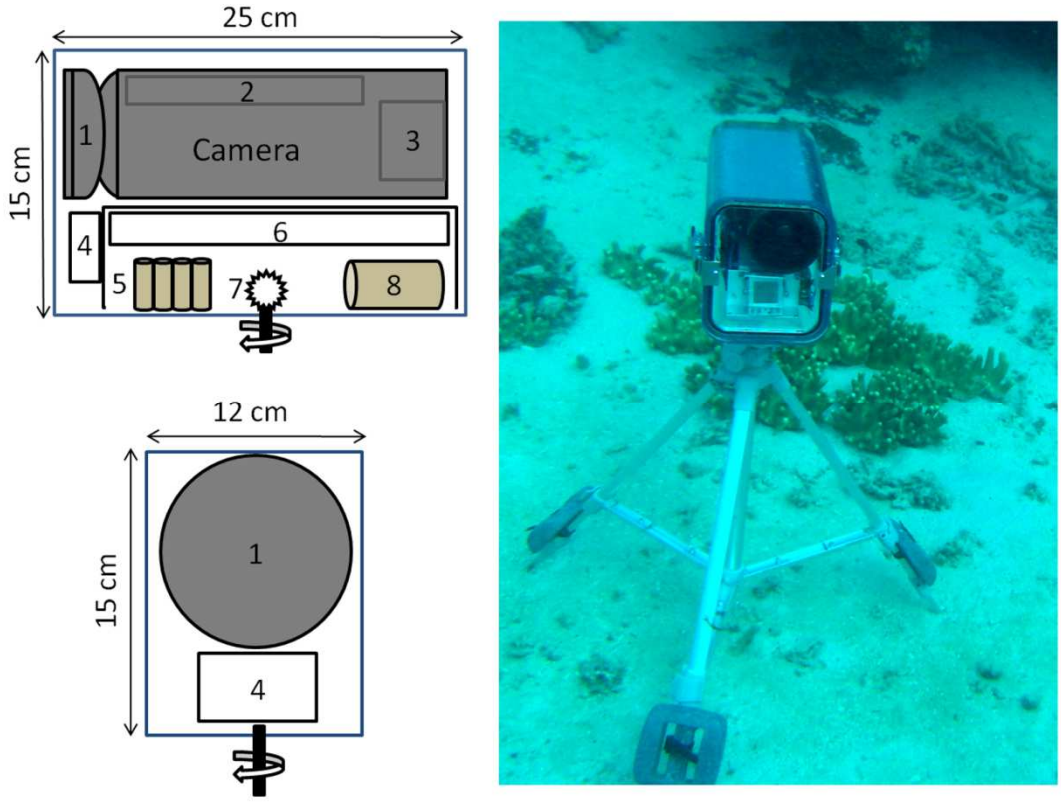

Figure 1. The MICADO system. On top left: side view of MICADO, bottom left: front view and on the right: picture of MICADO underwater. 1: Wide angle lens; 2: internal hard drive of the camera; battery of the camera; 4: Timer; 5: rechargeable batteries to power the electronic card and the timer, 6: control circuit commanding the entire system; 7: engine inducing the rotation; and 8: 1,5V battery powering the engine.

The system is directly set on sea bottom by a diver or a snorkeler, depending on depth. It is then left in place for the duration of the study. To minimize disturbance during observation, there is no surface marker and no artificial light used.

For the present study, the capacity of the batteries and of the camera internal drive allowed to record ten footages of around eight minutes per day over three consecutive days. The duration of video sequence and their frequency could be programmed in different ways depending on the study's objective.

2.2. Study area

The present study was conducted in the Southwest Lagoon of New Caledonia, South Pacific. The study area encompasses the Aboré Reef Marine Protected Area (MPA) located 20 km off Nouméa city (22°26' S, 166°21' W). This MPA was declared a no-take area in 1996. It includes the barrier reef and associated inner reef slope, and the southern reef pass. Observations were recorded in two locations of the inner reef slope. Locations were 300 m apart and correspond to distinct living coral micro-habitats: branched corals (*Acropora)* at 5 m depth, and a less complex habitat with massive corals (*Porites)* at 7 m depth. These are here below respectively referred to as "Branched coral" and "Massive coral" habitats.

2.3 Data collection

Data were collected over a week in 2012, from the September 27th to October 3rd. The two MICADO systems were placed at the same time in their respective locations. Each MICADO was programmed to record during two complete rotations every hour from sunrise to sunset. In order to have enough light for the camera, the first sequence in the morning was programmed 30 minutes after the sunrise and the last one in the afternoon 30 minutes before the sunset (0600 h, 0715 h, 0830 h, 0945 h, 0011 h, 1215 h, 1330 h, 1445 h, 1600 h and 1715 h). Due to energy constraints, each system was replaced by a similar one (empty memory camera, full batteries) on day 3. At each location, the exact distance from the camera to corals colonies were measured on the last day of the experiment, in order to assist the evaluation of distances during image analysis.

2.4. Image analysis

To avoid any observer effect (Thompson and Mapstone, 1997), Mallet et al. unpublished data.) all footages were performed by the first author. The procedure for image analysis was described in Pelletier et al. (2012), except that in the present study, only two rotations were analyzed per footage (instead of three in the cited paper). For each rotation, the observer identified and counted each individual detected on the

images at the highest taxonomic level. Species of interest include fish, as well as sea snakes, turtles and dugongs. To minimize potential double counting, particular attention was given to the direction of fish with respect to camera rotation. Small species were identified within a virtual cylinder of 5 m radius, while large species were identified within the visibility range limited to a maximum of 10 m. A species was considered as "small" when the maximum species size was less than 30 cm. In addition to species counts, habitat was characterized for each video using the medium-scale approach (Clua et al., 2006) (see Pelletier et al., 2012 for details).

2.5. Data analysis

We first investigated the frequency and abundance density of each taxonomic family in the data. Secondly, overall density and species richness per hour and station were computed and their variations assessed from permutational multivariate analysis of variance (PERMANOVA, Anderson, 2001). In a third step, we focused on the abundance of one key fished species in New Caledonia: the yellowfin surgeonfish (*Acanthurus xanthopterus*). Because count data were not normally distributed, we used the Kruskal-Wallis test (Sokal and Rohlf, 1981) to determine if fish abundance significantly differed among the ten time periods considered. Finally, we investigated the frequency of occurrence as a function of hour for four important species in the study area: yellowfin surgeonfish (*Acanthurus xanthopterus*), coral trout (*Plectropomus leopardus*), bulbnose unicornfish (*Naso tonganus*) and blue-spotted stingray (*Dasyatis kuhlii*). The first three species are important target species in the region, and the last one is an emblematic species. For each of these species, presence/absence was then modeled using a binomial GLM model to test the effect of hour.

3. Results

3.1. Field implementation

The first systems were set at 10 a.m. on September 27th. The last video footages were recorded at 5.15 p.m. on October 3rd. Over the 7 consecutive days, the MICADO in the

branched coral habitat and the MICADO in the massive coral habitat respectively recorded 67 and 52 video footages. The latter encountered a battery problem resulting in a smaller number of footages recorded.

3.2. Image analysis: species and abundance observed

A total of 52 hrs and 30 mn were necessary to complete the analysis of the 119 video footages by the same observer. All footages were analyzed within a radius of 6 m around the system, corresponding to the minimum visibility observed during the study. This corresponds to an observation range of ca. 113 m^2 per MICADO.

During the seven observation days, a total of 11914 individuals belonging to 88 species, 53 genera and 26 families were observed at the Branched coral location and 1410 individuals belonging to 43 species, 33 genera and 20 families at the Massive coral location (Table 1). 4927 individuals of the Branched coral habitat not identified at species level (representing 41% of all individuals observed) were mostly sedentary Pomacentridae (2934 ind.) and Scaridae (1857 ind.). In the Massive coral habitat, only 103 individuals were not identified at species level (representing 7 % of all individuals observed); most of them being Scaridae (74 ind.).

In the Branched coral habitat, the most frequently observed families were, by decreasing order, Acanthuridae, Chaetodontidae, Labridae, Lethrinidae, Nemipteridae, Pomacentridae, Scaridae and Serranidae (Table 1), while in the Massive coral habitat, the most frequently observed families were, by decreasing order, Acanthuridae, Chaetodontidae, Labridae, Pomacentridae and Scaridae. In both locations, Pomacentridae, Caesionidae, Scaridae and Acanthuridae displayed the largest densities (Table 1). Nine families were only observed in the Branched coral habitat (Apogonidae, Echeneidae, Ginglymostomatidae, Hemiramphidae, Monacanthidae, Myliobatidae, Nemipteridae, Siganidae and Tetraodontidae), while three families were only observed in the Massive coral habitat (Gobiidae, Haemulidae and Kyphosidae).

Table 1. Frequency, abundance density, number of species and genera per family at each location. freq: Frequency (in %); density: mean density (ind\100m^2) observed per video; sp: number of species and ge: number of genera identified on all videos. Families with frequency higher than 50% are shown in bold.

	Branched coral habitat				**Massive coral habitat**			
Family	Freq	density	sp	ge	freq	density	sp	ge
Acanthuridae	**100**	**5**	**8**	**4**	**94**	**2.3**	**7**	**4**
Apogonidae	2	0.6	0	1	0	0	0	0
Aulostomidae	19	0.5	1	1	2	0.4	1	1
Balistidae	43	0.5	2	2	2	0.4	1	1
Caesionidae	27	5.9	1	1	14	2.3	1	1
Carangidae	10	0.6	2	2	2	0.4	0	0
Carcharhinidae	9	0.5	2	2	4	0.4	1	1
Chaetodontidae	**99**	**2.7**	**13**	**2**	**69**	**1.2**	**6**	**1**
Dasyatidae	3	0.4	2	2	8	0.4	1	1
Echeneidae	5	0.6	1	1	0	0	0	0
Ginglymostomatidae	2	0.4	1	1	0	0	0	0
Gobiidae	0	0	0	0	31	0.7	1	1
Haemulidae	0	0	0	0	4	0.4	0	1
Hemiramphidae	2	0.6	0	0	0	0	0	0
Kyphosidae	0	0	0	0	4	0.4	1	1
Labridae	**100**	**3.4**	**13**	**10**	**79**	**1.2**	**7**	**6**
Lethrinidae	**82**	**0.7**	**5**	**2**	14	0.6	2	1
Lutjanidae	3	0.4	2	2	21	0.7	2	2
Monacanthidae	2	0.4	1	1	0	0	0	0
Mullidae	48	0.7	5	1	6	0.6	1	1
Myliobatidae	2	0.4	1	1	0	0	0	0
Nemipteridae	**63**	**0.7**	**1**	**1**	0	0	0	0
Pinguipedidae	10	0.6	1	1	19	0.6	1	1
Pomacanthidae	34	0.8	2	2	2	0.9	1	1
Pomacentridae	**100**	**67.3**	**6**	**5**	**98**	**7.6**	**2**	**2**
Scaridae	**100**	**17.7**	**8**	**4**	**73**	**3**	**9**	**4**
Serranidae	**60**	**0.7**	**6**	**2**	39	0.6	2	2
Siganidae	43	0.8	3	1	0	0	0	0
Tetraodontidae	8	0.6	1	1	0	0	0	0
Total		114.1	88	53		25.4	47	33

3.3. Overall species richness and density

In both locations, mean species richness significantly differed according to hour (one way PERMANOVA, $p < 0.05$) (Figure 2, top). In the Branched coral habitat, there were always more species observed in the morning (0600 h, mean ± SE = 29.3 ± 2.6) and in

late afternoon (1715 h, mean ± SE = 28.9 ± 1.5), than at midday (Figure 2 top and Table 2). In the Massive coral habitat, species richness was higher at 0600 h (mean ± SE = 10.4 ± 1.0), 1215 h (mean ± SE = 10.4 ± 2.5) and 1715 h (mean ± SE = 9.8 ± 1.9) than in the middle of the morning (between 0715 and 0945 h) and in the middle of the afternoon (between 1330 and 1600 h) (Figure 2 bottom and Table 2).

With regard to density, the overall density in the Branched coral habitat was significantly higher early in the morning (0600 h, mean ± SE = 136.6 ± 10.5 ind/100m^2) and in late afternoon (1715 h, mean ± SE = 126.0 ± 12.7 ind/100m^2), than around midday (one-way PERMANOVA, $p < 0.01$) (Figure 2, bottom and Table 2). In reverse, overall density did not significantly differ according to time of the day in the Massive coral habitat (one way PERMANOVA, $p > 0.05$). In the Branched coral habitat, overall density clearly decreased when sunlight was highest (between 1100 and 1600 h), while it peaked when sunlight was lowest, i.e. in the morning (0600 h) and late afternoon (1715 h).

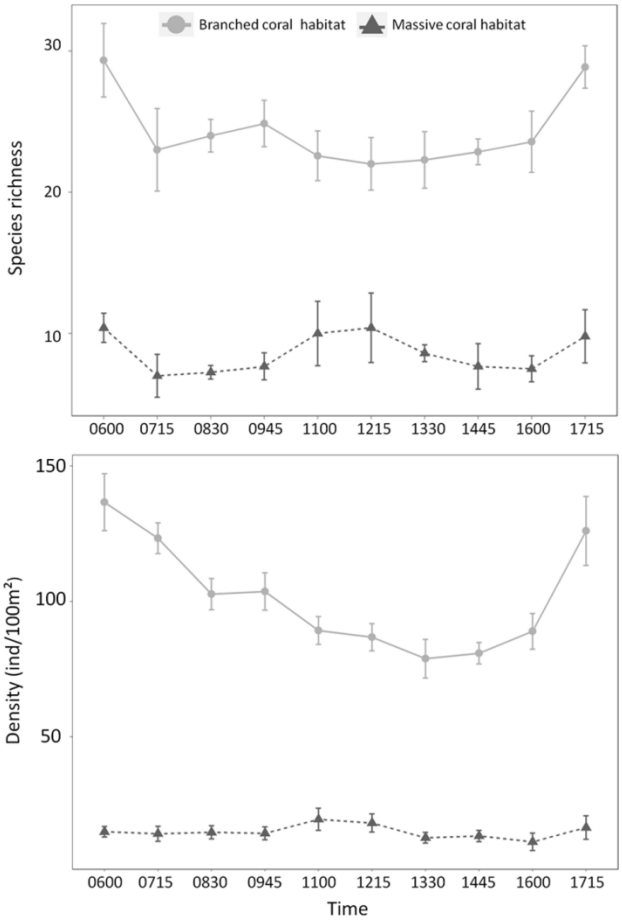

Figure 2. Species richness (top) and abundance density (bottom) as a function of time of the day for each MICADO system.

Table 2. Mean species richness ± SE and mean density (ind/100m^2) ± SE observed per hour for each habitat sampled. Higher observations are shown in bold.

	Branched coral habitat		**Massive coral habitat**	
Time	mean SR	mean density	mean SR	mean density
06:00	**29.3 ± 2.6**	**136.6 ± 10.5**	**10.4 ± 1.0**	14.9 ± 1.9
07:15	23.3 ± 2.9	123.3 ± 5.7	7.0 ± 1.5	14.2 ± 2.8
08:30	24.0 ± 1.2	102.7 ± 5.7	7.3 ± 0.5	14.7 ± 2.4
09:45	24.9 ± 1.6	103.6 ± 6.9	7.7 ± 1.0	14.4 ± 2.4
11:00	22.6 ± 1.8	89.2 ± 5.1	**10.0 ± 2.3**	19.5 ± 4.1
12:15	22.0 ± 1.9	86.8 ± 5.0	**10.4 ± 2.5**	18.2 ± 3.3
13:30	22.3 ± 2.0	78.9 ± 7.1	8.6 ± 0.6	12.7 ± 2.0
14:45	22.9 ± 0.9	80.8 ± 3.9	7.7 ± 1.6	13.4 ± 2.1
16:00	23.6 ± 2.2	88.9 ± 6.6	7.5 ± 1.0	11.2 ± 3.2
17:15	**28.9 ± 1.5**	**126.0 ± 12.7**	**9.8 ± 1.9**	16.5 ± 4.3

Beyond differences according to time of the day, observed species richness and density were always much larger in the Branched coral habitat than in the Massive coral habitat. For density, the observed difference was mostly due to damselfish (Pomacentridae), sedentary species which were very abundant in the Branched coral habitat. The influence of habitat and time of the day was also observed on mobile species, such as the yellowfin surgeonfish (*Acanthurus xanthopterus)*. This herbivorous species is abundant in New Caledonia and is an important fishery target species. In the Branched coral habitat, observed densities significantly differed according to time of the day (Kruskal-Wallis test, $p < 0.05$), but no significant difference was observed in the Massive coral habitat (Kruskal-Wallis test, $p > 0.05$) (Figure 3). In this habitat, more individuals were observed in the morning (0830 and 0945 h) than at any other time of the day. Observed densities of yellowfin surgeonfish were in addition larger than in the Branched coral habitat at these hours.

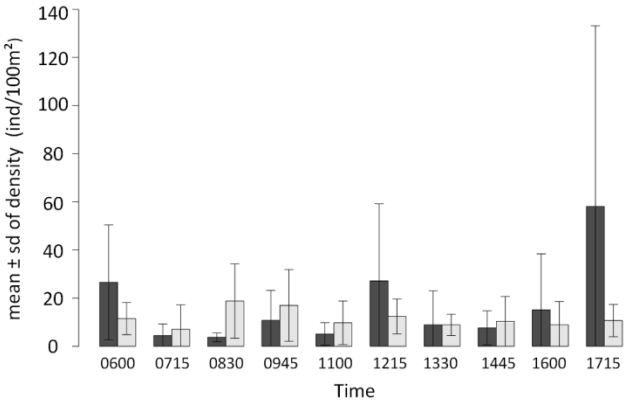

Figure 3. Mean ± SE density (ind/100m^2) observed for yellowfin surgeonfish (Acanthurus xanthopterus) as a function of time of the day for each MICADO system. Branched coral habitat is in dark grey and Massive coral habitat is in light grey. Outcomes of the Kruskal-Wallis test performed on densities observed per time are reported as follows: *: $p < 0.05$, and NS: $p > 0.05$.

3.4. Species occurrence

In the Branched coral habitat, 11 species occurred in more than 75% of all footages, 17 occurred in 30-75%, 24 occurred in 10-30% and 36 occurred in less than 10% of all footages, while in the Massive coral habitat, 3 species occurred in more than 75% of all footages, 6 occurred in 30-75%, 10 occurred in 10-30% and 24 occurred in less than 10% of all footages (see Appendix for details on species occurrences).

For instance, yellowfin surgeonfish (*Acanthurus xanthopterus)* occurred in 81% of all footages in each habitat. Minimum frequency per hour was observed at 1330 h in the Branched coral habitat (57%) and at 0715 h in the Massive coral habitat (40%). On the other hand, this species was systematically observed at 0600 h and 1715 h in the Branched coral habitat, and at 0600, 1215, 1330 and 1715 h in the Massive coral habitat (Figure 4). Another favorite target species, the coral trout *(Plectropomus leopardus),* was observed in 43% of all footages in the Branched coral habitat and in 31% of all footages in the Massive coral habitat. It was more often observed in the late afternoon than during the day in both habitats. The bulbnose unicornfish *(Naso tonganus)* was observed in 61% of all footages in the Branched coral habitat and in 40% of all footages in the Massive coral habitat. Contrary to many other species, it was never observed at 0600, 1600 and 1715 h in neither habitat. In reverse, in the Branched coral habitat where this species was most often observed, it displayed large frequencies of occurrence at 1100 h (57%) and 1215 h (71%). Finally, an emblematic species, the blue-spotted stingray (*Dasyatis kuhlii*) was seen once at 1715h in the Branched coral habitat, and four times in

the Massive coral habitat (Figure 4). A binomial GLM model of presence/absence per species did not evidence any significant effect of time of the day for none of these four species.

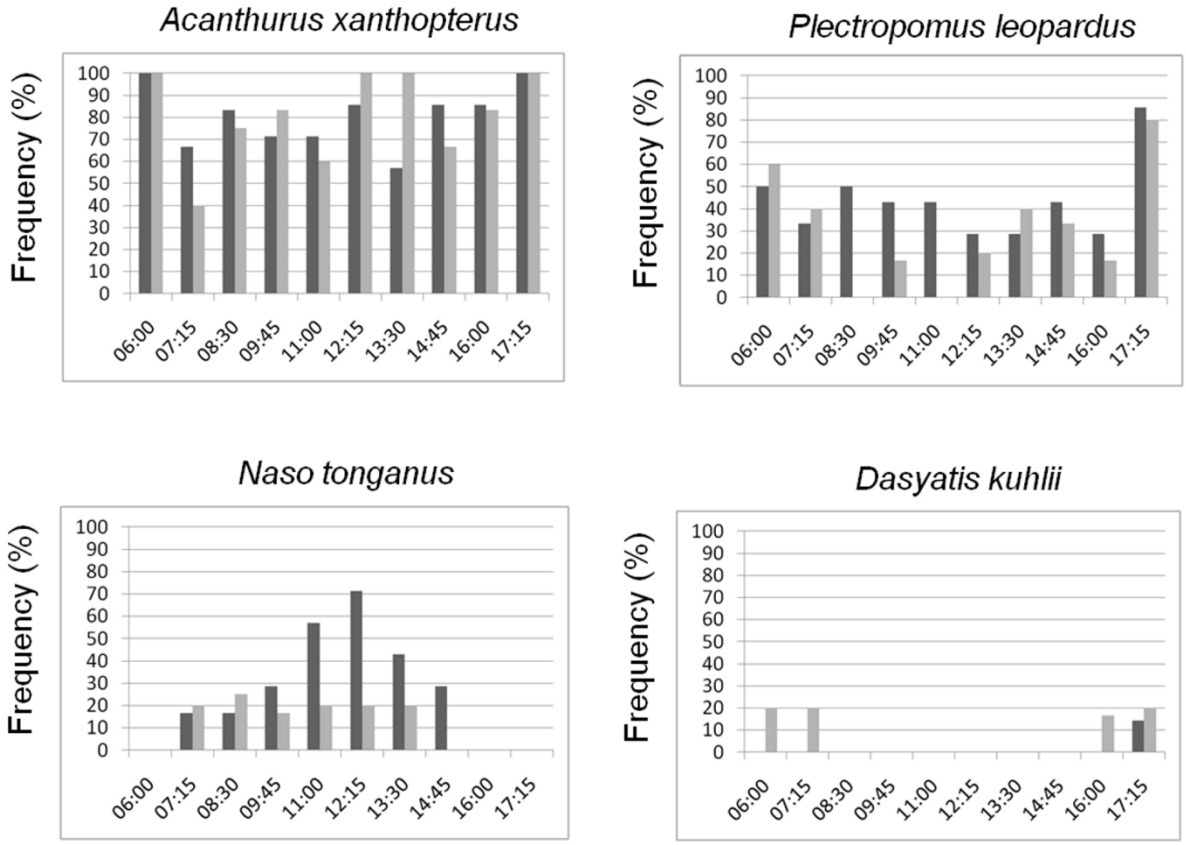

Figure 4. Frequency of occurrence as a function of time of the day for each habitat sampled for the four species studied. Branched coral habitat is in dark grey and Massive coral habitat is in light grey.

4. Discussion

4.1. A tool to study temporal variations of fish assemblages

The 119 video footages analyzed in the present study, first enabled us to evidence a significant difference in species richness according to hour in the two studied habitats. Second, overall densities were found to significantly differ according to hour in the Branched coral habitat but not in the Massive coral habitat. Third, species occurrences varied depending on hour, although not significantly for all species. These results are in

accordance with previous studies on daily variations of fish community structures (Colton and Alevizon, 1981; Irigoyen et al., 2013; Spyker and Van Den Berghe, 1995) showing that sampling should be confined to the same periods each day because species exhibit different patterns of variation throughout the day. Spyker and Van Den Berghe (1995) suggested that any time of day from 3 hrs after sunrise to 3 hrs before sunset was suitable for sampling fish in general. However, Colton and Alevizon (1981) did not observe any single pattern of variation within days among species; and thus suggested that there is no one 'best' time period in which to sample, but rather that repeated sampling should be carried out within the same time period each day. Our results are consistent with those from Colton and Alevizon (1981).

The MICADO systems used in this study allowed to observe many different species (88 species in the Branched coral habitat and 47 species in the Massive coral habitat) and many individuals (11914 and 4927 individuals observed by each MICADO system), from the sunrise to the sunset during an entire week. The Aboré Reef MPA had been previously studied by different authors (Amand et al., 2004; Ferraris et al., 2005; Kulbicki et al., 2007; Preuss et al., 2009). These studies relied on Underwater Visual Censuses (UVC) (strip transects) performed in several habitats and depths. For instance, in this area, Kulbicki et al. (2007) observed 305 species from the major families, compared to 73 species from the Branched coral habitat and 40 species from the Massive coral habitat. These numbers cannot be directly compared as the surface area, the habitat sampled, and the observation dates (two years in Kulbicki et al., 2007) and duration were strikingly different in UVC and in the present study. Also, there are differences in observations made from UVC and from underwater video, as illustrated in comparable areas in the New Caledonian lagoon (see Pelletier et al. (2011) for UVC strip transects versus diver-operated video transects and by Mallet et al. (2014) for UVC fixed points versus unbaited rotating videos).

Despite these differences, it is however interesting to note that the observed proportion of species numbers per family (for the major families observed in the area) in our study did not strikingly differ from those observed by Kulbicki et al. (2007) (Table 3). Therefore, the number of species per family observed at a very small spatial scale (~113 m^2) from the MICADO is roughly consistent with the one observed by UVC at a much larger spatial scale (~69000 m^2) in the same area. In other words, the sampling effort deployed over time in a reduced area by using MICADO qualitatively compensates to some extent the sampling effort deployed over space by UVC during a limited amount

of time. Some differences were still observed for small or cryptic species such as Pomacentridae, Apogonidae, Holocentridae and Blennidae. These findings are consistent with the results of Mallet et al. (2014) which found that small species (species having with a maximum size of 30 cm) and cryptic species are less well observed by this underwater video technique.

In a sense, the MICADO system shares some features with the VideoSolo system of Chabanet et al. (2012), as both aim at high-frequency sampling of reef fish. The main difference is that MICADO provides a 360° overview with an observation protocol designed to ensure a panoramic shot. MICADO observations are thus consistent with those obtained from the STAVIRO system aimed at spatial survey (Pelletier et al., 2012). The MICADO protocol presented here is intended for monitoring activities. However, the MICADO system may also be utilized for specific research studies requiring high-frequency sampling per day without external intervention.

Table 3. Total number of species observed for the major families on the Aboré reef MPA. Kulbicki et al. (2007) data were derived from 69 UVC transects performed over two years in different habitat and depth (69 000 m^2 sampled). MICADO data derived from to fixed stations performed at different time of days (2 x 113 m^2 sampled). sp: number of species ; prop: proportion (percentage) of the total number of species per family compared to all families observed (taking into account only families in the table).

	Kulbicki *et al.* 2007 (69 000 m^2)		**Branched coral habitat (116 m^2)**		**Massive coral habitat (116 m^2)**	
Family	**sp**	**prop**	**sp**	**prop**	**sp**	**prop**
Labridae	69	22.6	13	17.8	7	17.5
Pomacentridae	52	17	6	8.2	2	5
Chaetodontidae	28	9.2	13	17.8	6	15
Scaridae	23	7.5	8	11	9	22.5
Acanthuridae	22	7.2	8	11	7	17.5
Serranidae	20	6.6	6	8.2	2	5
Balistidae	14	4.6	2	2.7	1	2.5
Lethrinidae	14	4.6	5	6.8	2	5
Siganidae	10	3.3	3	4.1	0	0
Lutjanidae	10	3.3	2	2.7	2	5
Mullidae	10	3.3	5	6.8	1	2.5
Apogonidae	8	2.6	0	0	0	0
Holocentridae	8	2.6	0	0	0	0
Blennidae	8	2.6	0	0	0	0
Pomacanthidae	9	3	2	2.7	1	2.5
Total	305		73		40	

4.2. Observations depend on small-scale habitat

A significant finding of our study is that temporal patterns may vary between habitats, even on the internal slope of a barrier reef, since observed species and densities markedly differed between the Branched coral habitat and the Massive coral habitat. These results are in accordance with many others previous studies evidencing significant variations in abundance, richness and composition of species among habitats (among many others Ault and Johnson, 1998; Galzin, 1987a; Levin, 1993). For instance, on the same reef, Ferraris et al. (2005) showed that fine-scale habitat description explained fish assemblage variations significantly better than reef type. Most reef fishes require particular habitats for food supply or reproduction; they need to find refuges to avoid predators (Bell and Galzin, 1984; Brokovich et al., 2006; Chabanet et al., 1997; Lefèvre and Bellwood, 2011). In fragmented habitats such as coral reefs, these requirements explain the importance of fine-scale habitat structure for fish assemblages. The above studies documented the link between these requirements and fish presence and abundance.

The MICADO system used in the present study provides additional insight in that it is inconspicuous and can be left in place for a long time, enabling observation of fish assemblages at critical times such as sunset and sunrise, and over a time range that cannot be matched by diver-based techniques. Due to its small size and low weight, the MICADO system can be used in a variety of habitats from reef flat to sandy bottoms, and provide high-frequency undisturbed observations.

4.3. Technical issues

In this study, the functioning of the systems was mainly limited by battery and information storage capacity, and by fouling on the system housing. The energy constraint was solved by using more powerful batteries for the engine (10000mA, 1.5V batteries), and lately by modifications of the electronic resulting in lower energy requirement (work in progress in the AMBIO project, http://wwz.ifremer.fr/ncal/Outils-pour-la-gestion/Protocoles-d-observation/La-biodiversite-a-travers-la-video-sous-marine). Image storage is not an issue any longer, as the size of camera hard drives or SD cards regularly increases. Finally, the fouling

problem could be solved by using a wiper linked via a control cable to an additional housing enclosing a battery and a timer as used by Chabanet et al. (2012) or by using other antifouling devices.

4.4. Perspectives

Aside from the footages analyzed in this paper, a total of 48 other MICADO stations were deployed since 2008 in New Caledonia resulting in almost 900 footages being recorded over variable durations (from 10 min to 72 hrs), in a range of habitats (coral reef, sea grass, sandy bottom, etc.) and depths (5m – 15m). Data from these samples are currently being analyzed for several issues linked to temporal variations of fish assemblages (D. Mallet and D. Pelletier, unpublished data). A number of MICADO stations were also collected in the northwestern Mediterranean within coastal MPAs (D. Pelletier and G. Hervé, unpublished data).

The MICADO system can be used in many different ways depending on the study objective: duration, timing and frequency of footages may be adjusted from a user interface connected to the timer. Envisaged applications include: i) calibrating spatial data collected at different timings with respect to daily temporal variations; ii) investigate long-term temporal patterns of fish and macrofauna by placing several systems in various habitats; and iii) study high-frequency variations of reef fish populations according to environmental factors.

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3. Synthèse

Les systèmes vidéo rotatifs présentés dans ce chapitre sont innovants puisqu'à ce jour aucune autre technique utilisant de la vidéo pour observer la biodiversité marine côtière n'effectue de rotation (observation à 360°). Ils ont été développés dans l'optique d'obtenir des informations complémentaires à celles obtenues jusqu'à présent par les méthodes traditionnelles (essentiellement les UVC). En effet, de par sa forte réplication spatiale, le système STAVIRO permet d'obtenir de nombreuses informations dans de nombreux habitats en multipliant les points d'observation (jusqu'à 30 vidéos enregistrées par jour en utilisant 2 systèmes simultanément, une embarcation, un équipage composé de 2 personnes plus un pilote pendant 6h en mer). Le système MICADO permet quant à lui, d'obtenir des informations en multipliant les points d'échantillonnage dans le temps. Ce dernier permet d'obtenir jusqu'à 10 enregistrements vidéo par jour pendant plusieurs jours (le nombre de jours échantillonnés dépend de la durée des vidéos enregistrées à chaque observation).

En résumé, ces techniques permettent :

1) d'observer l'ichtyofaune marine et son habitat sans la présence de plongeur sous l'eau,
2) d'échantillonner toujours de la même façon avec un géoréférencement très précis, et donc d'envisager un recoupement rigoureux des données,
3) d'obtenir une forte couverture spatiale (STAVIRO) et temporelle (MICADO) avec la même technique basée sur une rotation de 60° toutes les 30 secondes,
4) d'obtenir de nombreuses images vidéo archivables et ré-analysables à des fins différentes.

De par leurs originalités techniques et méthodologiques, ces systèmes vidéo permettent donc de traiter des questions difficiles à étudier par les méthodes traditionnelles. Afin de mieux comprendre et connaître la complémentarité, les atouts et les limitations des différentes techniques, il m'a semblé important de comparée les informations obtenues à partir de ces systèmes vidéo rotatifs avec celles obtenues par les méthodes les plus utilisées actuellement (UVC).

CHAPITRE 4

Evaluation des observations obtenues à partir de systèmes vidéo rotatifs en haute définition

Les systèmes vidéo rotatifs présentés dans le chapitre précédant visent à évaluer la diversité de l'ichtyofaune et de ses habitats en effectuant des échantillonnages à partir d'enregistrements vidéo. La technique vidéo sous-marine rotative qu'elle soit programmable (MICADO) ou non (STAVIRO) fonctionne sur le même principe (rotation de 60° toutes les 30 secondes). Les images enregistrées, une fois analysées, permettent d'obtenir des informations sur les espèces (richesse spécifique, abondance, fréquence d'occurrence ainsi que des informations sur le comportement) et sur les habitats. Mais quelle est la représentativité de ces observations ? Ce chapitre vise à évaluer la représentativité des données obtenues à partir des images enregistrées par ces systèmes vidéo. Cette évaluation se fera en deux temps :

1) comparer des observations appariées obtenues en utilisant la technique STAVIRO (Pelletier et al., 2012) avec des UVC en point fixe rotatif (Bohnsack & Bannerot, 1986 ; Wantiez et al., 2006),

2) étudier la sensibilité aux observateurs des estimations issues de l'analyse des images

Les résultats issues de la comparaison STAVIRO / UVC ont fait l'objet d'un article publié dans le journal PLOS ONE en Janvier 2014 et présenté comme « l'article 4 » dans ce chapitre. Cet article permet d'obtenir des informations sur les atouts et les limites des systèmes d'observation vidéo rotatifs au regard d'une technique UVC régulièrement utilisée dans la zone d'étude. La confrontation des données obtenues par quatre personnes analysant indépendamment les mêmes vidéos permet, quant à elle, de quantifier les incertitudes associées à l'analyse des images enregistrées par les systèmes vidéo rotatifs[14].

[14] Il n'est pas prévu de publier cette analyse autrement que dans le cadre de cette thèse.

1. Article 4. Complémentarité entre STAVIRO et UVC pour évaluer la richesse spécifique, la fréquence et la densité des poissons sur les pentes récifales coralliennes

Résumé de l'article 4:

L'estimation de la diversité et de l'abondance des espèces de poissons est fondamentale pour comprendre la structure des communautés et la dynamique des récifs coralliens. Lors de la conception d'un protocole d'échantillonnage, une étape cruciale est le choix de la technique la plus appropriée, qui est un compromis entre les questions abordées, les moyens disponibles et la précision requise. L'objectif de cette étude est de comparer la capacité de deux techniques à observer les communautés de poissons récifales dans les mêmes emplacements et en utilisant deux méthodes de comptage en point fixe rotatif similaires: le recensement visuel en plongée (UVC) et la vidéo rotative (STAVIRO). Les observations UVC et STAVIRO ont été effectuées sur les mêmes 26 points de la pente d'un récif intermédiaire et de récifs barrières internes. Les systèmes STAVIRO étaient toujours déployés 30 min à 1 heure après les UVC et positionnés exactement aux mêmes emplacements. Notre étude montre que: (i) les observations des communautés de poissons par UVC et STAVIRO différaient significativement, (ii) la richesse spécifique et la densité des espèces de grande taille (espèces dont la taille maximum connue est supérieure à 30 cm) n'étaient pas significativement différentes entre les techniques, (iii) la diversité et la densité des espèces de petite taille (espèces dont la taille maximum connue est inférieure à 30 cm) étaient plus élevés avec les UVC; (iv) la densité des espèces pêchées était plus élevée avec les STAVIRO et (v) seuls les UVC ont détecté des différences significatives dans la structure des assemblages de poissons en fonction du type de récif à l'échelle spatiale étudiée. Nous recommandons d'utiliser les deux techniques en complémentarité afin d'échantillonner une vaste zone en un court laps de temps. Les UVC pourraient évaluer les poissons récifaux des habitats complexes ou au niveau des zones très peu profondes comme le platier récifal ; alors que les STAVIRO permettraient la réalisation d'un grand nombre d'observations axées sur les grandes espèces ainsi que sur les espèces fuyant le plongeur, en particulier dans les zones non couvertes par les UVC (contraintes de temps et de profondeur). Ce type de protocole permettrait d'augmenter considérablement la couverture spatiale et le niveau de réplication des études de suivi des poissons récifaux.

Article 4

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PLOS ONE

Complementarity of Rotating Video and Underwater Visual Census for Assessing Species Richness, Frequency and Density of Reef Fish on Coral Reef Slopes

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Abstract

Estimating diversity and abundance of fish species is fundamental for understanding community structure and dynamics of coral reefs. When designing a sampling protocol, one crucial step is the choice of the most suitable sampling technique which is a compromise between the questions addressed, the available means and the precision required. The objective of this study is to compare the ability to sample reef fish communities at the same locations using two techniques based on the same stationary point count method: one using Underwater Visual Census (UVC) and the other rotating video (STAVIRO). UVC and STAVIRO observations were carried out on the exact same 26 points on the reef slope of an intermediate reef and the associated inner barrier reefs. STAVIRO systems were always deployed 30 min to 1 hour after UVC and set exactly at the same place. Our study shows that; (i) fish community observations by UVC and STAVIRO differed significantly; (ii) species richness and density of large species were not significantly different between techniques; (iii) species richness and density of small species were higher for UVC; (iv) density of fished species was higher for STAVIRO and (v) only UVC detected significant differences in fish assemblage structure across reef type at the spatial scale studied. We recommend that the two techniques should be used in a complementary way to survey a large area within a short period of time. UVC may census reef fish within complex habitats or in very shallow areas such as reef flat whereas STAVIRO would enable carrying out a large number of stations focused on large and diver-averse species, particularly in the areas not covered by UVC due to time and depth constraints. This methodology would considerably increase the spatial coverage and replication level of fish monitoring surveys.

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Introduction

Coral reefs and their adjacent ecosystems (mangroves, seagrass and algae beds, unvegetated soft bottoms, etc.) have high diversity, comparable to tropical rainforests [1]. Ecosystem services delivered by coral reefs are extremely important (fisheries, aquaculture, medicines, building material, tourism, etc.). Coral reefs are also an important natural protection for the coast and, in some parts of the world, human populations are closely related to coral reefs for their cultures and food supply. Nevertheless, despite their overt usefulness it is estimated that coral reefs have lost 20% of their area world wide due to human activity, especially in highly urbanized coastal areas. Globally 75% of reefs are currently threatened and 60% are immediately under direct threat [2].

Estimating diversity and abundance of fish is fundamental for understanding community structure and dynamics of coral reefs. When designing a sampling protocol, one crucial step is the choice of the most suitable sampling technique which is a compromise between the questions addressed, the available means and the precision required [3,4,5]. Therefore it is essential to compare the capacity of each technique to estimate biodiversity and abundance in order to disentangle the differences due to the technique used from real spatial or temporal patterns.

In the marine environment, capture techniques are generally used to estimate the abundance of species and can be performed with explosives/ichtyocides [3,6], trapping [7,8], trawling/netting [9,10] and hook and line [11]. Direct observation techniques include Underwater Visual Census (UVC), video, acoustics [12,13] and photographic techniques [14,15]. Direct observation techniques have been used to estimate diversity and abundance of marine organisms. In coral reefs, UVCs are by far the most commonly used technique, and include strip transects [16], line transects [17], rapid visual census [18] or stationary point counts [19]. However, video techniques are increasingly used based on either mono [20] or stereo cameras [21] and are either unbaited [22] or baited [23] with systems either operated by divers [24], towed [25] or remote [26].

With respect to coral reefs, many studies compared UVC and video techniques (whatever the techniques used) but few examine the remote underwater video technique (RUV which is remote,

unbaited, not-towed and not operated by a diver). Francour et al. [27] and Burge et al. [28] compared RUV with the stationary point count UVC technique in the same area. They compared the species richness and abundance observed between the two techniques, but observations were not performed at the same locations or at concurrent times. They both showed that the overall species richness and abundance recorded were higher for UVC than for RUV. To our knowledge there is no study comparing observations obtained by RUV and UVC using the same sampling strategy that can be considered as paired (less than an hour difference between observations, same day and location).

The objective of the present study is to compare the ability of two techniques, currently used in New Caledonia, to sample reef fish communities: the UVC stationary point counts technique [19,29] and the rotating video technique (STAVIRO for French "STAtion Video ROtative) [30]. For both techniques, fish are counted over 360° at fixed points. This study was conducted during a regular annual survey of coral reefs within a marine protected area using the UVC stationary point counts technique. Comparisons were performed at the same locations, where both techniques were usable, on two types of reef (intermediate and inner barrier) in order to investigate the following hypotheses: (1) there will be significant differences between each technique in the resulting fish assemblage data; (2) a greater number of small species is sampled with UVC; (3) target species are better observed with STAVIRO.

Materials and Methods

Ethics Statement

No specific permits were required for the described field studies. During the field study, only the video systems and divers were immersed in water; no animals (including endangered or protected species) were collected or manipulated. Field work did not require any permission in the study area; it was accomplished with the approval of the Direction de l'Environnement of the South Province in charge of managing the study area. Our field work activites fully complied with New Caledonian environmental regulations (Code of the Environment, http://www.province-sud.nc/images/stories/pdf/environnement/Code.pdf).

Sampling Protocol

The study was conducted, from 5th to 16th October 2009, in the Southwest Lagoon of New Caledonia, South Pacific. The study area encompassed the MPA of Ouano (21°50′S, 165°45′E) and the nearby unprotected areas. This MPA was created in 2004 and rules have been enforced since 2007. Three lagoon-reef components (fringing reef, intermediate reef and barrier reef), seagrass beds and mangroves are present in this study area. UVC and STAVIRO observations were carried out on the exact same 26 points on the reef slope of the intermediate reef and the inner barrier reefs (Fig. 1). In order to avoid the known influence of divers on fish behavior [31,32,33], STAVIRO systems were always deployed 30 min to 1 hour after UVC. Once their counts were completed, divers left a weighted buoy to mark sampling sites, so that STAVIROs were set at the exact same place.

Data Collection

The STAVIRO technique used for this study is autonomous, remote, unbaited, and rotates by 60° each 30 sec. Videos are recorded without any external disturbance for around 10 min. at each site, with at least three complete rotations [30].

The UVC technique used is a modification of the point count technique [19]. All observed species are recorded by 2 stationary divers back to back, over a 10 minute period of time with in a virtual cylinder extending from surface to bottom. One diver sampled mobile species and the other sampled small species. A measuring tape was set on the sea bottom before performing the counts to validate distance estimates only for UVC.

Due to the protocol constraints of each technique, small species were identified in a virtual cylinder of 3 m radius for UVC [29,34] and 5 m radius for STAVIRO [30], and large species were identified within the visibility range limited to a maximum of 10 m for both techniques. A species was considered as "small" when the maximum species size was less than 30 cm (see Table S1 for the list of small and large species).

Species Identification

For both techniques, all individuals were identified at the highest possible taxanomic level. Species of the same genus, which differed by a characteristic that was difficult to distinguish on video images particularly beyond a few meters from the camera (blue eyes, small black dot, etc.), were aggregated only for the STAVIRO analyses as (i) *Stegastes gp* for *Stegastes fasciolatus*/*Stegastes nigricans*/*Stegastes punctatus*; (ii) *Ctenochaetus gp* for *Ctenochaetus striatus*/*Ctenochaetus binotatus*/*Ctenochaetus cyanocheilus*; (iii) *Acanthurus gp* for *Acanthurus blochii*/*Acanthurus dussumierii* and (iv) *Kyphosus gp* for *Kyphosus vaigiensis*/*Kyphosus cinarescens*/*Kyphosus sydneyanus*. These species were not aggregated for the UVC technique as divers were fully confident about their identifications.

Images Analysis

A single observer analyzed all videos using the procedure explained in Pelletier et al. [30]. Individuals were counted per sector and then summed over the six sectors of a rotation (360°). Thus, for each station and species, three counts were obtained, each corresponding to one of the three rotations analyzed. Then, abundance per species at a given station was calculated as the maximum count taken over the three rotations. To minimize potential double counting from one sector to another, particular attention was given to the direction of fish movement with respect to camera rotation. For the STAVIRO technique, distances were estimated with previously-taken footage using a database of screenshots of plastic fish silhouettes of several sizes (0.2 m, 0.4 m, 0.6 m, 0.8 m and 1 m) and colors (bright and dark ones), taken at several distances from the same camera (2 m, 5 m, 7 m and 10 m). This method has been proven to be helpful to estimate distances on footage, even if the screenshots used were not taken in the study area [35].

Statistical Analysis

We first compared the species assemblages observed by each technique using the Sørensen Index (S) where $S = 2a/(2a+b+c)$ with a = number of species observed by both methods; b = number of species not observed with STAVIRO; and c = number of species not observed with UVC [36]. Pearson correlation tests were then used to compare species richness (SR) per station (number of species observed), fish density (number of individual per square meter), number of genus and families observed by each technique per station. The factor "species size" referred to maximum species size and was qualified as "large" or "small" in the following parts (see Table S1 for details). The influence of species size on observed species richness per station and density was analysed using 2-way repeated measures ANOVA (same site sampled by the 2 techniques) with factors species size (small or large) and technique (UVC and STAVIRO) as fixed factors. The homoscedasticity of variances was obtained on log transformed data (Levene's test for homogeneity of variance, $p>0.05$; [37]).

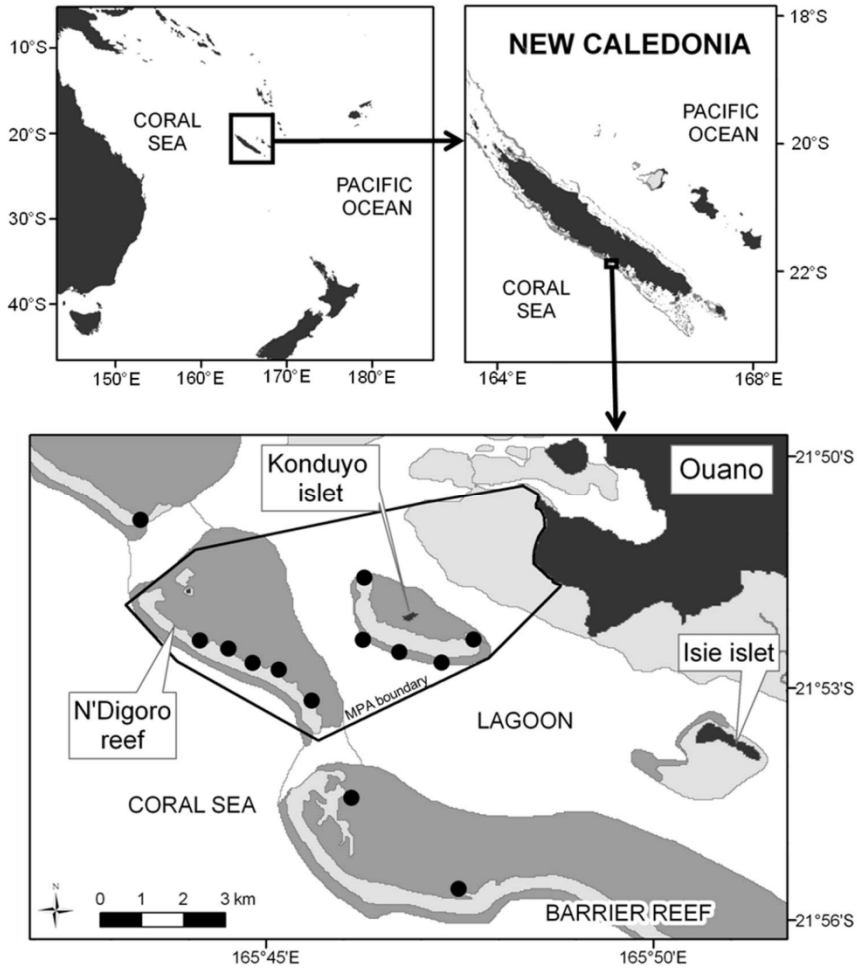

Figure 1. Study area. Each black dot contains 2 censused points (one on the top of the reef slope and one on the bottom of the reef slope).
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When interactions between techniques and species size were significant, differences between techniques according to species-size were further tested using pairwise comparison tests performed at $\alpha = 0.05$.

Paired Student t-tests were then used to compare observations between techniques (SR per station and density depending on size of species observed) for commonly seen families (i.e. encountered in more than 50% of stations for both techniques).

We assessed the ability of each technique to observe target species by analysing the effect of a species being a fishery target (target or non-target, see Table S2 for the list of target species in New Caledonia) on observed species richness and density. This was achieved by 2-way repeated measures ANOVA with factors fishery target (target or non-target) and technique (UVC and STAVIRO) as fixed factors. The homoscedasticity of variances was obtained on square root transformed data (sqrt(x+1)) for species richness and on log transformed data (log(x+0.1) for the density (Levene's test for homogeneity of variance, $p>0.05$; [37]). When interactions between technique and fishery target were significant, differences between techniques according to fishery target were further tested from pairwise comparison tests between group levels performed at $\alpha = 0.05$.

In the study area, assemblage structure may differ according to reef habitat and environmental factors. We investigated whether the techniques detected similar assemblage structures using a Factorial Correspondence Analysis (FCA; [38]) performed on densities per species and station. A Hierarchical Ascending Classification (HAC; [37]) was performed on the first seven axes of the FCA. These extracted more than 50% of total inertia (52% for UVC and 54.5% for STAVIRO). The HAC used the Euclidean distance and the aggregation method of Ward [38]. For each of the assemblages defined, a species was deemed characteristic of the assemblage when its relative contribution to the first seven axes of the correspondence analysis was higher than 30%.

Results

Fish Identification and Detection

With the STAVIRO technique, 1941 individuals corresponding to 118 species, 63 genera and 30 families, were counted (Table 1).

121 (i.e. 6.2%) individuals were identified only at the genus level and 129 (i.e. 6.6%) only at the family level. For the vast majority of these (119 Scaridae, 48 Pomacentridae, 37 Caesionidae, 13 Acanthuridae, 10 Chaetodontidae, 8 Lethrinidae, 5 Labridae, 3 Serranidae, 3 Sphyraenidae, 2 Mullidae, 1 Blenniidae and 1 Haemulidae), the fish were either too far away, too small or swam through the field of the camera too quickly to be identified at the species level.

With the UVC technique, 2124 individuals, corresponding to 164 species, 73 genera and 28 families were counted (Table 1). 167 (i.e. 7.9%) individuals were identified only at genus level and none were identified only at family level. Among the 167 individuals only identified at genus level, 59 were Scaridae (mainly juveniles), 40 Acanthuridae, 28 Lethrinidae, 20 Siganidae, 18 Holocentridae, 1 Labridae and 1 Serranidae. Individuals were either too far away or hidden in holes in the reef substrate to be identified at the species level.

In all, 194 distinct species were observed with either technique, 88 (i.e. 45.8%) being observed with both techniques, 76 (i.e. 39.6%) only with UVC and 28 (i.e. 14.6%) only with STAVIRO. Among the 76 species only observed with the UVC technique, 14 were cryptic (Apogonidae, Blenniidae, Cirrhitidae and some Chaetodontidae and Pomacentridae), 20 species were too small to be identified with the video technique (15 species of Pomacentridae and 5 species of Labridae), while others were only seen with the UVC technique due to sampling variability as

Table 1. Overall abundance, species and genus number per family observed by each technique.

	STAVIRO				UVC			
Numbers observed	**Freq**	**ind**	**sp**	**ge**	**Freq**	**ind**	**sp**	**ge**
Acanthuridae	**96.2**	**175**	**10**	**4**	**96.2**	**189**	**13**	**4**
Apogonidae	0	0	0	0	11.5	5	4	2
Aulostomidae	7.7	2	1	1	0	0	0	0
Balistidae	**57.7**	**29**	**3**	**3**	**65.4**	**32**	**3**	**3**
Blenniidae	7.7	2	1	1	30.8	20	5	4
Caesionidae	23.1	98	2	2	19.2	141	2	1
Carangidae	3.8	1	1	1	3.8	1	1	1
Carcharhinidae	7.7	2	1	1	0	0	0	0
Chaetodontidae	**88.5**	**84**	**15**	**3**	**100**	**115**	**19**	**3**
Cirrhitidae	0	0	0	0	15.4	5	2	2
Diodontidae	7.7	2	2	1	0	0	0	0
Fistulariidae	3.8	1	1	1	0	0	0	0
Gobiidae	3.8	1	1	1	15.4	5	2	2
Haemulidae	3.8	1	0	0	3.8	3	2	2
Holocentridae	0	0	0	0	3.8	18	0	1
Kyphosidae	3.8	14	1	1	0	0	0	0
Labridae	**100**	**131**	**20**	**11**	**100**	**245**	**30**	**15**
Lethrinidae	46.2	62	5	3	30.8	65	3	4
Lutjanidae	15.4	58	3	2	23.1	99	4	1
Monacanthidae	7.7	3	2	2	11.5	5	1	1
Mullidae	**65.4**	**78**	**5**	**1**	**73.1**	**53**	**6**	**1**
Nemipteridae	**76.9**	**154**	**2**	**1**	**80.8**	**130**	**3**	**1**
Ostraciidae	3.8	1	1	1	3.8	1	1	1
Pinguipedidae	15.4	4	2	1	38.5	13	4	1
Pomacanthidae	**34.6**	**15**	**2**	**1**	**57.7**	**29**	**4**	**2**
Pomacentridae	**88.5**	**656**	**15**	**9**	**96.2**	**604**	**29**	**10**
Priacanthidae	7.7	12	1	1	11.5	5	1	1
Scaridae	**88.5**	**286**	**13**	**3**	**76.9**	**132**	**12**	**3**
Serranidae	**19.2**	**28**	**3**	**3**	**53.8**	**39**	**5**	**3**
Siganidae	23.1	35	3	1	38.5	61	5	1
Sphyraenidae	3.8	3	0	1	3.8	100	1	1
Stegostomatidae	3.8	1	1	1	0	0	0	0
Synodontidae	0	0	0	0	3.8	2	1	1
Tetraodontidae	7.7	2	1	1	19.2	7	1	1
Total		1941	118	63		2124	164	73

Freq: Frequency (in %); ind: number of individuals; sp: number of species and ge: number of genera. Families with frequency higher than 50% are shown in bold.
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observations were not performed simultaneously, such as some Labridae, Lethrinidae and Siganidae. Some species could be identified with the UVC technique but not with STAVIRO although they were recorded with the video technique. This was probably the case, for instance, for many Scaridae, Pomacentridae and Caesionidae identified with the STAVIRO technique at species ("sp.") and genus ("ge.") levels only. For instance, 16 species of Pomacentridae were identified with the UVC technique and not with the STAVIRO technique, while 48 individuals of Pomacentridae were recorded with STAVIRO but not identified at species level during the image analyses.

Among the 28 species only recorded with STAVIRO, 6 were shy and may have avoided divers, such as some *Lethrinus* spp. The other species only observed with the STAVIRO technique were mostly due to sampling variability such as some *Diodon* spp., *Scarus* spp., *Siganus* spp. and Labridae.

The Sørensen index computed on paired stations ranged from 0.1 to 0.53, with mean 0.37 and Standard Error (SE) 0.1, indicating that species sampled with each technique were different. At each station, roughly one third of the species was observed with both techniques, one third was only observed with UVC and one third was only observed with STAVIRO.

Species Numbers and Overall Density

Correlation between observations with each technique at the station level was low but significant for species richness ($R = 0.54$, p-value <0.01), the number of genus and families ($R = 0.64$ and 0.73 respectively, p-values <0.01) and fish densities ($R = 0.54$, p-value <0.01).

The two-way ANOVAs with factors technique and species size displayed a significant interaction between factors for species richness ($p<0.01$) (Fig. 2 top), with more small species recorded with UVC (mean $\pm$ SE $= 14.58 \pm 0.91$) than with STAVIRO (mean $\pm$ SE $= 7.46 \pm 0.47$) (pairwise comparisons test, $p<0.01$). On the other hand, the number of large species was not significantly different between techniques (pairwise comparisons test, $p>0.05$). However, on average a little more large species were observed with STAVIRO (mean $\pm$ SE $= 11.50 \pm 1.14$) than with UVC (mean $\pm$ SE $= 10.23 \pm 0.73$).

Regarding density, interaction between technique and species size was significant (2-way ANOVA, $p<0.01$) (Fig. 2 bottom). With the UVC technique more individuals were recorded from small species (mean $\pm$ SE $= 7.14 \pm 0.97$ ind/10 m^2) than with the STAVIRO technique (mean $\pm$ SE $= 2.13 \pm 0.50$ ind/10 m^2) (pairwise comparisons test, $p<0.01$). In contrast, the number of individuals from large species did not significantly differ between techniques (pairwise comparisons test, p-value >0.05), although on average more individuals from large species were identified with STAVIRO (mean $\pm$ SE $= 1.31 \pm 0.25$ ind/10 m^2) than with UVC (mean $\pm$ SE $= 0.82 \pm 0.12$ ind/10 m^2).

Most Frequent Families

Species richness per station did not differ significantly between techniques for small Serranidae, Nemipteridae, Mullidae, Chaetodontidae, large Pomacanthidae, large Labridae, Scaridae, Acanthuridae and Balistidae (paired t.test, $p>0.05$) (Fig. 3 left). For large Serranidae, Pomacentridae and small Labridae, significantly more species per station were observed with the UVC technique (paired t.test, $p<0.05$) (Table 2). Densities were not significantly different between techniques for small Serranidae, Nemipteridae, Mullidae, large Pomacanthidae, large Labridae and Balistidae (paired t.test, $p>0.05$) (Fig. 3 right). Chaetodontidae, small Pomacanthidae, Pomacentridae and small Labridae densities were significantly higher for UVC (Table 3). In contrast, densities of Scaridae and Acanthuridae (which comprise only large species) were significantly greater for STAVIRO (paired t.test, $p<0.05$) (Table 3).

Observation of Target Species

The two-way ANOVAs with factors technique and fishery target displayed a significant interaction for species richness ($p<0.01$), indicating that more non-target species were recorded with the UVC technique (mean $\pm$ SE $= 20.69 \pm 1.20$) than with the STAVIRO technique (mean $\pm$ SE $= 14.27 \pm 0.94$) (pairwise comparisons test, $p<0.01$) (Fig. 4 top). The number of target species observed per station did not significantly differ between techniques (STAVIRO: mean $\pm$ SE $= 4.69 \pm 0.66$, and UVC mean $\pm$ SE $= 4.12 \pm 0.52$) (pairwise comparisons test, $p>0.05$).

Regarding densities, the two-way ANOVA led to a significant interaction between factors ($p<0.01$), indicating that more individuals from non-target species were recorded with the UVC technique (mean $\pm$ SE $= 7.71 \pm 0.97$ ind/10 m^2) than with the STAVIRO technique (mean $\pm$ SE $= 2.86 \pm 0.51$ ind/10 m^2) (pairwise comparisons test, $p<0.01$) (Fig. 4 bottom). In contrast, more individuals from target species were recorded with the STAVIRO technique (mean $\pm$ SE $= 0.57 \pm 0.11$ ind/10 m^2) than with the UVC technique (mean $\pm$ SE $= 0.26 \pm 0.04$ ind/10 m^2) (pairwise comparisonstest, $p<0.05$).

The fished species observed with each technique were all large species and indeed not the same. Only 17 species were observed with both UVC and STAVIRO: 3 species of Acanthuridae, 1 Labridae, 1 Mullidae, 1 Priacanthuridae, 9 Scaridae, 1 Serranidae and 1 Siganidae. Target species only observed with the STAVIRO technique (10 species) were composed of 1 species of Acanthuridae, 1 Carangidae, 1 Kyphosidae, 4 Lethrinidae and 3 Scaridae, and target species only observed with the UVC technique (15 species) were composed of 4 species of Acanthuridae, 1 Carangidae, 1 Haemulidae, 3 Scaridae, 2 Serranidae and 4 Siganidae.

Do the Techniques see Similar Assemblages?

For the UVC technique, three assemblages could be identified from the FCA and HAC: one intermediate reef community and two barrier reef communities (Fig. 5 left). The intermediate reef community (group I) was characterized by fish species associated with lagoonal coral reefs. These species were all small, mostly sedentary (1 mobile and 3 sedentary species) and only observed with UVC (see Table S3 for the list of species characterizing each group). The first barrier reef community (group B1) was characterized by species usually found at the back of the inner barrier reef with rock, rubble and algae. These species were (1) as much sedentary as mobile (10 sedentary and 8 mobile species), (2) equally large and small (11 large and 8 small species), and (3) 9 species were observed with both techniques and 9 other species were only observed with UVC technique. The second barrier reef community (group B2) was characterized by fish species associated with branching *Acropora*. These species were (1) more sedentary than mobile (7 sedentary and 3 mobile species), (2) equally large and small species (5 large and 5 small species), and (3) 6 species were observed with both techniques and 4 other species were only observed with UVC technique. Four stations from the barrier reef were included in the group I which means that the assemblages observed on these stations were closer to the intermediate reef assemblage than the inner barrier reef ones.

With the STAVIRO technique no similar organization was highlighted at this spatial scale (Fig. 5 right). As for UVC, the analysis also shows the existence of three different groups with 54.5% of inertia (compared to 52% of inertia for UVC) and one

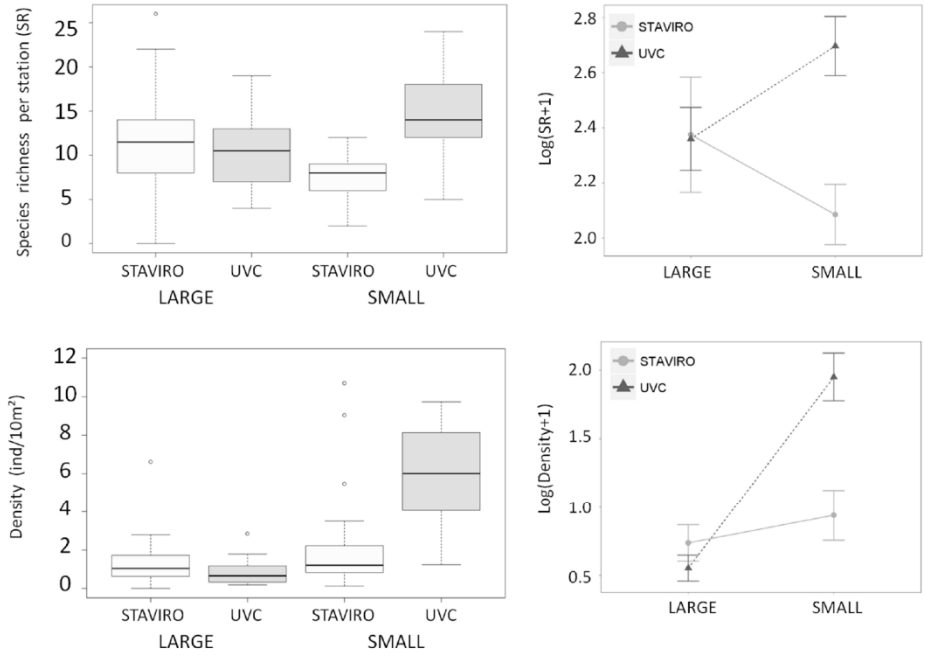

Figure 2. Species richness and density (number of individuals per 10 m^2) observed per station according to technique and species size. Three outlying values were not reported for better readability of the density plot: 14.85, 17.33 and 23.52 ind/10 m^2 for small UVC. On the right of each boxplot, interaction plots on log-transformed averages are shown.
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single particular station (B.3: station from the inner barrier reef). Compared to UVC, these groups have no spatial organization that can be related to an ecological pattern in the area, both spatially and geomorphologically. Each group contains a mix of intermediate (from 33% to 43%) and barrier (from 57% to 67%) reefs.

Discussion

Many studies have compared UVC and video techniques, and in particular strip transect UVC and baited underwater video system (BRUV) [28,39–45], except Lowry et al. [46] who used the stationary point count technique for UVC. Other studies

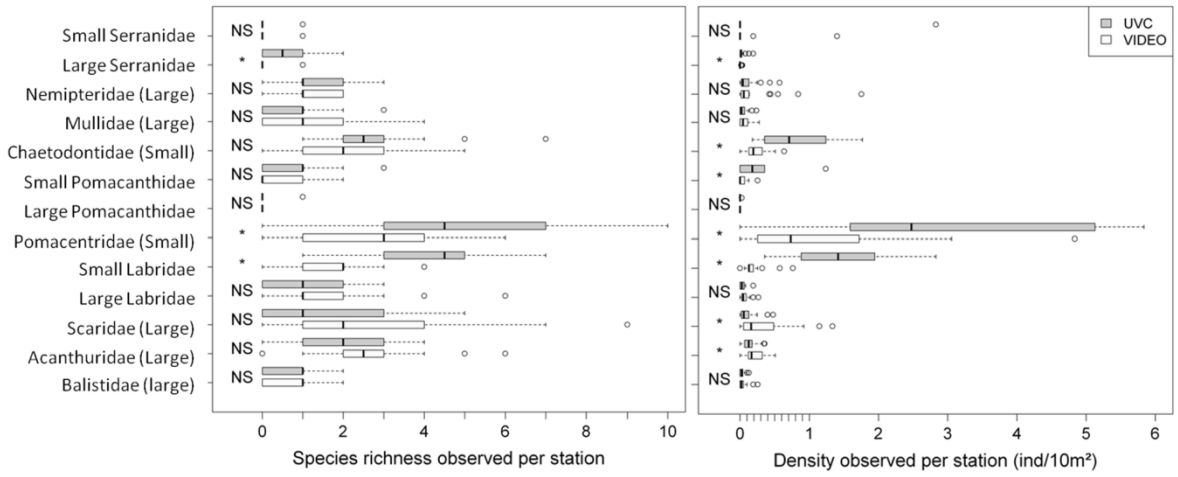

Figure 3. Species richness and density observed per station for the 10 main families observed, distinguishing the size class of the species observed as small or large (see previous paragraph). A size class in brackets indicates that all species observed in the family are characterized by the same size group. The result of the Student t-test on the difference between techniques is reported on the left side of the plot. NS: $p>0.05$; *: $p<0.05$.
doi:10.1371/journal.pone.0084344.g003

Table 2. Mean number of species per station (±SE) recorded for main families observed with UVC and STAVIRO.

	STAVIRO	UVC
Serranidae (Small)	0.04±0.06	0.04±0.06
Serranidae (Large)	**0.12±0.10**	**0.58±0.20**
Nemipteridae (Large)	1.12±0.24	1.31±0.27
Mullidae (large)	1.31±0.39	1.04±0.28
Chaetodontidae(Small)	1.96±0.43	2.92±0.53
Pomacanthidae (Small)	0.42±0.20	0.73±0.25
Pomacanthidae (Large)	0.00±0.00	0.04±0.06
Pomacentridae (Small)	**2.81±0.57**	**4.89±0.88**
Labridae (Small)	**1.85±0.28**	**4.19±0.53**
Labridae (Large)	1.58±0.43	1.19±0.53
Scaridae (Large)	2.42±0.72	1.77±0.52
Acanthuridae (Large)	2.65±0.45	1.96±0.34
Balistidae (Large)	0.69±0.22	0.73±0.19

Significant differences between techniques according to Student t-test are in bold ($p<0.05$).

doi:10.1371/journal.pone.0084344.t002

Table 3. Mean density (±SE) (ind/m^2) recorded for main families observed with UVC and STAVIRO.

	STAVIRO	UVC
Serranidae (Small)	0.06±0.09	0.11±0.18
Serranidae (Large)	**0.01±0.01**	**0.03±0.01**
Nemipteridae (Large)	0.19±0.12	0.10±0.05
Mullidae (large)	0.07±0.03	0.04±0.02
Chaetodontidae(Small)	**0.21±0.05**	**0.78±0.16**
Pomacanthidae (Small)	**0.04±0.02**	**0.19±0.08**
Pomacanthidae (Large)	0.00±0.00	0.01±0.01
Pomacentridae (Small)	**1.61±0.75**	**4.11±1.49**
Labridae (Small)	**0.19±0.05**	**1.41±0.21**
Labridae (Large)	0.06±0.02	0.04±0.01
Scaridae (Large)	**0.33±0.12**	**0.10±0.04**
Acanthuridae (Large)	**0.20±0.04**	**0.15±0.03**
Balistidae (Large)	0.04±0.02	0.03±0.01

Significant differences between techniques according to Student t-test are in bold ($p<0.05$).

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compared strip transects or point counts UVC with (i) remote underwater video system (RUV) (stereo or mono) [27,28,47–53], (ii) towed video system (TOWV) [43,54,55], and (iii) diver-operated video (DOV) [56–63].

Many previous studies (whatever the technique used) did not conduct sampling at the same time and at the same place. If the comparison is focused on isolating the influence of diver on observation, apart from DOV, it is not possible to simultaneous conduct UVC and video activities. Therefore, most comparisons were not paired in space (e.g. [44] and [53]), or in time (e.g. Colton and Swearer [45] had from 1 to 39 days between BRUV and UVC censuses), and relied on different observation durations (e.g. [41] and [62]), or different observed surface areas (e.g. [54]). The most common finding of these published comparisons between the different observational techniques is that no single technique provides representative information on all fish species [39,55,64]. In the present study, observations were both paired in time (one hour lag between the UVC and the STAVIRO), space and duration.

Techniques and Species Identification

From the data available (26 paired stations on the reef slope), about 30% more species were identified with UVC than with STAVIRO (164 vs. 118). More than half of the 76 species solely identified with UVC were small and sedentary (46 species), while the rest was large and mobile. In contrast, 24 out of the 28 species only identified with STAVIRO were large and mobile. At the station scale, thespecies assemblages recorded with STAVIRO and UVC also differed, as shown by relatively low correlations and Sørensen Indices. Thus, the two techniques used together allowed to observe a combined species richness of 194 species (compared to 164 or 118 for each technique alone), and with only 45% of speciesrecorded with both techniques (88 out of 194 species).

Difference in species identification can be partially explained by the techniques used. Tillett et al. [65] highlighted that, irrespective of the technique used, species identification is not always possible, and this is especially true when fish morphologies are similar. This effect is amplified when using autonomous underwater video systems since a close examination of details that are essential to discriminate some species with confidence is constrained by video quality and zooming performance during image analysis. In contrast, divers have the possibility to take a very close look at individuals difficult to identify. This could explain why many more small species were identified with UVC than with STAVIRO. Moreover, Francour et al. [27] observed that underwater perception by a diver was better than the one recorded by a video camera. Having a better 3D-vision underwater could also explain the difference in species identification between the two techniques as well as the large number of individuals identified only at genus level from video (2D-vision) [66].

Differences between the two techniques may also be explained by protocol constraints. The present study was coupled with a regular UVC survey. STAVIRO stations had to be implemented after UVC at prescribed locations of the routine monitoring. The STAVIRO technique has therefore not been used to its optimum capacity (choice of station location and with the usual level of spatial replication). In a comparative study of UVC and DOV transects, Pelletier et al. [62] found no significant effect of carrying out DOV before or after UVC, but both techniques were diver-based. In the present comparison, only one technique requires a diver. The effect of conducting UVC before STAVIRO was not formally tested, but did not seem to affect the STAVIRO sampling as we did not observe any correlations between observations. Thus, 1 hr time lag seemed a reasonable compromise to avoid the confounding effect of divers. However, we suggest that future comparison studies should attempt to randomize the order of the methods to formally test this possible bias.

Many studies have examined the response of fishes to diver presence, but to our knowledge none investigated the effect of an unbaited video system upon fish behavior. The presence of a video system underwater could also influence fish behavior. However, fish are not commonly exposed to this type of intrusion compared to divers who are increasingly present in the coastal environment [67]. Therefore, even if the system can influence the behavior of some fishes, this influence should be less intrusive than divers and should be the same in all habitats. Independently of fish behavior, observer effects have been studied many times including diver

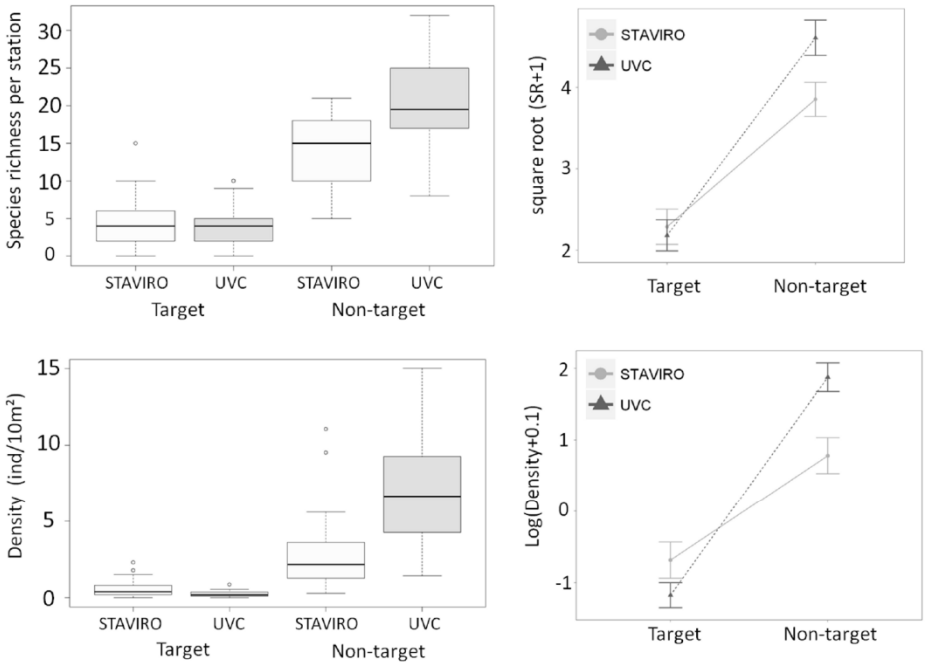

Figure 4. Species richness and density (number of individuals per 10 m^2) observed per station according to technique and to fishery target. Two outlying values were not reported for better readability of the density plot: 17.48 and 23.84 ind/10 m^2 for non-target UVC. On the right of each boxplot, interaction plots of log- and x^2-transformed averages are shown.
doi:10.1371/journal.pone.0084344.g004

swim speed and search intensity [68], observer experience, and training level [69,70]. For STAVIRO, the only possible observer effect is during the images analysis. Compared to UVC, video techniques have the advantage of generating images visible by different experts, at different times and support the comparison between observers for the same videos.

Differences in Observations According to Species Size and Fishery Target

With regard to species size, UVC technique appeared more effective to census small species, both in terms of species numbers and densities. Regarding large species, the 2 techniques did not record the same species (43 species in common, 30 species only seen with UVC and 24 species only seen with STAVIRO) but appeared similarly effective, in terms of number of species and individuals sampled, as our results show no significant difference between techniques for the species richness per station and density observed for large species. The abilities of each technique to census small or large species can be associated with the ability of each technique to see underwater. The better perception of divers underwater can explain their enhanced ability to observe, count and identify small species. Our results are consistent with Bozec et al. [71] who studied the detection distance of reef fish from a large number of UVC transects performed in New Caledonia and French Polynesia. They showed that fish body size is the primary factor in determining fish detection. Individuals smaller than 30 cm are not well observed at distances larger than 4 m and larger fish are better observed beyond 3 m due to diver avoidance (large fish tending to be diver-averse). In our study, all individuals from the small species class were smaller than 30 cm (see Material and Methods) and therefore more difficult to observe as distance increases. Small species were not censused over the same area by the 2 techniques (3 m radius for UVC and 5 m radius for STAVIRO). Therefore, if species were detected with both techniques within their respective observation radius, density estimates should be comparable and species richness should be higher for STAVIRO. But, small species being less well detected at large distances, video density and species richness estimates of small species were smaller. Indeed, the STAVIRO protocol yielded a list of 26 families comprising mostly large species (including all fished species), Chaetodontidae, emblematic fish species, turtles, and Dugongidae (see [30] for details). In the present analysis, to produce a complete comparison between the two techniques, images were analyzed taking into account all species, and therefore, including small species within a radius of 5 meters. Our results show that image resolution does not allow the observation of all small species at such distance. For a better observation of small species, e.g. in specific ecological studies, the video systems need to be positioned closer to the species (e.g. [72]), with a reduced radius of observation.

With regard to fishery target species, UVC was found to observe more species and individuals from non-target species than STAVIRO. This outcome is consistent with results on species size, as many small species are not targeted by fishery. In contrast, more individuals from target species were observed with STAVIRO than with UVC technique. This could be due to the fact that some species may avoid divers' presence [40,73]. Note however that the target species observed by each technique were not the same, with only one third of species observed by both techniques over all stations. The low density of target species observed (STAVIRO mean = 0.58 ind/10 m^2 and UVC mean = 0.26 ind/10 m^2) could be explained by past fishing

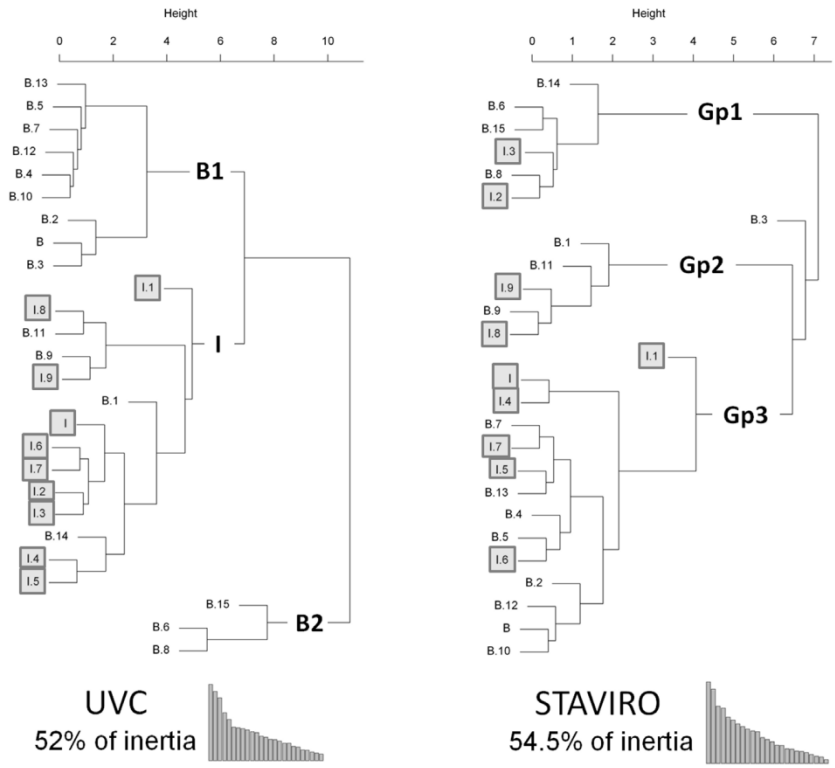

Figure 5. Dendrogram of the stations. B: Barrier reef and I: Intermediate reef. Clusters are represented on the graph in bold: B1 = 1st cluster on the barrier reef; I = cluster on the intermediate reef; B2 = 2nd cluster on the barrier reef; Gp1, 2 and 3 = clusters not explained by habitat characteristics. Intermediate reef stations are in grey and barrier reef stations are in white.
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pressures in the area even if the study was conducted in an MPA. STAVIRO also censused more target species inhabiting lagoon bottoms (Lethrinidae). Januchowski-Hartley et al. [33] showed that spear fishing pressure influences the behavior of targeted reef fish and that these behavioral changes varied according to family.

Our results are consistent with previous studies that showed overall greater species richness and abundance observed by UVC compared to video technique ([27] for RUV vs UVC; [60,62] for DOV vs UVC; [42,44–46] for BRUV vs UVC). Our study details which species are better detected on lagoon reef slopes and explain differences by species size and fishery target. In addition, since observations are truly paired, other sources of variability are minimized.

Consequences at Family Level

As a consequence of the above results, UVC appeared more effective to census families composed of small species, such as Pomacentridae, Pomacanthidae, Chaetodontidae and also small species of Labridae. Five out of the eight families composed of large species (Nemipteridae, Mullidae, Pomacanthidae, Labridae and Balistidae) were not detected in a significantly different way by the two techniques. However, a higher SR and greater density of large Serranidae species was observed with UVC. This could be explained by the fact that most individuals observed were smaller than 20 cm, and thus difficult to identify and count from videos.

Morevover, the study area has previously been subject to high fishing pressure, and large individuals are still quite scarce, compared to other MPAs in New Caledonia, and the densities observed for Serranidae were very low with both techniques (mean STAVIRO = 0.01 ind/10 m^2 and mean UVC = 0.03 ind/10 m^2).

In contrast, significantly greater densities of Scaridae and Acanthuridae were recorded with STAVIRO than with UVC (no significant difference in SR for these families). The greater densities of Acanthuiridae and Scaridae are mostly due to a higher abundance of *Zebrasoma* spp. and *Ctenochaetus* spp. not targeted in New Caledonia, and of juveniles of Scaridae.

Differences in Detecting Community Structures

Three species assemblages were identified from UVC data: an intermediate reef assemblage characterized by lagoonal species, and two inner barrier reef assemblages characterized by species associated with live coral for the first one, and with rock, rubble and algal cover for the second one. These results were in accordance with two other UVC-based studies in the same region. First, Sarramégna [74] showed that substrate characteristics were the primary factor explaining fish assemblage structure, followed by the inshore-offshore gradient and finally by protection status. Second, Wantiez et al. [75] found that assemblages were organized along a nearshore-offshore gradient, but with a first explanatory factor being the protection status. In contrast, fish assemblages could not be discriminated according to reef type with the STAVIRO data. This is because in the 26 stations sampled in this study, the species that characterize the assemblage of the intermediate reef from UVC data were all small species, which as

shown previously were not as well detected with the STAVIRO protocol used in the present comparative study. However, as explained above, the STAVIRO technique was not implemented with the usual protocol involving a high level of spatial replication. Studies using this regular STAVIRO protocol for monitoring fish assemblages are currently being conducted by some of the authors.

Implications of Techniques

Even though both techniques used the same protocol, they may have different influences on the observations. Firstly, distances were not evaluated in a similar way. For STAVIRO, distances on footage were estimated using a database of screenshots of plastic fish silhouettes of different sizes, colours and distances from the camera. They were thus not measured in the field. On the other hand, for UVC a measuring tape set on the sea bottom before performing the counts was used to validate size and distance estimates. Therefore, the distances estimated from image analysis were less precise than those estimated by UVC. With regard to small species, differences between observations were more likely to be due to the observation radius used by each technique (3 m for UVC and 5 m for STAVIRO). For large species, no significant differences in densities were observed within the maximum range of observation (maximum visibility limited to 10 m) suggesting that differences in the surface area sampled were not significant.

Secondly, even if a particular attention was given to the direction of fish movement with respect to camera orientation, there is a risk of double counting inherent to video techniques, which is greatly reduced with UVC. In the present study, the total number of individuals observed (all levels of species identification confounded) over the 26 stations only slightly differed between techniques, since 2124 individuals were observed from STAVIRO versus 1941 ind. from UVC, i.e. a relative difference of 9% (Table 1). Considering in addition that small species were counted on a larger radius from STAVIRO than from UVC, we would expect a much larger abundance observed from STAVIRO under the assumption of repeated double counting. This was obviously not the case according to our results.

Thirdly, for the video technique, additional 35 hours were necessary to analyze the 26 stations for all species and individuals present on the images within a maximum radius of 10 m. This additional time required for image analysis should be taken into account when designing a study of an area as it is different according to the diversity and habitat complexity, and depends on the person analyzing footage. This time can also be reduced by taking into account a predefined list of species depending on the aim of the study. The STAVIRO protocol for spatial survey is generally based on a subset of species (26 families) and cost-efficiency issues of the technique were discussed in Pelletier et al. [30].

Finally, we did not carry out any comparison of fish size estimates between UVC and STAVIRO since exact sizes cannot be estimated with the STAVIRO technique (single camera). Size estimation was not central in the development of the STAVIRO system which gave priority to light portable systems aimed at highly replicated designs. For the purpose of monitoring major changes in fish assemblages, abundances per size class (small, medium and large) were thus preferred. Estimating individual size can be achieved from stereo-video systems [21] or from UVC to provide more precise biomass estimates based on known length-weight relationships, e.g. [34].

Conclusion

Our study shows that from the 26 paired stations sampled on the reef slope; (i) UVC and STAVIRO did not detect the same fish assemblages; (ii) they did not significantly differ for large species (in both species richness and density); (iii) UVC detected more small species (for both species richness and density); (iv) STAVIRO detected a higher density of target species; and (v) only UVC detected differences in fish assemblages according to reef type. Main results of the present study were summarized in table 4.

In the present study, the location of the observations was dictated by the UVC sampling design. During field work, a large number of unpaired stations were also deployed in other habitats: i) fringing reefs and sea grass beds (UVC and STAVIRO); ii) reef flats (UVC); and other soft bottoms (STAVIRO). Indeed, the two techniques may be coupled to survey a much larger area within a short period of time. UVC may focus on reef fishes within complex habitats, and particularly where live coral cover is high (e.g. reef slope), or in very shallow areas such as reef flats, or when visibility is low for STAVIRO but sufficient for UVC. Over the same period of time, STAVIRO would enable carrying out a large number of stations focused on large and diver-averse species. In particular, back reef areas, soft bottoms, sea grass beds, and more generally the areas not covered by UVC due to time and depth constraints could then be surveyed. This survey methodology would considerably increase the spatial coverage and replication level of fish monitoring activities when biomass and size estimation is not central to assessment.

Table 4. Synthesis of results obtained in the present study: comparison of observations performed on 26 paired stations on reef slopes by UVC and STAVIRO.

Metrics	Results
Overall fish population	SR and density : UVC>STAVIRO
Small species	SR and density : UVC>STAVIRO
Large species	SR and density : UVC = STAVIRO
Non-target species	SR and density: UVC>STAVIRO
Target species	SR : UVC = STAVIRO; density : STAVIRO>UVC
Main families observed in the area studied	
Small Serranidae	SR and density : UVC = STAVIRO
Nemipteridae	SR and density : UVC = STAVIRO
Mullidae	SR and density : UVC = STAVIRO
Large Pomacanthidae	SR and density : UVC = STAVIRO
Large labridae	SR and density : UVC = STAVIRO
Balistidae	SR and density : UVC = STAVIRO
Large Serranidae	SR and density : UVC>STAVIRO
Pomacentridae	SR and density : UVC>STAVIRO
Small Labridae	SR and density : UVC>STAVIRO
Scaridae	SR : UVC = STAVIRO; density : STAVIRO>UVC
Acanthuridae	SR : UVC = STAVIRO; density : STAVIRO>UVC
Chaetodontidae	SR : UVC = STAVIRO; density : UVC>STAVIRO
Small Pomacanthidae	SR : UVC = STAVIRO; density : UVC>STAVIRO

In the table. ">" and "<" correspond to significant difference between techniques with $p<0.05$ and "=" correspond to results of no significant difference ($p>0.05$) (see text for details on tests).
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Supporting Information

Table S1 Lists of species observed.
(PDF)

Table S2 Target species in New Caledonia.
(PDF)

Table S3 Species observed characterizing structure's groups.
(PDF)

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Author Contributions

Conceived and designed the experiments: DM LW. Performed the experiments: DM LW SL. Analyzed the data: DM LW SL LV DP. Wrote the paper: DM LW LV DP.

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Table S1. Lists of species observed.

A species was considered as "small" when the maximum species size was less than 30 cm. The mobility of each species was characterized as: "HM": highly mobile species, "MO": mobile species and "SE": sedentary species; following Kulbicki et al. (unpublished data).

List of species observed with both techniques (88 species)

family	genus	species	size	mobility
Acanthuridae	*Acanthurus*	*blochii*	large	MO
Acanthuridae	*Acanthurus*	*nigrofuscus*	large	SE
Acanthuridae	*Acanthurus*	*olivaceus*	large	MO
Acanthuridae	*Acanthurus*	*xanthopterus*	large	HM
Acanthuridae	*Ctenochaetus*	*striatus*	large	SE
Acanthuridae	*Naso*	*unicornis*	large	MO
Acanthuridae	*Zebrasoma*	*scopas*	large	SE
Acanthuridae	*Zebrasoma*	*veliferum*	large	SE
Balistidae	*Pseudobalistes*	*fuscus*	large	SE
Balistidae	*Rhinecanthus*	*aculeatus*	large	SE
Balistidae	*Sufflamen*	*chrysopterum*	large	SE
Blenniidae	*Meiacanthus*	*atrodorsalis*	small	SE
Caesionidae	*Pterocaesio*	*tile*	large	HM
Chaetodontidae	*Chaetodon*	*auriga*	small	SE
Chaetodontidae	*Chaetodon*	*bennetti*	small	SE
Chaetodontidae	*Chaetodon*	*citrinellus*	small	SE
Chaetodontidae	*Chaetodon*	*ephippium*	small	SE
Chaetodontidae	*Chaetodon*	*flavirostris*	small	SE
Chaetodontidae	*Chaetodon*	*lunulatus*	small	SE
Chaetodontidae	*Chaetodon*	*mertensii*	small	SE
Chaetodontidae	*Chaetodon*	*pelewensis*	small	SE
Chaetodontidae	*Chaetodon*	*plebeius*	small	SE
Chaetodontidae	*Chaetodon*	*trifascialis*	small	SE
Chaetodontidae	*Chaetodon*	*ulietensis*	small	SE
Chaetodontidae	*Chaetodon*	*vagabundus*	small	SE
Chaetodontidae	*Heniochus*	*acuminatus*	small	SE
Gobiidae	*Amblygobius*	*phalaena*	small	SE
Labridae	*Anampses*	*neoguinaicus*	small	MO
Labridae	*Cheilinus*	*chlorourus*	large	SE
Labridae	*Cheilinus*	*trilobatus*	large	SE
Labridae	*Cheilinus*	*undulatus*	large	SE
Labridae	*Coris*	*aygula*	large	MO
Labridae	*Coris*	*dorsomacula*	large	SE
Labridae	*Coris*	*gaimard*	large	SE
Labridae	*Gomphosus*	*varius*	small	SE
Labridae	*Halichoeres*	*hortulanus*	small	SE
Labridae	*Halichoeres*	*trimaculatus*	small	MO
Labridae	*Hemigymnus*	*melapterus*	large	MO
Labridae	*Labroides*	*dimidiatus*	small	SE
Labridae	*Novaculichthys*	*taeniourus*	large	MO
Labridae	*Thalassoma*	*hardwicke*	small	MO

Labridae	*Thalassoma*	*lunare*	small	MO
Labridae	*Thalassoma*	*lutescens*	small	MO
Lethrinidae	*Monotaxis*	*grandoculis*	large	MO
Lutjanidae	*Lutjanus*	*fulviflamma*	large	MO
Lutjanidae	*Lutjanus*	*quinquelineatus*	large	MO
Monacanthidae	*Oxymonacanthus*	*longirostris*	small	SE
Mullidae	*Parupeneus*	*barberinoides*	large	HM
Mullidae	*Parupeneus*	*barberinus*	large	HM
Mullidae	*Parupeneus*	*multifasciatus*	large	MO
Mullidae	*Parupeneus*	*pleurostigma*	large	MO
Nemipteridae	*Scolopsis*	*bilineata*	large	MO
Nemipteridae	*Scolopsis*	*trilineata*	large	MO
Ostraciidae	*Ostracion*	*cubicus*	large	MO
Pinguipedidae	*Parapercis*	*clathrata*	small	SE
Pinguipedidae	*Parapercis*	*hexophtalma*	small	SE
Pomacanthidae	*Centropyge*	*bicolor*	small	SE
Pomacanthidae	*Centropyge*	*tibicen*	small	SE
Pomacentridae	*Abudefduf*	*sexfasciatus*	small	SE
Pomacentridae	*Amblyglyphidodon*	*curacao*	small	SE
Pomacentridae	*Amphiprion*	*akindynos*	small	SE
Pomacentridae	*Chrysiptera*	*biocellata*	small	SE
Pomacentridae	*Chrysiptera*	*rollandi*	small	SE
Pomacentridae	*Chrysiptera*	*taupou*	small	SE
Pomacentridae	*Dascyllus*	*aruanus*	small	SE
Pomacentridae	*Dascyllus*	*reticulatus*	small	SE
Pomacentridae	*Dascyllus*	*trimaculatus*	small	SE
Pomacentridae	*Pomacentrus*	*chrysurus*	small	SE
Pomacentridae	*Pomacentrus*	*coelestis*	small	SE
Pomacentridae	*Pomacentrus*	*moluccensis*	small	SE
Pomacentridae	*Stegastes*	*nigricans*	small	SE
Priacanthidae	*Priacanthus*	*hamrur*	large	MO
Scaridae	*Chlorurus*	*microrhinos*	large	HM
Scaridae	*Chlorurus*	*sordidus*	large	MO
Scaridae	*Hipposcarus*	*longiceps*	large	HM
Scaridae	*Scarus*	*altipinnis*	large	HM
Scaridae	*Scarus*	*chameleon*	large	MO
Scaridae	*Scarus*	*frenatus*	large	SE
Scaridae	*Scarus*	*ghobban*	large	HM
Scaridae	*Scarus*	*rivulatus*	large	MO
Scaridae	*Scarus*	*schlegeli*	large	MO
Serranidae	*Epinephelus*	*merra*	large	SE
Serranidae	*Plectropomus*	*laevis*	large	MO
Serranidae	*Pseudanthias*	*hypselosoma*	small	SE
Siganidae	*Siganus*	*argenteus*	large	HM
Chaetodontidae	*Forcipiger*	*flavissimus*	small	SE
Labridae	*Thalassoma*	*nigrofasciatum*	small	MO
Tetraodontidae	*Canthigaster*	*valentini*	small	SE

List of species only observed with UVC

76 species: 30 large + 46 small and 46 SE + 20 MO + 10 HM

family	genus	species	size	mobility
Acanthuridae	*Acanthurus*	*albipectoralis*	large	HM
Acanthuridae	*Acanthurus*	*dussumieri*	large	MO
Acanthuridae	*Acanthurus*	*pyroferus*	large	SE
Acanthuridae	*Acanthurus*	*thompsoni*	large	MO
Acanthuridae	*Naso*	*annulatus*	large	HM
Apogonidae	*Apogon*	*aureus*	small	SE
Apogonidae	*Apogon*	*cyanosoma*	small	SE
Apogonidae	*Cheilodipterus*	*macrodon*	small	SE
Apogonidae	*Cheilodipterus*	*quinquelineatus*	small	SE
Blenniidae	*Atrosalarias*	*holomelas*	small	SE
Blenniidae	*Ecsenius*	*bicolor*	small	SE
Blenniidae	*Plagiotremus*	*rhinorhynchos*	small	SE
Blenniidae	*Plagiotremus*	*tapeinosoma*	small	SE
Caesionidae	*Pterocaesio*	*trilineata*	large	HM
Carangidae	*Carangoides*	*orthogrammus*	large	HM
Chaetodontidae	*Chaetodon*	*melannotus*	small	SE
Chaetodontidae	*Chaetodon*	*speculum*	small	SE
Chaetodontidae	*Chaetodon*	*unimaculatus*	small	SE
Chaetodontidae	*Heniochus*	*chrysostomus*	small	SE
Chaetodontidae	*Heniochus*	*monoceros*	small	SE
Cirrhitidae	*Cirrhitichthys*	*falco*	small	SE
Cirrhitidae	*Paracirrhites*	*forsteri*	small	SE
Gobiidae	*Istigobius*	*rigilius*	small	SE
Haemulidae	*Diagramma*	*pictum*	large	MO
Haemulidae	*Plectorhinchus*	*lineatus*	large	MO
Labridae	*Anampses*	*caeruleopunctatus*	small	MO
Labridae	*Cheilio*	*inermis*	large	MO
Labridae	*Choerodon*	*anchorago*	large	MO
Labridae	*Choerodon*	*graphicus*	large	MO
Labridae	*Cirrhilabrus*	*punctatus*	small	SE
Labridae	*Halichoeres*	*margaritaceus*	small	MO
Labridae	*Halichoeres*	*marginatus*	small	SE
Labridae	*Macropharyngodon*	*meleagris*	small	SE
Labridae	*Pseudocheilinus*	*evanidus*	small	SE
Labridae	*Stethojulis*	*bandanensis*	small	MO
Labridae	*Stethojulis*	*notialis*	small	MO
Labridae	*Stethojulis*	*strigiventer*	small	MO
Labridae	*Thalassoma*	*amblycephalum*	small	SE
Lethrinidae	*Gnathodentex*	*aureolineatus*	large	SE
Lethrinidae	*Lethrinus*	*xanthochilus*	large	HM
Lutjanidae	*Lutjanus*	*fulvus*	large	MO
Lutjanidae	*Lutjanus*	*kasmira*	large	MO
Mullidae	*Parupeneus*	*ciliatus*	large	HM
Mullidae	*Parupeneus*	*cyclostomus*	large	HM
Nemipteridae	*Scolopsis*	*temporalis*	large	HM

Pinguipedidae	*Parapercis*	*australis*	small	SE
Pinguipedidae	*Parapercis*	*millepunctata*	small	SE
Pomacanthidae	*Centropyge*	*bispinosa*	small	SE
Pomacanthidae	*Pomacanthus*	*imperator*	large	SE
Pomacentridae	*Amblyglyphidodon*	*leucogaster*	small	SE
Pomacentridae	*Amphiprion*	*melanopus*	small	SE
Pomacentridae	*Chromis*	*lepidolepis*	small	SE
Pomacentridae	*Chromis*	*viridis*	small	SE
Pomacentridae	*Chrysiptera*	*rex*	small	SE
Pomacentridae	*Neopomacentrus*	*azysron*	small	SE
Pomacentridae	*Plectroglyphidodon*	*dickii*	small	SE
Pomacentridae	*Plectroglyphidodon*	*lacrymatus*	small	SE
Pomacentridae	*Pomacentrus*	*adelus*	small	SE
Pomacentridae	*Pomacentrus*	*amboinensis*	small	SE
Pomacentridae	*Pomacentrus*	*bankanensis*	small	SE
Pomacentridae	*Pomacentrus*	*lepidogenys*	small	SE
Pomacentridae	*Pomacentrus*	*pavo*	small	SE
Pomacentridae	*Pomacentrus*	*philippinus*	small	SE
Pomacentridae	*Pomacentrus*	*vaiuli*	small	SE
Pomacentridae	*Stegastes*	*punctatus*	small	SE
Scaridae	*Scarus*	*globiceps*	large	SE
Scaridae	*Scarus*	*niger*	large	MO
Scaridae	*Scarus*	*rubroviolaceus*	large	HM
Serranidae	*Epinephelus*	*maculatus*	large	SE
Serranidae	*Plectropomus*	*leopardus*	large	MO
Siganidae	*Siganus*	*corallinus*	large	SE
Siganidae	*Siganus*	*puellus*	large	MO
Siganidae	*Siganus*	*spinus*	large	MO
Siganidae	*Siganus*	*vulpinus*	large	MO
Sphyraenidae	*Sphyraena*	*jello*	large	HM
Synodontidae	*Synodus*	*dermatogenys*	small	MO

List of species only observed with STAVIRO

28 species: 24 large + 4 small and 6 SE + 16 MO + 6 HM

family	genus	species	size	mobility
Acanthuridae	*Naso*	*tonganus*	large	HM
Aulostomidae	*Aulostomus*	*chinensis*	large	MO
Caesionidae	*Caesio*	*caerulaurea*	large	HM
Carangidae	*Caranx*	*melampygus*	large	HM
Carcharhinidae	*Triaenodon*	*obesus*	large	MO
Chaetodontidae	*Chaetodon*	*lineolatus*	small	SE
Diodontidae	*Diodon*	*holocanthus*	large	MO
Diodontidae	*Diodon*	*hystrix*	large	MO
Fistulariidae	*Fistularia*	*commersonii*	large	HM
Kyphosidae	*Kyphosus*	*gp*	large	MO
Labridae	*Bodianus*	*bilunulatus*	large	MO
Labridae	*Coris*	*batuensis*	large	SE
Labridae	*Hologymnosus*	*annulatus*	large	MO
Lethrinidae	*Lethrinus*	*atkinsoni*	large	MO
Lethrinidae	*Lethrinus*	*Harak*	large	MO
Lethrinidae	*Lethrinus*	*lentjan*	large	MO
Lethrinidae	*Lethrinus*	*rubrioperculatus*	large	MO
Lutjanidae	*Macolor*	*niger*	large	MO
Monacanthidae	*Paraluteres*	*prionurus*	small	SE
Mullidae	*Parupeneus*	*spilurus*	large	HM
Pomacentridae	*Chromis*	*retrofasciata*	small	SE
Pomacentridae	*Neoglyphidodon*	*melas*	small	SE
Scaridae	*Scarus*	*flavipectoralis*	large	MO
Scaridae	*Scarus*	*oviceps*	large	SE
Scaridae	*Scarus*	*psittacus*	large	MO
Siganidae	*Siganus*	*doliatus*	large	MO
Siganidae	*Siganus*	*punctatus*	large	MO
Stegostomatidae	*Stegostoma*	*fasciatum*	large	HM

Table S2. Target species in New Caledonia

Family	Genus	species
Acanthuridae	*Acanthurus*	*achilles*
Acanthuridae	*Acanthurus*	*blochii*
Acanthuridae	*Acanthurus*	*dussumieri*
Acanthuridae	*Acanthurus*	*lineatus*
Acanthuridae	*Acanthurus*	*mata*
Acanthuridae	*Acanthurus*	*nigricans*
Acanthuridae	*Acanthurus*	*nigricauda*
Acanthuridae	*Acanthurus*	*olivaceus*
Acanthuridae	*Acanthurus*	*pyroferus*
Acanthuridae	*Acanthurus*	*sp.*
Acanthuridae	*Acanthurus*	*xanthopterus*
Acanthuridae	*Naso*	*annulatus*
Acanthuridae	*Naso*	*brachycentron*
Acanthuridae	*Naso*	*brevirostris*
Acanthuridae	*Naso*	*hexacanthus*
Acanthuridae	*Naso*	*lituratus*
Acanthuridae	*Naso*	*sp.*
Acanthuridae	*Naso*	*tuberosus*
Acanthuridae	*Naso*	*unicornis*
Acanthuridae	*Naso*	*vlamingii*
Carangidae	*Atule*	*mate*
Carangidae	*Carangoides*	*chrysophrys*
Carangidae	*Carangoides*	*dinema*
Carangidae	*Carangoides*	*ferdau*
Carangidae	*Carangoides*	*fulvoguttatus*
Carangidae	*Carangoides*	*orthogrammus*
Carangidae	*Caranx*	*lugubris*
Carangidae	*Caranx*	*melampygus*
Carangidae	*Caranx*	*papuensis*
Carangidae	*Caranx*	*sexfasciatus*
Carangidae	*Decapterus*	*russelli*
Carangidae	*Elagatis*	*bipinnulata*
Carangidae	*Gnathanodon*	*speciosus*
Carangidae	*Pseudocaranx*	*dentex*
Carangidae	*Selar*	*crumenophthalmus*
Chanidae	*Chanos*	*chanos*
Clupeidae	*ge.*	*sp.*
Clupeidae	*Herklotsichthys*	*quadrimaculatus*
Clupeidae	*Spratelloides*	*sp.*
Gerreidae	*Gerres*	*oyena*
Haemulidae	*Diagramma*	*pictum*
kyphosidae	*Kyphosus*	*cinerascens*
kyphosidae	*Kyphosus*	*sp.*
kyphosidae	*Kyphosus*	*vaigiensis*
Labridae	*Bodianus*	*perditio*
Labridae	*Cheilinus*	*undulatus*
Lethrinidae	*Gymnocranius*	*euanus*
Lethrinidae	*Gymnocranius*	*grandoculis*
Lethrinidae	*Gymnocranius*	*sp.*
Lethrinidae	*Lethrinus*	*atkinsoni*
Lethrinidae	*Lethrinus*	*genivittatus*
Lethrinidae	*Lethrinus*	*harak*
Lethrinidae	*Lethrinus*	*lentjan*
Lethrinidae	*Lethrinus*	*miniatus*
Lethrinidae	*Lethrinus*	*nebulosus*
Lethrinidae	*Lethrinus*	*obsoletus*
Lethrinidae	*Lethrinus*	*rubrioperculatus*
Lethrinidae	*Lethrinus*	*variegatus*
Lutjanidae	*Aphareus*	*furca*
Lutjanidae	*Aprion*	*virescens*
Lutjanidae	*Lutjanus*	*adetii*
Lutjanidae	*Lutjanus*	*argentimaculatus*
Lutjanidae	*Lutjanus*	*sebae*
Lutjanidae	*Lutjanus*	*vitta*
Mugilidae	*ge.*	*sp.*
Mugilidae	*Valamugil*	*sp.*
Mullidae	*Parupeneus*	*barberinus*
Priacanthidae	*Priacanthus*	*hamrur*
Scaridae	*Bolbometopon*	*muricatum*
Scaridae	*Calotomus*	*carolinus*
Scaridae	*Cetoscarus*	*bicolor*
Scaridae	*Chlorurus*	*microrhinos*
Scaridae	*Chlorurus*	*sordidus*
Scaridae	*ge.*	*sp.*
Scaridae	*Hipposcarus*	*longiceps*
Scaridae	*Leptoscarus*	*vaigiensis*
Scaridae	*Scarus*	*altipinnis*
Scaridae	*Scarus*	*chameleon*
Scaridae	*Scarus*	*dimidiatus*
Scaridae	*Scarus*	*flavipectoralis*
Scaridae	*Scarus*	*forsteni*
Scaridae	*Scarus*	*frenatus*
Scaridae	*Scarus*	*ghobban*
Scaridae	*Scarus*	*globiceps*
Scaridae	*Scarus*	*longipinnis*
Scaridae	*Scarus*	*niger*
Scaridae	*Scarus*	*oviceps*
Scaridae	*Scarus*	*psittacus*
Scaridae	*Scarus*	*rivulatus*
Scaridae	*Scarus*	*rubroviolaceus*
Scaridae	*Scarus*	*schlegeli*
Scaridae	*Scarus*	*sp.*
Scaridae	*Scarus*	*spinus*

Scombridae	*Euthynnus*	*affinis*
Scombridae	*Grammatorcynus*	*bilineatus*
Scombridae	*Rastrelliger*	*kanagurta*
Scombridae	*Scomberomorus*	*commerson*
Serranidae	*Anyperodon*	*leucogrammicus*
Serranidae	*Cephalopholis*	*argus*
Serranidae	*Cephalopholis*	*leopardus*
Serranidae	*Cephalopholis*	*miniata*
Serranidae	*Cephalopholis*	*sonnerati*
Serranidae	*Cephalopholis*	*urodeta*
Serranidae	*Cromileptes*	*altivelis*
Serranidae	*Epinephelus*	*areolatus*
Serranidae	*Epinephelus*	*coioides*
Serranidae	*Epinephelus*	*cyanopodus*
Serranidae	*Epinephelus*	*fuscoguttatus*
Serranidae	*Epinephelus*	*hexagonatus*
Serranidae	*Epinephelus*	*howlandi*
Serranidae	*Epinephelus*	*lanceolatus*
Serranidae	*Epinephelus*	*macrospilos*
Serranidae	*Epinephelus*	*maculatus*

Serranidae	*Epinephelus*	*malabaricus*
Serranidae	*Epinephelus*	*merra*
Serranidae	*Epinephelus*	*ongus*
Serranidae	*Epinephelus*	*polyphekadion*
Serranidae	*Epinephelus*	*rivulatus*
Serranidae	*Epinephelus*	*tauvina*
Serranidae	*Plectropomus*	*leopardus*
Serranidae	*Variola*	*louti*
Siganidae	*Siganus*	*argenteus*
Siganidae	*Siganus*	*canaliculatus*
Siganidae	*Siganus*	*corallinus*
Siganidae	*Siganus*	*doliatus*
Siganidae	*Siganus*	*lineatus*
Siganidae	*Siganus*	*puellus*
Siganidae	*Siganus*	*punctatus*
Siganidae	*Siganus*	*spinus*
Siganidae	*Siganus*	*vermiculatus*
Siganidae	*Siganus*	*vulpinus*
Sillaginidae	*Sillago*	*sp.*
Sparidae	*Acanthopagrus*	*berda*

Table S3. Species observed characterizing structure's groups.

A species was considered as "small" when the maximum species size was less than 30 cm. The mobility of each species was characterized as: "HM": highly mobile species, "MO": mobile species and "SE": sedentary species; following Kulbicki et al. (unpublished data).

B1 = 1st cluster on the barrier reef; I = cluster on the intermediate reef; B2 = 2nd cluster on the barrier reef

family	genus	species	size	mobility	Groups from clustering analysis	Observed with technique
Acanthuridae	*Ctenochaetus*	*striatus*	large	SE	B1+B2	UVC and STAVIRO
Acanthuridae	*Zebrasoma*	*scopas*	large	SE	B1	
Caesionidae	*Pterocaesio*	*tile*	large	HM	B1	
Chaetodontidae	*Chaetodon*	*auriga*	small	SE	B1+B2	
Chaetodontidae	*Chaetodon*	*ulietensis*	small	SE	B1+B2	
Mullidae	*Parupeneus*	*multifasciatus*	large	MO	B1+B2	
Pomacentridae	*Amblyglyphidodon*	*curacao*	small	SE	B1	
Pomacentridae	*Chrysiptera*	*taupou*	small	SE	B1	
Pomacentridae	*Dascyllus*	*aruanus*	small	SE	B2	
Pomacentridae	*Pomacentrus*	*coelestis*	small	SE	B2	
Scaridae	*Chlorurus*	*microrhinos*	large	HM	B1	
Siganidae	*Siganus*	*argenteus*	large	HM	B1	
Acanthuridae	*Acanthurus*	*dussumieri*	large	MO	B1	UVC
Blenniidae	*Atrosalarias*	*holomelas*	small	SE	I	
Labridae	*Cirrhilabrus*	*punctatus*	small	SE	I	
Labridae	*Halichoeres*	*margaritaceus*	small	MO	I	
Labridae	*Thalassoma*	*amblycephalum*	small	SE	B1+B2	
Lethrinidae	*Lethrinus*	*xanthochilus*	large	HM	B1+B2	
Lutjanidae	*Lutjanus*	*kasmira*	large	MO	B1	
Mullidae	*Parupeneus*	*cyclostomus*	large	HM	B1+B2	
Pomacentridae	*Amblyglyphidodon*	*leucogaster*	small	SE	B1	
Pomacentridae	*Pomacentrus*	*pavo*	small	SE	I	
Pomacentridae	*Pomacentrus*	*philippinus*	small	SE	B1	
Serranidae	*Epinephelus*	*maculatus*	large	SE	B1+B2	
Sphyraenidae	*Sphyraena*	*jello*	large	HM	B1	

2. Comparaison des analyses vidéo impliquant différents observateurs

Les biais inhérents aux observations effectuées par des plongeurs ont été largement étudiés et sont maintenant bien connus de la communauté scientifique (voir §3.1 du chapitre1). En utilisant des systèmes vidéo, l'identification et le dénombrement des espèces sont effectués en aval de l'observation, c'est-à-dire lors de l'analyse des images au laboratoire. C'est à cette étape qu'une variabilité entre observateurs peut être introduite et éventuellement affecter les données (pas de différence entre les personnes déployant le système vidéo possible[15]). L'objectif de la présente étude est d'évaluer les variations entre observateurs pouvant advenir lors de l'analyse des vidéos. Tout comme différents plongeurs n'observent pas forcément les mêmes individus sous l'eau, différentes personnes peuvent observer, dénombrer et identifier différemment les individus lors de l'analyse des vidéos. Cette source d'incertitude sera évaluée en étudiant la variabilité des résultats obtenus par différentes personnes analysant les mêmes vidéos indépendamment et appliquant le même protocole, afin de répondre aux questions suivantes :

- Les données issues de l'analyse des vidéos dépendent-elles du niveau d'expérience de l'observateur ?
- Si oui, à partir de quelle niveau d'expérience peut-on considérer les données issues de l'analyse des vidéos comme fiables ?
- Peut-on définir une liste d'espèces considérées comme « facilement identifiables » à partir de l'analyse des vidéos ?

[15] L'effet d'un système vidéo non appâté, sur la macrofaune n'a jamais été étudié à notre connaissance. Voir discussion sur l'étude du potentiel impact de la technique de vidéo rotative sur l'ichtyofaune

2.1. Matériels et méthodes

Protocole

Neuf vidéos ont été analysées par quatre personnes ayant différents niveaux d'expérience en analyse vidéo au moment de l'étude[16] (Obs1 avait 5 ans d'expérience, Obs2 avait 2 ans d'expérience, Obs3 avait 6 mois d'expérience et Obs4 n'avait aucune expérience). Les 9 vidéos ont été sélectionnées à partir d'une campagne d'échantillonnage réalisée en 2007[17] dans le lagon du Grand Nouméa, sur la base de critères liés à la complexité de l'habitat (Tableau 2.1).

Tableau 2.1. Descriptif des vidéos analysées.

Vidéo	Complexité de l'habitat
vidéo 1	Récif corallien (forte complexité)
vidéo 2	Récif corallien (forte complexité)
vidéo 3	Récif corallien (forte complexité)
vidéo 4	fond meuble avec recouvrement d'algues (complexité moyenne)
vidéo 5	fond meuble avec recouvrement d'algues (complexité moyenne)
vidéo 6	fond meuble avec recouvrement d'algues (complexité moyenne)
vidéo 7	fond meuble avec un faible couvert végétal (complexité faible)
vidéo 8	fond meuble avec un faible couvert végétal (complexité faible)
vidéo 9	fond meuble avec un faible couvert végétal (complexité faible)

Chaque observateur a analysé les 9 vidéos indépendamment, en suivant le même protocole (Pelletier et al., 2012) (voir chapitre 2 sur la méthodologie d'analyse des images vidéo). Sur chaque vidéo, les poissons ont été identifiés et comptés par espèce suivant une liste de 498 espèces (Tableau 2.2). Cette liste comprend toutes les familles ayant des espèces de poissons côtiers pêchés, ainsi que des espèces emblématiques de la Nouvelle-Calédonie (uniquement certains genres pour la famille des Labridae, les poissons papillons (Chaetodontidae), *Zanclus cornutus* (Zanclidae), les requins (Carcharhinidae et Stegostomatidae) et les raies (Dasyatidae et Myliobatidae)).

[16] Dans cette étude, le niveau d'expérience d'un observateur est uniquement évalué par rapport au temps qu'il a déjà passé à analyser des images vidéo en partant d'aucune expérience (dénombrement et identification d'espèces de poissons récifaux).

[17] Vidéo enregistrées lors d'une campagne financée par IFREMER/IRD/ZoNéCo

Tableau 2.2. Liste des familles prises en compte lors de l'analyse des images (d'après Pelletier et al., 2012). Les nombres en face de chaque famille correspondent au nombre d'espèces recensées en Nouvelle-Calédonie (Fricke et al., 2011).

Acanthuridae	40	Kyphosidae	5	Myliobatidae	5
Balistidae	19	Labridae:		Priacanthidae	7
Carangidae	43	*Bodianus*	14	Scaridae	28
Carcharhinidae	15	*Cheilinus*	5	Scombridae	13
Chaetodontidae	36	*Choerodon*	6	Serranidae	95
Chanidae	1	*Coris*	7	Siganidae	12
Dasyatidae	9	*Epibulus*	1	Sphyraenidae	8
Ephippidae	3	*Hemigymnus*	2	Stegostomatidae	1
Haemulidae	12	*Oxycheilinus*	6	Zanclidae	1
Hemiramphidae	6	Lethrinidae	24		
Holocentridae	31	Lutjanidae	43		

Analyses des données

La concordance des données entre observateurs a été évaluée en comparant (1) les dénombrements d'individus et d'espèces (test Student apparié effectué sur les coefficients des droites de régressions linéaires de type II obtenues entre observateurs 2 à 2 et coefficient de corrélation de Pearson noté « ρ » dans la suite de l'étude), (2) les identifications (indices de similarité de Sørensen), et (3) les structures observées (test de similarité).

L'indice de similarité de Sørensen (S) (Legendre & Legendre, 1998) permet de comparer les identifications entre 2 observateurs. Cet indice est compris entre 0 (pas de similarité) et 1 (totale similarité) et calculé comme suit :

$$S = \frac{2a}{2a + b + c}$$

où a = nombre d'espèces observées en commun

b = nombre d'espèces observées uniquement par un des 2 observateurs

c = nombre d'espèces observées uniquement par l'autre observateur

Compte tenu du faible nombre de vidéos analysées dans cette étude, nous avons considéré que la similarité était forte quand S > 0,80 et faible lorsque S < 0,80[18].

[18] Un fort indice de similarité entre 2 observateurs indique uniquement une forte similarité entre les 2 au niveau des identifications. 2 observateurs peuvent être très proches vis-à-vis de cet index, mais en ayant fait les mêmes erreurs d'identification ou tout simplement les mêmes oublis lors de l'analyse d'image.

Les structures d'assemblages (abondances observées par espèce) peuvent varier d'un observateur à l'autre et d'une vidéo à l'autre. De ce fait, nous avons regardé si les structures d'assemblages observées différaient significativement entre observateurs (variabilité inter-observateur) et entre vidéos (variabilité écologique) en utilisant une analyse factorielle des correspondances (AFC ; Legendre & Legendre, 1998) effectuée sur la matrice des abondances par espèce et par couple d'observateurs/vidéos. Un modèle linéaire multivarié à un facteur est ensuite appliqué sur les coordonnées des 7 premiers axes de l'AFC (extrayant 71% de l'inertie totale), d'une part pour le facteur « observateur », et d'autre part pour le facteur « vidéo ». Enfin, une analyse discriminante canonique (AD ; Gittins, 1988) a été effectuée sur chaque modèle afin de tester séparément la significativité des facteurs « observateur » et « vidéo » sur les structures observées. Deux AD distinctes ont ainsi été effectuées pour visualiser la relation entre les structures d'assemblages observées avec (1) les observateurs et (2) les vidéos.

2.2. Résultats

2.2.1. Dénombrement des individus

Les abondances les plus élevées ont été observées sur les vidéos n°1, 2, 3, 6, 8 et 9 (de 25 à 116 individus observés) ; alors que les abondances les moins élevées ont été observées sur les vidéos n°4, 5 et 7 (de 1 à 7 individus) (Annexe C1).

Les abondances relevées sur chacune des vidéos sont fortement corrélées entre observateurs ($0,81 < \rho < 0,96$; $p < 0,01$) et ne sont pas significativement différentes les unes des autres (pentes des droites de régression non significativement différentes de 1 et ordonnées à l'origine non significativement différentes de 0) sauf entre les observateurs 1 et 4 (Figure 2.1). L'observateur 4 a observé significativement moins d'individus que l'observateur 1 sur les vidéos où l'abondance observée était forte (pente significativement différente de 1 mais ordonnée à l'origine non significativement différente de 0) (Annexe C2). De plus, les plus grandes différences entre observateurs se situent sur les vidéos ayant les plus fortes abondances (dans l'ordre décroissant : vidéo n°9, 8 et 3) ce qui influence les droites de régression (Figure 2.1).

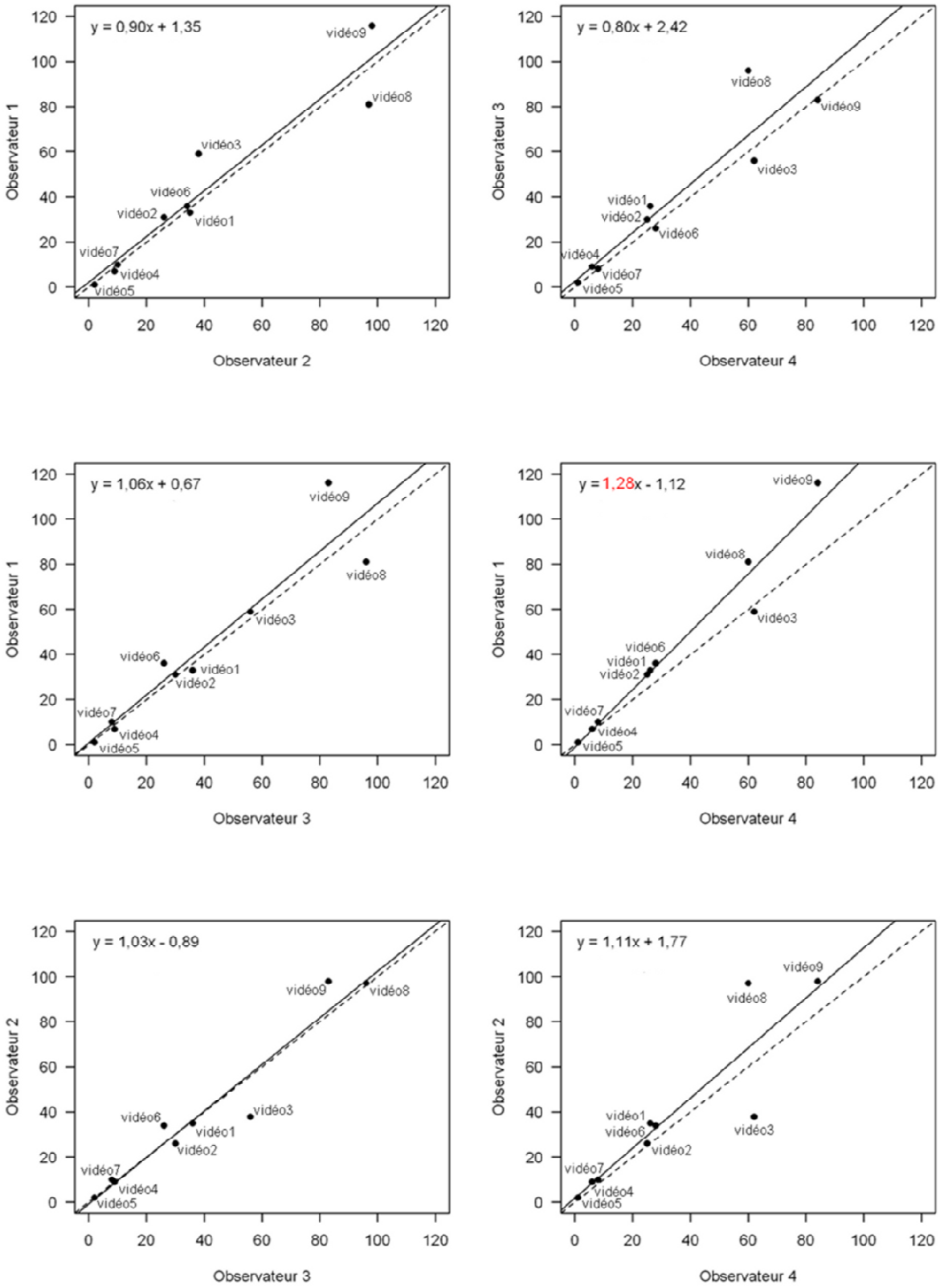


Figure 2.1. Abondances observées sur chacune des vidéos en fonction des observateurs. Les droites de régression apparaissent en noir (équation écrite dans le graphique pour chacune d'elle). Les droites en pointillés correspondent aux droites théoriques correspondantes à des observations similaires entre les observateurs (y=x). Les pentes significativement différentes de 1 et les ordonnées à l'origine significativement différentes de 0 des droites de régression (test de Student) sont indiquées en rouge quand $p < 0,05$ dans les équations.

2.2.2. Identification des individus

Sur les neuf vidéos, cinquante-huit espèces appartenant à la liste des familles prises en compte ont été identifiées par l'ensemble des observateurs. Vingt-sept de ces espèces ont été identifiées par les quatre observateurs, neuf espèces ont été identifiées par trois observateurs, cinq espèces ont été identifiées par deux observateurs et dix-sept espèces ont été identifiées par un seul observateur (Figure 2.7 et Annexe C3). L'observateur le plus expérimenté (Obs1) a identifié le plus grand nombre d'espèces (44) et l'observateur le moins expérimenté (Obs4) en a identifié le moins (37). Certaines espèces ont été uniquement identifiées par un observateur (7 espèces par Obs1, 6 par Obs2, 1 par Obs3 et 3 par Obs4).

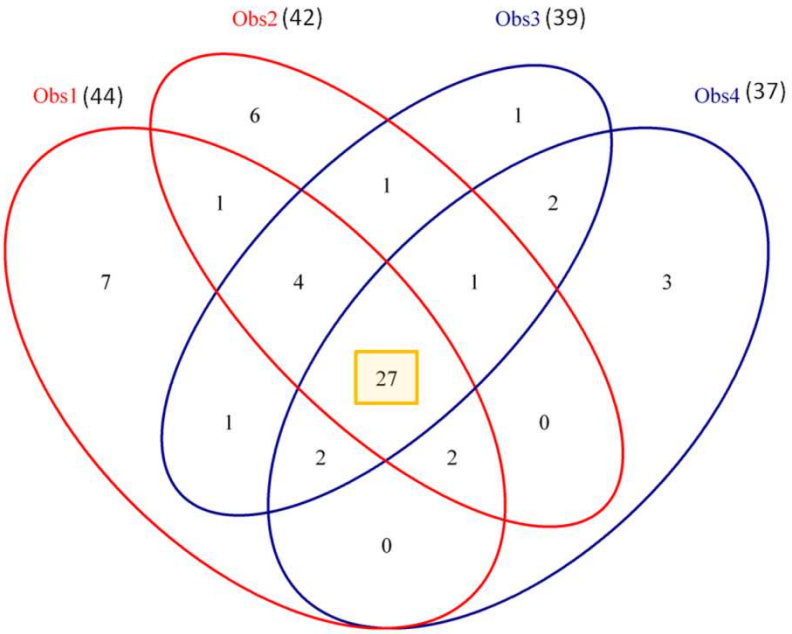


Figure 2.7. Diagramme de Venn des espèces identifiées sur l'ensemble des vidéos par les 4 observateurs (les observateurs ayant le plus d'expérience sont représentés en rouge et les observateurs avec le moins d'expérience sont représentés en bleu). Les chiffres entre parenthèses représentent le nombre total d'espèces identifiées par chaque observateur. Le chiffre encadré, au centre du graphique, représente le nombre d'espèces identifiées par les 4 observateurs.

Le nombre d'espèces identifiées sur chacune des vidéos est fortement corrélé entre observateurs ($0,92 < \rho < 0,98$; $p < 0,01$) et n'est pas significativement différente entre eux (pentes des droites de régression non significativement différentes de 1 et

ordonnées à l'origine non significativement différentes de 0), à l'exception des observateurs 1 et 3. L'observateur 1 a identifié significativement plus d'espèces que l'observateur 3 quand la diversité était faible (ordonnée à l'origine significative) et moins quand la diversité était forte (pente significative), (Figure 2.8 et Annexes C1 et C2).

Cependant, une richesse spécifique non significativement différente entre observateurs ne signifie pas que les espèces observées sont identiques. En ce sens, les indices de similarité de Sørensen moyens montrent que sur l'ensemble des neuf vidéos, les identifications au niveau de l'espèce sont significativement différentes entre tous les observateurs ($0,62 < S_{moyen} < 0,76$) sauf entre les observateurs les plus expérimentés (Obs1 et Obs2 ; $S_{moyen} = 0,88$). La vidéo n°9 est l'unique vidéo présentant de forts indices de similarités entre tous les observateurs ($S > 0,86$). Cette vidéo présente une faible diversité spécifique (entre 3 et 4 espèces identifiées selon les observateurs) (Annexe C1). Vingt-six des cinquante-quatre indices calculés entre observateurs (soit 54%) montrent une faible similarité entre les observateurs au niveau des espèces identifiées ($S < 0,80$). Les indices de similarité les plus faibles ont été obtenus pour les observateurs 1 et 3 ($0 < S < 0,91$ et $S_{moyen} = 0,62$) alors que les indices de similarités les plus forts ont été obtenus par les observateurs 1 et 2 (forts indices de similarité pour sept des neuf vidéos ; $0,67 < S < 1$ et $S_{moyen} = 0,88$). Les observateurs les moins expérimentés (Obs3 et Obs4) présentent une forte similarité sur six des neuf vidéos. Les valeurs extrêmes des indices de Sørensen calculés entre observateurs pour la vidéo n°5 ($S = 0$ ou $S = 1$) sont dues à la très faible diversité de cette vidéo. En effet une seule espèce a été identifiée par les observateurs les plus expérimentés (Obs1 et Obs2) alors que les individus n'ont pas été identifiés jusqu'à l'espèce par les observateurs les moins expérimentés (Obs3 et Obs4). Enfin, l'absence de similarité ($S = 0$) entre les observateurs 3 et 4 au niveau de la vidéo n°8 a une explication différente puisque les observateurs ont identifié deux espèces chacun mais leurs identifications n'étaient pas les mêmes. Sur cette vidéo, l'observateur 3 a identifié *Chanos chanos* (Chanidae) et *Gnathadodon speciosus* (Carangidae) alors que l'observateur 4 a identifié *Pseudocaranx dentex* (Carangidae) et *Seriola lalandi* (Carangidae) (les observateurs expérimentés ayant tous deux identifié les 3 mêmes espèces: *Chanos chanos*, *Pseudocaranx dentex* et *Gnathanodon speciosus*).

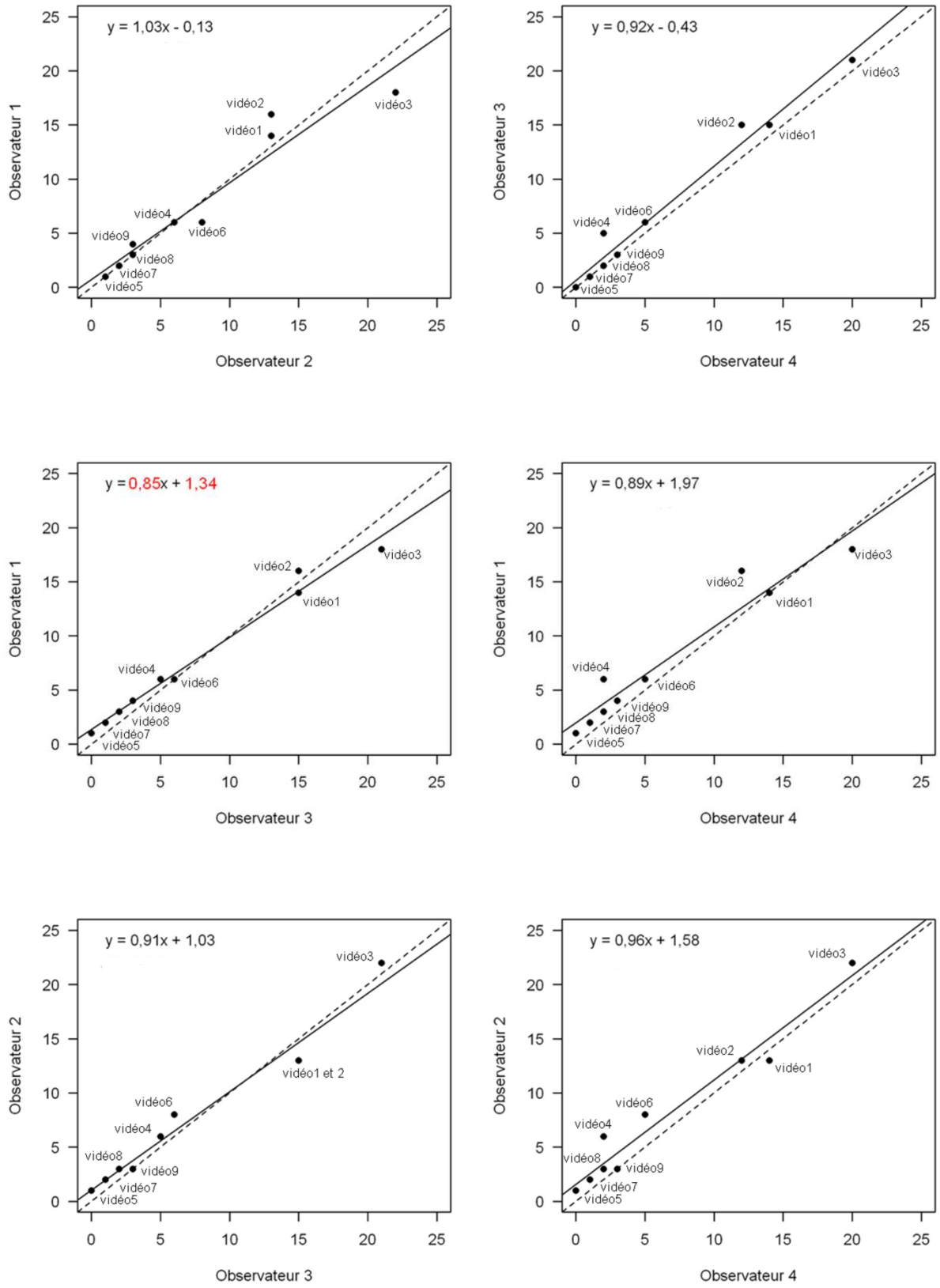


Figure 2.8 Nombre d'espèces observées sur chacune des vidéos en fonction des observateurs. Les droites de régression apparaissent en noir (équation écrite dans le graphique pour chacune d'elle). Les droites en pointillés correspondent aux droites théoriques correspondantes à des observations similaires entre les observateurs (y=x). Les pentes significativement différentes de 1 et les ordonnées à l'origine significativement différentes de 0 des droites de régression (test de Student) sont indiquées en rouge quand $p < 0,05$ dans les équations.

Tableau 2.5. Indices de similarité de Sørensen calculés entre les espèces identifiées par chaque observateur sur chacune des vidéos analysées. S_{moyen} : indice de Sørensen moyen calculé entre 2 observateurs sur les 9 vidéos. Les faibles indices de similarité (S < 0,80) sont représentés en rouge dans le tableau.

Observateurs	vidéo 1	vidéo 2	vidéo 3	vidéo 4	vidéo 5	vidéo 6	vidéo 7	vidéo 8	vidéo 9	S_{moyen}
Obs1 vs Obs2	0,67	0,73	0,80	1	1	0,86	1	1	0,86	0,88
Obs1 vs Obs3	0,71	0,76	0,79	0,50	0	0,91	0,67	0,40	0,86	0,62
Obs1 vs Obs4	0,76	0,81	0,77	0,91	0	1	0,67	0,80	0,86	0,73
Obs2 vs Obs3	0,74	0,80	0,86	0,50	0	0,77	0,67	0,40	1	0,64
Obs2 vs Obs4	0,79	0,79	0,88	0,91	0	0,86	0,67	0,80	1	0,74
Obs3 vs Obs4	0,83	0,89	0,88	0,57	NA*	0,91	1	0	1	0,76

* *aucune espèce identifiée par Obs3 et Obs4 sur cette vidéo (individus observés mais non identifiés jusqu'à l'espèce)*

2.2.3. Structure d'assemblage observée

Selon l'analyse de variance effectuée sur un modèle linéaire appliqué sur les coordonnées des 7 premiers axes de l'AFC (elle-même effectuée sur les abondances observées par espèce et par couple observateur/vidéo), les assemblages de poissons observés diffèrent significativement entre vidéo ($p < 0,05$) mais pas entre observateur ($p > 0,05$). Les analyses discriminantes effectuées sur les regroupements par observateur et par vidéo illustrent la similarité des structures de poissons observées entre observateurs (pas de variabilité inter-observateurs) (Figure 2.9A) et la différence des structures d'assemblages observées entre les vidéos (variabilité écologique) (Figure 2.9B). Selon ces résultats, les observations obtenues sont plus influencées par la diversité ichtyologique des vidéos que par la personne analysant les vidéos, quelque soit le niveau d'expérience de l'observateur. En effet, les vidéos sont séparées les unes des autres sur le plan en 2 dimensions de la représentation graphique de l'analyse discriminante (Figure 2.9B représentant 85,5% de variabilité). Seules, les vidéos présentant la plus faible diversité (la vidéo n°5 : 1 à 2 individus pour 0 à 1 espèce identifiée et la vidéo n°7 : 8 à 10 individus pour 1 à 2 espèces identifiées selon les observateurs) se recoupent sur le plan en 2 dimensions.

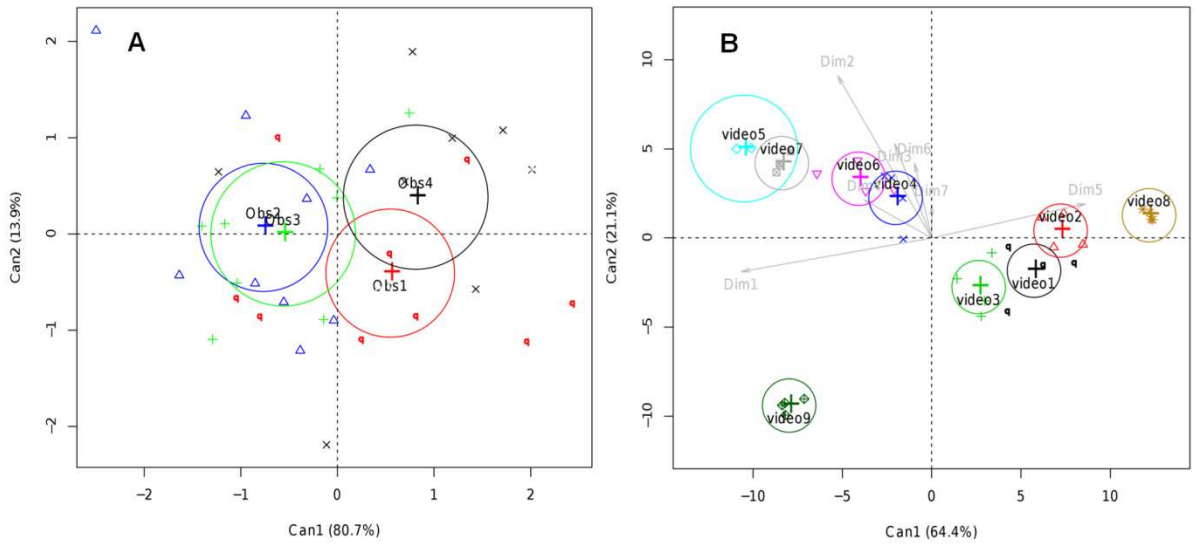


Figure 2.9 Représentation graphique des analyses discriminantes effectuées sur les nombres d'individus observés par espèce par observateur (A) et par vidéo (B). Les cercles représentent les intervalles de confiance à 95% des regroupements.

2.3. Discussion

Conformité des observations et niveau d'expérience nécessaire pour analyser les vidéos

Les résultats de la présente étude montrent que les dénombrements et les identifications des poissons des observateurs 1 et 2 n'étaient pas significativement différentes sur les neuf vidéos analysées. Par contre, l'observateur 4 a montré des différences avec au moins un des trois autres observateurs aussi bien au niveau du dénombrement que de l'identification des individus, alors que l'observateur 3 a présenté des différences avec les autres observateurs uniquement au niveau des identifications (Tableau 2.7).

Tableau 2.7. Synthèse des principaux résultats obtenus entre observateurs selon les métriques étudiées. Obs1 : 5 ans d'expérience, Obs2 : 2 ans d'expérience, Obs3 : 6 mois d'expérience et Obs4 : aucune expérience. « = » : différence non significative ($p > 0,05$), « < », « > » et «≠ » : différence significative ($p < 0,05$).

	Similarités	Différences
Abondance	Obs1 = Obs2 = Obs3	Forte abondance : Obs4 < Obs1 Faible abondance : Obs4 > Obs1
Identification	Nombre d'espèces identifiées par vidéo : Obs1 = Obs2 = Obs4 Identification : Obs1 = Obs2	Forte diversité : Obs3 > Obs1 Faible diversité : Obs3 < Obs1 Identification : Obs3 et Obs4 ≠ Obs1 et Obs2 Plus d'individus non identifiés chez Obs3 et Obs4
Structure	Entre observateurs	Entre vidéos

Les différences observées entre observateurs au niveau des identifications des individus peuvent avoir plusieurs origines : (1) différence d'identification d'un individu, (2) observation ou non de l'espèce, et (3) identification effectuée à un niveau taxonomique différent (espèce, genre ou famille). Le niveau d'expérience des observateurs influe sur le troisième point en engendrant des identifications moins précises mais toujours correctes. En ce sens, l'observateur le plus expérimenté (Obs1) a identifié le plus grand nombre d'individus au niveau de l'espèce (266 individus identifiés jusqu'à l'espèce) alors que les observateurs les moins expérimentés en ont identifiés le moins (Obs3 : 237 individus identifiés au niveau de l'espèce ; Obs4 : 232 individus identifiés au niveau de l'espèce) (Annexes C4 et C5). De plus, sur chacune des vidéos le nombre d'espèces identifiées uniquement au niveau du genre ou de la famille était relativement faible voir nul pour les observateurs ayant la plus grande expérience, alors que les observateurs les moins expérimentés n'ont pas identifié d'individu(s) jusqu'à l'espèce sur chaque vidéo.

Ces résultats ne sont pas surprenants étant donné la différence de niveau d'expérience des observateurs de cette étude. En effet, les observateurs 1 et 2 étaient les plus expérimentés (5 ans et 2 ans d'expérience en identification d'espèces respectivement) alors que les observateurs 3 et 4 n'avaient qu'une faible expérience (6 et 0 mois d'expérience respectivement). De ce fait, il n'est pas étonnant de conclure que

plus les observateurs ont de l'expérience et moins leurs analyses se différencient (Obs1 = Obs2 > Obs3 > Obs4).

En ce sens, différentes études comparant plusieurs observateurs effectuant des UVC montrent l'importance de la formation des personnes non spécialistes pour acquérir une aptitude suffisante au comptage et à l'identification des poissons (notamment au niveau des récifs coralliens) (e.g. Darwall & Dulvy, 1996 ; Thompson & Mapstone, 1997 ; Bernard et al., 2013). Par exemple, Darwall & Dulvy (1996) et Thompson & Mapstone (1997) ont montré que des observateurs non spécialistes peuvent, avec une formation adéquate, recueillir des données fiables pour les suivis basés sur les poissons récifaux. De plus, Bernard et al. (2013) ont montré que les données sur l'ensemble des communautés de poissons recueillies par des bénévoles étaient d'une qualité nettement inférieure à celles recueillies par les observateurs expérimentés. Cependant, les observateurs expérimentés et les bénévoles obtenaient des données similaires concernant les espèces dominantes. Cette différence au niveau des communautés, n'a pas pu être testée dans ma comparaison puisque les observateurs ne devaient prendre en compte qu'une liste non exhaustive d'espèces (liste comportant près de 500 espèces issue de Pelletier et al., 2012 ; voir Matériel et Méthode) régulièrement utilisée dans le cadre du projet AMBIO[19]. De ce fait, la présente étude ne permet pas de conclure sur la capacité des différents observateurs à évaluer l'abondance et la diversité de l'ensemble des espèces présentes sur les images vidéo. .

Peut-on définir une liste d'espèces considérées comme « facilement identifiables » à partir de l'analyse des vidéos ?

La plupart des individus non identifiés jusqu'à l'espèce étaient de la famille des Lethrinidae (Annexe C5) signifiant que les poissons de cette famille ont été plus difficile à identifier jusqu'à l'espèce par les observateurs dans notre étude. Cependant, du fait du nombre limité de vidéos analysées et de la faible diversité taxonomique de certaines d'entre elles, cette étude ne permet pas de conclure sur les espèces identifiables ou non selon les observateurs lors de l'analyse des vidéos. En effet, une espèce difficilement

[19] Projet AMBIO ("Aires Marines Protégées, Biodiversité et Patrimoine inscrit") sous la responsabilité de Dominique Pelletier, IFREMER : http://wwz.ifremer.fr/ncal/Biodiversite-et-ressources/Suivi-de-la-biodiversite

identifiable en routine (petite taille, cryptique, très mobile, etc.) peut avoir été identifiée facilement par les quatre observateurs en raison d'un comportement particulier (passage près de la caméra, individu isolé ou immobile, etc.). Pour répondre rigoureusement à cette question, plusieurs aspects devraient être pris en compte dans une même comparaison : i) analyser un plus grand nombre de vidéos ; ii) analyser des vidéos ayant une forte abondance et diversité ; iii) prendre en compte toutes les espèces présentes sur les images et iv) établir une analyse de référence pour chaque vidéo (par exemple à travers une analyse conjointe de plusieurs experts).

Perspectives et conclusion

Les vidéos peuvent être analysées par différentes personnes conjointement ou séparément, ré-analysées pour différentes études (e.g. comportement des individus) et les observations obtenues peuvent être confrontées entre différents observateurs. L'observation simultanée est d'ores et déjà pratiquée dans certains cas en UVC. En ce sens, Bernard et al. (2013) préconisent d'évaluer les communautés de poissons en binôme afin d'assurer une qualité suffisante aux données, (notamment lorsque l'étude à recours à des observateurs non spécialistes). La vérification des observations, est une pratique très utilisée dans de nombreux domaines scientifiques (notamment en médecine ou chimie analytique où les observations sont validées en rejouant 5 à 10% des analyses). Le fait de répéter l'analyse d'un certain nombre de vidéos permettrait de certifier de la fiabilité des données. La certification de l'observation ne peut pas être effectuée avec les techniques traditionnelles pour des raisons pratiques (dû aux fluctuations naturelles des populations dans le temps), alors qu'elles sont très faciles à mettre en œuvre avec les techniques vidéo rotatives (ré-analyse d'un certain nombre de vidéos) et autres techniques faisant appel à de la vidéo ou de la photo par exemple.

Nos observations montrent que les différences entre observateurs, même si elles existent, peuvent être considérées comme négligeables lorsque l'on s'intéresse aux indices globaux pour une liste définie d'espèces, à partir du moment où les observateurs ont suffisamment d'expérience en identification. Il est toutefois, essentiel de considérer les différents effets inter-observateurs possibles lors de la conception de programmes de surveillance. En particulier lorsque ces derniers impliquent plusieurs observateurs

sur des suivis multi-spécifiques à grandes échelles spatiales ou temporelles. En ce sens, afin de valider la qualité des informations recueillies, je préconise de faire ré-analyser un certain nombre des vidéos par un expert ainsi que d'effectuer les analyse d'images en binôme régulièrement.

3. Synthèse

Dans ce chapitre les capacités des systèmes vidéo rotatifs (programmable ou non) à étudier l'ichtyofaune ont été évaluées. L'article 4 permet de mieux comprendre les atouts et les limites de l'information obtenue à partir de cette technique vidéo par rapport à une technique UVC similaire (couramment utilisée dans la zone d'étude). Cette étude a montré que les 2 techniques d'observation n'obtiennent pas la même image de l'ichtyofaune lorsqu'on les utilise sur les mêmes points à moins d'une heure d'écart. Selon cette étude : (1) la similarité entre les observations est faible en termes d'espèces observées, (2) les petites espèces[20] sont mieux observées avec les UVC aussi bien qualitativement (richesse spécifique) que quantitativement (densité), (3) aucune différence significative entre les techniques en termes de nombre d'espèces et d'individus de grande taille[21] n'a été observée, (4) une plus grande quantité d'individus d'espèces pêchées ont été observés avec les STAVIRO, (5) les UVC ont permis de mettre en évidence une structure des peuplements en fonction du type de récifs avec uniquement 26 stations sur les pentes récifales à l'inverse des STAVIRO (principalement dû aux observations des espèces de petite taille).

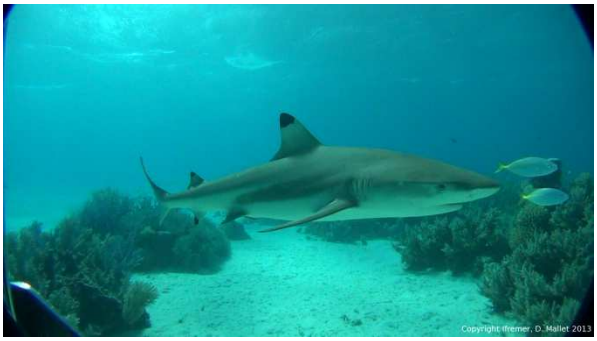
L'étude sur la comparaison des observations obtenues sur les mêmes vidéos par différents observateurs a montré que sur une liste d'espèces définie (grandes espèces + Chaetodontidae) les dénombrements d'individus et d'espèces ainsi que les identifications des poissons peuvent être considérés comme similaires entre observateurs à partir du moment où l'observateur a un minimum d'expérience (plus de 6 mois dans notre étude). Cependant, je préconise d'analyser les vidéos en binôme ainsi que de vérifier la compatibilité des observations effectuées lorsque plusieurs observateurs sont impliqués dans une étude en ré-analysant un certain nombre des vidéos (notamment lors de suivis multi-spécifiques à grandes échelles spatiales et/ou sur de longues périodes).

D'un point de vue méthodologique, ces résultats apportent des informations sur les atouts et les limites de ces systèmes d'observation. Ces derniers seront pris en compte dans la suite de ce travail.

[20] Espèces dont la taille maximum connue est inférieure à 30 cm.
[21] Espèces dont la taille maximum connue est supérieure à 30 cm.

CHAPITRE 5

Utilisation des systèmes d'observation MICADO pour étudier les variations diurnes à haute fréquence temporelle d'une communauté de poissons coralliens



Les variations journalières des communautés de poissons présentent une périodicité naturelle due à la rotation de la terre formant une alternance régulière de phase diurne et nocturne. Cette périodicité est assez bien connue et de nombreux travaux de recherche ont étudiés ces cycles jour/nuit. Cependant, comme le soulève Bijoux et al. (2013), les variations naturelles des poissons sont rarement prises en compte lors de la conception de protocoles expérimentaux ainsi que pour interpréter les observations.

Les systèmes « MICADO » présentés dans le chapitre 3, permettent d'enregistrer de nombreuses vidéos sur une même station avec une intervention extérieure très minime (présence humaine uniquement pour changer les batteries des systèmes : tous les 3 jours). Ils sont de ce fait parfaitement adaptés pour étudier les variations temporelles de l'ichtyofaune à petit échelle, en conditions naturelles.

Dans ce chapitre je m'intéresse particulièrement aux variations diurnes des communautés de poissons en milieu corallien. L'utilisation de la vidéo permettra d'obtenir un grand nombre de vidéos enregistrées à des intervalles réguliers du lever au coucher du soleil pendant plusieurs jours. Ces observations permettront de traiter les questions suivantes :

(1) Est-ce que l'heure de la journée et l'état de la marée influencent la présence, l'abondance et la diversité de l'ichtyofaune d'un même habitat ?

(2) Peut-on regrouper les espèces selon leur comportement et ainsi définir des « profils types » de comportement des espèces en fonction de l'heure de la journée et de l'état de la marée?

1. Article 5. Variations diurnes à haute fréquence temporelle d'un peuplement de poissons de récif corallien étudiées par vidéo sous-marine

Résumé de l'article 5:

La répartition des poissons récifaux est soumise à de fortes variations dans le temps et l'espace. Malgré le nombre important d'études portant sur les variations spatio-temporelles des populations de poissons récifaux, ces questions ont rarement été étudiées à petite échelle. L'objectif de cette étude est de caractériser les variations diurnes observées dans un habitat de coraux branchus selon l'heure de la journée et l'état de la marée en utilisant des observations vidéo enregistrées à haute fréquence temporelle. L'enregistrement de 10 vidéos par jour pendant 34 jours consécutifs a permis de construire une base de 256 vidéos exploitables et recenser un total de 50031 poissons appartenant à 113 taxons, 66 genres et 31 familles. Les herbivores et les carnivores dominaient la structure trophique des assemblages observés par vidéo. D'importantes variations horaires ont été observées avec notamment une richesse spécifique et une densité d'individus plus importantes tôt le matin et en fin d'après-midi. Nos résultats ont révélé une influence significative de la marée sur les densités de poissons mais pas sur leur diversité spécifique. Une analyse typologique a montré que parmi les taxons fréquemment observés, 31 n'étaient influencés ni par l'heure de la journée, ni par la marée alors que 21 affichaient des profils temporels d'abondance bien définis. Parmi ceux-ci, l'abondance de 3 espèces variait en fonction de l'heure de la journée, 13 taxons étaient influencés par la marée et 9 taxons étaient influencés à la fois par l'heure de la journée et par la marée. Aucun de ces 21 taxons n'étaient piscivores ; 10 étaient herbivores, 9 carnivores et 2 étaient planctonophages.

La cohérence des tendances temporelles observées dans cette étude fournit des renseignements nouveaux sur les variations de l'ichtyofaune des récifs coralliens. Cette étude suggère de prendre en compte les variations à petite échelle temporelle lors de l'étude de la connectivité entre les habitats ainsi que pour les suivis des communautés de poissons récifaux.

Article 5

Journal of Experimental Marine Biology and Ecology (en prep.)

High frequency diurnal temporal variation of a coral reef fish assemblage studied with underwater video

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Abstract

Small-scale spatial and temporal variability in coral reef fish abundance plays a crucial role in habitat connectivity and ecosystem functioning but remains largely unknown. In this study, we used the MICADO video system and recorded fish assemblages every hour for 34 consecutive days in a branching coral micro-habitat of the lagoon of New-Caledonia. In total, 50031 individuals belonging to 113 species, 66 genera and 31 families were observed in 256 hourly videos. Herbivore-detritus feeders and carnivores dominated the trophic structure. We found significant variations in the composition of fish assemblages between hours of the day. Species richness and density were greater in the early morning and in the late afternoon than during the day. Tidal state influenced fish density but not species richness. Cluster analysis showed that among the frequent species, 31 were influenced neither by time of day nor by tidal state and 21 displayed well-defined patterns. Among these, 3 were only influenced by time of day, 13 were only influenced by tidal state, and 9 were influenced by both time of day and tidal state. None of these 21 species were piscivores, 10 were herbivore-detritus feeders, 9 were carnivores and 2 were plankton feeders. Observed patterns are likely to be related to a diel feeding migration from feeding grounds to shelters areas.

The consistency of the temporal patterns observed in this study provides new information on reef fish movements in coral reefs. It shows the importance of taking into account movements at small temporal scale when studying connectivity between habitats and monitoring reef fish communities.

Keywords. coral reef fish / high frequency sampling / temporal variation / animal movements / underwater video

1. Introduction

Coral reef ecosystems are characterized by high diversity and complex co-evolved relationships between organisms (Sale, 1991). They are highly dynamic with variable natural and anthropogenic disturbances acting at various spatial and temporal scales and affecting biological processes, such as recruitment, competition, and predation (Ricklefs, 2004; Helfman et al., 2009; Bonaldo et al., 2012). These ecosystems contain the most diverse fish assemblages to be found anywhere on earth. For example, the archipelago of New Caledonia in the South-Pacific has a total of 2328 recorded species belonging to 246 families (Fricke et al., 2011). Understanding the functioning of such complex ecosystem and gathering information on the biology of such diverse fish assemblages is challenging. Yet, it is crucial for appropriate coral reef management, especially in the current context of reef degradation at a global scale (Hughes et al., 2003; Burke et al., 2011).

Despite the large number of studies focused on spatial and temporal variations of reef fish populations, these questions have rarely been studied at small scales (Bijoux et al., 2013). Most existing studies concerned annual, seasonal or monthly variations (Galzin, 1987b; Fisk and Harriott, 1990; Kingsford, 1992; Winemiller, 1990; Connell and Jones, 1991; Jenkins and Wheatley, 1998; Condal et al., 2012). Others compared diurnal and nocturnal fish assemblages (Hobson, 1965; Colton and Alevizon, 1981; Galzin, 1987b; Rooker and Dennis, 1991; Danilowicz and Sale, 1999; Toobaie et al., 2013) and reported minimum abundances during the night and maximums around midday. Some of these studies also identified changeovers in behavior, distribution and abundance of reef fish at sunrise and sunset (Hobson, 1972; Galzin, 1987b; Santos et al., 2002; Danilowicz and Sale, 1999). They identified several periods in the temporal organization of reef fish assemblages with for example a period at dusk when diurnal fishes seek cover followed by a mass emergence of nocturnal species after an interim period. They also found that predation risk was significantly higher at dusk and during nocturnal periods than during the day.

Most surveys were performed by one observer using Underwater Visual Census (UVC). Due to diving constraint, sampling frequency was necessarily limited, typically less than 7 counts per day during few consecutive days (e.g. Colton and Alevizon, 1981; Rooker and Dennis, 1991; Spyker and Van Den Berghe, 1995; Santos et al., 2002; Thompson and Mapstone, 1997; Willis et al., 2006; Irigoyen et al., 2013). Some authors also have studied spatio-temporal variations in reef fish assemblages using fishing techniques (e.g. seine hauls of Félix-Hackradt et al., 2010) or underwater video systems (Birt et al., 2012; Chabanet et al., 2012). They showed that the abundance of certain species significantly varied according to the time of day. For instance, Chabanet et al. (2012) found that average fish abundance remained relatively constant between days, but Acanthuridae were more numerous in the morning, whereas Scaridae abundance was higher at sunrise and sunset. Such results provide new lights on fish home-range, movement patterns, migration, space use, activity patterns and site fidelity of fish. These processes are most effectively studied by acoustic telemetry (Lowe et al., 2003; Egli and Babcock, 2004; Meyer et al., 2007). However, for practical reasons, it is not possible to tag all individuals of a study area and thus most acoustic studies are species-specific (e.g. Zeller, 1997; Egli and Babcock, 2004; Wetherbee et al., 2004; Eristhee and Oxenford, 2005; Meyer et al., 2007). Because small-scale spatio-temporal variations in fish abundance may involve a significant fraction of the assemblages (Colton and Alevizon, 1981; Spyker and Van Den Berghe, 1995), the use of underwater video systems permanently deployed on the reef may provide useful complementary information to both UVC surveys and acoustic telemetry. As UVC, video can record many species and. as acoustic telemetry, it can provide data at high spatial and temporal frequency. Conversely to fishing techniques, video is non destructive and can therefore be used in protected areas (review by Mallet and Pelletier, 2014).

The purpose of this study was to characterize the patterns of reef fish abundance in a live branching coral micro-habitat in relation to time of day and tidal state. To achieve this, we used a new rotating video system (MICADO, Mallet et al., in prep.) and recorded hourly videos from sunrise to sunset for 34 consecutive days. The following hypotheses were then investigated: (1) time of day and tidal state affect reef fish abundance patterns in this habitat; (2) the impact of these factors on reef fish abundance depends on species functional traits such as diet; and (3) most reef fish species display a well defined abundance pattern depending on the time of day and/or on tidal state.

2. Materials and methods

2.1. Study area

The study was conducted in the Marine Protected Area (MPA) of Aboré Reef located 20 km off Nouméa (22°26' S, 166°21' W) in the Southwest Lagoon of New Caledonia in the South Pacific (Figure 1). This MPA has a total area of 80 km^2 and has been closed to fishing since 1996. The reserve is composed of a barrier reef bordered by a strip of sand and by submerged reefs (Kulbicki et al., 1996). Observations were recorded in one location of the inner barrier reef slope. For the study, one permanent video system was deployed at 5 m depth on sand surrounded by branching corals (mostly *Acropora* spp.) (Figure 2).

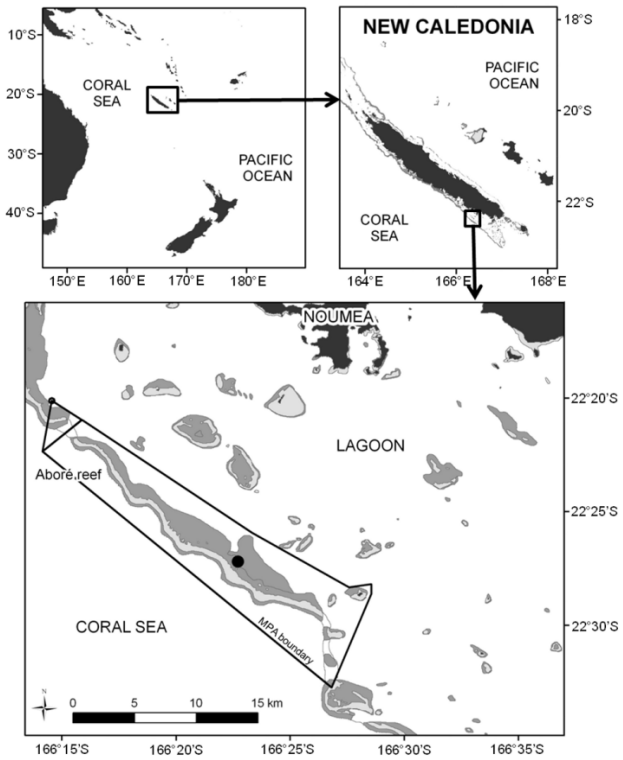

Figure 1. Study area. The polygon indicates the boundaries of Arboré Reef MPA. The MICADO video station is represented by a black dot.

Figure 2. Picture of the MICADO system in the study area

2.2. Sampling technique and design

Censuses were conducted from 27th of September 2012 to 31st of October 2012. The MICADO underwater video rotating system is programmable, remote and autonomous. It was fully described by Mallet et al. (in prep.). For the present study, the system was programmed to rotate a sector of 60° every 30 s and record 2 full (360°) rotations every hour from 30 min after sunrise to 30 min before sunset. This resulted in 10 videos per day recorded with each video lasting 7 minutes (2 rotations x 6 sectors of 60° x 30 s per sector + 1 minute of rotation).

2.3. Video analyses

Videos from the MICADO rotating system were analyzed by a single observer (DM) in a very similar way than others video systems (see review by Mallet and Pelletier, 2014). For each video sequence, all individuals were identified at the highest taxonomic level possible within a radius of 6 meters around the camera. Individuals were counted per sector (sequence of 30 sec) and then summed over the six sectors of a rotation (360°). In the present study, species richness was calculated as the maximum count of different species taken over the 2 rotations and abundance per species at a given station was calculated as the maximum count taken over the two rotations. To minimize potential double counting from one sector to another, particular attention was given to the direction of fish movement with respect to camera rotation. The radius of 6 meters corresponded to the poorest water visibility observed at the sampling site during the experiment and was defined by measuring distances from the camera to several coral colonies in the field of view of the camera. As for other studies using remote video

camera systems, we used abundance as a proxy of abundance to minimize the risk of repeatedly counting the same fish (Harvey et al., 2007). In order to provide results in the same units than other techniques such as UVC, a proxy of fish density was calculated by dividing our proxy of fish abundance by the sampled surface (πR^2=113m^2). In coral reefs, many fish species are similar and difficult to distinguish on videos unless they are close enough to the camera. In order to address this issue, species which were impossible to distinguish on videos were grouped in the following taxa: (i) *Stegastes gp* for the group *Stegastes fasciolatus*, *S. Nigricans*, *S. punctatus*; (ii) *Ctenochaetus gp* for *Acanthurus nigrofuscus*, *Ctenochaetus striatus*, *C. Binotatus*, *C. cyanocheilus*; (iii) *Acanthurus gp* for *Acanthurus blochii*, *A. dussumierii*; (iv) *Chromis gp* for *Chromis viridis*, *C. Atripectoralis*, *Pomacentrus pavo*, *P. coelestis.* Each complex will be addressed as a single species in the analysis (species richness: identified species + complex).

2.4. Trophic groups

All fishes (identified species, genus and family + complex) were assigned in the following trophic groups based on Kulbicki et al. (2011): “P” for piscivores that feed predominantly on fishes; “H” for herbivore-detritus feeders that feed predominantly on epilithic algal; “K” for plankton feeders that feed predominantly on invertebrate material in the water column and “C” for carnivores that feed predominantly on sessile and mobile benthic invertebrates. Species were also classified depending on their frequency of occurrence (noted “Freq.” here below) in the videos as permanent (Freq. > 75%), frequent (30% < Freq. < 75%), scarce (10% < Freq. < 30%) or rare species (Freq. < 10%).

2.5. Statistical analyses

Species richness and density (ind/10m^2) were analysed as a function of time of day and tidal state using permutational multivariate analysis of variance (PERMANOVA; Anderson, 2001). PERMANOVA were run for all observations together and for each diet group. Unlike parametric tests, permutation tests do not assume normal distribution of data. The analyses were conducted with 999 permutations on raw videos for species richness and density datasets. When PERMANOVAs showed significant differences depending on hours or tidal states, pairwise comparison tests based on the Tukey method between group levels was performed to study differences between classes of each factor.

The different patterns at taxa level (identified and unidentified species + complex) between hours or tidal states were identified using cluster analysis. Mean densities for each taxa per hour or tidal state were clustered using Hierarchical Ascending Classification method (HAC; Legendre and Legendre, 1998) and the Ward aggregation procedure (Lebart et al., 1997). In order to formally test the differences between clusters, a between-class analysis (BCA, Chessel et al., 2004; Dray and Dufour, 2007) including a Monte-Carlo test with 999 random permutations was conducted using time of day or tidal state as factor in the BCA. Data of each cluster were standardized per taxa to avoid that the most abundant taxa drive the patterns. Standardized data of each cluster were analyzed as a function of time of day and tidal state using PERMANOVA. Differences between classes of each factor were tested using pairwise comparison tests based on the Tukey method between group levels. Because both cluster and between-class analysis can be sensitive to rare occurrences, rare species were removed from dataset prior to analysis.

3. Results

3.1. Reef fish diversity

A total of 50032 individuals belonging to 114 species (110 species and 4 complex), 66 genera and 31 families were observed in the 256 videos analyzed (Table 1, Appendix A). 55% (27576) of individuals were identified at species level, 25% (12311) were identified at complex level (96% of Pomacentridae) and another 20% (10145 fish) of individuals could not be identified at species level. Most of them were Scaridae (8690) and Caesionidae (612) (Table 1).

The most frequent famillies were Acanthuridae (Freq. = 100% with 6 species and 2 complex), Pomacentridae (Freq. = 100% with 4 species and 2 complex), Scaridae (Freq. = 100% with 13 species), Labridae (Freq. = 99.6% with 19 species), Chaetodontidae (Freq. = 98.4% with 14 species), Lethrinidae (Freq. = 75% with 5 species) and Serranidae (Freq. = 67.2% with 6 species). The most frequent species were diurnal carnivores and herbivore-detritus feeders (Table 2). Many species (61 species and 1 complex i.e. 55%) were observed in less than 10% of the videos and for some families, only one species was seen in a single video (Belonidae, Hemiramphidae, Monacanthidae and Myliobatidae) or in two videos (Ginglymostomatidae and Stegostomidae). These

rare families were mostly carnivores and piscivores (Table 2) and composed of large mobile often predatory species (e.g. sharks or rays) passing by the field of view of the camera or small cryptic species (e.g. filefishes) (see Appendix B for details on fish observed).

Table 1. Number of genera, species (complex) and individuals recorded per family. Complex represent a group of resembling species (see methods) and infomations corresponding to these special groups are represented in brackets in the table. Freq: Frequency (in %). Number of individuals is decomposed between identified and unidentified individuals at species level. Families are sorted in decreasing order of frequency of occurrence in the 256 analysed videos.

Family	**Freq.**	**Genus**	**Species**	**Individuals.**	
				Identified	**not identified**
Acanthuridae	100	4	6 (2)	3104 (511)	51
Pomacentridae	100	5	5 (2)	16795 (11800)	269
Scaridae	100	6	13	3178	8690
Labridae	99.6	12	19	1437	407
Chaetodontidae	98.4	2	14	1140	3
Lethrinidae	75	2	5	277	31
Serranidae	67.2	3	6	278	38
Nemipteridae	47.7	1	1	175	0
Pomacanthidae	44.9	2	3	151	0
Balistidae	43.4	2	2	126	0
Mullidae	42.6	1	6	182	4
Siganidae	32.4	1	4	152	0
Caesionidae	30.1	1	1	371	612
Aulostomidae	18.4	1	1	53	0
Pinguipedidae	13.3	1	1	34	0
Carcharhinidae	9.8	2	2	25	2
Carangidae	8.2	4	6	29	18
Echeneidae	6.2	1	1	21	0
Lutjanidae	5.1	3	3	14	0
Apogonidae	4.7	1	0	0	16
Tetraodontidae	4.7	1	1	11	1
Dasyatidae	3.1	2	2	8	0
Ostraciidae	1.6	1	1	4	0
Diodontidae	1.2	1	1	3	0
Gobiidae	1.2	1	1	1	2
Ginglymostomatidae	0.8	1	1	2	0
Stegostomatidae	0.8	1	1	2	0
Belonidae	0.4	1	1	1	0
Hemiramphidae	0.4	0	0	0	1
Monacanthidae	0.4	1	1	1	0
Myliobatidae	0.4	1	1	1	0
Total		66	110 (4)	27576 (12311)	10145

Table 2. Number of species (sp), genera (ge.), families (fa.), individuals (nb ind), and number of species per diet category for permanent (Freq. > 75%), frequent (30% < Freq. < 75%), scarce (10% < Freq. < 30%) or rare species (Freq. < 10%). P: piscivores, H: herbivore-detritus, K: plankton feeders, C: carnivores. Data corresponding to complex (group of species) are represented in brackets in the table.

Freq.	sp.	ge.	fa.	nb ind	Diet
Permanent	8 (3)	11	4	29577 (12286)	4 H, 4 K, 3 C
Frequent	21	14	10	5313	11 C, 7 H, 4 P
Scarce	20	15	11	2165	9 C, 4 H, 4 K, 3 P
Rare	61 (1)	47	27	666 (25)	34 C, 15 P, 10 H, 4 K
All videos	110 (4)	66	31	37721 (12311)	55 C, 25 H, 22 P, 11 K

3.2. Effect of time of day

Species richness (SR) and density significantly varied with time of day (one way PERMANOVA, $p < 0.01$ for both variables) (Figure 3A and 3C). More species were observed in the early morning (06:00, mean ± SE: 28.33 ± 0.91 species) and in the late afternoon (17:15, 29.08 ± 0.83 species) (pairwise comparison, $p < 0.01$). SR did not significantly differ between 07:15 and 16:00 (range of means: 22.76 species at 12:15 – 25.27 species at 16:00; pairwise comparison, $p > 0.05$, Figure 3A). Density also displayed a U-shaped curve (Fig. 3C). It was maximal in the early morning and late afternoon, gradually decreased between 06:00 and 11:00, remained constant and minimum between 11:00 and 14:45 and increased between 14:45 and 17:15 (Figure 3C).

PERMANOVA performed for each trophic group showed that speciesspecies richness and density of herbivore-detritus feeders and plankton feeders changed significantly with time of day ($p < 0.01$) but remained statiscally constant for both piscivores and carnivores (Figure 3B,D). Pairwise comparisons indicated that SR of herbivore-detritus feeders was significantly higher at 06:00 (12.85 ± 0.33 species) and 17:15 (12.38 ± 0.38

species) than at any other times (9.04-10.79 species in average) ($p < 0.01$, Figure 3B). Similar results were observed for densities with significantly higher values at 06:00 (5.79 ± 0.32 ind/10m^2) and 17:15 (5.00 ± 0.47 ind/10m^2) than at any other times (1.42-3.46 ind/10m^2 in average) ($p < 0.01$, Figure 3D). Species richness of plankton feeders was significantly higher in late afternoon (16:00 = 6.12 ± 0.24 and 17:15 = 6.08 ± 0.19 species) ($p < 0.05$) compared to the rest of the day (4.92-5.26 species in average). However, the density of these species did not significantly differ between hours ($p > 0.05$, Figure 3D).

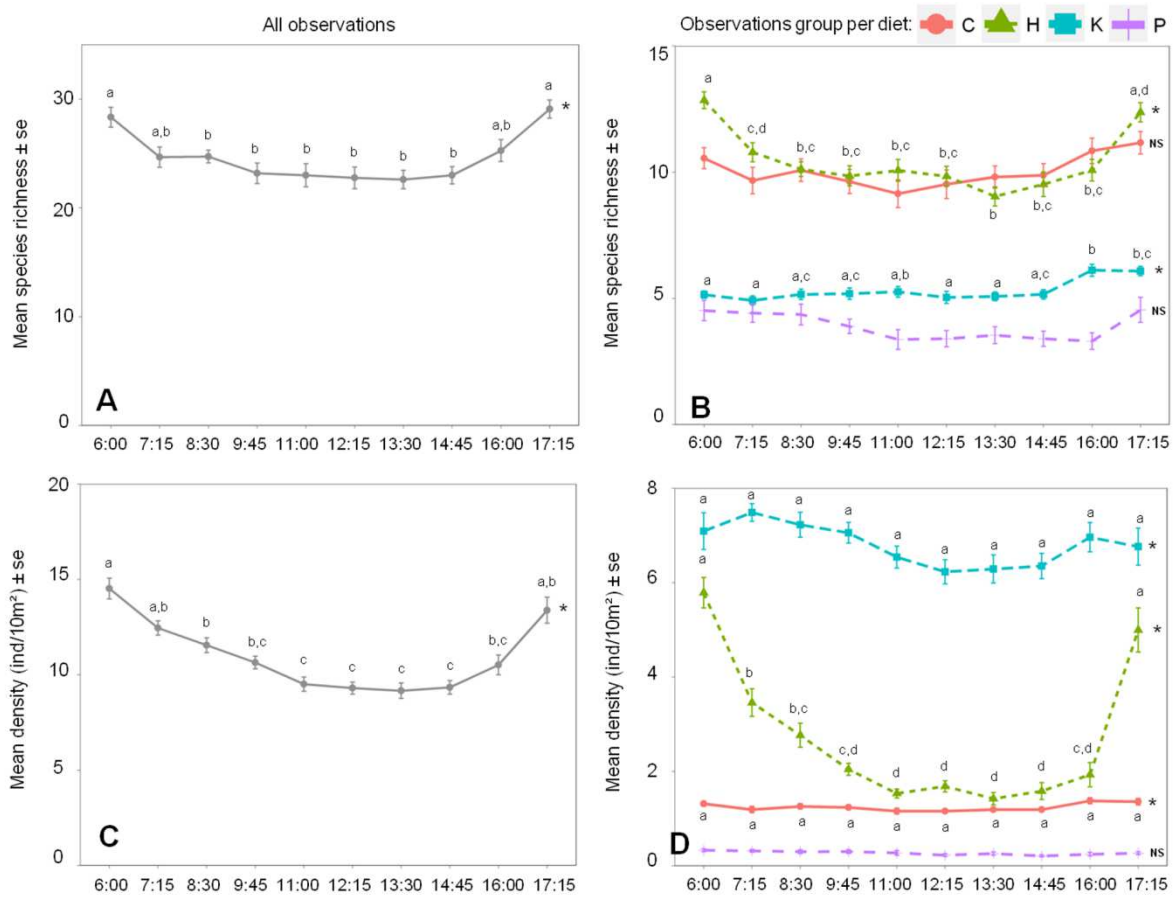

Figure 3. Average species richness (A,B) and density (ind/10m^2) (C,D) per hour. Mean species richness and density recorded for all observations are represented on the left and observations per diet group are represented on the right. The significance of the hour effect for each pattern plotted is reported as "*": $p < 0.05$ and NS: $p > 0.05$. Results from pairwise comparisons are represented by letters on patterns when hour effect was found significant from PERMANOVA: same letter represent $p > 0.05$ and different letters when $p < 0.05$.

Hierarchical cluster analysis performed on fish density through time revealed that taxa grouped into three main clusters (Figure 4). The BCA revealed a highly significant difference between these 3 clusters (Monte-Carlo test with 999 random permutations, p

< 0.01). Cluster 1 displayed a relatively flat pattern and was composed of 46 taxa and all trophic groups (Appendix C). The other two clusters displayed significant temporal patterns. Cluster 2 was composed of 2 species of parrotfish (*Scarus rivulatus*, *Scarus schlegeli)* and other unidentified Scaridae (juveniles and adults) more abundant in the early morning. Cluster 3 was composed of 6 species of herbivore-detritus feeders (*Acanthurus xanthopterus*, *Hipposcarus longiceps, Scarus chameleon, Scarus ghobban*, *Siganus doliatus* and *Zebrasoma scopas*) and 1 species and 1 taxon of plankton feeders (*Pterocaesio tile* and unidentified Caesionidae) more abundant in the late afternoon.

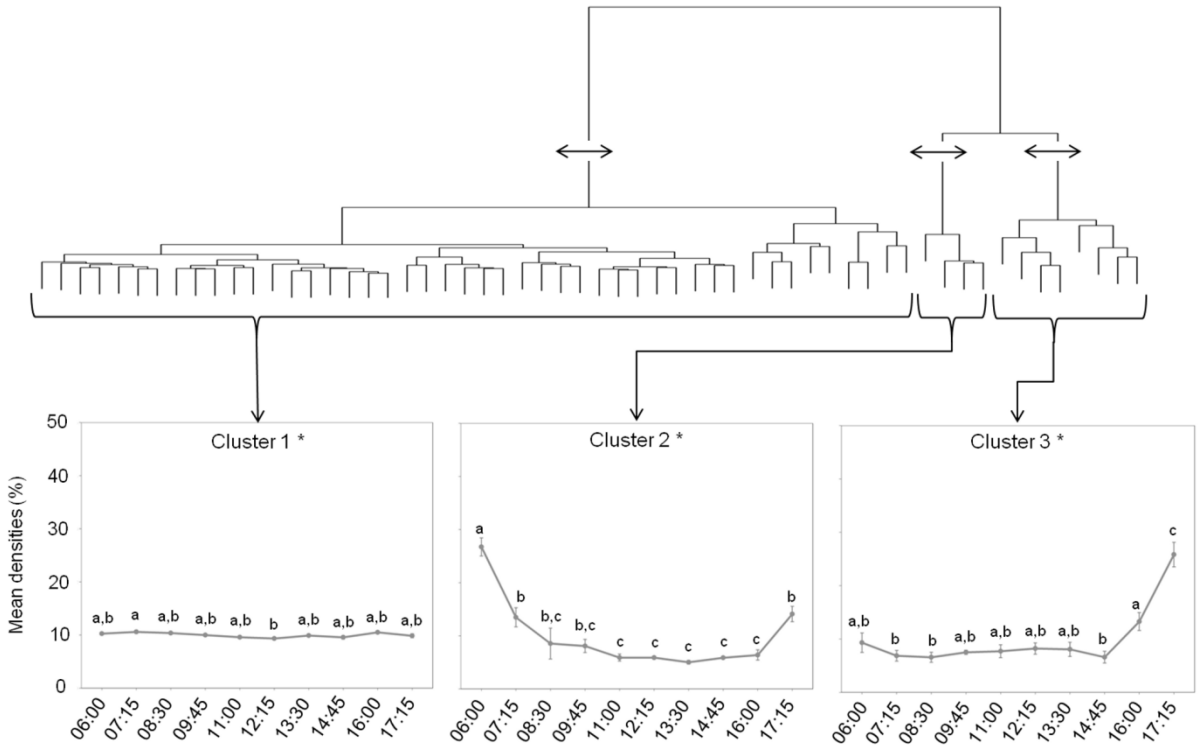

Figure 4. Clustering of taxa based on average density per hour (rare species excluded). At the top: Classification tree from HAC and at the bottom: average patterns of each cluster. The significance of the hour effect in a PERMANOVA for each cluster is reported as "*": p < 0.05. Differences between hours from pairwise comparisons are represented by letters on patterns: same letter represent p > 0.05 and different letters when p < 0.05.

3.3. Effect of tidal state

Species richness was not significantly different between tidal states whatever the trophic group (p > 0.05) (Figure 5A and 5B). In contrast, density was significantly different depending on tidal states (p < 0.01) with higher values at high tide (12.07 ± 0.40 ind/10m^2) than at low tide (10.20 ± 0.35 ind/10m^2) (pairwise comparisons p < 0.01) (Figure 5C). The tidal effect was significant on herbivore-detritus feeders and plankton feeders densities (p < 0.05). The density of plankton feeders was significantly

lower at low tide (6.22 ± 0.17 ind/10m^2) than at high tide (7.15 ± 0.16 ind/10m^2) and falling tide (7.18 ± 0.19 ind/10m^2) ($p < 0.05$). The density of herbivore-detritus feeders was significantly higher at high tide (3.33 ± 0.31 ind/10m^2) than at falling tide (2.11 ± 0.20 ind/10m^2) ($p < 0.05$). No significant difference was observed for carnivores and piscivores (Figure 5D).

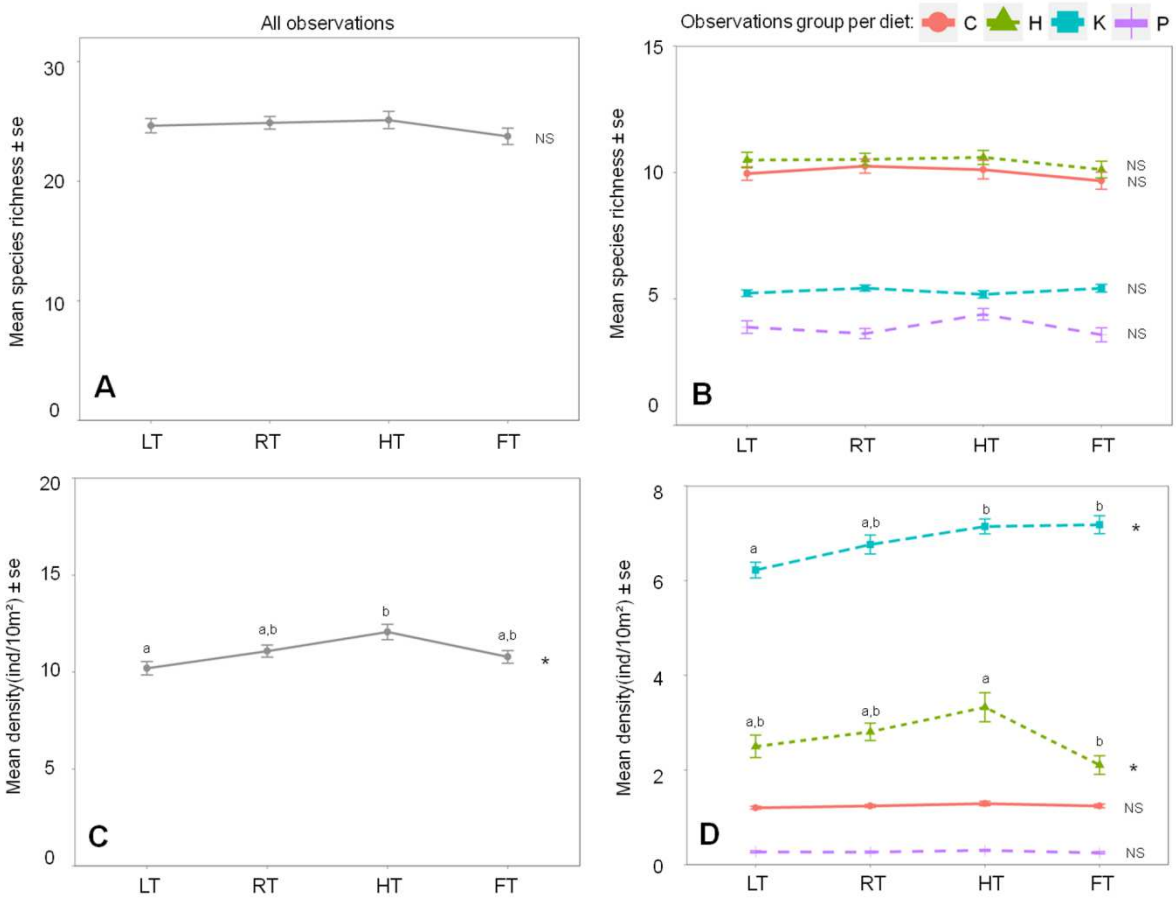

Figure 5. Average species richness (A,B) and density (ind/10m^2) (C,D) per tidal state (LT: Low Tide; RT: Rising Tide; HT: High Tide and FT: Falling Tide). Mean species richness and density recorded for all observations are represented on the left and observations per diet group are represented on the right. The significance of the tidal state effect for each pattern plotted is reported as "*": $p < 0.05$ and NS: $p > 0.05$. Results from pairwise comparisons are represented by letters on patterns when tidal state effect was found significant from PERMANOVA: same letter represent $p > 0.05$ and different letters when $p < 0.05$.

Three main clusters were identified for tidal state effect (Figure 6), and these clusters differed significantly (BCA, Monte-Carlo test with 999 random permutations, $p < 0.01$). The first cluster was composed of 6 species and 1 taxon of herbivore-detritus feeders (*Acanthurus nigricauda*, *Chlorourus sordidus*, *Scarus chameleon*, *S. rivulatus*, *S. schlegeli*, *Zebrasoma scopas* and unidentified Scaridae juveniles), 2 carnivorous species

(*Gomphosus varius* and *Parupeneus barberinus*) and 1 plankton feeding taxon (unidentified Caesionidae). These taxa occurred in higher densities at high tide (32 ± 1 % of total density) than at other tidal states (19-23 % of total density) ($p < 0.05$) (Figure 6, cluster 1). The second cluster included 36 taxa with a relatively flat pattern although their density was significantly higher at rising tide (26 ± 0 % of total density) than at other tidal states (25 ± 0 % of total density) ($p < 0.05$) (Figure 6, cluster 2). The last cluster included 7 carnivorous species (*Chaetodon auriga, C. benneti*, *C. ephippium*, *C. plebeius*, *C. trifascialis*, *Hologymnosus annulatus* and *Scolopsis bilineata*), 3 herbivore-detritus feeding species (*Acanthurus xanthopterus*, *Scarus ghobban* and *Siganus doliatus*) and 2 plankton feeding taxa (unidentified Pomacentridae and *Stegastes gp*). The density of these taxa in the assemblage was significantly higher at low(28 ± 1% of total density) and high tides (27 ± 1% of total density) than at rising (22 ± 1% of total density) and falling tides (23 ± 1% of total density) ($p < 0.05$) (Figure 6, cluster 3).

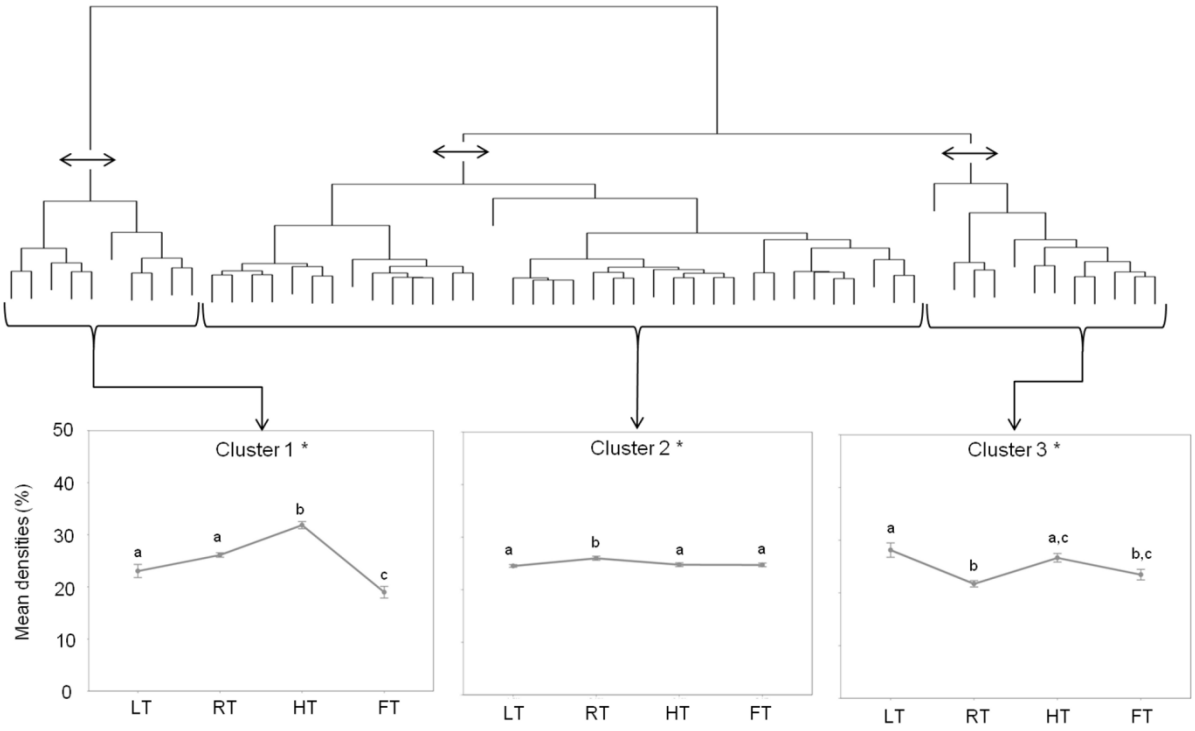

Figure 6. Clustering of taxa based on average density per tidal state (rare species excluded). On the top: Classification tree from HAC and on the bottom: average pattern of each cluster defined. The significance of the tidal state effect (PERMANOVA) for each cluster is reported as "*": $p < 0.05$. Differences between tidal states from pairwise comparisons are represented by letters on patterns: same letter represent $p > 0.05$ and different letters when $p < 0.05$.

4. Discussion

Temporal variation of reef fish assemblages at different temporal scale is a well known process. It has been described at large and medium temporal scales (annual, seasonal or monthly) and linked to various factors, such as breeding/spawning (Ogden and Quinn, 1984; Gladstone, 2007; Meyer et al., 2007) and recruitment/settlement (Sale et al., 1984; Valles et al., 2006; Grorud-Colvert and Sponaugle, 2009; Salinas-de-León et al., 2012). At smaller scales (day, hour, minute) temporal variation can be influenced by habitat type, competition, predation and feeding activities (Hobson, 1973; Letourneur et al., 1997; Danilowicz and Sale, 1999; Fischer et al., 2007; Lefèvre and Bellwood, 2011). This short term temporal variability has rarely been studied at the high frequency replication of the present study (Bijoux et al., 2013). Our 256 hourly videos revealed a relatively stable fish assemblage for 52 species (including 3 complex) while 62 other species (including 1 complex) were rare (Freq. < 10%). This is consistent with the know fact that in any ecosystem a majority of the species are relatively rare (Jones et al., 2002). Moreover, herbivore-detritus feeders and carnivores dominated the trophic structure recorded as described by UVC for coral reefs in New Caledonia (Kulbicki et al., 2007; Chabanet et al., 2010; Guillemot et al., 2011).

We found significant variations in the composition of fish assemblages between hours as species richness and density were greater in the early morning and in the late afternoon than during the day. This variability was mostly driven by herbivore-detritus and plankton feeding species. This pattern contrasts with numerous previous studies from both temperate and tropical environments (Colton and Alevizon, 1981; Rooker and Dennis, 1991; Spyker and Van Den Berghe, 1995; Thompson and Mapstone, 2002; Willis et al., 2006) that had not found evidence of any temporal pattern of fish assemblages within days. However, our results are consistent with Birt et al. (2012) and Chabanet et al. (2012) who used different baited and unbaited video techniques. They observed that fish assemblages were variable within and between days. For instance, Chabanet et al. (2012) found that Acanthuridae were more numerous in the morning whereas Scaridae abundance was higher at sunrise and sunset. These findings corroborate our results in a sens, as Acanthuridae and Scaridae are herbivorous-detritus feeders. However, in the

present study we highlighted that species from these families did not present the same temporal patterns depending on time of day.

Tidal states only influenced density. The absence of tidal influence on species richness was also observed by Connell and Kingsford (1998) and Irigoyen et al. (2013), while the variability of density with tidal states observed in the present study was also shown by Unsworth et al. (2007a,b). They found that seagrass fish assemblages were more abundant at high tides in both coral reef and seagrass habitats. The tide effect observed in the present study may be explained by the location of the video station in a branching coral microhabitat. Indeed, tides may create periodic feeding opportunities such as access to shallow areas of the reef flat during high tide (Bray, 1981). Our study was not performed on the reef flat but species movements (timing, distance and direction of migration such as ritualized feeding migration) between the observation site and the reef flat could have occurred for some species during high tide. The reef flat was located 800 m from our study site, which is compatible with distances traveled by different species, from at least several kilometers to just a few meters (Mumby, 2006; Apperldoorn et al., 2009).

Almost half (41%) of the 52 frequent species displayed a significant temporal pattern of abundance within and/or among days. The observed patterns were probably directly related to fish behavior and habitat selection. For instance, the larger fish assemblages observed early in the morning and late in the afternoon may be related to the known diel feeding migration from feeding areas to shelters places to seek refuges for the night. Moreover, afternoon feeding activity of herbivore-detritus feeders may be linked to a diurnal variation in the nutritional value and/or palatability of algal food (Letourneur et al., 1997; Polunin and Klumpp, 1989*).* It could also reflect an increase in food availability and quality early in the morning (Klumpp and Polunin, 1990).

In highly diverse fish assemblages such as the coral reef fish of New Caledonia, many species resemble each other and are difficult to identify. In the present study, 45% of the individuals recorded (including complex) by our video system were not identified at the species level. Despite this large number, we believe that this posed no particular issues for this study on temporal variations of fish assemblages. Indeed, by grouping resembling species into complex we could reduce the number of unidentified individuals at 20% and still perform a coherent analysis in terms of species traits since resembling species are generally phylogenetically and functionally very close. Moreover, by taking

into account unidentified species at genus or family level, we were able to highlight daily movement of some taxa such as juveniles of Scaridae showing a U-curve pattern depending on hours.

The consistency of the temporal patterns observed in this study provides important information on reef fish movements in coral reefs. It shows the importance of taking into account small scale temporal movements when studying the connectivity between habitats and monitoring reef fish communities particularly in studies involving large species.

Acknowledgements

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Appendix (*L'ensemble de ces documents sont consultables en Annexe D de cette thèse*)

Appendix A. Summary of videos observed. Density (ind/m^2), species richness, number of genus, number of family, day, time of day and tidal state corresponding to each video sequence recorded.

Appendix B. Summary per species observed on all videos recorded (256).

Appendix C Summary of time of the day and tidal state effects detected from cluster analysis (rare species excluded).

2. Synthèse

Partant du constat de Bijoux et al. (2013), montrant que les variations des poissons associés à des cycles diurnes, horaires ou induits par la marée, ne sont que rarement prises en compte dans les études d'évolution temporelle des assemblages de poissons de récif, nous avons utilisé les systèmes « MICADO » afin d'étudier ces variations. L'article 5 permet de mettre en évidence des variations diurnes cycliques de l'ichtyofaune dans un habitat corallien. Nous avons, en effet, constaté des fluctuations naturelles du nombre d'espèces et d'individus observés en fonction de l'heure de la journée et de l'état de la marée au niveau d'un même habitat. Cette étude à également permis de mettre en évidence que l'influence de ces facteurs était différente selon les groupes trophiques et les espèces étudiées.

Ces résultats apportent une connaissance nouvelle sur les variations naturelles de l'ichtyofaune d'un même habitat, insuffisamment étudié à l'heure actuelle. Par exemple, nous avons constaté qu'une grande partie des espèces présentant des cycles diurnes étaient des espèces de grandes tailles, mobiles et pour la plupart ciblées par la pêche en Nouvelle-Calédonie. Ce constat témoigne du besoin particulièrement important de prendre en compte les variations temporelles naturelles des espèces dans les travaux de recherche traitant, par exemple, de l'effet des AMP et de l'impact de la pression de pêche.

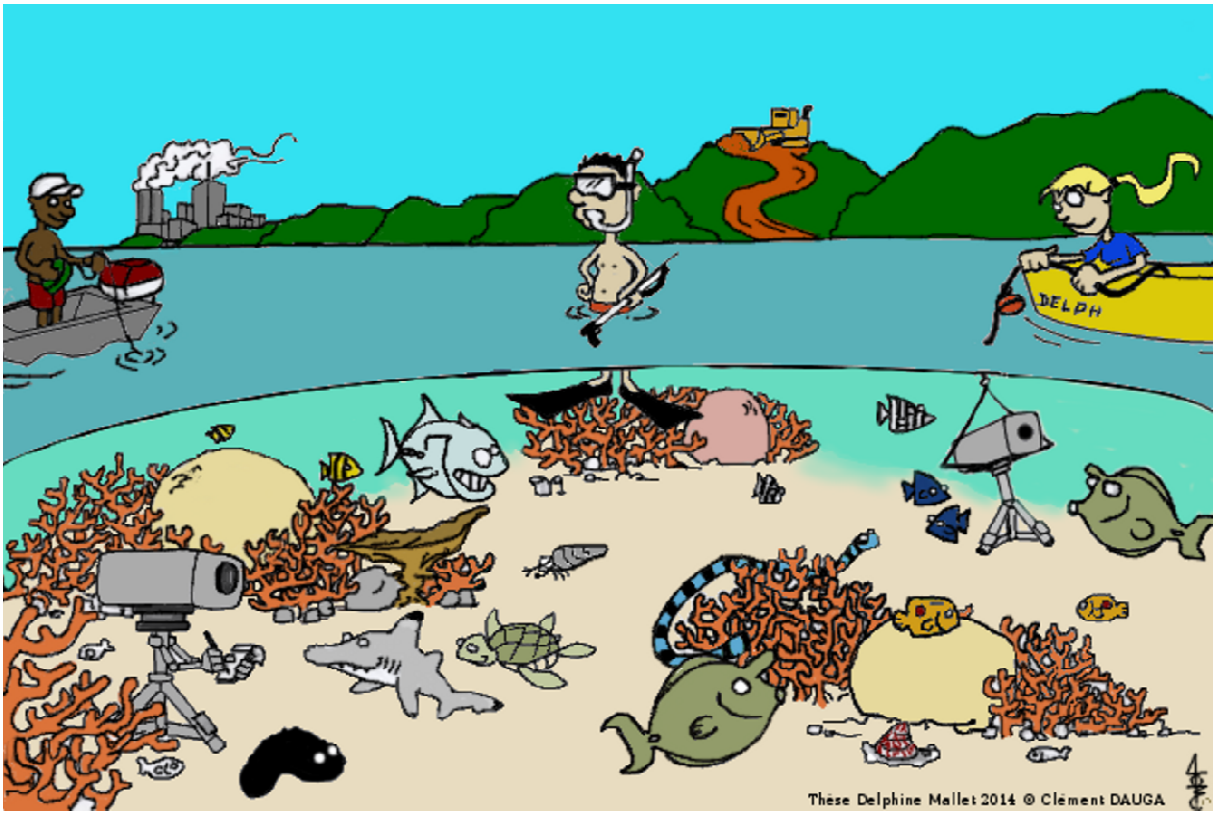
Pour des raisons logistiques, un seul habitat très localisé a été examiné dans cette étude. Afin de mieux comprendre les variations à petits échelles des communautés des poissons récifaux, il serait nécessaire d'étudier simultanément différents habitats. Un tel protocole pourrait être mis en œuvre en utilisant les systèmes « MICADO » et permettrait de répondre aux questions suivantes :

- Est ce que les profils de variations observés dans l'article 5 sont également observés dans d'autres habitats ? Si oui, lesquels ? Et quelles espèces présentent ces profils ?

- Peut-on établir une connectivité entre les variations observées sur des habitats suffisamment proches ?

CHAPITRE 6

Discussion générale et perspectives



Malgré la somme de connaissances acquises, la biodiversité des écosystèmes coralliens, son fonctionnement et sa dynamique sont loin d'être complètement connus, décrits et caractérisés. L'objectif de ce travail de thèse était de synthétiser l'ensemble des travaux publiés sur les techniques vidéo (chapitre 2), présenter deux techniques vidéo rotatives complémentaires (chapitre 3), d'évaluer la qualité de l'information obtenue à partir de ces dernières (chapitre 4) et d'utiliser les systèmes rotatifs programmables (MICADO) pour étudier les variations temporelles de l'ichtyofaune corallienne à l'échelle de l'heure de la journée et de la marée (chapitre 5). Ce travail répond ainsi au besoin de définir de nouvelles techniques d'observations complémentaires des techniques traditionnelles afin d'enrichir notre connaissance du fonctionnement et de la dynamique des écosystèmes coralliens (Mumby & Steneck 2008 ; Guillemot, 2009). L'ensemble des résultats obtenus sera discuté et mis en perspective dans ce sixième et dernier chapitre. Des éléments de réponses seront apportés aux trois questions posées en introduction :

1) Quels sont les atouts et les limites des techniques vidéo rotatives ?
2) Quelles sont les améliorations possibles à apporter aux différents systèmes afin de combler certaines de leurs limites ? Cette réflexion s'appuiera sur les connaissances et expériences acquises (chapitre 2) ainsi que sur les limites des systèmes existants identifiées dans le chapitre 3.
3) Quels sont les éléments de réponses apportés par l'étude des variations temporelles de l'ichtyofaune grâce à ces systèmes vidéo ? Quelles sont les perspectives et recommandations d'utilisation des techniques vidéo rotatives présentées dans cette thèse ?

1. Les systèmes vidéo rotatifs comme outils d'observation de l'ichtyofaune

1.1. Synthèse des résultats obtenus

Deux systèmes vidéo rotatifs complémentaires (STAVIRO et MICADO) développés en Nouvelle-Calédonie par L'IFREMER (en collaboration avec l'IRD et l'ADECAL pour le STAVIRO) ont été présentés dans le chapitre 3. Le développement de ces systèmes ainsi que de leurs protocoles d'utilisation s'est fait en amont de cette thèse (STAVIRO en 2007

et MICADO en 2008). De ce fait, le présent travail ne concerne pas les choix méthodologiques effectués sur ces systèmes (comme la rotation de 60° toutes les 30 secondes). Cependant, ces techniques (systèmes + protocoles) étant relativement nouvelles dans le paysage scientifique (tout au moins au début de cette thèse), leur présentation était indispensable. De plus, comme toute nouvelle technique, la qualité et la représentativité des informations obtenues à partir des enregistrements vidéo ont dû être évaluées afin d'en connaître les atouts et les limites. Le chapitre 4 a permis d'évaluer la technique STAVIRO au regard d'une technique UVC utilisant une méthodologie similaire (plongeur en point fixe rotatif) dans un premier temps. Dans un second temps, les données obtenues par différentes personnes analysant les mêmes vidéos ont été comparées afin d'évaluer la sensibilité des analyses d'images à l'observateur. Ces analyses ont permis de montrer que:

1) les techniques STAVIRO et UVC n'obtiennent pas la même image de l'ichtyofaune lorsqu'on les utilise pour échantillonner les mêmes points à moins d'une heure d'intervalle ;
2) la similarité entre les espèces identifiées est faible entre les techniques UVC et STAVIRO ;
3) les petites espèces[22] sont mieux observées avec les UVC aussi bien qualitativement (richesse spécifique) que quantitativement (densité) ;
4) aucune différence significative n'a été observée entre les techniques en termes de nombre d'espèces et d'individus des grandes espèces[23] ;
5) plus d'individus d'espèces pêchées ont été observés avec les STAVIRO ;
6) les UVC ont permis de mettre en évidence une structure des peuplements du site étudié en fonction du type de récif avec uniquement 26 stations échantillonnées sur les pentes récifales et pas les STAVIRO ;
7) les analyses vidéo effectuées sur une liste prédéfinie d'espèces[24] par des observateurs ayant 2 ans et 5 ans d'expérience n'étaient pas significativement différentes.
8) une formation à l'analyse des vidéos des observateurs est nécessaire afin de recouper les données impliquant différentes personnes (différences des observations entre les observateurs ayant le moins d'expérience (0 à 6 mois) avec ceux ayant une plus grande expérience (2 à 5 ans)). La durée de cette formation dépend de chaque

[22] Espèces dont la taille maximum connue est inférieure à 30 cm.
[23] Espèces dont la taille maximum connue est supérieure à 30 cm.
[24] Espèces emblématiques et d'intérêt halieutique en Nouvelle-Calédonie, voir chapitre 3

personne et la vérification des analyses vidéo par un observateur formé est nécessaire pendant au moins 6 mois.

1.2. Atouts et limites des techniques vidéo rotatives

Les systèmes MICADO et STAVIRO fonctionnent de la même façon en effectuant des rotations de 60° toutes les 30 seconds. Ils partagent de ce fait la plupart de leurs atouts et de leurs limites. Les principaux atouts de ces techniques résident dans le fait de ne pas nécessiter de plongeur pendant l'observation, d'obtenir une vision panoramique (rotation à 360° de la caméra) et de permettre de relever de nombreuses observations avec un effort relativement limité en mer. Ne pas nécessiter de plongeur lors de l'observation permet de s'affranchir de l'effet de l'Homme sur l'ichtyofaune, d'obtenir des informations sur des sites plus profonds avec une fréquence plus élevée que ne pourrait physiquement le faire un plongeur (limite du nombre de plongée par jour par personne, de la profondeur et du temps d'observation). La vision panoramique, obtenue par la rotation de la caméra à 360° permet quant à elle, de multiplier les observations des espèces, qu'elles soient sédentaires ou mobiles, augmentant la diversité des espèces recensées comparativement par exemple à un système vidéo non rotatif et non appâté[25]. L'enregistrement de nombreuses vidéos en un temps relativement faible en mer, permet de limiter les coûts associés à la récolte des données induit par le financement des moyens navigants, du pilote ainsi que du personnel déployant les systèmes vidéo. En effet, une moyenne de 30 vidéos par jour peuvent être enregistrées en utilisant 2 systèmes STAVIRO simultanément pendant 6 h en mer, quelle que soit la profondeur d'observation (jusqu'à 20 à 30 m). Les systèmes MICADO présentés dans cette thèse, permettent d'enregistrer 10 vidéos de 7 minutes par jour sans intervention extérieure pendant 3 jours consécutifs. A l'heure actuelle, ces systèmes sont limités par la capacité des batteries ainsi que par les organismes se développant au niveau du hublot du système, au-delà de 3 jours.

A l'inverse, les principales limites de ces techniques résident dans le fait de n'estimer qu'une partie de l'ichtyofaune présente (article 4, chapitre 2) ainsi que dans la difficulté à estimer les distances avec précision. De plus ces techniques ne permettent pas

[25] Les « systèmes vidéo appâtés » attirent les poissons près de l'objectif afin d'observer l'ensemble des individus présent sur un site (article 1, chapitre 2)

d'estimer les tailles des poissons (utilisation d'une mono-caméra) et l'analyse des vidéos nécessite un temps additionnel au laboratoire. Le fait de n'estimer qu'une partie de l'ichtyofaune permet uniquement d'étudier les assemblages de poissons au travers des espèces observées et identifiables sur les images vidéo. La difficulté à estimer précisément les distances due à l'utilisation d'un système vidéo composé d'une seule caméra, induit une incertitude au niveau de la superficie de la zone observée et donc des densités estimées. Ne pas estimer les tailles des individus[26], ne permet pas d'obtenir des estimations de biomasses précises en se basant sur les relations taille-poids. Enfin, le temps additionnel nécessaire pour analyser les vidéos doit être pris en compte dans les délais impartis aux études utilisant des systèmes vidéo. Le tableau 6.1 synthétise les principaux atouts et limites des techniques vidéo rotatives présentées dans cette thèse sur la base du protocole défini par Pelletier et al. (2012).

Tableau 6.1. Atouts et limites des techniques vidéo rotatives (STAVIRO et MICADO) présentées dans cette thèse

Atouts	Limites
• Ne nécessite pas de plongeur • Observations standardisées • Possibilité de réaliser un grand nombre d'observations par jour de mer • Ne nécessite pas d'expert en mer • Système maniable, non encombrant et facile à mettre en œuvre • Caractérisation de l'habitat et identification des poissons simultanée • Archivage d'une grande quantité de données • Plusieurs analyses des vidéos possibles • Possibilité de vérifier/valider les analyses vidéo	• Temps additionnel nécessaire pour analyser les vidéos au laboratoire • Influence de la visibilité (champ de vision restreint) • Taille non estimée • Difficulté à estimer les distances et donc la taille réelle des zones observées • Possibilité de double comptage • Difficulté d'identification au niveau de l'espèce des espèces cryptiques, des petites espèces, des espèces morphologiquement proches, des jeunes individus et des individus passant trop vite dans le champ de vision de la caméra

[26] Selon le protocole définit par Pelletier et al. (2012), les tailles des individus sont qualifiées en 3 classes (petit, moyen ou grand) par rapport à la taille maximum de l'espèce connue. Cet aspect n'a pas été traité dans cette thèse.

1.3. Zoom sur certaines limites : améliorations éventuelles

Les techniques vidéo rotatives présentent une gamme étendue d'applications qui pourrait être développées en perfectionnant certains aspects techniques et méthodologiques. Les éventuelles évolutions de ces techniques discutées dans cette partie permettraient de pallier en partie certaines limites définies précédemment.

Difficulté à identifier les petites espèces et les petits individus

Le protocole d'utilisation des systèmes STAVIRO ne prévoit pas de relever les espèces de petites tailles (taille maximum inférieure à 30 cm) autres que les Chaetodontidae (article 2, chapitre 2). Cependant, dans cette thèse, toutes les espèces observées sur les vidéos ont été prises en compte dans les différentes études afin de tester les limites des techniques vidéo rotatives. Dans le chapitre 4, nous avons mis en évidence que les espèces de petite taille étaient moins bien observées en utilisant les STAVIRO qu'en effectuant des UVC. Mon expérience en analyse vidéo (5 ans) confirme cette constatation puisque la plupart des espèces de petites tailles sont difficiles à observer et à différencier les unes des autres sur les vidéos en appliquant le protocole d'analyse défini par Pelletier et al. (2012). Ce protocole ne semble donc pas adaptée pour observer les petites espèces telles que les demoiselles (Pomacentridae), les barbiers (*Pseudanthias sp.*, Serranidae), les apogons (Apogonidae), etc.. Toutefois, le protocole d'échantillonnage peut être adapté à l'étude de ces petites espèces dans certains cas. En effet, lors de l'analyse des images, de nombreuses espèces de petite taille ont pu être observées à partir du moment où ces dernières se situaient suffisamment proches de l'objectif de la caméra. Par exemple, un des deux systèmes MICADO déployé au niveau du récif Aboré en 2012 (chapitre 4), se situait juste en face d'un « terrier de gobies » (Gobiidae). Sur ces images, j'ai observé de façon permanente (sur chaque séquence vidéo enregistrée) les allers et venues de 3 gobies (*Amblygobius phalaena*, Gobiidae) au cours du temps. Ces vidéos pourraient être utilisées afin d'étudier le comportement de ces individus en fonction du temps et des paramètres environnementaux (ce travail n'a pas été effectué au cours de cette thèse, faute de temps). L'étude de certains aspects de l'écologie d'espèces de petite taille, notamment leur comportement, est donc possible en utilisant

ces systèmes vidéo à partir du moment où le système est placé suffisamment proche du domaine vital de(s) l'espèce(s) à étudier (adaptation du protocole selon les besoins).

Possibilité de double comptage de certains individus

Même si une attention particulière est accordée à la direction de déplacement des poissons par rapport à l'orientation de la caméra lors de l'analyse des vidéos, il est possible de compter plusieurs fois un même individu. Ceci est vrai pour l'ensemble des techniques d'observation, cependant dans notre cas ce risque est accentué par la rotation de la caméra puisqu'il est difficile de suivre un individu d'un secteur à un autre. Comme discuté dans l'article 4, ce risque ne semble pas avoir de conséquence significative sur la qualité des données obtenues. En effet, les dénombrements des individus n'étaient pas significativement différent entre UVC et STAVIRO. Cependant, un effort particulier est requis lors de l'analyse d'image car une concentration particulière et une prise de décision sont nécessaires de la part de l'observateur sur la plupart des séquences, ce qui ralentit l'analyse des vidéos De plus, comme une prise de décision est nécessaire, les interprétations peuvent varier d'une personne à une autre.

Quatre caméras montées sur un même système, filmant en même temps les 360° obtenue par la rotation actuelle, permettraient de limiter de façon significative les risques de « double comptage » en observant les 360° simultanément. Un tel système nécessiterait 3 caméras supplémentaires par rapport au système actuel. Ces systèmes utilisent des caméras Sony en haute définition. Différents modèles sont utilisés aujourd'hui dans le cadre du projet AMBIO (SR11, XR500, PJ740) et une caméra coûte environ 1000€ (coût d'un système STAVIRO complet en 2013 est de 4800€). Utiliser 4 caméras pour un seul système augmenterait le coût d'investissement de 3000€, soit près de 60% et augmenterait l'encombrement du système. La qualité, la taille et le prix des caméras miniaturisées de nouvelle génération sont très attractifs (moins de 500 € avec le caisson étanche). Ces caméras sont utilisées depuis plus de deux ans par certaines équipes en Australie (Letessier et al., 2013a) et en Nouvelle-Calédonie depuis septembre 2012 (L. Vigliola & L. Wantiez, Com. Pers.). Ces caméras disposent aujourd'hui d'une autonomie pouvant aller jusqu'à 4h (suffisante pour STAVIRO et MICADO) et sont utilisées sur des profondeurs allant jusqu'à 40 mètres.

Si une solution basée sur plusieurs caméras doit être retenue, se pose la question de la procédure d'analyse des images. Afin de dénombrer et identifier les poissons présents sur les images, il serait indispensable d'analyser les 4 vidéos simultanément, par exemple en utilisant 4 écrans disposés côte à côte. Il serait nécessaire de tester ce type de configuration avant de statuer sur les avantages et inconvénients d'un tel changement.

Difficulté à estimer les tailles et les distances avec précision

La taille des individus est un élément important de la structure des communautés et du fonctionnement des écosystèmes marins (Fisher et al., 2010) pour différentes raisons. Ainsi, le taux de croissance des poissons (Hurley & Elliott, 1995 ; Sogard, 1997), leur maturité sexuelle (Johnson & Hixon, 2011) et les relations prédateurs-proies (Osenberg & Mittelbach, 1989) sont liés à la taille des individus. La sélectivité des engins de pêche (ligne, filet, chalut, senne, drague ou palangre[27]) dépend essentiellement de la taille individuelle (Peng et al., 2013). Les effets des activités de pêche sur les structures de tailles des communautés ichtyologiques ont été démontrés par de nombreux travaux (e.g. Rice et al., 1996 ; Graham et al., 2005 ; Kulbicki et al., 2007 ; Wilson et al., 2010 ; Langlois et al., 2012a) et de nombreux poissons associés aux récifs coralliens sont soumis à une pression de pêche professionnelle et/ou récréative (e.g. pour la Nouvelle-Calédonie : Guillemot, 2009 ; Jollit, 2012 ; Preuss, 2012).

Un des avantages indéniables des techniques vidéo par rapport aux autres techniques d'observations traditionnelles, est de pouvoir utiliser la technique dite de « stéréo-vidéo » afin de mesurer la taille des poissons observés. La stéréo-vidéo utilise 2 caméras montées sur un même axe filmant un plan fixe (Harvey & Shortis, 1995, 1998 ; Harvey et al., 2010 et article 1). Elle permet d'estimer les tailles et les distances des individus avec précision (Harvey et al., 2001a,b). Mesurer les individus permet également de les différencier plus aisément, et donc de limiter les risques de double comptage (Harvey et al. 2007). Différentes études ont montré que les estimations étaient bien plus précises en utilisant la stéréo-vidéo que les estimations obtenues en utilisant une seule caméra (Harvey et al. 2002b) ou un plongeur (Harvey et al., 2001a, b, 2002a, 2004). Cette technique est par ailleurs, de plus en plus souvent appliquée aux différentes techniques

[27] http://wwz.ifremer.fr/peche/Le-monde-de-la-peche/La-peche/comment/Les-engins

vidéo (article 1). C'est notamment le cas en Australie et en Nouvelle-Calédonie, où la grande majorité des équipes de recherche utilise maintenant la stéréo-vidéo (par exemple : Cappo et al., 2011 ; Mclean et al., 2011 ; Harvey et al., 2012a ; Langlois et al., 2012b).

Les systèmes vidéo rotatifs présentés dans cette thèse utilisent une seule caméra. Lors du développement des systèmes vidéo rotatifs, la priorité a été orientée sur la légèreté du système afin d'effectuer de nombreuses observations aisément et sur le coût compte tenu du matériel disponible sur le marché à cette époque. Afin d'obtenir une information robuste aux incertitudes d'évaluation des tailles due à l'utilisation d'une mono-caméra, l'abondance par 3 classes de taille (qualifié de « petit », « moyen » et « grand » par rapport à la taille maximum de l'espèce connue) a été préférée pour suivre les changements majeurs des peuplements de poissons (Pelletier et al., 2012, chapitre 3).

Adapter les systèmes actuels avec 2 caméras disposées en stéréo permettrait d'obtenir les tailles exactes des individus observés. Ces informations permettraient de fournir des estimations de biomasse en se basant sur des relations longueur-poids connues (Kulbicki, 2006), et d'étudier la structure de taille des espèces. De plus cette amélioration, permettrait de mesurer la superficie de la zone échantillonnée, ce qui n'est pas le cas avec les systèmes actuels. Cependant, un aspect freine encore ce développement. Si le coût additionnel du fait d'utiliser 2 caméras n'est plus un problème aujourd'hui (discuté précédemment), les images doivent être analysées à partir d'un package logiciel onéreux, par exemple EventMeasure software package (www.seagis.com) développé en Australie et payant (investissement global de 10000€ nécessaire : cube de calibration, système vidéo et logiciel d'analyse ; L. Vigliola, Com. Pers.). Du point de vue technique, une distance de près d'1 mètre entre les deux caméras est nécessaire afin d'obtenir une image de qualité suffisante (Harvey & Shortis, 1995). Dans le cas d'un système effectuant une rotation de 60° toutes les 30 secondes, il semble compliqué de faire tourner une plateforme composée de 2 caméras distantes de près d'1 mètre. Le système de largage du STAVIRO devrait également être élargi afin de ne pas s'emmêler avec les caméras au moment de la rotation[28] (Figure 6.1). De plus, ce type d'adaptation affecterait la portabilité souhaitée des systèmes actuels.

[28] Ce qui n'est pas le cas pour le système MICADO qui ne possède pas de système de largage

Même si ces changements ne paraissent pas être adaptés pour le moment aux systèmes vidéo rotatifs, il est important de garder un œil attentif sur les technologies qui progressent très vite dans ce domaine. Ce type d'adaptation est également en réflexion dans l'équipe dirigée par Marc Bouchoucha (IFREMER, Toulon, France) en Méditerranée dans un environnement moins complexe et diversifié que les récifs coralliens. Ces derniers utilisent les systèmes vidéo rotatifs actuels pour étudier l'impact des pressions anthropiques sur les peuplements de poissons (développement d'indicateurs de qualité en utilisant le système STAVIRO) ainsi que les évolutions circadiennes des peuplements de poissons associés aux fonds coralligènes (définition des fonctionnalités de cet habitat typique en utilisant le système MICADO) (M.Bouchoucha Comm Pers.[29]).

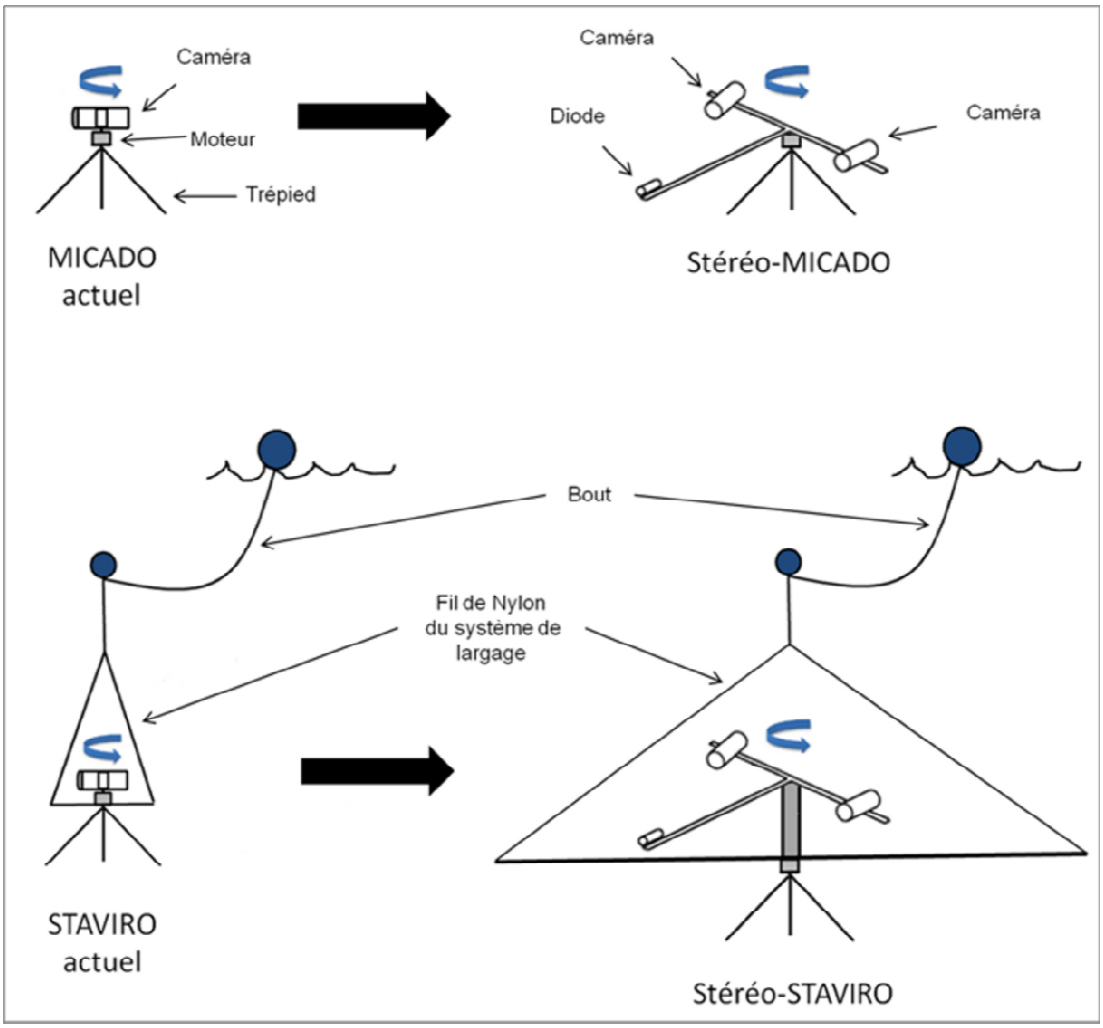


Figure 6.1. Schéma des systèmes vidéo rotatifs actuels (STAVIRO et MICADO) et représentation de la configuration de ces derniers utilisant des systèmes de stéréo-vidéos.

[29] Projet à venir au sein de cette équipe de recherche: Caractérisation des peuplements de poissons côtiers à l'échelle de la façade méditerranéenne : réponse au manque de connaissance identifié par le groupe de réflexion par l'utilisation couplée d'UVC et de STAVIRO.

2. Applications et perspectives d'utilisation des systèmes vidéo rotatifs

Une grande partie du travail présenté dans cette thèse concerne la méthodologie et les techniques d'observation vidéo rotatives, ne laissant que peu de place pour développer les applications de ces dernières. De nombreuses applications pourraient être effectuées avec ces systèmes : étude du comportement des poissons, étude de variations spatio-temporelles des espèces identifiables, etc. Afin de finaliser cette analyse des systèmes vidéo rotatifs, cette dernière section présente les principaux résultats de l'étude des variations temporelles de l'ichtyofaune effectuée en appliquant la technique vidéo MICADO et propose certaines applications des STAVIRO et des MICADO qu'il serait intéressant d'approfondir.

2.1. Application des techniques MICADO pour étudier les variations temporelles journalière d'une communauté de poissons coralliens : résultats et perspectives

Les variations temporelles à petites échelles (heure, jour) de l'ichtyofaune sont rarement considérées dans la conception de protocoles expérimentaux ou en tant que cause de changement lors de l'interprétation des résultats (voir chapitre 5 et la synthèse bibliographique sur les variations temporelles des assemblages de poissons récifaux de Bijoux et al. (2013)). Dans le chapitre 5, les systèmes MICADO ont été utilisés pour étudier ces variations temporelles dans un même habitat. L'article 5 met en évidence les variations cycliques journalières de l'ichtyofaune en fonction de l'heure de la journée et de l'état de la marée. Nous avons en effet, constaté des fluctuations régulières du nombre d'espèces et d'individus en fonction de l'heure de la journée et de l'état de la marée. Cette étude a également permis de mettre en évidence que l'influence de ces facteurs était différente selon les groupes trophiques et des « profils types » de mouvements par rapport à ces facteurs ont pu être mis en évidence pour certains groupes d'espèces. Ces résultats contribuent à la connaissance sur l'activité et les mouvements de l'ichtyofaune d'un même habitat, des aspects qui ne sont que rarement pris en compte dans les études d'évolution temporelle des assemblages de poissons de récif (Bijoux et al., 2013).

Dans la mesure où la structure de l'habitat influence la répartition de nombreuses espèces (Bozec, 2006 ; Yahya et al., 2011 ; Coker et al ., 2013 ; Graham & Nash, 2013), les résultats de cette étude ne peuvent pas être généralisés à l'ensemble des poissons récifaux ainsi qu'à d'autres habitats. Afin de caractériser les mouvements des espèces coralliennes sur différents sites, il serait nécessaire d'utiliser plusieurs systèmes MICADO synchronisés et disposés dans différents habitats. Ce type d'observation permettrait de renseigner l'influence des facteurs environnementaux sur l'ichtyofaune en fonction de la complexité de l'habitat et contribuerait à la caractérisation des variations temporelles à petites échelles de l'ichtyofaune encore insuffisamment connue. Comme le soulève Bijoux et al. (2013), ignorer ces variations augmente la part inexpliquée de la variation des observations (« bruit de fond ») ce qui complique la détection des changements dans les peuplements de poissons et réduit l'efficacité des observations. Les systèmes MICADO sont parfaitement adaptés à ce type d'étude et permettent de renseigner ces variations ainsi que de les prendre en compte lors de la conception de protocoles expérimentaux.

2.2. **Perspective méthodologique** *: Etudier l'impact d'un système vidéo rotatif sur l'ichtyofaune*

Toute perturbation de l'environnement peut influencer l'ichtyofaune, que ce soit par un ajout ou une extraction d'un élément. De ce fait, l'introduction d'un système vidéo rotatif dans un milieu peut entraîner des changements de comportement de l'ichtyofaune (attraction/répulsion). L'impact de la présence d'un système vidéo non appâtée n'a jamais été étudié à notre connaissance alors que l'effet d'un plongeur sur l'ichtyofaune a suscité plus d'études (par exemple : Chapman et al., 1974 ; Edgar et al., 2004 ; Bozec et al., 2011). Même si les UVC sont beaucoup plus souvent utilisés comme technique d'observation de l'ichtyofaune, ce constat est étonnant au vu de l'augmentation du nombre de travaux de recherches impliquant des systèmes vidéo ces 10 dernières années (122 publications entre 2002 et 2012 ; voir article 1, chapitre 1). Une étude méthodologique complémentaire serait, de ce fait, nécessaire afin de caractériser l'effet d'un système vidéo rotatif sur l'ichtyofaune. Deux aspects pourraient être abordés : la présence d'un système vidéo et l'impact du bruit de la rotation sur l'ichtyofaune.

Effet du déploiement, de la présence et de la récupération d'un système vidéo rotatif STAVIRO.

Selon le protocole défini dans l'article 2, les systèmes vidéo rotatif STAVIRO sont déployés depuis une petite embarcation, laissés sur le substrat pendant 12 minutes au minimum puis remontés à bord de l'embarcation. Les observations de l'ichtyofaune avant, pendant et après le déploiement de STAVIRO (appelé « système acteur ») seraient comparées les unes avec les autres à partir de vidéos enregistrées depuis un système vidéo fixe (appelé « système observateur »). Ce « système observateur » serait déployé avant l'étude proprement dite afin que les poissons de la zone s'habituent à sa présence et que ce dernier n'ait pas d'effet sur les observations. L'ensemble des poissons seraient dénombrés et identifiés dans un rayon de 10 mètres[30] autour du « système acteur » par section d'observation de 3 minutes (temps correspondant à une rotation). Afin d'obtenir une image représentative de la réponse de l'ichtyofaune à la mise en œuvre de station vidéo, ces observations devraient être suffisamment répliquées au sein des mêmes habitats ainsi que dans différents habitats (récif vivant, fond détritique, herbier, algueraie, fond lagonaire). Les données obtenues depuis le « système observateur » permettraient de répondre aux questions suivantes :

a) Est-ce que l'abondance et la richesse spécifique observées peuvent être considérées comme similaires avant, pendant et après le déploiement d'un système vidéo ?
b) Observe-t-on une évolution du nombre d'individus et d'espèces dans le temps (diminution ou augmentation de l'ichtyofaune entre les plages de 3 min d'observation montrant une attraction ou une répulsion des poissons en réponse au déploiement du système) ?
c) Quel est le délai avant stabilisation de l'ichtyofaune ? Autrement dit, quelle durée attendre avant d'enregistrer la vidéo après immersion du système ?

Effet du bruit induit par la rotation d'un système vidéo rotatif.

En plus de l'introduction d'un élément extérieur, les systèmes vidéo rotatifs génèrent un bruit induit par la rotation de la caméra qui peut influencer l'ichtyofaune. Une étude similaire à la précédente serait également nécessaire afin de statuer sur cet effet potentiel. Pour cela, 2 systèmes programmables (MICADO) devraient être utilisés: un rotatif (« système acteur ») et un non rotatif (« système observateur »). Sur le même

[30] Distance correspondante à la taille maximum des zones échantillonnées selon le protocole de Pelletier et al. (2012)

principe que précédemment le « système observateur » serait utilisé pour enregistrer des vidéos du « système acteur » et de la réponse de l'ichtyofaune due à la mise en rotation de ce dernier (qualification et quantification de l'ichtyofaune présente dans un rayon de 10 m autour du « système acteur »). Dans la pratique, les 2 systèmes seraient déployés en même temps et programmés pour réaliser l'étude quelques jours plus tard afin que l'ichtyofaune s'habitue à leurs présences. Le jour de l'étude, le « système observateur » filmerait le « système acteur » avant, pendant et après la mise en rotation de ce dernier (temps de rotation préalablement programmée). La comparaison entre le nombre d'individus et d'espèces, leurs comportements ainsi que la diversité ichtyologique observés entre les différentes phases étudiées permettrait de tester si le bruit induit par la rotation affecte significativement ou non les observations obtenues à partir des systèmes vidéo rotatifs.

2.3. **Perspective d'application** : Etude de l'ichtyofaune présente au niveau des fonds lagonaires

La Nouvelle-Calédonie possède le plus grand lagon du monde (surface de plus de 20000 km^2 ; Andréfouët et al., 2009). Par conséquent, il est difficile, voir techniquement impossible, de suivre et d'étudier l'ensemble de cette étendue avec les techniques traditionnelles. Certaines études se sont consacrées à l'étude de certains fonds meubles de Nouvelle-Calédonie, montrant que ces derniers étaient caractérisés par des habitats hétérogènes composés d'une grande diversité ichtyologique, rendant leurs estimations complexes (Kulbicki & Wantiez, 1990 ; Wantiez, 1994a,b ; Wantiez et al., 1996 ; Kulbicki et al., 2000). Ces auteurs soulèvent, la nécessité de combiner plusieurs méthodes pour évaluer les principaux composants des stocks de poissons associés aux fonds meubles. Les systèmes vidéo rotatifs sont parfaitement adaptés à l'étude de cette partie du paysage récifo-lagonaire. En effet, la surface uniforme des fonds meubles offre moins de possibilités de se cacher aux organismes qui y vivent rendant leur observation plus aisée (hormis les espèces s'enfouissant dans le sable). De plus, le positionnement des systèmes vidéo rotatifs ne présente pas de difficulté particulière dans ce type de fond, ni de restriction due à la profondeur (jusqu'à 20 à 30 m). Les chances d'observer les espèces mobiles sont amplifiées par l'observation à 360° plutôt que dans une seule direction comme le font les autres techniques utilisant la vidéo. Enfin, l'analyse des

vidéos enregistrées dans ce type d'habitat est également facilitée par la faible complexité de ce dernier. En effet, l'analyse des vidéos en vitesse accélérée permet de rapidement détecter la présence ou l'absence d'espèces sur les images.

2.4. **Perspective d'application** : Croiser les informations obtenues à partir de systèmes vidéo rotatifs avec les informations sur les pressions anthropiques appliquées sur le lagon

L'évolution de l'ichtyofaune au regard des pressions anthropiques est une question cruciale et générale (Davenport & Davenport, 2006 ; Selkoe et al., 2009 ; McClanahan, 2011 ; Brewer et al., 2013) dans la mesure où les activités humaines peuvent affecter l'équilibre des écosystèmes coralliens de différentes façon. Parmi les diverses activités susceptibles d'affecter significativement les écosystèmes récifaux, notons : les activités extractives comme la pêche (Brewer et al., 2013 ; Sangil et al., 2013) ou l'exploitation de poissons en aquariophilie (Andrews, 1990), les activités associée à l'urbanisme comme les rejets domestiques et industriels ainsi que la transformation du littoral (Pastorok & Bilyard, 1985 ; Grigg, 1994) et les activités récréatives (Medeiros et al., 2007). Les impacts des activités récréatives non contrôlées sur les milieux marins ont été démontrés par de nombreux travaux présentant l'effet du piétinement (Eckrich & Holmquist, 2000), de l'ancrage des bateaux (Backhurst & Cole, 2000), de la plongée sous-marine et de la plongée en apnée (Meyer & Holland, 2008) ainsi que de l'alimentation artificielle (Milazzo et al., 2005).

Dans ce contexte global, les systèmes vidéo rotatifs permettraient d'obtenir de nombreuses observations aux niveaux spatial et temporel avec un effort en mer relativement faible. Ces informations pourraient être recoupées avec des données issues de suivis de la fréquentation et de la pression de pêche appliquées sur le lagon afin d'évaluer les impacts des principaux usages sur certaines espèces de poisson.

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Annexe A

Nombre d'espèces endémiques et totales recensées par famille en Nouvelle-Calédonie selon Fricke et al. (2011)

(chapitre 1)

Famille	Nombre d'espèces	Nombre d'espèces endémiques
Total	**2328**	**107**
Gobiidae	190	9
Labridae	129	
Pomacentridae	112	
Serranidae	95	4
Apogonidae	81	3
Blenniidae	64	
Macrouridae	52	9
Myctophidae	52	
Scorpaenidae	52	
Muraenidae	49	
Carangidae	42	
Lutjanidae	43	
Syngnathidae	43	5
Acanthuridae	40	
Chaetodontidae	36	
Bothidae	35	10
Holocentridae	31	
Tetraodontidae	30	
Tripterygiidae	29	2
Ophichthidae	28	4
Scaridae	28	
Phosichthyidae	26	
Ophidiidae	24	2
Callionymidae	24	8
Lethrinidae	24	
Congridae	23	3
Monacanthidae	22	
Mullidae	21	1
Pomacanthidae	21	
Balistidae	19	
Exocoetidae	17	
Mugilidae	17	
Platycephalidae	17	1
Synodontidae	17	
Nemipteridae	16	
Carcharhinidae	15	
Paralepididae	15	
Pinguipedidae	15	2
Gempylidae	14	1
Ptereleotridae	14	1
Caesionidae	13	
Pseudochromidae	13	2
Scombridae	13	
Galaxiidae	12	1
Haemulidae	12	
Moridae	12	1
Siganidae	12	1
Triglidae	12	4
Antennariidae	11	
Eleotridae	11	
Melamphaidae	11	
Cirrhitidae	10	
Clupeidae	10	
Leiognathidae	10	
Bramidae	9	
Dasyatidae	9	
Ostraciidae	9	
Samaridae	9	5
Sternoptychidae	9	
Bythitidae	8	1
Carapidae	8	
Engraulidae	8	
Soleidae	8	1
Sphyraenidae	8	
Synanceiidae	8	
Synaphobranchidae	8	
Acropomatidae	7	
Aploactinidae	7	
Atherinidae	7	1
Belonidae	7	
Chlopsidae	7	
Diodontidae	7	
Gobiesocidae	7	
Malacanthidae	7	
Peristediidae	7	
Plesiopidae	7	
Priacanthidae	7	
Hemiramphidae	6	
Istiophoridae	6	
Ogcocephalidae	6	
Pempheridae	6	1
Percophidae	6	
Tetrarogidae	6	
Triacanthodidae	6	1
Anguillidae	5	
Berycidae	5	
Echeneidae	5	
Gerreidae	5	
Kyphosidae	5	
Myliobatidae	5	

Nomeidae	5	
Serrivomeridae	5	1
Trachichthyidae	5	1
Bregmacerotidae	4	
Champsodontidae	4	
Chiasmodontidae	4	
Etmopteridae	4	2
Kuhliidae	4	
Microdesmidae	4	
Molidae	4	
Moringuidae	4	
Pentacerotidae	4	
Polynemidae	4	
Scopelarchidae	4	
Scyliorhinidae	4	3
Sparidae	4	3
Squalidae	4	1
Trichiuridae	4	
Alopiidae	3	
Ambassidae	3	
Aphyonidae	3	1
Bembridae	3	1
Callanthiidae	3	
Caproidae	3	
Cetomimidae	3	
Chimaeridae	3	
Ephippidae	3	
Evermannellidae	3	
Grammicolepididae	3	
Lamnidae	3	
Opisthoproctidae	3	
Opistognathidae	3	
Scatophagidae	3	
Setarchidae	3	
Terapontidae	3	
Trichonotidae	3	
Uranoscopidae	3	
Urolophidae	3	3
Zeniontidae	3	
Albulidae	2	
Alepisauridae	2	
Alepocephalidae	2	
Ammodytidae	2	
Anomalopidae	2	
Argentinidae	2	
Arhynchobatidae	2	
Bathylagidae	2	
Chaunacidae	2	
Cheilodactylidae	2	
Cichlidae	2	
Colocongridae	2	
Coryphaenidae	2	
Creediidae	2	
Cynoglossidae	2	
Cyprinidae	2	
Dalatiidae	2	
Derichthyidae	2	
Draconettidae	2	
Emmelichthyidae	2	
Fistulariidae	2	
Hexanchidae	2	
Howellidae	2	
Ipnopidae	2	
Linophrynidae	2	
Macroramphosidae	2	
Nemichthyidae	2	
Nettastomatidae	2	
Notosudidae	2	
Paraulopidae	2	1
Parazenidae	2	
Pleuronectidae	2	1
Poeciliidae	2	
Polymixiidae	2	
Rhinobatidae	2	
Rhyacichthyidae	2	2
Sillaginidae	2	
Solenostomidae	2	
Sphyrnidae	2	
Triakidae	2	
Xenisthmidae	2	
Anacanthobatidae	1	
Anoplogastridae	1	
Aracanidae	1	
Ariommatidae	1	
Ateleopodidae	1	
Atherionidae	1	
Aulopidae	1	
Aulostomidae	1	
Banjosidae	1	
Barbourisiidae	1	
Bathyclupeidae	1	
Centrarchidae	1	
Centriscidae	1	
Centrolophidae	1	

Centrophoridae	1	
Cepolidae	1	
Ceratiidae	1	
Chanidae	1	
Chirocentridae	1	
Chlorophthalmidae	1	
Clinidae	1	1
Dactylopteridae	1	
Diretmidae	1	
Drepaneidae	1	
Echinorhinidae	1	
Elopidae	1	
Epigonidae	1	
Euclichthyidae	1	
Eupharyngidae	1	
Gigantactinidae	1	
Giganturidae	1	
Ginglymostomatidae	1	
Gonorynchidae	1	
Halosauridae	1	
Himantolophidae	1	
Hoplichthyidae	1	
Kraemeriidae	1	
Lampridae	1	
Lobotidae	1	
Lophiidae	1	
Megalopidae	1	
Menidae	1	
Microstomatidae	1	
Monocentridae	1	
Monodactylidae	1	
Muraenesocidae	1	
Myrocongridae	1	1
Neoscopelidae	1	
Neosebastidae	1	
Odontaspididae	1	
Omosudidae	1	
Osphronemidae	1	
Ostracoberycidae	1	
Paralichthyidae	1	
Pegasidae	1	
Platytroctidae	1	
Plectrogenidae	1	
Plotosidae	1	
Pseudocarchariidae	1	
Rajidae	1	
Rhincodontidae	1	
Rhinochimaeridae	1	
Rondeletiidae	1	
Scombrolabracidae	1	
Sebastidae	1	
Stegostomatidae	1	
Stylephoridae	1	
Symphysanodontidae	1	
Trachipteridae	1	
Triodontidae	1	
Veliferidae	1	
Xiphiidae	1	
Zanclidae	1	1
Zeidae	1	

Annexe B

Matériels supplémentaires de l'article 1 : Synthèse bibliographique de 60 ans de publications sur les techniques vidéo sous-marines utilisées pour observer la biodiversité marine côtière: (1952 – 2012)
(chapitre 2)

Supplementary material A. Geographical distribution of reviewed studies. Numbers after each region correspond to references available at the end of this document. They are classified from the oldest to the most recent reference for each region.

Technique	Region	Published years
RUV	United Kingdom [9, 10, 11, 31, 7]	1952 - 2002
	USA [6, 108, 23, 136, 59, 8, 30, 78, 126]	1957 - 2012
	Bahamas [106, 12, 104, 105, 157, 158, 48, 160, 98, 159, 107, 147, 138, 41, 42, 134, 135, 43, 154]	1962 - 1973
	Mediterranean sea [62, 46, 52, 146, 1, 45]	1979 - 2012
	Canada [103, 145, 58, 56, 61, 57]	1994 - 2008
	New Zealand [79, 80, 68, 81, 82, 83, 84, 77, 85, 87]	1995 - 2007
	Australia [16, 35, 89, 171, 17, 65, 122, 123, 172, 15, 66, 67, 130, 49, 94, 93, 95, 167, 18, 96, 114, 168]	2003 - 2012
	Ireland [101, 72]	2004 - 2009
	Baltic sea [63]	2007
	Taiwan [100]	2007
	Gulf of Mexico [175]	2008
	Thailand [51]	2010
	South Africa [14, 19]	2010 - 2012
	Brazil [117]	2012
	Japan [125]	2012
	New Caledonia [144]	2012
	Reunion Is. [39]	2012
TOWV	Mediterranean sea [120, 155]	1975 - 2007
	United Kingdom [97, 153]	1977 - 2006
	Philippines [169]	1997
	USA [141, 151, 162, 156, 150, 75]	1997 - 2008
	New Zealand [26, 133, 37]	1999 - 2009
	Dubai [148]	2001
	Australia [127, 132]	2006 - 2012
	Hawaï [102]	2006
	Japan [91]	2006
	Baltic sea [27]	2007
	Canary Is. [4]	2007
	Iceland [73]	2012
	Norway [28]	2012

Technique	Region	Published years
DOV	Venezuela [2]	1975
	USA [2, 50, 74, 131, 115, 3, 149]	1975 - 2001
	Gulf of Mexico [24, 25]	1991 - 1994
	Georgia [142]	1994
	Australia [38, 139, 76, 140, 171, 112, 174]	1995 – 2010
	Philippines [169]	1997
	Reunion Is. [164, 165]	2005
	China [109]	2006
	Hawaï [102]	2006
	Mariana Is. [99]	2006
	Egypt [116, 166]	2007 - 2008
	Brazil [47]	2008
	New Caledonia [143]	2011
BRUV	Hawaï [60]	1995
	Gulf of Mexico [70]	1996
	New Zealand [5, 177, 179, 180, 53, 54, 178, 111, 133, 87, 13]	1999 - 2011
	Australia [35, 176, 32, 171, 33, 34, 92, 121, 170, 181, 173, 112, 174, 40, 44, 129, 36, 118, 128, 20, 55, 64, 69, 86, 88, 90, 110, 113, 119, 132, 152, 182]	2003 - 2012
	Mediterranean sea [161]	2007
	USA [163, 29]	2008 - 2012
	Fiji [71]	2011
	North sea [124]	2011
	Belize [22]	2012
	United Kingdom [21]	2012

Supplementary material B. Main outcomes of the studies comparing a video technique with UVC (62% of comparative studies, Table 7). H-BRUV=Horizontal Remote Underwater Video, RUV=Remote Underwater Video, SRUV=stereo remote underwater video, DOV= Diver-Operated Video, TOWV= towed video, UVC=underwater visual census, V-BRUV=Vertical Remote Underwater Video.

	Main outcomes
RUV UVC	Highlight known taxa-specific attraction or repulsion effects with respect to diver[68]. Divers could make observations that were not possible from RUV (underwater perception & mobility)[68]. Density estimates of the five most abundant fish species were always greater from UVC than from RUV[68]. RUV permitted the detection of the most species and the largest number of individuals[46]. RUV was more cost-effective than UVC[68]. Variable visibility was the main limitation of the video technique[46].
SRUV UVC	Highlight diver effect (difference in estimates made by beginners vs. experienced scientific divers)[81, 82, 83]. Low variability around true lengths estimates made by SRUV[81, 83]. The coefficient of variation of fish length estimate was significantly lower for SRUV than for UVC[81, 82]. The power to detect changes in mean length was higher with SRUV[81, 82]. Diver-based estimates were more accurate (mean error 0.87 cm) than UVC but less precise (SD 5.29 cm)[83] and precision depended on the distance[84]. The error in the estimates increased as the individual moved away from the diver[84]. Diver-based estimates were less accurate than the stereo-video technique[83]. Distance was underestimated by divers[84].
BRUV UVC	BRUV recorded a larger number of species[110, 172, 176], more mobile predators[48] and a larger abundance of *Lethrinidae*[175] than UVC UVC recorded larger species richness and abundance (in terms of all species, herbivores, cryptic species, and most territorial species), higher richness, and higher biodiversity[44, 111, 165]. Data from BRUV could not be converted into density estimates per unit area[133]. BRUV was not suitable for the estimation of small snapper densities in an area of very high juvenile densities[133].
V-BRUV UVC	Density and average size was significantly larger for V-BRUV than for UVC[176, 178]. UVC recorded a larger abundance and diversity of fish[110]. Relative fish density was similar for both methods[178]. V-BRUV was an effective (and sometimes superior) alternative to UVC methods for estimating relative densities of predatory reef fish[176]. Lethrinidae and Serranidae did not approach the video system when the camera was above them[110].
TOWV UVC	Species richness, abundance, overall sampling effort and total surveyed area (121.968 ha vs. 0.310 ha) were higher when using TOWV[4]. TOWV estimates provided the most accurate coverage of major categories of benthic substrate[116]. TOWV only partially detected the very small fish but was more appropriate for larger individuals[133]. TOWV was more effective in term of observed size range, abundance estimates and cost[133].
DOV UVC	UVC recorded more red algae taxa than DOV, and DOV tended to overestimate the percent cover of rock and articulated coralline algae[115] DOV detected more individuals but UVC identified more species[74]. UVC was more accurate, better detected trends over time[109], recorded larger abundance and species richness[143], and was more cost-effective[115]. DOV provided representative observations of fish abundance and species diversity, although fewer species and individuals were detected[143]. Coral cover estimates were similar, but DOV-based cover estimates were higher for coral bleaching, gorgonians and macroalgae[149]. UVC overestimated the percent coral cover in coral-rich areas[109]. DOV and UVC yielded similar values for coral cover[149]. Browsing DOV detected more individuals and species than straight DOV, conducting DOV before or after UVC did not affect DOV observations[143]. The proportion of fish that were not identified up to the species level was 3.3% in High Definition video observations vs 1.7% in UVC[143].

Supplementary material C. Main outcomes of comparisons between video techniques (19% of all comparative studies, Table 7)

Techniques	Main outcomes
stereo-RUV RUV	Estimates were significantly more accurate and precise with the stereo-RUV than with the monovideo[84].
stereo-RUV stereo-BRUV	Species richness based on stereo-RUV was larger in diversified habitat and lesser in lower reef relief, while species richness based on stereo-BRUV was similar in the 2 habitats, and the relative abundance of rare and large predators and species richness were larger[172]. None of the techniques sampled small cryptic species (s.a. Gobiidae and Blenniidae)[172].
Stereo-RUV Stereo-DOV	Stereo-DOV recorded more species (42 vs. 23) and sampled more smaller or cryptic species than other methods (divers looked for them)[172]. Labridae richness was higher from stereo-RUV[172]. Both techniques detected a larger number of species in diversified habitat and a lesser number in lower reef relief[172]. None of the techniques identified small cryptic species (s.a. Gobiidae and Blenniidae)[172].
RUV BRUV	BRUV recorded difference in fish assemblages between habitats (in both temperate and tropical regions)[87]. The bait attracted a larger number of carnivores and scavengers without decreasing the representativeness of other trophic groups such as herbivores or omnivores[87].
H-BRUV V-BRUV	H-BRUV detected more fish individuals than V-BRUV[111]. (which was found to work well in New Zealand[176, 178]) H-BRUV recorded 14 species versus 3 species from V-BRUV[111].
stereo-BRUV DOV	DOV detected a larger number of species in diversified habitat and lesser in lower reef relief[172]. DOV detected a larger abundance of small Pomacentridae, Labridae and Scaridae[171]. Species richness based on stereo-BRUV was similar in the 2 habitats, and the relative abundance of rare and large predators and species richness were larger[172]. Stereo-BRUV observed larger species richness, larger relative biomasses of generalist carnivores. Spatial and temporal changes in fish assemblage were better detected from stereo-BRUV[110]. Stereo-BRUV was cost-effective for monitoring fish assemblages[110]. Observed species richness was 40% higher with stereo-BRUV compared to DOV. The number and abundance of large target species were larger, as well as many non target species[171]. None of the techniques detected small cryptic species (s.a. Gobiidae and Blenniidae)[172]. No difference in the biomass of herbivores observed by the 2 techniques[110].
V-BRUV TOWV	Data from BRUV could not be converted into density estimates per unit area[133]. BRUV were not suitable for the estimation of small snapper densities in an area of very high juvenile densities[133]. TOWV only partially detected the very small fish but was more appropriate for larger individuals[133]. TOWV was more effective in term of observed size range, abundance estimates and cost[133].

Supplementary material D. Main outcomes of comparisons between a video technique and fishing or acoustics (14% of all comparative studies about fishing techniques and 5% about acoustics, Table 7)

Techniques	Main outcomes
RUV Fishing	RUV detected more species and individuals[46]. Variable visibility was the main limitation of the video technique[46].
BRUV Fishing	BRUV recorded more species and individuals than fishing[46]. Trawling recorded mostly sedentary, cryptic and demersal species, but also more nocturnal species[32]. BRUV recorded larger and more mobile species[32].
V-BRUV Fishing	Observed size structures were consistent between the two techniques[178]. Relative densities were similar for both techniques[178]. Fishing recorded the largest species number[133]. Data from V-BRUV could not be converted into density estimates per unit area[133]. V-BRUV was not suitable for the estimation of small snapper densities in an area of very high juvenile densities[133].
TOWV Fishing	Fishing recorded the largest species number[133]. TOWV only partially detected the very small fish but was more appropriate for larger individuals[133]. TOWV was more effective in term of observed size range, abundance estimates and cost[133].
BRUV Acoustic	Acoustics coupled with a video camera produced complementary estimates of reef fish abundance[70]. Video data provided species identifications and abundance estimates that may vary with water clarity[70]. Acoustic data were not dependent on visibility[70].

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Annexe C

Annexes associées à la comparaison des analyses vidéo effectuées par différents observateurs (chapitre 4)

Annexe C1. Nombre de familles, genres, espèces et individus observé par les différents observateurs sur chacune des vidéos.

	Nombre de famille				Nombre de genre			
	Obs1	ObS2	Obs3	Obs4	Obs1	Obs2	Obs3	Obs4
vidéo 1	9	11	11	9	9	14	14	12
vidéo 2	11	9	11	10	15	12	14	12
vidéo 3	10	11	11	12	18	20	19	16
vidéo 4	6	7	6	4	6	7	6	4
vidéo 5	1	1	1	1	1	1	1	1
vidéo 6	6	7	7	5	6	6	6	5
vidéo 7	2	2	2	2	2	2	2	2
vidéo 8	2	2	2	1	3	3	2	2
vidéo 9	2	2	2	2	3	2	2	2
Toutes	15	15	15	14	30	28	25	26

	Nombre d'espèce				Nombre d'individu			
	Obs1	Obs2	Obs3	Obs4	Obs1	Obs2	Obs3	Obs4
vidéo 1	14	13	15	14	33	35	36	26
vidéo 2	16	13	15	12	31	26	30	25
vidéo 3	18	22	21	20	59	38	56	62
vidéo 4	6	6	5	2	7	9	9	6
vidéo 5	1	1	0	0	1	2	2	1
vidéo 6	6	8	6	5	36	34	26	28
vidéo 7	2	2	1	1	10	10	8	8
vidéo 8	3	3	2	2	81	97	96	60
vidéo 9	4	3	3	3	116	98	83	84
Toutes	44	42	39	37	374	349	346	300

Annexe C2. Significativité des coefficients des droites de régressions linéaires ("y = ax+b" = ou ≠ "y=x") (test de Student). « a » : pente de la droite de régression et « b » ordonnée l'origine de la droite de régression.

	Famille		Genre		Espèce		Individu	
Observateurs	**a**	**b**	**a**	**b**	**a**	**b**	**A**	**b**
Obs1 vs Obs2	1,01 NS	0,26 NS	1,04 NS	0,17 NS	1,03 NS	-0,13 NS	0,90 NS	1,35 NS
Obs1 vs Obs3	0,89 NS	0,21 NS	0,86 NS	0,68 NS	0,85 **	1,34 *	1,06 NS	0,67 NS
Obs1 vs Obs4	0,89 NS	0,89 NS	1,02 NS	0,64 NS	0,89 NS	1,97 NS	1,28 *	-1,12 NS
Obs2 vs Obs3	0,93 NS	0,29 NS	0,98 NS	0,28 NS	0,91 NS	1,03 NS	1,03 NS	-0,89 NS
Obs2 vs Obs4	0,92 NS	1,09 NS	1,15 NS	0,26 NS	0,96 NS	1,58 NS	1,11 NS	1,77 NS
Obs3 vs Obs4	0,94 NS	-0,43 NS	0,84***	0,08 NS	0,92 NS	-0,43 NS	0,80 NS	2,42 NS

***NS** : non significatif ; * : p<0,05 ; ** : p<0,01 ; *** : p<0.001*

Annexe C3. Liste des espèces identifiées par chaque observateur sur l'ensemble des vidéos. Les espèces observées par les 4 observateurs sont représentées en gras. La colonne « commentaire » donne une possible explication au espèce qui n'ont pas été observée par les 4 observateurs.

			identification			
Famille	**Genre**	**espèce**	**Obs1**	**Obs2**	**Obs3**	**Obs4**
Acanthuridae	Acanthurus	blochii	non	oui	non	non
Acanthuridae	**Acanthurus**	**nigricauda**	**oui**	**oui**	**oui**	**oui**
Acanthuridae	Acanthurus	nigrofuscus	oui	non	non	non
Acanthuridae	Acanthurus	thompsoni	non	non	oui	oui
Acanthuridae	Acanthurus	xanthopterus	oui	non	non	non
Acanthuridae	**Ctenochaetus**	**striatus**	**oui**	**oui**	**oui**	**oui**
Acanthuridae	**Naso**	**unicornis**	**oui**	**oui**	**oui**	**oui**
Acanthuridae	Zebrasoma	scopas	oui	non	non	non
Balistidae	Balistapus	undulatus	non	oui	non	non
Balistidae	**Sufflamen**	**chrysopterum**	**oui**	**oui**	**oui**	**oui**
Balistidae	Sufflamen	fraenatum	oui	oui	oui	non
Carangidae	Gnathanodon	speciosus	oui	oui	oui	non
Carangidae	Pseudocaranx	dentex	oui	oui	non	oui
Carangidae	Seriola	lalandi	non	non	non	oui
Carcharhinidae	**Triaenodon**	**obesus**	**oui**	**oui**	**oui**	**oui**
Chaetodontidae	**Chaetodon**	**auriga**	**oui**	**oui**	**oui**	**oui**
Chaetodontidae	Chaetodon	speculum	oui	non	oui	oui
Chaetodontidae	Chaetodon	unimaculatus	non	oui	oui	non
Chaetodontidae	**Heniochus**	**acuminatus**	**oui**	**oui**	**oui**	**oui**
Chaetodontidae	Heniochus	monoceros	oui	non	oui	oui
Chanidae	Chanos	chanos	oui	oui	oui	non
Haemulidae	**Diagramma**	**pictum**	**oui**	**oui**	**oui**	**oui**
Labridae	Bodianus	loxozonus	non	oui	non	non
Labridae	**Bodianus**	**perditio**	**oui**	**oui**	**oui**	**oui**
Labridae	**Cheilinus**	**chlorourus**	**oui**	**oui**	**oui**	**oui**
Labridae	Choerodon	anchorago	non	non	non	oui
Labridae	Choerodon	graphicus	oui	non	non	non
Labridae	Coris	batuensis	oui	non	non	non
Labridae	**Hemigymnus**	**melapterus**	**oui**	**oui**	**oui**	**oui**
Lethrinidae	**Lethrinus**	**atkinsoni**	**oui**	**oui**	**oui**	**oui**
Lethrinidae	**Lethrinus**	**nebulosus**	**oui**	**oui**	**oui**	**oui**
Lethrinidae	Lethrinus	rubrioperculatus	non	oui	non	non
Lethrinidae	Monotaxis	grandoculis	non	oui	non	non
Lutjanidae	Lutjanus	bohar	oui	oui	non	oui
Lutjanidae	Lutjanus	gibbus	non	oui	oui	oui
Lutjanidae	Lutjanus	vitta	oui	oui	oui	non
Lutjanidae	**Macolor**	**niger**	**oui**	**oui**	**oui**	**oui**
Mullidae	**Parupeneus**	**barberinoides**	**oui**	**oui**	**oui**	**oui**
Mullidae	**Parupeneus**	**barberinus**	**oui**	**oui**	**oui**	**oui**

Mullidae	**Parupeneus**	**heptacanthus**	**oui**	**oui**	**oui**	**oui**
Mullidae	**Parupeneus**	**multifasciatus**	**oui**	**oui**	**oui**	**oui**
Mullidae	**Parupeneus**	**pleurostigma**	**oui**	**oui**	**oui**	**oui**
Mullidae	Parupeneus	spilurus	oui	non	non	non
Mullidae	Upeneus	tragula	oui	non	non	non
Scaridae	**Chlorurus**	**sordidus**	**oui**	**oui**	**oui**	**oui**
Scaridae	**Hipposcarus**	**longiceps**	**oui**	**oui**	**oui**	**oui**
Scaridae	Scarus	chameleon	oui	non	oui	non
Scaridae	Scarus	ghobban	oui	oui	non	non
Scaridae	Scarus	psittacus	non	oui	oui	oui
Scaridae	**Scarus**	**schlegeli**	**oui**	**oui**	**oui**	**oui**
Serranidae	Cephalopholis	argus	non	oui	non	non
Serranidae	Cephalopholis	boenak	non	non	non	oui
Serranidae	**Epinephelus**	**maculatus**	**oui**	**oui**	**oui**	**oui**
Serranidae	Epinephelus	tauvina	non	non	oui	non
Serranidae	**Plectropomus**	**leopardus**	**oui**	**oui**	**oui**	**oui**
Siganidae	**Siganus**	**doliatus**	**oui**	**oui**	**oui**	**oui**
Siganidae	**Siganus**	**puellus**	**oui**	**oui**	**oui**	**oui**
Zanclidae	**Zanclus**	**cornutus**	**oui**	**oui**	**oui**	**oui**

Annexe C4. Nombre d'individus identifiés et non identifiés au niveau de l'espèce (ind.) et nombre d'espèces identifiées (esp.) ou non (sp.) correspondantes, par vidéo pour chaque observateur. Les nombres entre parenthèses représentent le pourcentage d'individus par vidéo pour chaque classe. Les espèces correspondantes aux individus non identifiés sont détaillées dans l'annexe suivante (Annexe C5).

	Obs1		Obs2		Obs3		Obs4	
	identifié	**non identifié**	**identifié**	**non identifié**	**identifié**	**non identifié**	**identifié**	**non identifié**
vidéo 1	30 ind. (91%) 14 esp.	3 ind. (9%) 2 sp.	29 ind. (83%) 13 esp.	6 ind. (17%) 3 sp.	31 ind. (86%) 15 esp.	5 ind. (14%) 3 sp.	25 ind. (96%) 14 esp.	1 ind. (4%) 1 sp.
vidéo 2	29 ind. (94%) 16 esp.	2 ind. (7%) 2 sp.	20 ind. (77%) 13 esp.	6 ind. (23%) 2 sp.	21 ind. (70%) 15 esp.	9 ind. (30%) 4 sp.	15 ind. (60%) 12 esp.	10 ind. (40%) 3 sp.
vidéo 3	45 ind. (76%) 18 esp.	14 ind. (24%) 4 sp.	36 ind. (95%) 22 esp.	2 ind. (5%) 2 sp.	41 ind. (73%) 21 esp.	15 ind. (27%) 7 sp.	55 ind. (89%) 20 esp.	7 ind. (11%) 4 sp.
vidéo 4	7 ind. (100%) 6 esp.	0	8 ind. (89%) 6 esp.	1 ind. (11%) 1 sp.	7 ind. (78%) 5 esp.	2 ind. (22%) 1 sp.	3 ind. (50%) 2 esp.	3 ind. (50%) 2 sp.
vidéo 5	1 ind. (100%) 1 esp.	0	2 ind. (100%) 1 esp.	0	0	2 ind. (100%) 1 sp.	0	1 ind. (100%) 1 sp.
vidéo 6	36 ind. (100%) 6 esp.	0	34 ind. (100%) 8 esp.	0	15 ind. (58%) 6 esp.	11 ind. (42%) 1 sp.	28 ind. (100%) 5 esp.	0
vidéo 7	10 ind. (100%) 2 esp.	0	10 ind. (100%) 2 esp.	0	5 ind. (63%) 1 esp.	3 ind. (38%) 1 sp.	7 ind. (88%) 1 esp.	1 ind. (12%) 1 sp.
vidéo 8	81 ind. (100%) 3 esp.	0	91 ind. (94%) 3 esp.	6 ind. (6%) 2 sp.	68 ind. (71%) 2 esp.	28 ind. (29%) 2 sp.	48 ind. (80%) 2 esp.	12 ind. (12%) 1 sp.
vidéo 9	27 ind. (23%) 4 esp.	89 ind. (77%) 1 sp.	58 ind. (59%) 3 esp.	40 ind. (41%) 1 sp.	49 ind. (59%) 2 esp.	34 ind. (41%) 1 sp.	51 (61%) esp.	33 ind. (39%) 1 sp.
Total	266 ind. (71%) 44 esp.	108 ind. (29%) 9 sp.	288 ind. (83%) 42 esp.	61 ind. (17%) 11 sp.	237 ind. (68%) 39 esp.	109 ind. (32%) 21 sp.	232 ind. (77%) 37 esp.	68 ind. (23%) 14 sp.

Annexe C5. Détails des observations où les individus non pas été identifiés jusqu'à l'espèce par vidéo pour chaque observateur.

Observateur 1 :

Vidéo	Famille	Genre	Espèce	Abondance
video1	Scaridae	ge.	sp.	1
video1	Serranidae	ge.	sp.	2
video2	Lethrinidae	Lethrinus	sp.	1
video2	Scaridae	Scarus	sp.	1
video3	Lethrinidae	Gymnocranius	sp.	1
video3	Lethrinidae	Lethrinus	sp.	9
video3	Acanthuridae	Naso	sp.	1
video3	Scaridae	ge.	sp.	3
video9	Lethrinidae	Lethrinus	sp.	89

Observateur 2 :

Vidéo	Famille	Genre	Espèce	Abondance
video1	Haemulidae	ge.	sp.	3
video1	Lethrinidae	Lethrinus	sp.	2
video1	Scaridae	Scarus	sp.	1
video2	Balistidae	ge.	sp.	1
video2	Scaridae	Scarus	sp.	5
video3	Acanthuridae	Acanthurus	sp.	1
video3	Scaridae	Scarus	sp.	1
video4	Lethrinidae	Lethrinus	sp.	1
video8	Lethrinidae	Lethrinus	sp.	3
video8	Scaridae	ge.	sp.	3
video9	Lethrinidae	Lethrinus	sp.	40

Observateur 3 :

Vidéo	Famille	Genre	Espèce	Abondance
video1	Scaridae	Chlorurus	sp.	1
video1	Haemulidae	ge.	sp.	2
video1	Lethrinidae	Lethrinus	sp.	2
video2	Scaridae	Chlorurus	sp.	2
video2	Lethrinidae	Lethrinus	sp.	1
video2	Acanthuridae	Naso	sp.	1
video2	Scaridae	Scarus	sp.	5
video3	Acanthuridae	Acanthurus	sp.	1
video3	Lethrinidae	Gymnocranius	sp.	1
video3	Lethrinidae	Lethrinus	sp.	2
video3	Lutjanidae	Lutjanus	sp.	6
video3	Acanthuridae	Naso	sp.	1
video3	Scaridae	ge.	sp.	3
video3	Scaridae	Scarus	sp.	1
video4	Lethrinidae	Lethrinus	sp.	2
video5	Lethrinidae	Lethrinus	sp.	3
video6	Carangidae	ge.	sp.	28
video7	Lethrinidae	Lethrinus	sp.	2
video8	Lethrinidae	Lethrinus	sp.	8
video8	Scaridae	ge.	sp.	3
video9	Lethrinidae	Lethrinus	sp.	34

Observateur 4 :

Vidéo	Famille	Genre	Espèce	Abondance
video1	Acanthuridae	Acanthurus	sp.	1
video2	Balistidae	ge.	sp.	1
video2	Scaridae	ge.	sp.	5
video2	Scaridae	Scarus	sp.	4
video3	Balistidae	ge.	sp.	1
video3	Carcharhinidae	ge.	sp.	1
video3	Labridae	Hemigymnus	sp.	2
video3	Scaridae	ge.	sp.	3
video4	Acanthuridae	Acanthurus	sp.	1
video4	Lutjanidae	Lutjanus	sp.	2
video5	Lethrinidae	Lethrinus	sp.	1
video7	Lethrinidae	Lethrinus	sp.	1
video8	Lethrinidae	Lethrinus	sp.	12
video9	Lethrinidae	Lethrinus	sp.	33

Annexe D

Matériels supplémentaires de l'article 5 : Variations diurnes à haute fréquence temporelle d'un peuplement de poissons de récif corallien étudiées par vidéo sous-marine (chapitre 5)

Appendix A. Summary of videos observed. Density (ind/m^2) , species richness (complex), number of genus, number of family, day, time of day and tidal stage corresponding to each recorded video. Complex represent a group of resembling species (see methods). Additional number of complex observed are represented in brackets in the table. Videos were deployed for 35 consecutives days, between 27th September (day 1) and 31st October (day 35). HT: High Tide; FT: Falling tide, …

Video	Density	Species richness (complex)	Genus	Family	Day	Time	Tidal stage
1	1,19	23 (3)	22	10	Day01	09:45	FT
2	0,80	29 (4)	25	10	Day01	11:00	LT
3	0,79	27 (3)	23	8	Day01	12:15	LT
4	0,59	15 (3)	18	8	Day01	13:30	RT
5	0,87	20 (3)	21	10	Day01	14:45	RT
6	1,03	30 (3)	29	12	Day01	16:00	RT
7	1,16	31 (4)	25	13	Day01	17:15	HT
8	1,64	32 (3)	25	12	Day02	06:00	HT
9	1,38	20 (3)	19	8	Day02	07:15	HT
10	1,25	23 (3)	24	10	Day02	08:30	FT
11	1,35	31 (3)	28	13	Day02	09:45	FT
12	1,14	23 (2)	24	12	Day02	11:00	LT
13	0,94	22 (3)	24	11	Day02	12:15	LT
14	0,95	28 (3)	26	11	Day02	13:30	LT
15	0,96	23 (3)	23	10	Day02	14:45	RT
16	1,05	26 (3)	26	11	Day02	16:00	RT
17	1,73	32 (3)	25	11	Day02	17:15	HT
18	1,65	31 (3)	26	13	Day03	06:00	HT
19	1,45	30 (2)	26	11	Day03	07:15	HT
20	1,23	27 (3)	26	10	Day03	08:30	HT
21	1,13	22 (3)	21	8	Day03	09:45	FT
22	0,91	22 (2)	23	9	Day03	11:00	FT
23	0,70	18 (3)	18	10	Day03	12:15	LT
24	0,53	18 (3)	21	9	Day03	13:30	LT
25	0,75	23 (3)	22	11	Day03	14:45	RT
26	1,08	19 (3)	22	10	Day03	16:00	RT
27	1,76	29 (2)	25	14	Day03	17:15	RT
28	1,47	35 (3)	29	14	Day04	06:00	RT
29	1,18	29 (1)	29	12	Day04	07:15	HT
30	0,96	26 (3)	23	12	Day04	08:30	HT
31	0,94	25 (2)	24	11	Day04	09:45	FT
32	1,02	25 (1)	24	8	Day04	11:00	FT
33	0,84	26 (3)	26	10	Day04	12:15	FT
34	0,74	21 (3)	22	10	Day04	13:30	LT
35	0,85	18 (3)	18	9	Day04	14:45	LT
36	0,74	21 (3)	23	10	Day04	16:00	RT
37	1,18	24 (3)	21	10	Day04	17:15	RT

38	1,19	19 (2)	20	10	Day05	06:00	RT
39	1,21	17 (3)	20	8	Day05	07:15	HT
40	0,87	23 (3)	24	11	Day05	08:30	HT
41	0,95	21 (2)	24	9	Day05	09:45	HT
42	0,76	15 (3)	18	7	Day05	11:00	FT
43	1,03	18 (3)	17	7	Day05	12:15	FT
44	0,96	25 (3)	23	9	Day05	13:30	LT
45	0,69	19 (2)	22	10	Day05	14:45	LT
46	0,87	17 (3)	17	7	Day05	16:00	RT
47	1,05	26 (3)	23	11	Day05	17:15	RT
48	1,17	24 (3)	21	9	Day06	06:00	RT
49	1,13	20 (3)	16	5	Day06	07:15	RT
50	0,91	22 (3)	21	9	Day06	08:30	HT
51	0,85	18 (3)	18	7	Day06	09:45	HT
52	0,80	18 (3)	20	10	Day06	11:00	FT
53	0,96	21 (2)	21	8	Day06	12:15	FT
54	0,81	15 (3)	18	8	Day06	13:30	LT
55	0,69	18 (3)	23	10	Day06	14:45	LT
56	0,59	14 (3)	16	8	Day06	16:00	LT
57	0,97	20 (3)	23	12	Day06	17:15	RT
58	1,07	26 (3)	22	10	Day07	06:00	RT
59	1,08	13 (3)	15	6	Day07	07:15	RT
60	1,09	16 (3)	19	7	Day07	08:30	HT
61	0,89	22 (3)	21	8	Day07	09:45	HT
62	0,91	17 (3)	19	8	Day07	11:00	HT
63	1,03	13 (3)	17	7	Day07	12:15	FT
64	0,97	24 (3)	25	10	Day07	13:30	FT
65	0,98	23 (3)	24	11	Day07	14:45	LT
66	0,92	23 (3)	22	9	Day07	16:00	LT
67	0,98	26 (3)	23	12	Day07	17:15	RT
68	1,22	15 (4)	17	8	Day08	06:00	RT
69	1,10	25 (3)	23	12	Day08	07:15	RT
70	0,98	19 (3)	18	6	Day08	08:30	RT
71	0,99	22 (3)	22	10	Day08	09:45	HT
72	1,02	20 (2)	19	9	Day08	11:00	HT
73	0,75	13 (3)	17	6	Day08	12:15	FT
74	0,83	19 (3)	20	9	Day08	13:30	FT
75	0,89	17 (3)	18	6	Day08	14:45	LT
76	0,98	20 (3)	22	9	Day08	16:00	LT
77	1,27	31 (3)	26	11	Day08	17:15	LT
78	1,27	25 (2)	20	9	Day09	06:00	LT
79	1,10	18 (3)	21	9	Day09	07:15	RT
80	0,95	21 (3)	24	9	Day09	08:30	RT
81	0,97	19 (3)	22	8	Day09	09:45	HT
82	0,79	15 (3)	17	6	Day09	11:00	HT
83	0,79	18 (3)	21	10	Day09	12:15	HT

84	1,01	17 (3)	19	7	Day09	13:30	FT
85	0,88	16 (3)	19	9	Day09	14:45	FT
86	0,93	25 (3)	24	10	Day09	16:00	LT
87	0,87	19 (3)	20	10	Day09	17:15	LT
88	1,23	30 (3)	26	11	Day10	06:00	LT
89	1,11	19 (3)	17	6	Day10	07:15	RT
90	1,12	26 (3)	25	10	Day10	08:30	RT
91	0,94	18 (3)	21	8	Day10	09:45	HT
92	0,72	11 (3)	15	5	Day10	11:00	HT
93	0,86	20 (3)	21	11	Day10	12:15	HT
94	1,05	15 (3)	18	8	Day10	13:30	FT
95	1,05	26 (3)	27	11	Day10	14:45	FT
96	0,87	26 (3)	22	11	Day10	16:00	LT
97	1,41	27 (3)	23	10	Day11	06:00	LT
98	1,26	27 (2)	24	11	Day11	07:15	RT
99	0,82	23 (2)	21	10	Day11	08:30	RT
100	0,70	19 (4)	18	10	Day11	09:45	RT
101	1,08	24 (3)	25	12	Day11	11:00	HT
102	0,76	25 (3)	24	11	Day11	12:15	HT
103	0,81	15 (3)	18	9	Day11	13:30	HT
104	0,97	21 (3)	21	8	Day11	14:45	FT
105	1,02	22 (3)	22	10	Day11	16:00	FT
106	1,09	23 (2)	22	9	Day12	06:00	LT
107	0,99	25 (3)	25	10	Day12	07:15	LT
108	1,22	24 (3)	22	10	Day12	08:30	RT
109	0,98	25 (3)	26	10	Day12	09:45	RT
110	0,76	23 (3)	24	11	Day12	11:00	RT
111	0,94	14 (3)	21	10	Day12	12:15	HT
112	0,97	22 (2)	21	10	Day12	13:30	HT
113	0,71	20 (1)	20	9	Day12	14:45	FT
114	0,87	17 (2)	21	9	Day12	16:00	FT
115	1,36	22 (3)	23	11	Day13	06:00	FT
116	0,99	21 (3)	21	10	Day13	07:15	LT
117	1,26	20 (3)	21	9	Day13	08:30	LT
118	0,71	14 (3)	14	6	Day13	09:45	LT
119	0,55	15 (3)	18	6	Day13	11:00	RT
120	1,09	17 (3)	18	7	Day16	09:45	RT
121	0,82	14 (3)	15	6	Day16	11:00	LT
122	0,84	16 (3)	17	5	Day16	12:15	LT
123	0,84	21 (3)	23	11	Day16	13:30	LT
124	0,67	17 (3)	18	8	Day16	14:45	RT
125	0,79	23 (3)	26	12	Day16	16:00	RT
126	1,17	22 (3)	20	11	Day16	17:15	HT
127	1,16	24 (3)	25	10	Day19	09:45	HT
128	0,86	19 (3)	19	8	Day19	11:00	FT
129	0,98	19 (4)	21	7	Day19	12:15	FT

130	0,92	19 (4)	22	9	Day19	13:30	LT
131	0,77	19 (3)	22	8	Day19	14:45	LT
132	1,16	16 (3)	20	9	Day19	16:00	LT
133	1,02	25 (3)	18	9	Day19	17:15	RT
134	1,36	29 (3)	23	10	Day20	06:00	RT
135	1,29	23 (3)	22	9	Day20	08:30	RT
136	1,18	16 (3)	20	7	Day20	13:30	HT
137	0,70	22 (3)	23	10	Day20	16:00	LT
138	1,51	24 (3)	25	14	Day20	17:15	RT
139	2,22	25 (3)	24	11	Day21	06:00	RT
140	0,81	23 (3)	23	12	Day21	17:15	RT
141	0,93	19 (4)	20	8	Day22	06:00	RT
142	1,15	22 (3)	21	7	Day22	09:45	RT
143	1,17	27 (3)	25	10	Day22	11:00	HT
144	1,01	24 (3)	23	8	Day22	12:15	HT
145	0,78	21 (3)	21	7	Day22	13:30	HT
146	1,05	23 (3)	22	8	Day22	14:45	HT
147	1,06	24 (3)	25	12	Day22	16:00	FT
148	1,02	30 (3)	27	15	Day22	17:15	FT
149	1,54	31 (2)	27	13	Day23	06:00	RT
150	1,34	28 (3)	30	14	Day23	07:15	RT
151	1,43	25 (3)	24	9	Day23	08:30	RT
152	1,23	20 (3)	21	6	Day23	09:45	RT
153	1,21	29 (3)	27	12	Day23	11:00	HT
154	1,05	24 (3)	24	9	Day23	12:15	HT
155	1,01	18 (2)	20	7	Day23	13:30	FT
156	1,12	23 (2)	25	11	Day23	14:45	FT
157	1,08	33 (3)	26	12	Day23	16:00	FT
158	1,75	33 (3)	28	14	Day23	17:15	LT
159	1,71	28 (3)	26	12	Day24	06:00	LT
160	1,29	27 (3)	26	12	Day24	07:15	LT
161	1,05	21 (3)	23	8	Day24	08:30	RT
162	1,19	20 (3)	20	7	Day24	09:45	RT
163	1,28	22 (2)	22	9	Day24	11:00	RT
164	1,19	17 (3)	20	8	Day24	12:15	HT
165	1,04	20 (3)	23	10	Day24	13:30	HT
166	1,09	23 (3)	25	12	Day24	14:45	FT
167	1,52	28 (2)	22	9	Day24	16:00	FT
168	1,61	30 (3)	24	12	Day24	17:15	FT
169	1,63	27 (3)	25	10	Day25	06:00	LT
170	1,04	24 (3)	26	12	Day25	07:15	LT
171	0,96	21 (3)	18	7	Day25	08:30	LT
172	1,06	19 (2)	22	9	Day25	09:45	RT
173	0,89	24 (3)	23	8	Day25	11:00	RT
174	1,15	21 (3)	23	9	Day25	12:15	HT
175	1,04	20 (3)	23	10	Day25	13:30	HT

176	0,94	13 (3)	17	8	Day25	14:45	HT
177	1,13	20 (3)	23	10	Day25	16:00	FT
178	1,20	27 (3)	23	11	Day25	17:15	FT
179	1,37	27 (3)	23	13	Day26	06:00	LT
180	1,24	20 (3)	22	8	Day26	07:15	LT
181	1,69	23 (3)	23	11	Day27	06:00	LT
182	1,44	23 (3)	23	10	Day27	07:15	LT
183	1,01	28 (3)	25	9	Day27	08:30	LT
184	1,14	22 (3)	20	10	Day27	09:45	RT
185	0,79	15 (2)	15	8	Day27	11:00	RT
186	1,35	29 (3)	24	9	Day28	08:30	LT
187	1,41	32 (3)	28	12	Day28	09:45	LT
188	1,35	28 (3)	28	10	Day28	11:00	RT
189	1,35	34 (3)	29	13	Day28	12:15	RT
190	1,47	32 (3)	30	14	Day28	13:30	RT
191	1,31	27 (3)	26	11	Day28	14:45	HT
192	1,34	29 (3)	26	11	Day28	16:00	HT
193	1,66	27 (3)	24	12	Day28	17:15	FT
194	1,57	29 (4)	24	11	Day29	06:00	FT
195	1,28	24 (2)	26	13	Day29	07:15	FT
196	1,17	21 (2)	23	10	Day29	08:30	FT
197	1,09	23 (2)	22	9	Day29	09:45	LT
198	0,89	22 (2)	21	8	Day29	11:00	LT
199	0,90	26 (3)	23	9	Day29	12:15	RT
200	0,93	21 (3)	20	9	Day29	13:30	RT
201	1,32	29 (2)	23	9	Day29	14:45	RT
202	1,59	34 (3)	27	14	Day29	16:00	HT
203	1,45	31 (3)	24	12	Day29	17:15	HT
204	1,54	29 (3)	26	12	Day30	06:00	HT
205	1,53	29 (4)	27	12	Day30	07:15	FT
206	1,38	24 (3)	21	11	Day30	08:30	FT
207	1,13	32 (2)	26	11	Day30	09:45	FT
208	1,22	28 (2)	26	9	Day30	11:00	LT
209	0,95	20 (2)	19	7	Day30	12:15	LT
210	1,13	27 (2)	23	9	Day30	13:30	RT
211	1,05	26 (2)	24	8	Day30	14:45	RT
212	1,69	26 (3)	20	9	Day30	16:00	HT
213	1,59	36 (4)	26	12	Day30	17:15	HT
214	2,04	33 (2)	26	10	Day31	06:00	HT
215	1,56	24 (4)	21	8	Day31	07:15	HT
216	1,13	23 (1)	24	12	Day31	08:30	FT
217	1,11	19 (2)	18	9	Day31	09:45	FT
218	1,09	29 (4)	26	11	Day31	11:00	LT
219	1,10	23 (3)	22	8	Day31	12:15	LT
220	1,18	22 (3)	25	11	Day31	13:30	LT
221	1,02	23 (3)	22	10	Day31	14:45	RT

222	1,32	23 (3)	22	10	Day31	16:00	RT
223	1,50	28 (3)	23	10	Day31	17:15	HT
224	1,40	28 (4)	23	11	Day32	06:00	HT
225	1,31	21 (3)	24	9	Day32	07:15	HT
226	1,40	21 (2)	20	9	Day32	08:30	HT
227	1,30	12 (3)	16	7	Day32	09:45	FT
228	0,90	16 (2)	19	8	Day32	11:00	FT
229	0,85	23 (3)	24	10	Day32	12:15	LT
230	0,76	20 (2)	19	8	Day32	13:30	LT
231	1,04	23 (3)	25	11	Day32	14:45	RT
232	1,10	23 (3)	22	10	Day32	16:00	RT
233	2,13	28 (2)	24	13	Day32	17:15	HT
234	1,45	28 (3)	23	9	Day33	06:00	RT
235	1,56	21 (3)	24	10	Day33	07:15	HT
236	1,42	23 (3)	24	9	Day33	08:30	HT
237	1,14	19 (3)	22	8	Day33	09:45	FT
238	0,89	23 (3)	21	8	Day33	11:00	FT
239	0,80	17 (3)	17	6	Day33	12:15	LT
240	0,67	25 (2)	21	8	Day33	13:30	LT
241	0,93	20 (3)	18	6	Day33	14:45	LT
242	0,96	26 (3)	28	11	Day33	16:00	RT
243	1,30	26 (3)	21	9	Day33	17:15	RT
244	1,42	24 (3)	20	8	Day34	06:00	RT
245	1,39	21 (3)	21	9	Day34	07:15	HT
246	1,51	23 (3)	25	11	Day34	08:30	HT
247	0,95	20 (2)	23	11	Day34	09:45	HT
248	1,06	21 (2)	21	9	Day34	11:00	FT
249	0,72	21 (3)	21	11	Day34	12:15	FT
250	0,64	20 (3)	20	8	Day34	13:30	LT
251	0,75	15 (4)	18	9	Day34	14:45	LT
252	0,96	19 (3)	19	8	Day34	16:00	RT
253	1,45	25 (3)	24	12	Day34	17:15	RT
254	1,54	26 (3)	23	9	Day35	06:00	RT
255	0,95	24 (4)	24	9	Day35	07:15	RT
256	1,15	20 (3)	21	7	Day35	08:30	HT

Appendix B. Summary per taxa observed on the 256 videos. "**Diet**" is characterized as P: piscivores, H: herbivore-detritus, K: plankton feeders, C: carnivores. "**Freq.**": frequency of occurrence; "**Total abundance**": sum of all individuals observed in all videos; and "**Mean abundance**": mean number of individuals observed per taxa on video sequences.

	Family	Taxa	Diet	Freq.	Total abundance	Mean abundance
Permanent species	Pomacentridae	*Abudefduf whitleyi*	C	100	2293	8.96
	Pomacentridae	*Dascyllus aruanus*	K	100	12505	48.85
	Pomacentridae	*Pomacentrus moluccensis*	K	100	1947	7.61
	Pomacentridae	*Chromis gp*	K	99.6	11077	43.44
	Acanthuridae	*Zebrasoma scopas*	H	99.2	1626	6.40
	Scaridae	*Hipposcarus longiceps*	H	97.7	776	3.10
	Scaridae	*ge. sp. (juveniles)*	H	96.9	7263	29.29
	Scaridae	*Chlorurus sordidus*	H	94.9	1089	4.48
	Acanthuridae	*Ctenochaetus gp*	H	91	486	2.09
	Pomacentridae	*Stegastes gp*	K	87.1	723	3.24
	Scaridae	*ge. sp.*	H	81.6	1427	13.21
	Labridae	*Gomphosus varius*	C	78.9	379	1.88
	Labridae	*Thalassoma lunare*	C	78.9	271	1.34
Frequent species	Chaetodontidae	*Chaetodon lunulatus*	C	73.8	306	1.62
	Lethrinidae	*Lethrinus atkinsoni*	C	70.3	240	1.33
	Scaridae	*Scarus schlegeli*	H	69.9	562	3.14
	Acanthuridae	*Acanthurus xanthopterus*	H	69.1	824	4.66
	Acanthuridae	*Naso unicornis*	H	64.8	247	1.49
	Chaetodontidae	*Chaetodon auriga*	C	59	234	1.55
	Pomacentridae	*ge. sp.*	K	55.1	269	1.91
	Serranidae	*Plectropomus leopardus*	P	51.6	181	1.37
	Labridae	*Oxycheilinus sp.*	P	50.8	152	1.17
	Scaridae	*Scarus chameleon*	H	50.4	254	1.97
	Labridae	*Thalassoma lutescens*	C	48.8	144	1.15
	Nemipteridae	*Scolopsis bilineata*	C	47.7	175	1.43
	Pomacanthidae	*Centropyge tibicen*	P	44.1	148	1.31
	Acanthuridae	*Acanthurus nigricauda*	H	43.8	193	1.72
	Labridae	*Hemigymnus melapterus*	C	40.6	122	1.17
	Labridae	*Oxycheilinus unifasciatus*	P	40.6	105	1.01
	Labridae	*ge. sp.*	-	39.8	217	2.13
	Labridae	*Labrichthys unilineatus*	C	39.1	112	1.12
	Chaetodontidae	*Chaetodon trifascialis*	C	37.1	121	1.27
	Balistidae	*Rhinecanthus aculeatus*	C	37.1	101	1.06
	Labridae	*Bodianus loxozonus*	C	33.6	91	1.06

	Chaetodontidae	*Chaetodon mertensii*	C	33.6	125	1.45
	Acanthuridae	*Naso tonganus*	H	33.6	157	1.83
	Scaridae	*Scarus ghobban*	H	32.8	233	2.77
Scarce species	Mullidae	*Parupeneus barberinus*	C	27.7	102	1.44
	Chaetodontidae	*Chaetodon bennetti*	C	25.8	78	1.18
	Chaetodontidae	*Chaetodon vagabundus*	C	24.6	91	1.44
	Scaridae	*Scarus rivulatus*	H	23.8	189	3.10
	Chaetodontidae	*Chaetodon plebeius*	C	22.7	65	1.12
	Acanthuridae	*Zebrasoma veliferum*	H	19.9	57	1.12
	Chaetodontidae	*Chaetodon ephippium*	C	19.1	64	1.31
	Aulostomidae	*Aulostomus chinensis*	K	18.4	53	1.13
	Pomacentridae	*Pomacentrus chrysurus*	K	18.4	49	1.04
	Caesionidae	*ge. sp.*	K	18	612	13.30
	Labridae	*Cheilinus chlorourus*	C	17.2	45	1.02
	Labridae	*Hologymnosus annulatus*	C	16.8	46	1.07
	Mullidae	*Parupeneus multifasciatus*	P	16.8	43	1.00
	Siganidae	*Siganus doliatus*	H	16.8	81	1.88
	Siganidae	*Siganus puellus*	H	16.4	56	1.33
	Caesionidae	*Pterocaesio tile*	K	14.8	371	9.76
	Serranidae	*Plectropomus laevis*	P	13.7	36	1.03
	Pinguipedidae	*Parapercis hexophtalma*	C	13.3	34	1.00
	Labridae	*Anampses neoguinaicus*	K	12.5	34	1.06
	Serranidae	*Epinephelus merra*	P	11.7	30	1.00
	Labridae	*Hemigymnus fasciatus*	C	10.9	29	1.04
Rare species	Labridae	*Labroides sp.*	C	9.8	31	1.24
	Lethrinidae	*Lethrinus obsoletus*	C	9.4	27	1.13
	Balistidae	*Pseudobalistes fuscus*	P	9.4	25	1.04
	Labridae	*Cheilinus undulatus*	C	9	23	1.00
	Acanthuridae	*Acanthurus gp*	H	8.6	25	1.14
	Labridae	*Labroides dimidiatus*	C	8.6	24	1.09
	Chaetodontidae	*Chaetodon lineolatus*	C	7.8	20	1.00
	Acanthuridae	*Acanthurus sp.*	H	7	32	1.78
	Carcharhinidae	*Carcharhinus melanopterus*	P	7	19	1.06
	Serranidae	*Epinephelus tauvina*	P	7	19	1.06
	Serranidae	*Plectropomus sp.*	P	6.6	18	1.06
	Echeneidae	*Echeneis naucrates*	C	6.2	21	1.31
	Scaridae	*Scarus oviceps*	H	6.2	17	1.06
	Scaridae	*Cetoscarus bicolor*	C	5.9	16	1.07
	Acanthuridae	*ge. sp.*	H	5.5	15	1.07
	Chaetodontidae	*Forcipiger flavissimus*	C	5.1	16	1.23
	Apogonidae	*Apogon sp.*	H	4.7	16	1.33
	Tetraodontidae	*Canthigaster valentini*	C	4.3	11	1.00

Serranidae	*Epinephelus sp.*	P	4.3	12	1.09
Serranidae	*Epinephelus polyphekadion*	P	3.9	11	1.10
Mullidae	*Parupeneus cyclostomus*	C	3.9	19	1.90
Siganidae	*Siganus punctatus*	H	3.9	14	1.40
Mullidae	*Parupeneus barberinoides*	K	3.5	15	1.67
Lethrinidae	*Lethrinus sp.*	P	3.1	9	1.13
Lutjanidae	*Lutjanus bohar*	P	3.1	8	1.00
Carangidae	*ge. sp.*	P	2.7	17	2.43
Carangidae	*Caranx ignobilis*	K	2.7	7	1.00
Dasyatidae	*Dasyatis kuhlii*	C	2.7	7	1.00
Lethrinidae	*Gymnocranius sp.*	C	2.7	18	2.57
Chaetodontidae	*Chaetodon ulietensis*	C	2.3	6	1.00
Serranidae	*ge. sp.*	P	2.3	7	1.17
Lutjanidae	*Aprion virescens*	C	2	5	1.00
Chaetodontidae	*Chaetodon flavirostris*	C	2	7	1.40
Carcharhinidae	*Triaenodon obesus*	P	2	6	1.20
Labridae	*Bodianus perditio*	C	1.6	4	1.00
Carangidae	*Caranx melampygus*	P	1.6	4	1.00
Labridae	*Cheilinus sp.*	C	1.6	4	1.00
Lethrinidae	*ge. sp.*	C	1.6	4	1.00
Lethrinidae	*Lethrinus olivaceus*	C	1.6	6	1.50
Ostraciidae	*Ostracion cubicus*	C	1.6	4	1.00
Chaetodontidae	*Chaetodon sp.*	C	1.2	3	1.00
Labridae	*Cheilinus fasciatus*	C	1.2	4	1.33
Scaridae	*Chlorurus microrhinos*	H	1.2	4	1.33
Diodontidae	*Diodon hystrix*	C	1.2	3	1.00
Acanthuridae	*Naso sp.*	H	1.2	4	1.33
Carangidae	*Pseudocaranx dentex*	P	1.2	3	1.00
Scaridae	*Scarus altipinnis*	H	1.2	4	1.33
Carcharhinidae	*ge. sp.*	P	0.8	2	1.00
Chaetodontidae	*Chaetodon speculum*	C	0.8	4	2.00
Chaetodontidae	*Chaetodon unimaculatus*	C	0.8	3	1.50
Carangidae	*Gnathanodon speciosus*	P	0.8	4	2.00
Gobiidae	*ge. sp.*	C	0.8	2	1.00
Labridae	*Hemigymnus sp.*	C	0.8	2	1.00
Lethrinidae	*Lethrinus nebulosus*	C	0.8	2	1.00
Lethrinidae	*Lethrinus xanthochilus*	C	0.8	2	1.00
Ginglymostomatidae	*Nebrius ferrugineus*	C	0.8	2	1.00
Pomacanthidae	*Pomacanthus sexstriatus*	C	0.8	2	1.00
Scaridae	*Scarus frenatus*	H	0.8	2	1.00
Scaridae	*Scarus longipinnis*	H	0.8	2	1.00
Stegostomatidae	*Stegostoma fasciatum*	C	0.8	2	1.00
Myliobatidae	*Aetobatus narinari*	C	0.4	1	1.00

Rare species

Rare species	Monacanthidae	*Aluterus scriptus*	K	0.4	1	1.00
	Gobiidae	*Amblygobius phalaena*	P	0.4	1	1.00
	Scaridae	*Bolbometopon muricatum*	H	0.4	30	30.00
	Carangidae	*Caranx papuensis*	P	0.4	1	1.00
	Carangidae	*Caranx sp.*	P	0.4	1	1.00
	Labridae	*Cheilinus trilobatus*	C	0.4	1	1.00
	Labridae	*Coris aygula*	C	0.4	1	1.00
	Pomacentridae	*Dascyllus trimaculatus*	K	0.4	1	1.00
	Labridae	*Epibulus insidiator*	C	0.4	1	1.00
	Serranidae	*Epinephelus cyanopodus*	P	0.4	1	1.00
	Hemiramphidae	*ge. sp.*	C	0.4	1	1.00
	Lutjanidae	*Macolor niger*	P	0.4	1	1.00
	Mullidae	*Parupeneus rubescens*	C	0.4	1	1.00
	Mullidae	*Parupeneus sp.*	C	0.4	4	4.00
	Mullidae	*Parupeneus trifasciatus*	C	0.4	2	2.00
	Dasyatidae	*Pastinachus sephen*	C	0.4	1	1.00
	Pomacanthidae	*Pomacanthus imperator*	H	0.4	1	1.00
	Serranidae	*Pseudanthias sp.*	K	0.4	1	1.00
	Carangidae	*Scomberoides lysan*	P	0.4	10	10.00
	Siganidae	*Siganus argenteus*	H	0.4	1	1.00
	Labridae	*Thalassoma hardwicke*	P	0.4	1	1.00
	Labridae	*Thalassoma sp.*	C	0.4	1	1.00
	Belonidae	*Tylosorus crocodilus*	C	0.4	1	1.00

Appendix C. Taxa observed in each cluster of the Time and Tide cluster analyses. Freq: Frequency (in %). "NA" when the species was not taken into account in the clustering due to its low occurrence in the videos (Freq. < 10%).

Family	species	Freq.	Time	Tide
Acanthuridae	*Acanthurus gp*	8.6	NA	NA
Acanthuridae	*Acanthurus nigricauda*	43.8	cluster 1	cluster 1
Acanthuridae	*Acanthurus sp.*	7	NA	NA
Acanthuridae	*Acanthurus xanthopterus*	69.1	cluster 3	cluster 3
Acanthuridae	*Ctenochaetus gp*	91	cluster 1	cluster 2
Acanthuridae	*ge. sp.*	5.5	NA	NA
Acanthuridae	*Naso sp.*	1.2	NA	NA
Acanthuridae	*Naso tonganus*	33.6	cluster 1	cluster 2
Acanthuridae	*Naso unicornis*	64.8	cluster 1	cluster 2
Acanthuridae	*Zebrasoma scopas*	99.2	cluster 3	cluster 1
Acanthuridae	*Zebrasoma veliferum*	19.9	cluster 1	cluster 2
Apogonidae	*Apogon sp.*	4.7	NA	NA
Aulostomidae	*Aulostomus chinensis*	18.4	cluster 1	cluster 2
Balistidae	*Pseudobalistes fuscus*	9.4	NA	NA
Balistidae	*Rhinecanthus aculeatus*	37.1	cluster 1	cluster 2
Belonidae	*Tylosorus crocodilus*	0.4	NA	NA
Caesionidae	*ge. sp.*	18	cluster 3	cluster 1
Caesionidae	*Pterocaesio tile*	14.8	cluster 3	cluster 2
Carangidae	*Caranx ignobilis*	2.7	NA	NA
Carangidae	*Caranx melampygus*	1.6	NA	NA
Carangidae	*Caranx papuensis*	0.4	NA	NA
Carangidae	*Caranx sp.*	0.4	NA	NA
Carangidae	*ge. sp.*	2.7	NA	NA
Carangidae	*Gnathanodon speciosus*	0.8	NA	NA
Carangidae	*Pseudocaranx dentex*	1.2	NA	NA
Carangidae	*Scomberoides lysan*	0.4	NA	NA
Carcharhinidae	*Carcharhinus melanopterus*	7	NA	NA
Carcharhinidae	*ge. sp.*	0.8	NA	NA
Carcharhinidae	*Triaenodon obesus*	2	NA	NA
Chaetodontidae	*Chaetodon auriga*	59	cluster 1	cluster 3
Chaetodontidae	*Chaetodon bennetti*	25.8	cluster 1	cluster 3
Chaetodontidae	*Chaetodon ephippium*	19.1	cluster 1	cluster 3
Chaetodontidae	*Chaetodon flavirostris*	2	NA	NA
Chaetodontidae	*Chaetodon lineolatus*	7.8	NA	NA
Chaetodontidae	*Chaetodon lunulatus*	73.8	cluster 1	cluster 2
Chaetodontidae	*Chaetodon mertensii*	33.6	cluster 1	cluster 2
Chaetodontidae	*Chaetodon plebeius*	22.7	cluster 1	cluster 3
Chaetodontidae	*Chaetodon sp.*	1.2	NA	NA
Chaetodontidae	*Chaetodon speculum*	0.8	NA	NA
Chaetodontidae	*Chaetodon trifascialis*	37.1	cluster 1	cluster 3
Chaetodontidae	*Chaetodon ulietensis*	2.3	NA	NA
Chaetodontidae	*Chaetodon unimaculatus*	0.8	NA	NA

Chaetodontidae	*Chaetodon vagabundus*	24.6	cluster 1	cluster 2
Chaetodontidae	*Forcipiger flavissimus*	5.1	NA	NA
Dasyatidae	*Dasyatis kuhlii*	2.7	NA	NA
Dasyatidae	*Pastinachus sephen*	0.4	NA	NA
Diodontidae	*Diodon hystrix*	1.2	NA	NA
Echeneidae	*Echeneis naucrates*	6.2	NA	NA
Ginglymostomatidae	*Nebrius ferrugineus*	0.8	NA	NA
Gobiidae	*Amblygobius phalaena*	0.4	NA	NA
Gobiidae	*ge. sp.*	0.8	NA	NA
Hemiramphidae	*ge. sp.*	0.4	NA	NA
Labridae	*Anampses neoguinaicus*	12.5	cluster 1	cluster 2
Labridae	*Bodianus loxozonus*	33.6	cluster 1	cluster 2
Labridae	*Bodianus perditio*	1.6	NA	NA
Labridae	*Cheilinus chlorourus*	17.2	cluster 1	cluster 2
Labridae	*Cheilinus fasciatus*	1.2	NA	NA
Labridae	*Cheilinus sp.*	1.6	NA	NA
Labridae	*Cheilinus trilobatus*	0.4	NA	NA
Labridae	*Cheilinus undulatus*	9	NA	NA
Labridae	*Coris aygula*	0.4	NA	NA
Labridae	*Epibulus insidiator*	0.4	NA	NA
Labridae	*ge. sp.*	39.8	cluster 1	cluster 2
Labridae	*Gomphosus varius*	78.9	cluster 1	cluster 1
Labridae	*Hemigymnus fasciatus*	10.9	cluster 1	cluster 2
Labridae	*Hemigymnus melapterus*	40.6	cluster 1	cluster 2
Labridae	*Hemigymnus sp.*	0.8	NA	NA
Labridae	*Hologymnosus annulatus*	16.8	cluster 1	cluster 3
Labridae	*Labrichthys unilineatus*	39.1	cluster 1	cluster 2
Labridae	*Labroides dimidiatus*	8.6	NA	NA
Labridae	*Labroides sp.*	9.8	NA	NA
Labridae	*Oxycheilinus sp.*	50.8	NA	NA
Labridae	*Oxycheilinus unifasciatus*	40.6	NA	NA
Labridae	*Thalassoma hardwicke*	0.4	NA	NA
Labridae	*Thalassoma lunare*	78.9	cluster 1	cluster 2
Labridae	*Thalassoma lutescens*	48.8	cluster 1	cluster 2
Labridae	*Thalassoma sp.*	0.4	NA	NA
Lethrinidae	*ge. sp.*	1.6	NA	NA
Lethrinidae	*Gymnocranius sp.*	2.7	NA	NA
Lethrinidae	*Lethrinus atkinsoni*	70.3	cluster 1	cluster 2
Lethrinidae	*Lethrinus nebulosus*	0.8	NA	NA
Lethrinidae	*Lethrinus obsoletus*	9.4	NA	NA
Lethrinidae	*Lethrinus olivaceus*	1.6	NA	NA
Lethrinidae	*Lethrinus sp.*	3.1	NA	NA
Lethrinidae	*Lethrinus xanthochilus*	0.8	NA	NA
Lutjanidae	*Aprion virescens*	2	NA	NA
Lutjanidae	*Lutjanus bohar*	3.1	NA	NA
Lutjanidae	*Macolor niger*	0.4	NA	NA
Monacanthidae	*Aluterus scriptus*	0.4	NA	NA

Mullidae	*Parupeneus barberinoides*	3.5	cluster 1	cluster 1
Mullidae	*Parupeneus barberinus*	27.7	NA	NA
Mullidae	*Parupeneus cyclostomus*	3.9	NA	NA
Mullidae	*Parupeneus multifasciatus*	16.8	cluster 1	cluster 2
Mullidae	*Parupeneus rubescens*	0.4	NA	NA
Mullidae	*Parupeneus sp.*	0.4	NA	NA
Mullidae	*Parupeneus trifasciatus*	0.4	NA	NA
Myliobatidae	*Aetobatus narinari*	0.4	NA	NA
Nemipteridae	*Scolopsis bilineata*	47.7	cluster 1	cluster 3
Ostraciidae	*Ostracion cubicus*	1.6	NA	NA
Pinguipedidae	*Parapercis hexophtalma*	13.3	cluster 1	cluster 2
Pomacanthidae	*Centropyge tibicen*	44.1	cluster 1	cluster 2
Pomacanthidae	*Pomacanthus imperator*	0.4	NA	NA
Pomacanthidae	*Pomacanthus sexstriatus*	0.8	NA	NA
Pomacentridae	*Abudefduf whitleyi*	100	cluster 1	cluster 2
Pomacentridae	*Chromis gp*	99.6	cluster 1	cluster 2
Pomacentridae	*Dascyllus aruanus*	100	cluster 1	cluster 2
Pomacentridae	*Dascyllus trimaculatus*	0.4	NA	NA
Pomacentridae	*ge. sp.*	55.1	cluster 1	cluster 3
Pomacentridae	*Pomacentrus chrysurus*	18.4	cluster 1	cluster 2
Pomacentridae	*Pomacentrus moluccensis*	100	cluster 1	cluster 2
Pomacentridae	*Stegastes gp*	87.1	cluster 1	cluster 3
Scaridae	*Bolbometopon muricatum*	0.4	NA	NA
Scaridae	*Cetoscarus bicolor*	5.9	NA	NA
Scaridae	*Chlorurus microrhinos*	1.2	NA	NA
Scaridae	*Chlorurus sordidus*	94.9	cluster 1	cluster 1
Scaridae	*ge. sp.*	81.6	cluster 2	cluster 2
Scaridae	*Hipposcarus longiceps*	97.7	cluster 3	cluster 2
Scaridae	*Scaridae-juvenile sp.*	96.9	cluster 2	cluster 1
Scaridae	*Scarus altipinnis*	1.2	NA	NA
Scaridae	*Scarus chameleon*	50.4	cluster 3	cluster 1
Scaridae	*Scarus frenatus*	0.8	NA	NA
Scaridae	*Scarus ghobban*	32.8	cluster 3	cluster 3
Scaridae	*Scarus longipinnis*	0.8	NA	NA
Scaridae	*Scarus oviceps*	6.2	NA	NA
Scaridae	*Scarus rivulatus*	23.8	cluster 2	cluster 1
Scaridae	*Scarus schlegeli*	69.9	cluster 2	cluster 1
Serranidae	*Epinephelus cyanopodus*	0.4	NA	NA
Serranidae	*Epinephelus merra*	11.7	cluster 1	cluster 2
Serranidae	*Epinephelus polyphekadion*	3.9	NA	NA
Serranidae	*Epinephelus sp.*	4.3	NA	NA
Serranidae	*Epinephelus tauvina*	7	NA	NA
Serranidae	*ge. sp.*	2.3	NA	NA
Serranidae	*Plectropomus laevis*	13.7	cluster 1	cluster 2
Serranidae	*Plectropomus leopardus*	51.6	cluster 1	cluster 2
Serranidae	*Plectropomus sp.*	6.6	NA	NA
Serranidae	*Pseudanthias sp.*	0.4	NA	NA

Siganidae	*Siganus argenteus*	0.4	NA	NA
Siganidae	*Siganus doliatus*	16.8	cluster 3	cluster 3
Siganidae	*Siganus puellus*	16.4	cluster 1	cluster 2
Siganidae	*Siganus punctatus*	3.9	NA	NA
Stegostomatidae	*Stegostoma fasciatum*	0.8	NA	NA
Tetraodontidae	*Canthigaster valentini*	4.3	NA	NA

Appendix D. Summary of time of the day and tidal state effects detected from cluster analysis (rare species excluded). See Appendix C for detailed on each species.

Influence detected	Family	Species
None		
	Acanthuridae	*Ctenochaetus gp, Naso tonganus, Naso unicornis, Zebrasoma veliferum*
	Aulostomidae	*Aulostomus chinensis*
	Balistidae	*Rhinecanthus aculeatus*
	Chaetodontidae	*Chaetodon lunulatus, Chaetodon mertensii, Chaetodon vagabundus*
	Labridae	*Anampses neoguinaicus, Bodianus loxozonus, Cheilinus chlorourus, Hemigymnus fasciatus, Hemigymnus melapterus, Labrichthys unilineatus, Thalassoma lunare, Thalassoma lutescens and* unidentified Labridae
	Lethrinidae	*Lethrinus atkinsoni*
	Mullidae	*Parupeneus multifasciatus*
	Pinguipedidae	*Parapercis hexophtalma*
	Pomacanthidae	*Centropyge tibicen*
	Pomacentridae	*Abudefduf whitleyi, Chromis gp, Dascyllus aruanus, Pomacentrus chrysurus, Pomacentrus moluccensis*
	Serranidae	*Epinephelus merra, Plectropomus laevis, Plectropomus leopardus*
	Siganidae	*Siganus puellus*
Only time effect :		
- Greater density in the morning	Scaridae	*Unidentified adults*
- Greater density in the afternoon	Caesionidae	*Pterocaesio tile*
	Scaridae	*Hipposcarus longiceps*
Only tide effect :		
- Greater density at high tide	Acanthuridae	*Acanthurus nigricauda*
	Labridae	*Gomphosus varius*
	Mullidae	*Parupeneus barberinoides*
	Scaridae	*Chlorourus sordidus*
- Greater density at high tide and low tide	Chaetodontidae	*Chaetodon auriga, Chaetodon bennetti, Chaetodon ephippium, Chaetodon plebeius, Chaetodon trifascialis*
	Labridae	*Hologymnosus annulatus*
	Nemipteridae	*Scolopsis bilineata*
	Pomacentridae	*Stegastes gp and unidentified Pomacentridae*
Time and tide effect:		
- Greater density in the morning and at high tide	Scaridae	*Scarus rivulatus, Scarus schlegeli and* unidentified juveniles Scaridae
- Greater density in the afternoon and at high tide	Acanthuridae	*Zebrasoma scopas*
	Caesionidae	Unidentified
	Scaridae	*Scarus chameleon*
- Greater density in the afternoon and at high tide and low tide	Acanthuridae	*Acanthurus xanthopterus*
	Scaridae	*Scarus ghobban*
	Siganidae	*Siganus doliatus*

Annexe E

Valorisation des travaux

Publications scientifiques

1. Pelletier D., Leleu K., **Mallet D**., Mou-Tham G., Hervé G., Boureau M., Guilpart N. (2012) Remote High-Definition Rotating Video Enables Fast Spatial Survey of Marine Underwater Macrofauna and Habitats. PLoS ONE 7, e30536

2. **Mallet, D.**, Wantiez, L., Lemouellic, S., Vigliola, L., Pelletier, D., 2014. Complementarity of rotating video and underwater visual census for assessing species richness, frequency and density of reef fish on coral reef slopes. PLoS ONE 9(1), e84344.

3. **Mallet, D.**, Pelletier, D., 2014. Underwater video techniques for observing coastal marine biodiversity: a review of sixty years of publications (1952-2012). Fisheries Research (accepté le 31/01/2014)

4. **Mallet D.**, Pelletier D. and Hervé G. The MICADO video system: A programmable Autonomous Remote High-Definition Rotating Video for High-Frequency observing fish assemblages. Estuarine, Coastal and Shelf Science. (en prep.)

5. **Mallet D**., Vigliola L., Wantiez L., Pelletier D. High frequency diurnal temporal variation of a coral reef fish assemblage studied with underwater video. Journal of Experimental Marine Biology and Ecology (en prep.)

Conférences

1. **Mallet D**. 2013. Présentation, évaluation et utilisation des techniques vidéo rotatives: principaux résultats de thèse. Conférence scientifique, IFREMER Brest, 30 Octobre 2013 : http://wwz.ifremer.fr/webtv/Conferences/Video-et-biodiversite

2. **Mallet D.,** 2013. Présentation, évaluation et utilisation des techniques vidéo rotatives: synthèse principaux résultats de thèse. Journée RBE IFREMER, Nantes, 5-6 Novembre 2013.

3. **Mallet D.,** Wantiez L., Pelletier D., Vigliola L. 2012. High-Definition Rotating Videos for monitoring reef fish and habitats. 12th International Coral Reef Symposium. 9-13 July 2012, Cairns, Queensland, Australia.

4. **Mallet D.,** Pelletier D., Leleu K., Vigliola L., Wantiez L. 2012. High-Definition Rotating Video: a powerful and cost efficient technique for monitoring coastal fish and habitat. 6th World Fisheries Congress. 7-11 May 2012, Edinburgh, Scotland.

5. **Mallet, D**., & D. Pelletier. 2011. Utilisation de la vidéo sous-marine haute définition pour suivre et étudier la richesse du lagon calédonien. Conférence grand public au 2ème Festival de l'Image Sous-marine de Nouvelle-Calédonie, 17 juin 2011.

6. Wantiez, L., E. Coutures, D. Pelletier, E. Gamp, B. Preuss, **D. Mallet**, Y. Reecht. 2011. Les réserves du Parc du Grand Nouméa: Comptages visuels, Vidéo rotative, Enquêtes plaisance et données mouillages. Colloque final du projet PAMPA, Paris, 30-31 mars.

Posters

1. **Mallet D.**, Vigliola L., Wantiez L., Pelletier D. 2013. Small-scale temporal variation of coral reef fish communities studied by underwater video. 3rd International Marine Protected Areas Congress. Marseille, 21-27 October 2013.

2. **Mallet D.,** Pelletier D., Leleu K., Mou-Tham G., Hervé G. 2011. La biodiversité sous-marine sous l'œil de STAtions Vidéo Rotatives (STAVIRO). *Contribution des aires marines protégées à la gestion écosystémique des milieux et de leurs usages : quelle stratégie scientifique ?* Paris, 22-24 Novembre 2011.

3. Pelletier D., Hervé G., **Mallet D.** 2010. Des stations vidéo sous-marines HD - La biodiversité du lagon calédonien sous l'œil de stations vidéo sous-marines en haute définition. http://www.biodiversite.nc/Des-stations-video-sous-marines-HD_a16.html. Poster pour la Fête de la Science, Nouméa (09/10/10), Koumac (05/10/10), Lifou (01/10/10) ainsi qu'au Colloque final du projet PAMPA, Paris, 30-31 mars 2011.

4. Pelletier, D., Hervé G., **Mallet D.** 2010. MICADO et STAVIRO, des observatoires au cœur du lagon. Poster pour la Fête de la Science, Maison de la Nouvelle-Calédonie, Paris, Octobre 2010.

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1. **Mallet D.** 2013. Comparaison des observations des communautés de poissons, obtenues par comptages en point fixe rotatif vidéo et en plongée, effectués sur les mêmes points de la pente récifale: Rapport AMBIO/Fiche A/1. IFREMER Nouméa. 19 p.

2. **Mallet D.** 2013. Etude des variations temporelles à petites échelles des communautés de poissons des récifs coralliens à l'aide de station vidéo MICADO : Rapport de mission 2012. Version du 17 Juillet 2013. Rapport AMBIO/A/2. IFREMER Nouméa. 20 p.

3. **Mallet D**. 2011. Projet de Doctorat. « La vidéo en haute définition pour étudier la biodiversité sous-marine : applications à l'analyse multi-échelles des variations spatiales et temporelles dans le lagon de Nouvelle-Calédonie ». 41p.

4. Pelletier, D., Y. Reecht, **D. Mallet**. 2011. Fiches de rendu par métrique WP2 – Stations vidéo rotatives Nouvelle-Calédonie. Document interne PAMPA/NC/WP2/5. 49 p.

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6. Drelon, J., **D. Mallet**, & D. Pelletier. 2010. Extraits photos des principales espèces observées au moyen des stations vidéos rotatives. Version provisoire d'un guide d'aide à l'identification des espèces sur les images vidéo. 90 p.

7. Guilpart, N., D. Pelletier, K. Leleu, **D. Mallet**, & G. Hervé. 2010. Suivre et observer la biodiversité et les ressources marines avec la vidéo sous-marine haute-définition. Guide méthodologique pour la mise en œuvre et l'analyse des stations vidéo rotatives. 61 p. http://www.crisponline.net; http://w3.ifremer.fr/blpintra/doc/00029/14032/.

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   -Fête de la Science en Nouvelle-Calédonie (1er oct Lifou, 5 oct. Koumac, 9 oct. Nouméa)
   -Aquarium de la Porte Dorée, 30 et 31 mars 2011

2. **Mallet, D**. 2010. Présentation de la technique d'observation par STAtions VIdéo ROtatives (STAVIRO). Montage vidéo (6'52'') :
   -Fête de la Science en Nouvelle-Calédonie (1er oct Lifou, 5 oct. Koumac, 9 oct. Nouméa)
   -Aquarium de la Porte Dorée, 30 et 31 mars 2011

3. **Mallet, D**. 2010. La biodiversité remarquable observée au moyen de stations vidéo rotatives. Montage vidéo (5'25'') :
   -Fête de la Science en Nouvelle-Calédonie (1er oct Lifou, 5 oct. Koumac, 9 oct. Nouméa)
   -Aquarium de la Porte Dorée, 30 et 31 mars 2011

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