Sommaire

Introduction générale

1. Les zones côtières : importance, menaces en enjeux d’avenir

Les espaces côtiers constituent des territoires à forts enjeux stratégiques environnementaux et humains (Halpern et al. 2012). Les écosystèmes marins associés à ces espaces y jouent un rôle majeur (Luisetti et al. 2010). Ils contribuent à la production des ressources vivantes marines (Liquete et al. 2013), ils assurent un grand nombre de processus et de fonctions écologiques à la bases de nombreux services écosystémiques (Annexe 1) comme la protection côtière ou le recyclage des nutriments (Leenhardt et al. 2015). On retrouve en zones côtières les habitats les plus variés et les plus productifs de la planète (Fletcher et al. 2011): baies, estuaires, zones humides, marais, vasières, récifs coralliens, forêts, mangroves. Les zones côtières jouent un rôle crucial dans le développement économique, social et politique de nombreux pays, car elles représentent une source significative de biens et de services pour les populations, locales ou non (Granek et al. 2010, Barbier 2012, Liquete et al. 2013).

Comme les environnements terrestres, la plupart des zones côtières à travers le monde sont soumises à de fortes pressions dues, par exemple, aux changements climatiques globaux, à la destruction d'habitats, à la surexploitation des ressources marines ou encore aux pressions anthropiques terrestres provenant des bassins versants (Halpern et al. 2008, Hoegh-Guldberg et Bruno 2010). Ces différentes pressions peuvent induire des changements rapides d’état des écosystèmes caractérisés par de fortes modifications de la biodiversité, avec des écosystèmes entiers cessant de fonctionner dans leur forme courante (Folke et al. 2004, Rocha et al. 2014). En conséquence, la pérennité des biens et des services produits par les zones côtières n'est plus assurée. Il en résulte des perturbations économiques et sociales évidentes pour les populations dont le mode de vie dépend de manière directe ou indirecte de la biodiversité côtière (Chapin et al. 2010, Niiranen et al. 2013). Comme les populations ne cessent de croître et les demandes en ressources marines ne cessent d'augmenter, les zones côtières se trouvent ainsi constamment soumises à de fortes pressions anthropiques qui menacent leur équilibre et leur intégrité. Ces symptômes persisteront si des décisions politiques et des mesures de gestions adéquates ne sont pas mises en œuvre (Liquete et al. 2013, Visconti et al. 2014).

Depuis plusieurs décennies, les acteurs du littoral ont pris conscience de l'importance, des menaces et des défis de gestion qui pèsent sur ces territoires ; ainsi parmi les scientifiques, les usagers de la mer (en particulier les pêcheurs, les opérateurs touristiques), les politiques et les collectivités locales, des champs de recherches, des réflexions, des propositions voient le jour dans le cadre d'une gestion intégrée des zones côtières. Modèle de gestion durable des territoires et activités côtières, elle s'intéresse aux différentes dimensions (environnementales, économiques, sociales) de la zone côtière, en intégrant bassins versants et partie marine. Elle vise à concilier développement durable (et les nombreux usages qui en découlent) et conservation, tout en reconnaissant les liens d'impacts qu'il peut y avoir entre les activités à terre et les écosystèmes marins.

Face à la multitude d'enjeux de gestion et à la complexité des systèmes à gérer, il est désormais nécessaire de s'appuyer sur des cadres méthodologiques et conceptuels afin d'appréhender les dynamiques complexes des territoires et de leur gestion. Ce travail de thèse se propose ainsi d'étudier les apports de l'approche socio-écologique appliquée à la gestion côtière.

2. L'approche socio-écologique

Pour penser les interactions entre les hommes et leur environnement il est possible de considérer le fonctionnement du monde comme un système (Ostrom 2009, Folke et al. 2010) où les interactions peuvent être de nature physique, écologique ou sociale. Le concept de système socio-écologique a été créé pour exprimer le fait que les interactions sociales et écologiques sont liées et qu'il est indispensable de les intégrer pour comprendre puis gérer le système qu'elles forment (Mathevet et Bousquet 2014). L'écologue Fikret Berkes et l'économiste suédois Carl Folke, définissent un système socio-écologique comme un assemblage de systèmes complexes dans lesquels les hommes font partie intégrante de la nature (Berkes et al. 2003). Ce système se rapproche de la notion de « territoire », utilisée par les géographes, dans lequel les caractéristiques et la dynamique sont issues des interactions entre acteurs et composantes de leur espace géographique. Ainsi un système socio-écologique se compose d'éléments physiques naturels (espèces, habitats, eau…), des produits des activités humaines ainsi que des formes d'interactions existant entre les hommes ou entre eux et leur environnement (Gunderson et Holling 2002) (Figure 1).

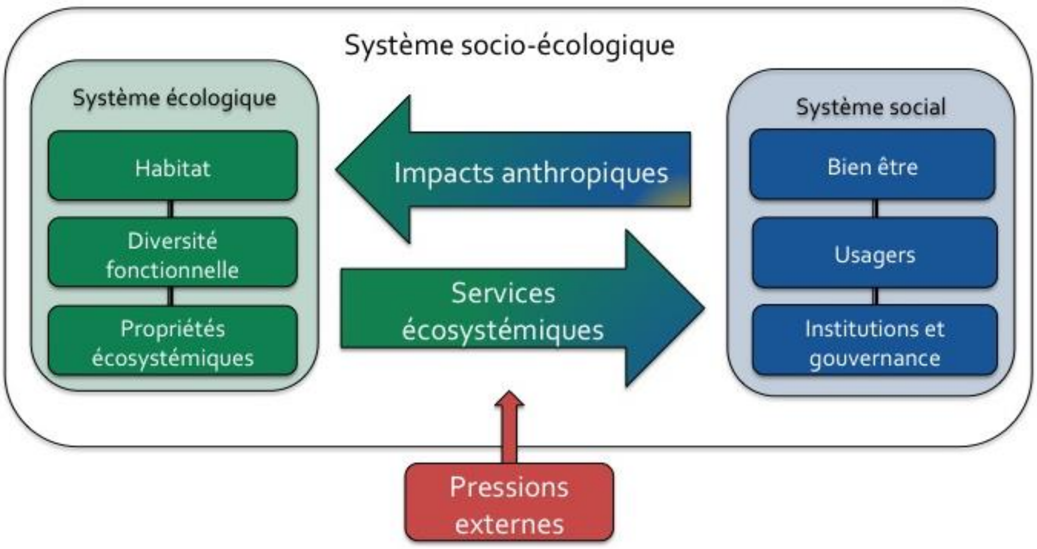

Figure 1 : schéma conceptuel du système socio-écologique.

Pour explorer les différentes facettes de l'approche socio-écologique, il est nécessaire de disposer d'une vision transdisciplinaire du système étudié afin de mieux comprendre les dynamiques socio-écologiques qui découlent d'usages ou de pratiques de gestion des milieux naturels. L'analyse des systèmes socio-écologiques se trouve à la croisée des sciences naturelles et des sciences de l'homme et de la société privilégiant aussi bien des perspectives fonctionnelles (des écosystèmes), les intérêts des parties prenantes que des systèmes de valeurs.

L'approche socio-écologique connaît actuellement un fort développement au sein de la littérature scientifique. La première étape consiste à décrire les limites d'un système et ses règles de fonctionnement, à quantifier certains de ses éléments (biomasses, valeurs) et à étudier les variables qui influencent ses dynamiques socio-écologiques. La deuxième étape consiste à étudier les interactions entre les variables et entre les différents niveaux d'organisation. La troisième étape consiste à analyser la gouvernance : qui sont les acteurs, quels jeux de pouvoir sont à l'œuvre ? Quelles sont les règles de gestion ? Quels sont les réseaux ? Le but est de soutenir la capacité du système à fournir des services à la société. La dernière étape consiste à comprendre la dynamique du système étudié ainsi que les composantes de sa résilience : quels états différents peut-il prendre ? Quelles variables le feront passer d'un état à l'autre et selon quels seuils ? L'approche socio-écologique consiste donc à assembler les données culturelles, sociales, économiques et écologiques qui nous révèlent les changements de ces systèmes ; cela consiste également à modéliser pour mieux comprendre les forces qui pilotent les dynamiques socio-écologiques et à mettre en place une gestion grâce à de nouveaux outils.

3. La démarche de l'étude

En milieu côtier, la majorité des recherches actuelles reste théorique et peu de cas d'étude appliqués à la gestion des zones côtières mettent à l'épreuve ce concept dans une démarche transdisciplinaire. Cette thèse a donc pour objectif principal de combler ce manque en explorant les concepts de l'approche socio-écologique appliquée à la gestion côtière. D'un point de vue théorique d'abord, nous réaliserons un état de l'art des connaissances afin d'explorer les concepts de l'approche socio-écologique appliquée à la conservation marine et à l'étude d'une aire marine protégée. Dans un second temps nous utiliserons ces connaissances théoriques sur le système socio-écologique du lagon de Moorea en Polynésie française où nous avons développé une approche quantitative pour modéliser les interrelations existant entre la biodiversité, les services écosystémiques qu'elle produit, les usages que l'Homme en fait et les outils de gouvernance qui régulent ces derniers. Nous avons également étudié les modifications de ces interrelations au sein des systèmes socio-écologiques sous l'influence de forçages régionaux ou globaux et de différents scénarios de gestion et de prise de décision. Le but était de guider l'adaptabilité et/ou la transformabilité des usages faits de la biodiversité afin d'en dériver de manière pérenne des biens et services face aux pressions anthropiques et climatiques intervenant à plusieurs échelles.

4. La structure de la thèse

Cette thèse est constituée de quatre chapitres. Chacun de ces chapitres correspond à un article dans une revue internationale à comité de lecture. Ils sont tous déjà publiés, sauf pour l'un d'entre eux qui est actuellement en review dans la revue *Marine Policy*. Je suis premier auteur sur l'ensemble de ces articles. A la fin de chaque chapitre, une synthèse en français fait les liens entre les principaux résultats et présente éventuellement quelques résultats non publiés. Enfin, la dernière partie de cette thèse est consacrée à la discussion générale de mon travail ainsi qu'à des perspectives. Tous les travaux cités, y compris au sein des articles, sont référencés en fin d'ouvrage. Les chapitres sont articulés comme suit :

Chapitre 1. L'approche socio-écologique appliquée à la gestion côtière : concepts, réflexions et perspectives de recherches. Ce chapitre passe en revue les enjeux, les idées et les concepts liés à l'approche socio-écologique appliquée à la gestion marine. Ce chapitre est illustré de quatre cas d'études. Il est publié comme suit : Leenhardt, P., Teneva, L., Kininmonth, S., Darling, E., Cooley, S., Claudet, J., 2015. Challenges, insights and perspectives associated with using social-ecological science for marine conservation. *Ocean and coastal Management* 115, 49-60.

Chapitre 2. La pêcherie récifo-lagonaire de Moorea : état de l'art et perspectives de recherches. Ce chapitre réalise à un état de l'art des études s'intéressant à la pêcherie récifo-lagonaire de cette île permettant de faire émerger la complexité du système socio-écologique étudié. Il est publié comme suit : Leenhardt, P., Lauer, M., Madi Moussa, R., Holbrook, S.J., Rassweiler, A., Schmitt, R.J., Claudet, J., 2016. Complexities and uncertainties in transitioning small-scale coral reef fisheries. *Frontiers in Marine Science*. 3:70.

Chapitre 3. Etude des dynamiques socio-écologiques au sein du lagon de Moore en Polynésie Française : Modélisation participative. Ce chapitre traite du système socio-écologique récifo-lagonaire de l'île de Moorea. Il explore les dynamiques socio-écologiques existantes au sein du lagon de Moorea grâce à de la modélisation participative ainsi qu'à une analyse exploratoire de données empiriques. Il est publié comme suit : Leenhardt, P., Stelzenmüller, V., Pascal, N., Probst, W.N., Aubanel, A., Bambridge, T., Charles, M., Clua, E., Féral, E., Quinquis, B., Salvat, B., Claudet, J., 2017. Exploring social-ecological dynamics of a coral reef resource system using participatory modeling and empirical data. *Marine Policy* 78 : 90-97.

Chapitre 4. Scénarios d'évolution du système socio-écologique du lagon de Moorea : modélisation par réseaux bayésiens. Ce chapitre traite du système socio-écologique récifo-lagonaire de l'île de Moorea. Il détaille la création et l'analyse de scénarios exploratoires des dynamiques socio-écologiques récifo-lagonaires de Moorea à l'aide de deux modèles de réseaux bayésiens. Il est actuellement en cours de relecture : Leenhardt, P., Stelzenmüller, V., Claudet, J., en révision. Identifying social-ecological trade-offs of direct and indirect drivers of change for coral reef ecosystem services using Bayesian Belief Networks. *Marine Policy*.

En annexe de ce travail de thèse, deux articles connexes à ce travail sont présentés :

Annexe 1. Ce chapitre d'ouvrage est une synthèse qui examine le rôle des aires marine protégées dans la provision des services écosystémiques marins côtiers. Il est publié comme suit : Leenhardt, P., Low, N., Pascal, N., Micheli, F., Claudet, J., 2015. The Role of Marine Protected Areas in Providing Ecosystem Services. *in* Aquatic functional biodiversity: An eco-evolutionary approach (eds. Belgrano, A., Woodward, G., Ute, J). Elsevier, London, UK

Annexe 2. Cet article a pour objectif de caractériser les activités de pêches récifo-lagonaires sur lîle de Moorea. Il propose une revue bibliographique de toutes les études halieutiques réalisées jusqu'ici à Moorea. Il est publié comme suit : Leenhardt, P., Madimoussa, R., Galzin, R, 2012. Reef and lagoon fisheries yields in Moorea: A summary of data collected. *SPC Fisheries Newsletter* 137 : 27-35.

Chapitre 1 : L'approche socio-écologique appliquée à la gestion côtière : concepts, réflexions et perspectives de recherches

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Challenges, insights and perspectives associated with using social-ecological science for marine conservation

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ABSTRACT

Here, we synthesize conceptual frameworks, applied modeling approaches, and as case studies to highlight complex social-ecological system (SES) dynamics that inform environmental policy, conservation and management. Although a set of "good practices" about what constitutes a good SES study are emerging, there is still a disconnection between generating SES scientific studies and providing decision-relevant information to policy makers. Classical single variable/hypothesis studies rooted in one or two disciplines are still most common, leading to incremental growth in knowledge about the natural or social system, but rarely both. The recognition of human dimensions is a key aspect of successful planning and implementation in natural resource management, ecosystem-based management, fisheries management, and marine conservation. The lack of social data relating to human-nature interactions in this particular context is now seen as an omission, which can often erode the efficacy of any resource management or conservation action. There have been repeated calls for a transdisciplinary approach to complex SESs that incorporates resilience, complexity science characterized by intricate feedback interactions, emergent processes, non-linear dynamics and uncertainty. To achieve this vision, we need to embrace diverse research methodologies that incorporate ecology, sociology, anthropology, political science, economics and other disciplines that are anchored in empirical data. We conclude that to make SES research most useful in adding practical value to conservation planning, marine resource management planning processes and implementation, and the integration of resilience thinking into adaptation strategies, more research is needed on (1) understanding social-ecological landscapes and seascapes and patterns that would ensure planning process legitimacy, (2) costs of transformation (financial, social, environmental) to a stable resilient social-ecological system, (3) overcoming place-based data collection challenges as well as modeling challenges.

1. Introduction

There are a variety of conceptual models of social-ecological systems (SESs) that depict and characterize human-nature interactions in integrative ways (Young et al., 2006). These models are increasingly used in natural resource management and often in marine conservation (Xu and Marinova, 2013; Kittinger et al., 2013). As anthropogenic pressures have increased across all ecosystems, environmental sciences have undergone a paradigm shift in recent years, recognizing the crucial need to take into account human–nature relationships to better inform and guide conservation and management (Mace, 2014).

Consequently, SES studies have expanded dramatically during the last decade (Young, 2006; Xu and Marinova, 2013), revealing a growing interest from researchers and the public at large to understand SES dynamics and the sustainability of human-nature

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interactions in terrestrial and marine environments (Liu et al., 2007a; Cinner et al., 2009b; Chapin et al., 2010; Diaz et al., 2011). Major scientific initiatives such as the Resilience Alliance (Folke et al., 2004), the Millennium Ecosystem Assessment (MA, 2005) and the establishment of the Sustainable Development Goals (SDGs) have provided comprehensive conceptual frameworks which link social and ecological systems. SES theories are based largely on the concept of resilience thinking (Gunderson and Holling, 2002; Hughes et al., 2005), which explores the dynamics and the organization of SESs, and their policy implications of SES contexts (Folke et al., 2004; Folke, 2006; Fischer et al., 2009; Deppisch and Hasibovic, 2011). For example, the Resilience Alliance has investigated SESs through a transdisciplinary lens with insights from complexity science (Holling, 2001; Berkes et al., 2003). Policy-relevant initiatives such as the Millennium Ecosystem Assessment (MEA) and Sustainable Development Goals (SDGs) are catalyzing meaningful research on ecosystem services and human well-being to fill a knowledge gap on the dynamics of human-nature interactions in SESs (MA, 2005). New scientific fields such as sustainability science (Kates, 2001, 2011; Clark, 2007; Bettencourt and Kaur, 2011) or land change science (Turner et al., 2007) have emerged from this thinking at the same time and also provided research and methodological guidelines for investigating SESs (Biggs et al., 2012a).

From this theoretical understanding, applied social-ecological science can provide case study approaches to investigations of place-based issues and can inform broader conservation and management (Parrott and Chion, 2012; Schlüter and Hinkel, 2014; Lowe et al., 2014). Ocean and coastal environments are complex adaptive SESs where social relationships of stewardship are diverse and resource use is most often unsustainable (Cinner et al., 2009b; Cinner, 2011, 2014; Kittinger et al., 2012, 2013). In marine environments, successful resource planning, therefore, requires diverse datasets and tools (Kittinger et al., 2014). Understanding how such complex adaptive systems are structured, evolve through time, respond to different pressures (e.g. environmental stressors, policy decisions, or management actions), and provide ecosystem services important for human wellbeing is crucial for social-ecological theory to inform marine conservation and management that produces long-term benefits for nature and people.

In this paper, we review the challenges of evolving social-ecological science towards applied outcomes to support resource management and marine conservation. We illustrate those challenges with insights coming from three distinct case studies. The paper has two main goals: 1) to elucidate the challenges of integrating social-ecological science into practical uses for natural resource management, conservation planning, and policy-making in marine ecosystems, and 2) to provide insights on how emerging transdisciplinary social-ecological science can best become an essential and practical decision-support tool in ocean spatial planning and conservation practice with clear linkages to how effective strategies for uptake into management and conservation can be developed. In effect, by unraveling marine environments as intricate peopled seascapes, social-ecological studies and resilience experts can unveil overlooked linkages in marine systems and provide paths to solutions (Kittinger et al., 2014). We base our review on a symposium workshop held during the International Marine Conservation Congress in 2014, as well as on emerging new research on the importance of social data in ocean and coastal environments.

2. The social-ecological challenges of marine conservation

2.1. From a transdisciplinary science to an interdisciplinary management

Transdisciplinarity — a research strategy that crosses disciplinary boundaries to create a holistic approach - is a prerequisite for investigations of SES properties or dynamics. For many years, the need for transdisciplinary collaborations in natural resource management and especially in marine conservation science had been underestimated (Christie, 2011; Fisher, 2012). However, complex marine conservation issues proved difficult to explore through the lens of a single discipline (Lade et al., 2013). Today, it is widely acknowledged that we need integrative approaches involving both social and natural sciences in order to capture a complete picture of complex SESs (Liu et al., 2007a; Ostrom, 2009; Carpenter et al., 2009). For example, transdisciplinary collaborations across biology, ecology, economics, geography, history, law, political science, anthropology, psychology, sociology and computer science can provide fundamental knowledge support for effective marine conservation and management (Carson et al., 2006; Clark, 2007; McDonald et al., 2008). However, while transdisciplinarity needs to be an academic endeavor, it is clear that interdisciplinarity is much more achievable in a management context (Fig. 1).

'Social-ecological system' is the commonly cited term in the scientific literature (Holling, 2001; Cinner et al., 2012d), but 'linked social-ecological systems' (Hughes et al., 2005), 'coupled human-environment systems' (Young et al., 2006), 'coupled human and natural systems' (Liu et al., 2007a) or 'social-environmental systems' (Diaz et al., 2011) are also used. The multiplicity of terms referring to the interplay of social and ecological systems reflects the different disciplinary fields and intellectual traditions within which the

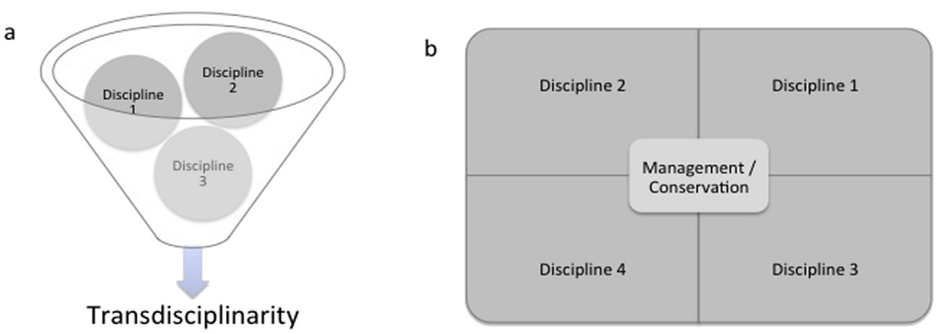

Fig. 1. a: Academic transdisciplinarity for the study of social-ecological systems. The academic way of creating a unified theory or concepts even before thinking about how this information may be useful or not for management. b: Interdisciplianrity or the reality of social-ecological conservation. Management objectives or conservation challenges require drawing out the most pertinent pieces of each discipline.

concept of SES has been developed. Indeed, several schools of thought, investigating notions and themes such as resilience, commons and complexity, political ecology, vulnerability, robustness, biodiversity and ecosystem services, have focused on social-ecological dynamics in the context of natural resource management creating several different approaches and terms. However, all these different terms can affect and obscure the relevance of the SES concept to applied conservation and management (Janssen et al., 2006). Today, some of this transdisciplinary thinking is housed within complexity science, which provides a new and useful paradigm to investigate linked social-ecological systems.

2.2. Connections between ecosystem-based management and social-ecological studies

Ecosystem-Based Management (EBM) is a relatively new approach in natural resource management, which aims for sustainable delivery of ecosystem services and benefits to human communities while simultaneously maintaining healthy, productive ecosystems. EBM is a practical response to theoretical research on social-ecological interactions in marine systems, taking a holistic approach which moves away from focusing management on single species and builds a complex management approach that considers cumulative impacts and interactions between ecosystem components as well as human resource users (McLeod et al., 2005). Successful implementation of EBM, however, requires deep knowledge of the feedbacks between social and ecological systems and the thresholds in these coupled systems that lead to shifts in ecosystem condition and social wellbeing (Leslie and McLeod, 2007). Therefore, EBM is a place-based approach rooted in understanding the linkages between people as resource users and the natural ecosystems communities depend. Inherently, the success of EBM hinges on insights from SES work that identifies connections, cumulative impacts, and multiple objectives in complex human-natural environments (Leslie and McLeod, 2007). Conceptually, EBM holds that natural resource management is about managing people's behavior in ecosystems, rather than the ecosystems themselves, and requires a holistic examination of how human activities affect all functions of the relevant ecosystem (Leslie and McLeod 2007), which in turn, is largely based on SES research in practical settings on different geographical scales. Such a shift in practical management challenges has also stemmed to a certain extent from SES insights and has led to EBM implementation policies in various regions, including the US West Coast, Australia, Canada, and the European Union (McLeod and Leslie, 2009).

2.3. Defining a complex systems approach to social-ecological systems

Social-ecological systems are complex adaptive systems sharing characteristic features of cross-scale linkages, emergent properties, non-linear dynamics and uncertainty (Gallopín et al., 2001; Gunderson and Holling, 2002; Buizer et al., 2011; Parrott and Meyer, 2012; Levin et al., 2012).

SES processes occur over a wide range of scales and induce **cross-scale linkages**. Applied SES science necessarily needs to cover broad spatial and temporal scales equally in order to tackle the full complexity of the SES under investigation (Gunderson and Holling, 2002). Complexity science stresses the hierarchical coupling of ecological and social systems across organizational, spatial and temporal scales. This paradigm highlights the nesting of local systems in larger ones (e.g. regional or global) and the cumulative effects of local processes on global processes (Bodin et al., 2006; Kininmonth et al., 2011). Likewise, complexity science emphasizes the local coupling of social and ecological systems at each scale, the embedding of smaller-scale processes in larger ones and the influence of larger-scale processes on smaller ones (Liu et al., 2007b). Gunderson and Holling (2002) summed up the concept of cross-scale interactions when stressing that "increasingly, local problems of the moment can have part of their cause located half a planet away and have causes whose source is from slow changes accumulated over centuries" (Gunderson and Holling, 2002).

One of the biggest challenges in social-ecological science is that SESs have unique **emergent properties**. Such properties do not belong to social or natural systems separately but emerge from the interactions across these linked systems (Liu et al., 2007b). The term emergence is used to describe unexpected or unpredictable spatial and/or temporal patterns of the structure and of the dynamics of a system, such as the resilience of an SES (Parrott, 2002). Emergent patterns may, in turn, have cross-scale feedbacks on different parts of the system. The observation of SES emergent patterns or properties is crucial to understand the dynamics of the system and has catalyzed scientific interests during the last decade (Folke, 2006). For example, Pollnac et al. (2010) used a meta-analytical approach to study SESs related to 127 marine reserves and showed that emergent patterns of social drivers modulated compliance behavior and thus ecological effectiveness of the reserves (Pollnac et al., 2010). As SESs are adaptive systems, emergence of new trajectories and dynamics are possible and likely when an SES is subjected to disturbances (Levin and Lubchenco, 2008), including, for example, in fisheries co-management settings (Ayers and Kittinger, 2014; Levine and Richmond, 2014). Thus, the response of a disturbed SES can be viewed as a unique and erratic trajectory for the system to regenerate, re-organize, or both from a disturbance (Plummer and Armitage, 2007).

An important characteristic of SESs involves **non-linear dynamics** that are difficult to predict. Thresholds, tipping points, and hysteresis all describe non-linear systems that evolve across multiple basins of attraction for dynamic systems subject to changing environmental pressures (Levin, 1998; Holling, 2001). Non-linearity generates interactions that can change as the system evolves (Folke, 2006). For example, Koch et al. (2009) demonstrated that the ecosystem service of coastal protection was non-linear and dynamic. They showed that there are many important factors, such as plant density and location, species, tidal regime, seasons, and latitude, that can also influence the patterns of non-linearity of this ecosystem services (Koch et al., 2009).

Finally, the cumulative effects of cross-scale, emergent properties are dynamic, non-linear interactions that create substantial and inherent **uncertainty** in socio-ecological systems. Uncertainty shapes SES trajectories (Fischer et al., 2009) and therefore the management of SESs is closely linked to the management of uncertainty, which conservation and resource management continue to struggle with, especially against the backdrop of climate change. While uncertainty is a key parameter emerging both from the cumulative complex interactions described above and from SES attributes, it remains difficult to incorporate into conservation and management (Wilson, 2006; Anderies et al., 2007; Polasky et al., 2011). Consequently, modeling SES dynamics requires tools and techniques to account for this inherent uncertainty (Olsson et al., 2008; Ostrom, 2009; Armitage et al., 2009).

2.4. Towards an empirical approach for the real world

2.4.1. Social-ecological monitoring

A key challenge of studying and managing socio-ecological systems has been a lack of standardized and rigorous data that link changes in ecological processes to responses in social dynamics and subsequent feedbacks between them. Monitoring dynamic and linked marine socio-ecological systems in the real world (e.g., coastal fisheries) is imperative for structured decision-making and adaptive management (Holling, 1978; Armitage et al., 2009), specifically in terms of human or environmental pressures (e.g., climate change, fishing effort) are mediated by management responses to affect social-ecological state and benefits. For example, Cinner et al. (2013) investigated the socio-ecological vulnerability of coral reef fisheries in Kenya to climate change using indicators of climate exposure, biological resistance and recovery, social sensitivity to change and social adaptive capacity to recover and reorganize. Importantly, this approach was the first to quantify the ecological vulnerability of coral reefs to climate change along with social vulnerability of fishing communities to changes in the ecological system, such as the dependence on fishing and the ability to learn from and adapt to climate shocks. By identifying vulnerable coastal communities in a changing climate, this approach assessed socio-economic and governance actions to reduce future vulnerability. This is one example of a rigorous, empirical monitoring data that strategically combine surveys of ecological and social systems (i.e., transdisciplinary studies) to inform conservation and management practices.

2.4.2. Perspectives from modeling

Modeling human behavior is key for the development of policy-relevant scenarios based on field studies facilitating the design of adaptive management initiatives (Österblom et al., 2013). More place-based SES studies are needed to build scenarios able to appropriately inform decision-makers and managers. Place-based SES studies require additional data collection methods and a more comprehensive suite of key indicators (Biggs et al., 2012b). In tropical environments, fine-tuned modeling and planning frameworks were used to deliver management with adaptation schemes (Cinner et al., 2009b, 2013; Cinner, 2011; Kittinger et al., 2012). Such creative and advanced methods need to be incorporated into more formal modeling procedures (Clark, 2004; Uusitalo, 2007; Aguilera et al., 2011), such as Qualitative Comparison Analysis (Bodin and Österblom, 2013), Structural Equation Modelling (Grace, 2006) or Bayesian Belief Networks (van Putten et al., 2013; Kininmonth et al., 2014).

2.4.3. The need for social data

Resource managers and conservationists are often trained to base their planning initiatives on biological, ecological, and physical data and consequently do not use social data in ocean planning (Le Cornu et al., 2014). However, high quality social data and the inclusion of people in decision-making in a top-down/bottom-up hybrid management or conservation planning process usually creates more robust and long-lasting governance structures (Koehn et al., 2013; Kittinger et al., 2014). The lack of social data relating to human-nature interactions in a particular context is now seen as an omission which can often erode the efficacy of any resource management or conservation action. For example, many studies have shown that when social data are not incorporated into planning decisions, the initiatives often have limited success and sometimes unintended outcomes (Christie, 2004; Cinner et al., 2009a; Fulton et al., 2011; Kittinger et al., 2013). This has led to the development of social indicators of food security, poverty alleviation, human well-being in the context of marine resource management, and conservation planning (Mills et al., 2013b; Ban et al., 2013; Milner-Gulland et al., 2014; Stephanson and Mascia, 2014). Kittinger et al. (2014) proposed a useful step-by-step guide for the incorporation of social data into effective and efficient ocean and coastal science, modeling and ultimately, planning and resource management. However, these efforts require a concerted effort by scientists to conceive, fund, and conduct joint SES studies to assess practical resource management and conservation tradeoffs (Ban and Klein, 2009; Koehn et al., 2013; Le Cornu et al., 2014; Kittinger et al., 2014). While theoretical frameworks of integrated social and ecological processes are available to inform conservation planning (Ban et al., 2013; Le Cornu et al., 2014), there are fewer case studies based on empirical datasets which include social data that may arguably hold more practically usable information for adaptive management.

3. Case studies: the importance of context and culture

The extent to which people in different regions of the world view themselves as a part of natural ecosystems has fundamental implications about how people in such different regions approach conservation, resource management and sustainability. Our deeply culturally ingrained legacies of people-nature relationships guide the level to which people conserve nature, and perceive connections between nature and their own wellbeing. Social-ecological research can unveil these connections in important ways, not only for the scholarly effort of understanding behavior, but also for finding extremely practical implications for effective resource management and conservation (Milner-Gulland et al., 2014).

One of the premises of SES modeling is that ecosystems and society are inextricably linked and that any delineation between the two is arbitrary (Berkes et al., 2003). Local communities' perceptions of natural resources and resource management regimes, as well as the perceptions of the underlying cultural, historical, nutritional, and appropriative ties of the community with the natural resources is recognized as critical management-relevant and conservation-planning information in both terrestrial and marine systems (Cinner and David, 2011; Kittinger et al., 2012; Bennett and Dearden, 2014; Stephanson and Mascia, 2014). Therefore, to have the highest likelihood of success for management and conservation decisions, social-ecological studies need to focus on the most appropriate place-based design and choice of relevant social and biophysical indicators (Bauer, 2003; Cinner and Pollnac, 2004; Koehn et al., 2013; Le Cornu et al., 2014; Kittinger et al., 2014).

Highlighting tradeoffs, synergies, costs and benefits between social and ecological outcomes is also critical for SES research (Ban and Klein, 2009) as case studies strive to identify enabling factors for a triple bottom-line of positive socio-economic, cultural, and environmental outcomes (Halpern et al., 2013). Tremendous insights have been gained from the development of generalizable frameworks for social-ecological relationships (Ostrom, 2007, 2009), as well as frameworks for particular types of ecosystems (e.g., coral reefs: Cinner, 2014; Kittinger et al., 2012). Cultural diversity is a significant factor modulating institutions of planning, both conservation planning as well as development planning. There is a strong role to be played by SES research to elucidate cultural aspects in a given natural resource management context that will facilitate the planning process (Poe et al., 2014). Here, we highlight the role of local context and culture with three case studies from the Pacific Ocean and one case study from the Baltic Sea.

3.1. The Polynesian context

Here, we discuss the cultural contexts of the Hawaiian Islands, French Polynesia, and American Samoa as examples of marine SESs that merit a thorough consideration of cultural, political, and historic drivers of natural resource management (cf. Fig. 1). Hawai'i, American Samoa, and French Polynesia all exist in a dichotomy, where Pacific island groups have Polynesian history and heritage but governed by typically western (North American and European) governance structures and management regimes (Ayers and Kittinger, 2014; Levine and Richmond, 2014; Gaspar and Bambridge, 2008). In all three locations, centralized top-down fisheries management approaches are implemented by the non-native governance agencies on many largely isolated rural areas. However, all these Pacific islands also have strong centuries-old cultural heritage of forms of resource stewardship, integrated mountain-to-sea (i.e., ridge-to-reef) management, and sustainable use of fisheries (Bambridge, 2012). Thus effective conservation and management that matters requires considering traditional cultural heritage and marine tenure systems within the contemporary structures of governance.

3.1.1. *Hawai'i, USA*

In Hawai'i, traditional management systems, such as the watershed-based tenure system known as *ahupua'a* (Kittinger et al., 2011; Levine and Richmond, 2014), were practiced successfully and sustainably for centuries, but have arguably not been well-integrated with the modern western management systems, which often seem to result in both erosion of traditional sustainable management as well as failure to meet management goals (Ayers and Kittinger, 2014). Often, the western management planning process does not appear conducive to multicultural inputs, with the potential to marginalize traditional ecological knowledge (TEK) of indigenous people from the rule-making process as well as the governance structures (Levine and Richmond, 2014). However, traditional marine resource management institutions in Hawai'i are increasingly seen by state government agencies as a system to learn from on the pathway to successfully leveraging Polynesian cultural heritage and localization of autonomy in the management of marine resources for abundance and sustained benefits to people (Ayers and Kittinger, 2014).

In 1994, Hawaii passed legislation for the establishment Community-Based Subsistence Fishery Areas (CBSFAs), which created a process for localizing rule-making processes and revitalizing community-based management (Levine and Richmond, 2014). While the CBSFA legislation was heralded as a step forward towards formalizing the process of co-management, the implementation of the new institution has not been as efficient as expected due to challenges with resource depletion, conflict (and lack of conflict resolution mechanisms), self-organization, consensus-building, and collective action (Ayers and Kittinger, 2014). As community collaborative management, or co-management, for small-scale fisheries continues to evolve and demonstrate success around the world (Berkes, 2010; Cinner et al., 2012a, 2012b, 2012c, 2012d; Gutiérrez et al., 2011), it becomes clear in Hawai'i that such local, place-based, collaborative management structures generate greater social and cultural legitimacy and ultimately greater management success when implemented within the local cultural context (Ayers and Kittinger, 2014).

3.1.2. *Moorea, French Polynesia*

Moorea, an island under French government jurisdiction in the South Pacific, is characterized by diverse resource users due to the island's proximity to an urban center and fish-market, Papeete, in Tahiti. Income from coral reef-associated recreational activities represents the main economic resource of the island. Resource users include Moorea residents, Polynesian (Tahitian) and international tourists who engage in scuba-diving, snorkeling and boating. Fishing activities are mostly driven by subsistence fishing and hold an important cultural role in the Polynesian society (e.g. enjoyment, identity, prestige and a life style) (Cinner, 2014) (cf. Figs. 2 and 3).

In order to manage recreational and fishing uses of the Moorea lagoon resources, a management plan, called PGEM ("Plan de Gestion de l'Espace Maritime"), was established in 2004, after 10 years of consultation with all users of the lagoon. The PGEM regulates the entire Moorea lagoon and the Moorea outer slope (down to 70 m depth). The management plan is a marine spatial planning tool that

Fig. 2. A) Convict tangs (*Acanthurus triostegus*; Hawaiian name: manini) drying on lava rock on Hawaii Island, Hawaii ((c) Conservation International, S. Kehaunani Springer); B) Hawaiian fisherman with net ((c) Conservation International, S. Kehaunani Springer); C) Variety of reef fish species caught in Moorea ((c) Pierre Leenhardt); D) Tourism in the no-take reserve in Moorea ((c) Thomas Vignaud).

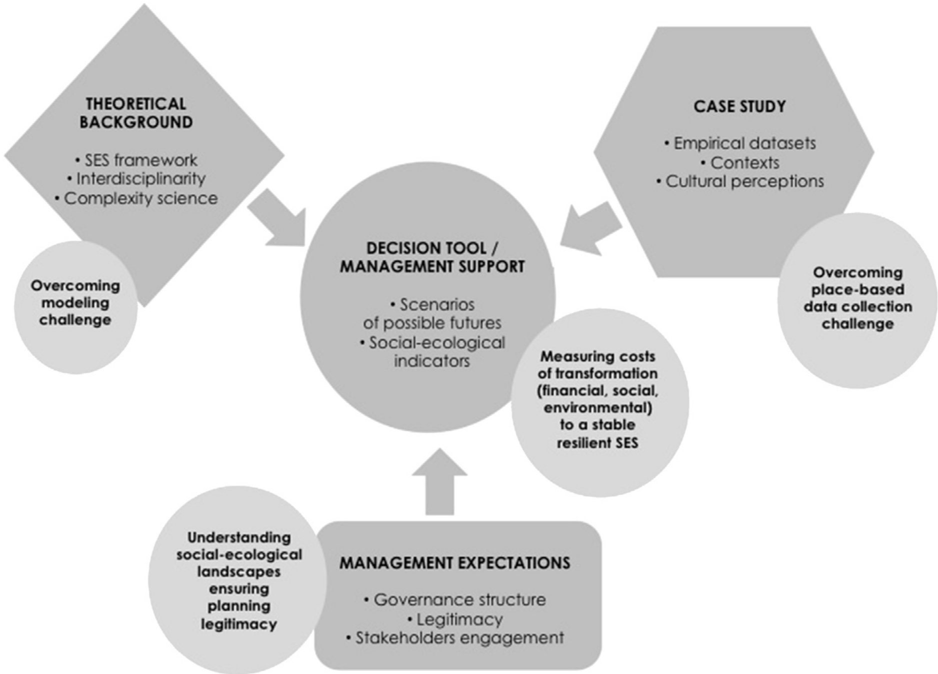

Fig. 3. Ingredients for making marine social-ecological science matter for conservation and management decisions: Theoretical backgrounds, real world case studies and consideration of management expectations contribute to decision tools and management support through scenario planning and stakeholder engagement.

includes a network of eight permanent marine protected areas (MPAs) implemented with the objectives of biodiversity conservation and fisheries management (i.e. 5 no-take zones and 3 fishing gear limitation zones). The MPAs are monitored annually since their implementation, but to date the monitoring program has focused only on the assessment of ecological benefits. After ten years of protection the ecological benefits of the network of MPAs were limited (Lison de Loma et al., 2008) (Thiault et al., pers com). Drivers of such a pattern may stem from natural processes: coral bleaching, a crown-of-thorns starfish (COTS) outbreaks (2006–2009), and a hurricane (2011) may have hampered the provision of benefits from the MPAs. However, social feedbacks are undoubtedly important, as compliance is not high in those MPAs (MacNeil et al., 2015).

From a social perspective, the PGEM has always been strongly criticized and still suffers from a process legitimacy issue. This social disappointment might stem from two cultural drivers: (1) many specific cultural ecosystem services important to the people of Moorea throughout their history are not directly the concern of the PGEM. Moreover, recreational activities and tourism did not have a dominant place in the system of Moorea fifty years ago, and (2) the Polynesian culture is largely reef oriented in terms of knowledge, traditions and resources. Tahitian and related languages in the different archipelagos of the Territory have more vernacular names for coral reef habitats and fauna and flora species than any other language in the world (Salvat and Pailhe, 2002). Moorea as well as all Polynesian islands represent a region where culture and nature are strongly connected and there is a deep cultural heritage of environmental stewardship. Moreover the Polynesian people have always viewed a continuous relationship between the lagoon and the land considering their natural resources "from the top of the mountain to the reef crest" at the same level (Bambridge, 2012).

3.1.3. *American Samoa, USA*

In 2000, the American Samoa Department of Marine and Wildlife Resources (DMWR) led a process to institutionalize co-management in the US territory through the development of a Community-Based Fisheries Management Program (CFMP). Although the intent on developing co-management agreements was similar in Hawai'i and American Samoa, the social, cultural, historic, and political context were different, and therefore had the potential for different outcomes (Levine and Richmond, 2014). American Samoa, lying more than 3700 km south of Hawai'i, is generally characterized by a less diverse and less affluent population than Hawai'i. In contrast to Hawai'i, American Samoa has retained a decentralized nature of marine resource management, as village councils maintain and uphold traditional land and marine tenure practices (Levine and Richmond, 2014).

The American Samoa government aimed to ensure process legitimacy in its development of the CFMP and was focused on village cooperation and involvement in the CFMP formulation (Levine and Richmond, 2014). The CFMP was designed as a voluntary scheme of co-management, wherein a village council, which had limited ability but strong interest in managing and enforcing marine resource use on a local level, would develop a collaborative management and enforcement plan best suited to the sustainability of the village's particular marine resource dynamics and local community needs. Twelve villages have successfully developed CFMPs with the American Samoa government; whereas, in Hawai'i, only one community has its co-management rules package accepted by the state government, even though the legal framework for co-management was available earlier in Hawai'i than in American Samoa.

3.2. *Ingredients for co-management success in the Pacific*

Research on place-based SESs has revealed that in Hawai'i, Polynesia and American Samoa, as well as in other parts of the world, there are exogenous and endogenous factors which control the success or lack of success in development of co-management agreements on a local level which target social-ecological resilience (Gutiérrez et al., 2011; Levine and Richmond, 2014; Ayers and Kittinger, 2014). Exogenous (or external) factors relate to the top-down imposition of a foreign natural resource management system on a culture, which has traditionally held a different human-nature connection begetting different marine resource use and management pattern. In this context, western-style bureaucratic management styles implemented in Moorea, with separate terrestrial and marine management have yielded 20 years of mismatches between state governance priorities and processes with traditional Polynesian environmental management styles. Such mismatches coupled with intensified human impacts on Pacific island terrestrial and marine environments due to increase in population density and proximity to urban centers have resulted in environmental decline (Cinner et al., 2012a, 2012b, 2012c, 2012d).

Some of the endogenous (or internal) factors that challenge the formulation of management initiatives that sustain social-ecological resilience in marine systems stem from the level of cultural and ethnic diversity as well as present or absent community structures. Studies have shown that group homogeneity or a singular cultural identity with little diversity of values and incentives can be a key factor for collective action in common-pool resource management (Baland and Platteau, 1996; Jentoft, 2000). Levine and Richmond (2014) propose that while traditional marine tenure systems, community structures, traditional social hierarchies and cultural identities are strong and remain intact in most locations in American Samoa, the same characteristics have been significantly disrupted in Hawai'i, where currently Hawaiians and part Hawaiians represent a minority and where local marine tenure systems and community leadership can gather momentum only in locations where traditions of subsistence fishing are still practiced. It is likely that the lack of village-level governance systems in Hawaii compared to American Samoa also has presented a barrier to developing community capacity for management and the implementation of the CBSFA legislation (Levine and Richmond, 2014).

In all three Polynesian island contexts presented here, the cultural heritage of stewardship holds much promise for initiatives in collaborative management with state government. However, if local contexts such as the political landscape, power balances, population density, cultural diversity, the level of community cohesion, and the leadership aspects are not fully considered, western-based planning processes may not be successfully integrated with community-level capacity for consensus-building and effective plans for management and adaptation to environmental change (Henly-Shepard et al., 2015). More SES studies are needed, specifically, community-based assessments and gap analyses for transformation, to highlight level of risk or low resilience.

3.3. The European context: the case of the Baltic Sea

The Baltic Sea is a semi-enclosed brackish sea that contains a depauperate set of marine and fresh water species (Österblom et al., 2007). The salinity gradient is highly influential on the species ranges and combined with seasonal ice conditions, wind patterns, fresh water inflows and variable Atlantic water inflows influences the biodiversity patterns and dynamics. Additionally over the past 100 years the impact of anthropogenic pressures such as toxic inputs, nutrient input, hunting and fishing have influenced the species distributions (Österblom et al., 2007; Lowe et al., 2014). The effect of a changing climate is also attributed to shifts in species abundances (Möllmann et al., 2009). The combined effects have resulted in a complex disturbance of the marine food web (Niiranen et al., 2013).

Managing the human activities on the Baltic Sea immerged as a necessity when clear indications of ecological and environmental change occurred (MacKenzie et al., 2011). Fisheries in particular were nationally regulated despite the Baltic Sea being shared between 9 countries. Regime shifts have been observed in multiple occasions with large increases in Cod (*Gadus morhua*) and herring (*Clupea harengus*) (Österblom et al., 2007). Seal numbers were reduced by 95%, mainly due to hunting, during the twentieth century with subsequent reduction in top down control for cod abundances. Eutrophication due to nutrient inputs has altered the bottom oxygen concentrations and has been blamed for the reduced spawning capacity of cod (Lindegren et al., 2014). Increased fishing pressure as a result of the cod high abundance combined with changes in benthic oxygen and salinity conditions led to a collapse of the cod populations in the late 1980's (Koster et al., 2005). Social changes have followed these ecological shifts with a marked reduction (93% in Sweden; Brookfield et al., 2005) of small-scale fishing operations.

In response to these changes and with an international convention on protection of the Baltic Sea (HELCOM) vision of restoring the Baltic Sea to a previously productive state there have been a number of initiatives. Eutrophication reduction is proving difficult due to sustained loads of nutrients despite the implementation of national and international policies. HELCOM for example has had in place the Baltic Sea Action Plan since 1970. More recently the European Union delivered a 2008 Marine Strategy Framework Directive but the problem still remains due to decision, implementation and ecosystem delays (Varjopuro et al., 2014). These delays can be measured in decades and it is proposed that monitoring activities combined with reflexive, participatory analysis of ecosystem dynamics can help understand the deferrals (Varjopuro et al., 2014). Managing the fisheries activities is not just about sustainable catch limits but involves the holistic appreciation of social and environmental factors (Lade et al., 2013; Niiranen et al., 2013). Top-down limits on fish catches imposed in recent years have failed to be realized as the cod abundances and size remained commercially unviable. The original HELCOM 1974 convention did not include territorial waters and limited the regulation of land based pollution. This was rectified in 1992 with a more comprehensive convention containing all the Baltic Sea countries and introducing concepts such as ecosystems (Blenckner et al., 2015). Two major challenges are facing the Baltic Sea management; Climate change and intensified energy installations. With a catchment of 1,720,000 km^2 containing 85 million of people the impact on ecosystem services is significant. Critical to the effectiveness of the management is the shift from isolated pressure – response actions to integrated state-based management that recognizes the complex interaction of people and environment (Österblom et al., 2013).

4. Towards a marine social-ecological conservation

4.1. Integration of social components into social-ecological system management

- Frameworks for MPA management effectiveness

Typically, marine resource management attempts to regulate fishing effort through the establishment of no-take marine protected areas (MPAs), gear restrictions or size limits on take. However, such restrictions often (especially in small-scale fisheries in the developing world) are not successful because they attempt to treat symptoms rather than root social context of resource exploitation, such as poverty traps, weak governance, lack of social welfare and economic safety nets, lack of alternative livelihoods (Cinner et al., 2009a; Kittinger et al., 2013). Particularly relating to MPAs, there is an emerging body of evidence to evaluate the social impacts of MPAs and identify socio-economic factors of MPA success or failure and elucidate trade-offs between social and ecological goals in integrated management (Ehler, 2003; Pomeroy et al., 2005;

Himes, 2007; Cinner et al., 2009b; Pajaro et al., 2010; Gurney et al., 2014). For example, Gurney et al. (2014) used a framework for assessing the impact of MPA management on poverty. Several components of poverty domains such as livelihood diversity, resource dependence, conflicts, well-being, financial capital, human capital, natural capital, resource access, influence in community and governance mechanism were used to help to examine the relationships between natural resource management and poverty. Clearly, social contexts are a fundamental goal of social-ecological systems management (Fig. 3). Moreover, the effect of conservation actions on people is likely to vary with project and context (Cinner et al., 2012c). Only through the construction of a portfolio of case studies can we obtain an understanding of the heterogeneous impacts of conservation, and provide insights to build new projects to better achieve social goals (Gurney et al., 2014).

- Towards the management of social-ecological resilience

The emerging strong interest in resilience across SESs also cautions that social-ecological studies need to be carefully designed to inform management for resilience. Insofar as SES research can provide insight into the transition and transformation towards sustainable and equitable marine resource use, as well as resilient ecosystems and social systems, some of the highest value in SES research lies in evaluating governance regimes, resource users' incentives (Ostrom, 2007; Smith and Stirling, 2010) and the level of dependence of social systems on maintained ecological benefits (Mills et al., 2013a; Gurney et al., 2014). SES studies have continued to focus on what the most appropriate social indicators in a given setting that should be monitored to provide useful information on local conditions that confer social-ecological resilience or vulnerability, as well as information that would directly facilitate improvements in management processes and outcomes (Biggs et al., 2012b; Cinner et al., 2013). This focus has guided research on SESs with understanding how the inextricably connected systems function can move the system to a more stable and resilient state (Turner et al., 2003a, 2003b, Ostrom, 2007, 2009).

A review on social indicators that monitor SES resilience and can inform management reveals several focal domains. Indicators key for insights into social resilience and effective management structures appears to focus on (1) empowerment which includes the capacity to organize and participate in decision-making; (2) ability to adapt, or retain flexibility, which can have various measures, including livelihood diversity in a household, household size, ability to learn, level of education, etc.; and (3) capital, including financial, material, and social capital (Cinner et al., 2009b; Mills et al., 2013b; Gurney et al., 2014; Stephanson and Mascia, 2014). Within this general realm of indicators, place-based SES research needs to be carefully attentive to local cultural values, social dynamics, and political landscapes in order to craft the most appropriate indicators.

- Insights from co-management

Furthermore, social-ecological studies on community-based marine collaborative management (co-management) initiatives reveal some of the keys to success in place-based management, with the academic effort of SES research directly serving to inform management improvements that take advantage of enabling conditions defined by integrated social-ecological indicators and historical studies of cultural decision contexts (Kittinger et al., 2013). Co-management can be differentiated in two main processes: (1) collaborative management involving the practical and technical aspects of management activities, and (2) shared governance, that is sharing the governance institutions and decision-making processes between a stakeholder group and a state agency (Berkes, 2010; Cinner et al., 2012a). The body of empirical studies on the level of participation and decision-making in the development of co-management institutions is growing (Berkes, 2010; Cinner et al., 2012a; Ayers and Kittinger, 2014). In analyzing more than 130 community-based co-management arrangements, Gutierrez et al. (2011) concluded that strong leadership is one of the most important enabling factors for successful and lasting co-management setting with benefits for both nature and people.

Several key factors that facilitate the localization of successful management, beyond the context of co-management frameworks, have emerged centering on the significance of the government agency leading the implementation of culturally legitimate processes congruent with local cultural values (Berkes, 2010; Fox et al., 2013; Kittinger et al., 2013). The agency leading the process has to ensure process legitimacy, equity, and transparency within the planning and implementation effort and carefully account for major process drivers, social incentives for engagement, community cohesion, costs, and timelines (Basurto et al., 2012; Fox et al., 2013; Gleason et al., 2013; Ayers and Kittinger, 2014). The enabling conditions for successfully transforming to socially sustainable management systems include: (1) conflict resolution mechanisms, (2) trust, (3) cohesion, high level of community organization, and shared development of problem and pathway, (4) clear definition of roles, responsibilities, and interests (Kauneckis et al., 2005).

To make SES research most useful in adding practical value to conservation planning, marine resource management planning processes and implementation, and the integration of resilience thinking into adaptation strategies (Levin and Lubchenco, 2008), more research is needed on (1) understanding social-ecological landscapes and seascapes and patterns that would ensure planning process legitimacy, (2) costs of transformation (financial, social, environmental) to a stable resilient social-ecological system, (3) overcoming place-based data collection challenges as well as modeling challenges (Fig. 3).

4.2. How to align social-ecological research with policy needs?

Although a set of "good practices" about what constitutes a good SES study are emerging, there is still a disconnect between generating SES scientific studies and providing decision-relevant information to policymakers. Classical single variable/hypothesis studies rooted in one or two disciplines are still most common, leading to incremental growth in knowledge about the natural or social system, but rarely both. Policymakers, meanwhile, especially those whose decisions are not motivated by environmental conservation, want to know who will be affected by changes in marine resource availability, where these effects will emerge, and when they will occur. There is an inherent mismatch in the detail and focus of the information provided by scientists and sought by decision makers.

Several obstacles stand in the way of developing and implementing fully fledged SES studies as described here. At present, funds and coordination to conduct SES studies at the levels of detail and practice outlined in this paper are not often available, simply because SES studies are generally larger and longer term than classical studies examining a few variables at a time (Langer, 2012; Rodrigo et al., 2013). SES studies also require bringing together scientists trained in many different traditions, but many scientists often simply do not know specialists from other disciplines with whom to collaborate. Once networks of multidisciplinary scientists are convened, communication must be ensured (e.g. by establishing a common "glossary") to overcome divergent vocabularies (Bracken

Table 1
Challenges, insights and perspectives of social-ecological science for conservation.

	Frame	Needs
Challenges	Transdisciplinarity	Integrative approach
	Complex system theory	To account for cross-scales linkages, non linear dynamics, emergent phenomena, uncertainty
	Social-ecological monitoring	To monitor standardized and rigorous data that link changes in ecological processes to responses in social dynamics for adaptive management
	Modeling	To have social data relating to the human-nature interactions that can be incorporated into models for decision help
Insights	Cultural	To account for deeply culturally ingrained legacies of people–nature relationships that guide the level to which people conserve nature, and perceive connections between nature and their own wellbeing
	Co-management	To account for level of cultural and ethnic diversity as well as present or absent community structures, cultural heritage of stewardship, political landscape, power balances, population density, cultural diversity, the level of community cohesion, and the leadership aspects are not fully considered
Perspectives	Management effectiveness	Integration of MPA social effectiveness indicators such as livelihood diversity, resource dependence, conflicts, well-being, financial capital, human capital, natural capital, resource access, influence in community and governance mechanism Integration of social Indicators to monitor SES resilience such as: (1) empowerment which includes the capacity to organize and participate in decision-making; (2) ability to adapt, or retain flexibility, which can have various measures, including livelihood diversity in a household, household size, ability to learn, level of education, etc.; and (3) capital, including financial, material, and social capital Socially sustainable management systems that include: (1) conflict resolution mechanisms, (2) trust, (3) cohesion, high level of community organization, and shared development of problem and pathway, (4) clear definition of roles, responsibilities, and interests. To align social-ecological science with marine resource management challenges through an *Ecosystem-Based Management* approach
	Social-ecological science	(1) Understanding social-ecological landscapes and seascapes and patterns that would ensure planning process legitimacy, (2) costs of transformation (financial, social, environmental) to a stable resilient social-ecological system, (3) overcoming place-based data collection challenges as well as modeling challenges.

and Oughton, 2006), and a shared theoretical framework must be established that all participants can work within (Binder et al., 2013). Products that report on the outcomes (e.g., peer-reviewed journal articles, reports, web sites, public presentations, etc.) must be planned that will be equally rewarding to all contributors, despite their different research interests, approaches, and ways in which contributors are evaluated (Table 1).

Providing decision-relevant information to policy-makers about an SES requires answering the who, what, when, where, and why-style questions mentioned above and clearly connecting this information to specific policy-makers' primary interests, such as voting constituents, resources of interest, laws to uphold, etc. Ideally, SES studies should be structured at the outset to provide insight on these questions (Ash et al., 2010). The integration of social indicators into SES management should directly facilitate improvements in management by providing decision-relevant information to policymakers about an SES (Fig. 1). When this is not the case, knowledge gained must be synthesized or extrapolated to answer policymakers' questions. Although this can be done in some instances, in others this approach risks increasing uncertainty or going beyond the limits of the study.

5. Conclusion

There have been repeated calls for a transdisciplinary approach to complex linked socio-ecological systems (SESs) that incorporates resilience, complexity science, emergent properties, non-linear dynamics and uncertainty. To achieve this vision, we need to embrace diverse research methodologies that incorporate ecology, sociology, anthropology, political science, economics and other disciplines that are anchored in empirical data. Here, we synthesize conceptual frameworks, applied modeling approaches, as well as case studies to highlight complex SES dynamics that inform environmental policy, conservation and management (Table 1). While a number of modeling approaches have been developed, robust social-ecological monitoring and empirical social datasets remain scarce, limiting our ability to fully consider the complex processes, functions and dynamics of SESs. Furthermore, the local context of political landscapes, power balances, population density, cultural diversity and community cohesion are crucial information for adapting conceptual frameworks towards case specific approaches (Kittinger et al., 2013). Finally, our case studies from the Pacific and the Baltic sea highlight that cultural perceptions of SESs need to be better integrated into management schemes in order to avoid mismatches between state governance priorities and traditional environmental management styles.

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Transition

Le premier chapitre de ce travail nous a permis de faire ressortir les défis et les perspectives d'application de l'approche socio-écologique à la gestion des ressources naturelles marines. Indéniablement, il existe encore une certaine déconnexion entre les études scientifiques utilisant cette approche et les outils et supports de décision utiles à la gestion des ressources naturelles. Alors que si une vision transdisciplinaire est certainement indispensable pour cerner les problématiques socio-écologiques, c'est véritablement l'intégration de la dimension sociale à la vision écosystémique qui permet d'adapter l'approche socio-écologique à la gestion des ressources naturelles marines. Par ailleurs, nous avons pu souligner que l'intégration de la science des systèmes complexes et l'utilisation des modèles permettent aussi d'explorer les dynamiques socio-écologiques qu'il est indispensable d'appréhender pour la gestion.

Après avoir détaillé différents aspects théoriques de l'approche socio-écologique, dans le chapitre suivant, nous étudierons le système socio-écologique récifo-lagonaire de l'île de Moorea en Polynésie Française en réalisant un état de l'art des études s'intéressant à sa pêcherie récifo-lagonaire. Ce travail nous permettra de faire émerger la complexité du système socio-écologique étudié.

Chapitre 2 : La pêcherie récifo-lagonaire de Moorea : état de l'art et perspectives de recherches

frontiers in Marine Science

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Complexities and Uncertainties in Transitioning Small-Scale Coral Reef Fisheries

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Coral reef fisheries support the development of local and national economies and are the basis of important cultural practices and worldviews. Transitioning economies, human development, and environmental stress can harm this livelihood. Here we focus on a transitioning social-ecological system as a case study (Moorea, French Polynesia). We review fishing practices and three decades of effort and landing estimates with the broader goal of informing management. Fishery activities in Moorea are quite challenging to quantify because of the diversity of gears used, the lack of centralized access points or markets, the high participation rates of the population in the fishery, and the overlapping cultural and economic motivations to catch fish. Compounding this challenging diversity, we lack a basic understanding of the complex interplay between the cultural, subsistence, and commercial use of Moorea's reefs. In Moorea, we found an order of magnitude gap between estimates of fishery yield produced by catch monitoring methods (~2 t km^{-2} year^{-1}) and estimates produced using consumption or participatory socioeconomic consumer surveys (~24 t km^{-2} year^{-1}). Several lines of evidence suggest reef resources may be overexploited and stakeholders have a diversity of opinions as to whether trends in the stocks are a cause for concern. The reefs, however, remain ecologically resilient. The relative health of the reef is striking given the socio-economic context. Moorea has a relatively high population density, a modern economic system linked into global flows of trade and travel, and the fishery has little remaining traditional or customary management. Other islands in the Pacific in similar contexts in Polynesia such as Hawaii, that continue to develop economically, may have small-scale fisheries that increasingly resemble Moorea. Therefore, understanding Moorea's reef fisheries may provide insight into their future.

Keywords: social-ecological systems, small-scale fisheries, coral reef fisheries, transitioning economy, catch monitoring, fishery yield, complexity, resilience

INTRODUCTION

Coral reef fisheries are vital to millions of people dwelling along the world's coasts (Johnson et al., 2013; Teh et al., 2013; Cinner, 2014). They support the development of local and national economies by providing food, income, and employment, and also are the basis of important cultural practices and identities. Yet the coral reefs upon which these fisheries depend are some of the globe's most threatened coastal systems (Mumby and Steneck, 2008). Until recently, coral reefs worldwide demonstrated the capacity to return to coral dominance following perturbations that cause landscape-scale loss of coral, such as cyclones and bleaching (Jackson, 1992; Pandolfi and Jackson, 2006). In the past two decades, however, a growing number of studies have documented cases where major perturbations cause long-lasting and potentially irreversible ecosystem shifts, one of the most common being a shift from a coral-dominated to a macroalgae-dominated state (Hughes, 1994; Shulman and Robertson, 1996; Hobbs et al., 2006; Rogers and Miller, 2006; Bruno et al., 2009). The dynamics of these state shifts are fundamental to understanding long-term sustainability of coral reefs and the fisheries that depend on them, yet the interacting human and ecological dynamics, including fisheries, that underpin coral reef resilience are poorly understood (Hughes et al., 2003, 2005, 2010).

Most coral reef fisheries are small-scale fisheries in that they involve simple technologies and are either subsistence-based, or supply small local markets, or roadside sellers. Despite their limited technological and economic scope, small-scale fisheries have been identified as a primary threat to coral reefs (Newton et al., 2007). Some studies suggest small-scale coral reef fisheries are experiencing declining fish biomass and size (Cinner J. E. et al., 2009) but the extent, magnitude, and variability of overexploitation is generally not well-documented (Jacquet and Pauly, 2008), and even the number of people involved in such fishing is poorly known (Teh et al., 2013). This paucity of understanding and uncertainty is attributable to the inherent complexity of small-scale coral reef fisheries. They evolve within locally specific social and ecological conditions, making them highly diverse. Variability arises from the diverse set of technologies used for harvesting marine resources, multiple overlapping social, economic, and cultural motivations for fishing, heterogeneous modes of governance, varied stakeholder organization, and complex interactions with other marine-use sectors and governance structures.

Here we explore the complexity of coral reef fisheries using Moorea, French Polynesia, as an example. Moorea presents an interesting case study in that economic development and intense exposure to globalization have not undermined the capacity of its coral reefs to recover from perturbations. Extensive, long-term ecological research on Moorea suggests that its reefs are quite resilient to disturbances (Done et al., 1991; Adjeroud et al., 2009; Adam et al., 2011, 2014; Trapon et al., 2011; Lamy et al., 2015, 2016; Galzin et al., 2016). Many Pacific islands have shown declines in the critical adaptive capacities that underpin resilience to environmental variability when they are more exposed to the pressures of globalization and global markets, have higher population densities, and widespread coastal development (Pauly and Chua, 1988; Brewer et al., 2012). Interestingly, Moorea enjoys a higher standard of living than most Pacific islands while its reefs have demonstrated high resilience to environmental perturbation. This may suggest that higher levels of socioeconomic development may reduce dependence on coral reefs and associated human impact (Cinner J. et al., 2009) or may reflect other social or ecological characteristics of the system.

We describe Moorea's small-scale coral reef fishery by documenting fishing practices and reviewing uncertainties associated with estimates of effort and landings over the last three decades. Fishing activities on Moorea are widely dispersed, both spatially around the island and temporally throughout the day and the night, making the collection of accurate catch data challenging. Existing statistical data provided by the Territorial government cannot be used for this purpose because they do not effectively assess non-commercial fishing, the most widespread fishing practice on the island. Moreover, we lack a basic understanding of the complex interplay between the cultural, subsistence, and commercial use of Moorea's reefs. Filling these gaps in our knowledge of Moorea's fishery will help enhance the development of marine resource management initiatives that seek long-term sustainability of reef fisheries and foster ecosystem resilience.

THE SOCIAL-ECOLOGICAL CONTEXT

The island of Moorea is surrounded by a barrier reef, broken by 11 passes, enclosing a 49 km^2 lagoon, whose width varies from 500 to 1500 m, with depths of 0.5–30 m (Bell and Galzin, 1984). The island has a marine spatial management plan (Plan de Gestion de l'Espace Maritime, PGEM) initiated in 2004, the first in French Polynesia. The PGEM has four objectives: (1) rational use of resources and sustainable development; (2) managing conflicts for space in the lagoon; (3) controlling pollution and physical damage to marine environments; and (4) protecting marine ecosystems and endangered species. Although the PGEM was carefully developed over a 10 year consultation process, certain segments of the fishing community voiced opposition when it was implemented in 2004 (Aubanel et al., 2013), and it continues to be a source of tension and controversy (Walker, 2001; Gaspar and Bambridge, 2008; Walker and Robinson, 2009).

The uses of Moorea's coral reefs have fundamentally changed over the last 100 years. Moorea gradually transitioned during the late nineteenth century from a subsistence economy based on small-scale gardening and fishing to an economy that by the 1940s was based on cash cropping of vanilla and copra. In the 1960s, French military activities drove a burgeoning economy and employment opportunities that drew migrants from other parts of French Polynesia to the capital city, Papeete (Henningham, 1992; Salvat and Pailhe, 2002). These economic changes in French Polynesia influenced Moorea's social-ecological system in several important ways. With regular ferry service established between Moorea and Tahiti, residents of Moorea were able to commute to jobs in Papeete. Moreover, many Papeete residents moved to nearby Moorea or visit the island on weekends and occasionally fish there. Most notably, however, was rapid growth in tourism that progressively became the mainstay of Moorea's economy. In 2011, Moorea was the most visited island in French Polynesia with over 70,000 tourists visiting the island's 22 major hotels and 48 smaller "pensions de famille" (ISPF, 2001). The transition to a tourism-led economy has sustained a level of economic prosperity in French Polynesia, and it continues to be one of the wealthiest Pacific Island nations with a USD 15,272 per capita GDP (Baudchon et al., 2008). An economy that was once dominated by small-scale food production and subsistence fishing was replaced with tourism and service sectors as well as some export-oriented non-indigenous agriculture, such as pineapple. In addition, fishing became just one of many marine-focused activities that include scuba diving and beach and boating activities, each exerting different pressures on the coral reefs and lagoon ecosystem.

One important outcome of these transformations was very high population growth, a portion of which was due to immigration from other islands. Census figures indicate that Moorea's population grew from 5058 to 16,893 between 1971 and 2012 (ISPF, 2013)—an annual growth rate of 2.39%, which is higher than the rate for French Polynesia as a whole (1.57%). The effect these demographic changes have had on Moorea's fishery is unknown, but throughout the region fishing pressure appears to be linked to the number of local inhabitants although the relationship is poorly understood (Russ and Alcala, 1989; Jennings and Kaiser, 1998).

FISHING CATEGORIES

Fishing has formed the backbone of Polynesian societies since their initial colonization of the region (Oliver, 1974) and continues to be an integral part of the subsistence economy and Polynesian identity. Today, Moorea's coral reefs directly support two fundamental livelihoods on the island: fishing and tourism. In strict economic terms fishing-based incomes are dwarfed by tourism-based incomes, which stem mostly from tourist accommodations and reef-based recreational activities. A recent economic assessment estimated that recreational activities stemming from Moorea's reefs provided approximately 27 M€/year while fishing activities provided 4M€/year including 2.8 M€ value placed on fish not sold but consumed within the fisher's household (Pascal and LePort, 2015). These figures, however, do not capture recreational fishing activities nor the high cultural value of reef fishing in Polynesian society (e.g., enjoyment, identity, prestige, worldview; Cinner, 2014).

Polynesian fishing activities can be lumped roughly into three categories: oceanic fisheries, coastal fisheries, and reef (or lagoon) fisheries. Reef fisheries are described as all activities involved in exploiting biological resources and carried out on the fringing and barrier reefs, channels, passes and *hoa* (small passes not always connected to the ocean) and down to the limits of coral growth (80–100 m depth; Galzin et al., 1989). According to Yonger (2002), Brenier (2009), and Leenhardt (2009) and our own observations, fishing is ubiquitous on Moorea with three broad categories of fishers: commercial fishers, subsistence fishers, and recreational fishers (**Table 1**). The latter term encompasses fishers not motivated by market imperatives or hunger, but cultural factors. The fisher population is composed of 69% recreational, 20% subsistence, and 11% commercial fishers but the categories are not mutually exclusive (Leenhardt, 2009; Brenier et al., 2014). Over half of the adult population fishes, with the vast majority of households having at least one person who fishes. While subsistence fishers are all Moorea residents, a certain number of commercial and recreational fishers come from the nearby Society Islands, mainly Tahiti (Leenhardt, 2009). It should be noted that nearly 70% of the people who fish on Moorea are recreational fishers, yet none of the catches from this category of fisher appear in the fisheries data collected in market surveys (**Figure 1**). Moreover, recreational fishing may account for 58% of the catches in the lagoon (Yonger, 2002), yet, a percentage of those catches are never recorded because they are directly destined for home consumption or shared among family or other community members. In addition, roadside sellers reported keeping a very small part of their catch on average for household consumption.

CAUGHT SPECIES

A diverse suite of species is targeted by fishing in Moorea's reefs. More than 40 genera of fishes can be found sold by the roadside. Three groups are caught most frequently: Iihi (soldierfish, *Myripristis* spp.), Paati (parrotfish, mixed species smaller than 50 cm; mostly *Scarus* spp. and *Chlorurus* spp.), and Ume (unicornfish, *Naso* spp.; **Table 2**).

FISHING GEAR TYPES

The wide diversity of species caught in part reflects the many fishing techniques that are employed, each adapted to specific suites of organisms. Given the many different techniques, individual fishers often use a multifaceted approach, using several techniques depending on their preferences and resources, on the frequency of fishing, season, weather conditions, target species, and time of day. The main gear types used in the lagoon are spear guns, lines (handlines, hook-and-line), nets (gillnets or nets with pot traps), harpoons, beach seines, and trolling (Yonger, 2002; Leenhardt, 2009; Brenier et al., 2014). Although a wide variety of fishing methods are used, spearfishing dominates the (commercial) roadside catch: sellers reported that a large majority of biomass had been taken by spear gun with the remainder split equally between hook and line and net fishing. Spearfishing occurs both during the day and at night with battery-powered torches. Night spearfishing is very effective, providing high yields per fishing trip. It accounts for about 29% of lagoon fish production in the Windward Islands (which include Moorea) as compared to 18% in the Leeward Islands (SPE, 2007). Night spearfishing is very selective but can lead to local overexploitation of stocks because most targeted species (80%) are non-migratory and tend to be confined to a specific habitat during the night (Lecaillon et al., 2000). Line fishing is done directly from the coastline or from small vessels

TABLE 1 | Classification and characteristics of fishers on Moorea.

Commercial fisher	Subsistence fisher	Recreational fisher
Two to five fishing trips per week	One to three trips per week	One to four trips per month
Sells catch	Some of the catch is sold and some is kept for home consumption	Catch is for home consumption
Fishing is the main source of income for the year	Fishing is a supplementary form of income	Fishing is primarily a recreational activity

FIGURE 1 | Reef fish sold along the roadside on Moorea. Boards in background are used by scientists to estimate sizes (Images: R. Madi Moussa).

powered by oars or 2–25 hp outboard motors. The different line fishing techniques include trolling, bottom longlining, fishing with artificial lures, using lines with one or more hooks, and fishing with natural and live bait. Nets can take a wide variety of forms: gillnet fishing; beach seine net fishing (used seasonally on bay floors to catch bigeye scad, *Selar crumenophthalmus*); funnel net fishing that includes a wire net that targets parrotfish, trevallies, surgeonfish, and goatfish; and cast nets and scoop nets, which are used to catch flying fish. Fish traps are widely used in the Tuamotu and Leeward Islands, where they can account for 90% of catches (Galzin et al., 1989), but are not used in Moorea's lagoon.

YIELD ESTIMATES

A variety of studies in the past three decades have attempted to assess fish production (Galzin, 1985) or reef fishery yields (Aubanel, 1993a; Yonger, 2002; Brenier et al., 2014) on Moorea (**Table 3**). As in other coral island settings, quantifying reef fisheries yield has proven to be a particularly difficult exercise for many reasons. Fishing is often done at night (with or without a boat), is widely dispersed, uses many different types of gear, and landings and sales do not take place at specific sites but rather anywhere along the coast, often on private stretches of coastline (**Figure 1**). Research methodologies used between the times of Galzin (1985) and Brenier (2009) have also evolved considerably. Over a period of three decades, five different studies attempted to evaluate Moorea's lagoon fishery yield, and only two studies used the same methodology (Aubanel, 1993a; Vieux, 2002), leading to a wide range of production estimates for Moorea's coral reefs. Yield estimates based on catch data provide relatively low figures (from 0.7 to 2.2 t km^{-2} $year^{-1}$), while, by contrast, data from consumption surveys or participatory surveys estimate fishing yields an order of magnitude higher (from 20 to 25 t km^{-2} $year^{-1}$).

Monitoring Catches, Landings, and Sales

Built in 1987, the Paopao market was once the single official point of sales where all fishers from the north side of the island were supposed to sell their fish. The centralized fish market was the result of a regulation that prohibited the sale of fish at roadside stands, although compliance with the law was low and eventually the Paopao market ceased to operate (Aubanel, 1993a). Galzin et al. (1989) estimated catches based on the tax the township levied on the fish sold at the Paopao market. Aubanel (1993a) estimated production and total catch based on fish sold both at roadside stands and at the Paopao market. These estimates were made by counting tuis, a string from which a collection of fish are hung, often of different species and sizes, and the unit by which fish are offered for sale (**Figure 1**). Vieux (2002) used the same protocol counting only roadside tuis (the market was closed by that time) to assess potential changes in total catch.

There were some methodological weaknesses of these assessments that most likely led them to underestimate fishery production. The tax-based approach (Galzin et al., 1989) did not account for non-market based sales (roadside sales and direct sales based on contracts), that were estimated afterwards to

TABLE 2 | Relative abundance (percent) of important fished taxa sold by the roadside on Moorea since 1991.

Tahitian name	Scientific name	1991 (Oct)	1992 (Mar)	2002 (June–July)	2007 (Jan–Sept)	2008 (Jan–Feb)	2012 (Jan–Mar)	2014–2015 (June–May)
Marava	*Siganus argenteus*	20	10	4	4	2	2	4
Vete	*Mulloidichthys vanicolensis*	16	10	2	2	1	1	0
Pahoro/Paati	*Scarus* spp. or *Chlorurus* spp.	26	19	10	26	17	33	41
Ume	*Naso unicornis*	8	20	13	31	33	5	4
Ume Tarai	*Naso lituratus*	1	14	23	7	10	4	1
Iihi	*Myripristis* spp.	NA	NA	22	7	8	10	11
Other	Other	29	28	26	24	28	45	39

Data from: Galzin et al., 1989; Aubanel, 1993b; Vieux, 2002; Yonger, 2002; Brenier, 2009; Kronen et al., 2009; Madi Moussa, 2010.

TABLE 3 | Yield estimates per surface area unit by type of survey.

Yield (t km^{-2} year^{-1})	Type of data	Source
24.5	Participatory surveys	Brenier, 2009
28.14	Socioeconomic surveys	Kronen et al., 2009
22.9	Direct consumption surveys	Yonger, 2002
1.01–2.2	Fish sold on roadside	Vieux, 2002
0.7–1.4	Fish sold on roadside	Aubanel, 1993a
1.2–1.4	Extrapolation of fishing data	Galzin et al., 1989

be about 60% of the total catch (Vieux, 2002). Yield estimates based solely on roadside surveys (Aubanel, 1993b; Vieux, 2002) were most likely underestimated for the same reasons. However, and although done 10 years apart, those two assessments based on roadside surveys led to similar yield figures. Surprisingly, the tax-based study done 10 and 20 years earlier, respectively, led to estimates in the same range, suggesting that the market oriented reef catches were similar for the various fishing/selling categories. Although the spatially dispersed nature of landings makes quantifying fish catches difficult, monitoring roadside sales can be an excellent way of discerning spatial patterns of fishing pressure (fish are typically sold in roadside stands near to where the fish were caught) as well as the species and sizes of the fish sold (**Figure 1**; Madi Moussa, 2010).

Consumption Surveys

An analysis of seafood consumption can be a good alternative for indirectly assessing fishery production (Paddon, 1997; Gilbert, 2006; Labrosse et al., 2006). This method requires a well-defined study area with low quantities of imported or exported reef and lagoon fish. On Moorea, catch exports are limited to recreational fishers who come from Tahiti on the weekends and the importation of fish is negligible, with only small amounts of pelagic fish from Tahiti or the Tuamotu Islands being brought to the island (Leenhardt, 2009; Brenier et al., 2014). On Moorea, annual consumption is nearly 110 kg per inhabitant (Yonger, 2002), far above the 23 kg per inhabitant that is the average annual consumption for the Pacific Islands region (Labrosse et al., 2006; Kronen et al., 2010). The gap between estimates in Moorea and other Pacific Island countries is intriguing and encourages consideration of possible methodological biases. Studies either sampled 5% of Moorea's household population (Yonger, 2002) or concentrated on a village and sampled 12% of its households (Kronen et al., 2010). However these two studies led to similar estimates. We believe a potential source of discrepancy with other similar studies in the region may be due to the fact that residents of Moorea consider leftovers to be a new individual meal (Gilbert, 2006). The one-off nature of the surveys also creates considerable uncertainty in the annual estimates, which were extrapolated from average weekly estimates. The methodology also assumed that eating habits and fishery production remain stable over time (Gilbert, 2006). Fish sizes were generally estimated with gauges, while size and weight conversions were calculated using biometric ratios. Size and weight ratios were not always calculated in a precise manner. In fact, length-weight relationships did not exist for the species studied, so relationships for similar species were used (Gilbert, 2006). Although the information collected from households was quantitative it involved substantial uncertainty because it relied on the short-term memory of the person interviewed and his or her ability to convert an image or a memory into a physical size (Gilbert, 2006).

Despite the drawbacks mentioned above, indirect studies based on household seafood consumption surveys offer a good alternative for studying fishery production in small-scale fisheries. In contrast to methods based on landings and sales monitoring, household consumption surveys take into account the catches of all types of fishers, including recreational fishers. They also have been conducted more frequently over the past few years (Yonger, 2002; Lagadec, 2003; Léopold et al., 2004; Kuster et al., 2006).

Participatory Methods

Participatory monitoring of reef fisheries through household surveys can be designed to collect data on consumption and fishing activities from large sample groups and can produce reliable data (Au et al., 2000; Nicholson et al., 2002). On Moorea, fishery production was estimated using surveys by schoolchildren (Brenier, 2009). Surveys consisted of questionnaires designed to gather general information (i) on the household's general fishing activities and fish consumption (including how often fish was eaten, origin of the fish eaten, number of boats and fishers in the household) and (ii) on the number of fishing trips of one fisher in the household over a 2-week period (to cover one spring tide period and one neap tide period) along with (iii) the names, sizes and number of fish eaten at meals over the previous 3 days. These surveys involved 4.4% of total household population and the questionnaire return rate was 68%. The fisher population was estimated at 77 fishers per km^2, with 1916 ± 530 motorboats and 481 ± 68 fishing trips per km^2 each month (Brenier, 2009). If this calculated fishing pressure is accurate, it is quite high considering that 5 fishers per km^2 is the upper limit at which coral reef resources can be safely exploited (McClanahan et al., 2002).

PERCEPTIONS OF STOCK STATUS

Perception surveys can also serve as a good indicator of fish stock status. On Moorea, perception surveys show mixed results with some indicating that Moorea has experienced a decline in the abundance and size of target fish species, increased scarcity of giant clams, decreased live coral cover, and increased cover of macroalgae (Brenier, 2009), while others suggest heterogeneity in perceptions between communities, with respondents from Afareaitu reporting more marine resource degradation than in southern Ha'apiti and Papetoai. Over the past decade, fishers in most districts report that they are still catching as many fish, yet most agree that their fishing effort has increased (Leenhardt, 2009), although there is some variation between districts. The varied perceptions about the health of fished stocks emphasize the difficulty of using such metrics to infer stock status. Responses are consistent with reefs that are either fully exploited or somewhat overexploited but show no evidence of collapse despite the heavy use.

DISCUSSION

Coral reef fisheries are multifaceted, and when fishers can fish for pleasure, identity, to eat or to sell, yields are very difficult to assess and large uncertainty is common. For instance, in Moorea's reef fisheries, there is considerable uncertainty on the magnitude of the catch or even the status of the stocks being fished. Over a period of 30 years, several studies have attempted to assess fishery production in Moorea's reefs, with nearly every study using a different methodology. Two approaches have yielded an order of magnitude gap between the estimates: ∼2 t km^{-2} year^{-1} using catch-monitoring methods vs. ∼24 t km^{-2} year^{-1} using consumption or participatory socioeconomic consumer surveys (**Table 2**). Market surveys are unable to capture many kinds of fishing activity (e.g., recreational fishing, fishing for household consumption, and contract fishing for private clients), so we expect that methods based on these surveys would underestimate fishery production. Methods involving socioeconomic surveys might potentially give more accurate fishery production estimates as they apply to all fish consumed on the island regardless of source, but they rely on recollections of fish recently consumed, rather than on direct observation, introducing other forms of uncertainty.

Similar to many small-scale coral reef fisheries, fishery activities in Moorea's lagoon are quite challenging to monitor and quantify because they vary greatly and are quite dispersed. While estimates of actual production are uncertain, the potential sustainable productivity of Moorea's lagoon fisheries is completely unknown. In fact, there may not be any reliable guidelines for the sustainable yield of many of these fish species, as their biomasses have been shown to change by a factor of five or more over time scales as short as a few years during rapid ecological transitions (Adam et al., 2011, 2014). At present, these variations in biomass are not predictable - some are driven by pulse disturbance events (Adam et al., 2014), and there is no infrastructure for monitoring stock status that would permit dynamic estimation of sustainable yield.

Adding to the complexity is the fact that Moorea's reefs have been subjected to several large perturbations in the past four decades, including in 2008–2010 (Adjeroud et al., 2009; Trapon et al., 2011; Adam et al., 2014; Lamy et al., 2015, 2016). In all cases, the coral community on the fore reef displayed high resilience to perturbation -returning to pre-disturbed coral cover (∼40–50%) within about a decade without undergoing a shift to high cover of macroalgae (Adjeroud et al., 2009; Trapon et al., 2011; Adam et al., 2014; Lamy et al., 2016) due in large part to herbivorous fishes preventing the establishment of macroalgae on the fore reef (Adam et al., 2011, 2014). Following the recent disturbances, the relative abundances and biomass of species targeted by Moorea's fishers changed, with several key groups of herbivores experiencing large increases.

The complexity of Moorea's coral reef fishery, in many ways, is representative of other small-scale coral reef fisheries around the world. A wide diversity of fish is caught with at least five major gear types and fishing occurs during day or night without any regular schedules or formalized protocols. Moorea's fishery, however, becomes more place-specific when we consider the socio-economic context and the motivations that underlie why people fish. Unlike many other small-scale coral reef fisheries in the Pacific and around the world, French Polynesia is a relatively rich country. For this reason Moorea households are not dependent on marine resources for protein or their livelihoods to the same extent as in poorer countries where necessity motivates the harvesting of marine resources. For this reason, only a small percentage of Moorea households identify fishing as their primary source of income or livelihood. Instead, fishing is vitally important for its non-material benefits. The primary motivation for fishing on Moorea is related to an important cultural factor: eating fresh reef fish. For Moorea's inhabitants the consumption of fresh reef fish is as fundamental to their identity as speaking the Tahitian language. It is pivotal to culturally important events such as Church gatherings, birthdays, Sunday feasts, and other events and continues to dominate the local diet. For these reasons, the three categories of fisher—subsistence, commercial, and recreational—that are frequently cited in the literature on small-scale fisheries do not fully capture the nature of fishing on Moorea. Culturally motivated fishing, although most similar to recreational fishing, translates into fishing behavior that cannot easily be analyzed within a cost-benefit or profit maximization model where the economic value generated by the activity forms the core of the analysis. To more deeply comprehend fishing on Moorea the non-material benefits related to the Polynesian lifestyle and identity must be considered.

Given the social and ecological complexity of Moorea's lagoon fisheries, any attempt to understand their dynamics will likely require integrated methods that consider both systems simultaneously. More integrated fieldwork is required to better evaluate the sustainability of the existing fisheries, in which social science techniques are paired with ecological field surveys to understand how fishing behavior depends on ecological state, livelihood opportunities, non-material benefits, cultural cohesion, and personal identity.

CONCLUSIONS

Understanding Moorea's lagoon fisheries is a major challenge, but also an opportunity. In important ways, Moorea may provide a window into the future of many other islands in the Pacific. Although the influence of globalization and economic development will inevitably vary across the Pacific, many Pacific Island nations are undergoing socio-cultural and economic changes similar to Moorea in that their population densities are increasing, their economies are modernizing and becoming more linked to global flows of trade and travel, and their fisheries are no longer managed through traditional marine tenure practices. If other island nations in the Pacific undergo similar changes, their small-scale fisheries may increasingly come to resemble Moorea's, where fishers are less dependent on the marine environment for subsistence or income and more motivated by non-material factors that sustain personal and cultural identity. Despite these changes on Moorea, its reefs are still superficially healthy with high coral cover and abundant fish. We acknowledge Moorea is unique in that it is economically and geopolitically linked to France, but studying Moorea's system might yield insight into how the processes of globalization can be effectively and sustainably navigated both ecologically and socially in similar contexts in Polynesia such as Hawaii.

AUTHOR CONTRIBUTIONS

PL wrote the first draft and all authors contributed substantially to revisions.

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Transition

Le précédent chapitre nous a permis d'étudier la pêcherie récifo-lagonaire de l'île de Moorea en Polynésie française. Les activités de pêche s'appuie sur un service écosystémique essentiel et majeur du système socio-écologique corallien de Moorea : la production de nourriture. Nous avons également montré que les activités de pêche regroupent une diversité d'usagers et de pratiques rendant difficile l'évaluation précise de l'intensité de l'exploitation. Aussi, une meilleure compréhension des dynamiques sociales et écologiques est nécessaire pour expliquer les comportements des acteurs vis-à-vis de l'exploitation et de la consommation des ressources halieutiques récifo-lagonaires. La relative bonne santé du système ainsi que sa capacité de résilience apparente face aux différentes perturbations écologiques ou anthropiques invitent à penser que le système socio-écologique de Moorea est un cas d'étude intéressant pour comprendre l'impact des perturbations environnementales et sociales sur l'ensemble de l'écosystème corallien et sur les services qu'il délivre et dont profite la pêcherie. Dans le chapitre suivant, nous proposons d'explorer les dynamiques socio-écologiques de ce système à l'aide d'un processus de modélisation participative et de l'analyse de données empiriques.

Chapitre 3 : Etude des dynamiques socio-écologiques au sein du lagon de Moore en Polynésie Française : Modélisation participative

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Exploring social-ecological dynamics of a coral reef resource system using participatory modeling and empirical data

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ABSTRACT

Coral reef resource systems are complex adaptive social-ecological systems providing vital and valuable ecosystem services for human societies such as food provision, coastal protection and recreational activities. Their sustainability is questioned in many places around the world as they experience combined effects of multiple chronic anthropogenic and natural drivers at local to global scales. From a management perspective, there is a crucial need to understand how the impact of these drivers cascade through the social-ecological system components. This study develops a transdisciplinary and participatory approach to investigating the social-ecological dynamics of a Polynesian coral reef coastal system. A preliminary conceptual model using the Driver-Pressure-State-Impact (DPSI) framework is first being built through participatory modeling workshops. Then, pressure-state relationships are assessed with the help of empirical datasets as a first step towards the validation of the DPSI model. Results shows striking social-ecological interactions with different patterns in the lagoon and in the fore reef. Local management should be: (1) less resource-focused to account more specifically to the existing typology of actors; (2) more spatially-explicit to better distinguish management objectives and actions for the lagoon and the fore reef sub-systems; and (3) more coordinated with terrestrial agencies for a coherent land-sea connection and integration that would both (i) account for existing land-sea interactions and (ii) better reflect the Polynesian cultural heritage that considers nature from ridge to reef as a whole. Such conceptual models of social-ecological systems are a useful tool to build exploratory scenarios to ultimately support planning decision-making processes.

1. Introduction

Coral reefs are among the most biologically diverse marine ecosystems in the world providing vital and valuable ecosystem services for mankind such as food provision, coastal protection, recreational activities and numerous cultural services [1–3]. Coral reef resource systems are social-ecological systems where human-nature interactions are particularly intricate [2]. Their sustainability is questioned in many places around the world as they experience combined effects of multiple chronic anthropogenic and natural drivers at local to global scales [4]. Local anthropogenic drivers such as overfishing, water pollution from terrestrial run-offs and coastal development interact with locally-experienced natural disturbances such as extreme climatic events and Crown Of Thorns Seastar (COTS) outbreaks, which may also increase in frequency and intensity in response to human activities [5–7]. Such multiple pressures induce ecological modifications impacting the provision of ecosystem services and consequently the local communities' uses and well-being [8,9].

From a place-based management perspective, there is a crucial need to understand how impacts of those multiple pressures cascade through social-ecological systems [5]. This requires capturing and understanding social-ecological interactions such as the role of people

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in the dynamics of coral reefs and the feedbacks of ecological change on human uses and well-being [10].

In many cases, coral reef management suffers from a data-poor context and has to draw often on expert opinion as it is often the best available source of information about coral reef social-ecological dynamics. In this study the term expert refers to anyone with relevant and extensive or in-depth experience in relation to a topic of interest. Experts include scientists, members of technical agencies, decision-makers as well as members of the civil society [11]. To gather expert opinion, participatory modeling workshops appear as key elements of knowledge acquisition and integration into natural resource management while coping with stakeholders involvement in the process [12]. Participatory modeling workshops provide a transdisciplinary common pool of knowledge delivered in the process of sharing learning by experts and enable elicitation and description of the complexity of social-ecological dynamics [12,13]. Expert inputs are knowledge systems that can be mental models (i.e. personal, internal representations of external reality [14]) or series of beliefs about the social-ecological system or its components [15].

One of the widely used methodologies in defining and structuring social-ecological components is the driver-pressure-state-impact (DPSI) conceptual framework [16–19]. The DPSI framework provides the means for organizing and integrating information extracted from a participatory workshop dealing with the current major state changes, the pressures on the environment producing these changes and the social and economic drivers leading to these pressures [20]. It allows to reflect a chain of causal links starting with 'driving forces' (e.g. demography, economic sectors, human activities, natural disturbances) through 'pressures' (e.g. emissions, waste) to 'states' (i.e. physical, chemical and biological) and 'impacts' on ecosystems and human health, eventually leading to political and management 'responses' (e.g. prioritization, target setting, indicators) [21,22]. Moreover, it is a flexible framework that contributes to the simplification of the complexity of environmental management and improves communication and cooperation among stakeholders [16,18]. It also helps to visualize feedback loops between social and ecological components of social-ecological systems and thus causality of environmental degradation [23].

In this paper, a transdisciplinary and participatory approach was developed to investigate the coral reef social-ecological dynamics of Moorea Island, French Polynesia. A preliminary conceptual model using the Driver-Pressure-State-Impact (DPSI) framework was built through participatory modeling workshops regrouping different groups of local stakeholders (decision-makers, technical agencies, cultural and environmental organizations, members of the civil society and natural and social scientists). Then, the validation of the preliminary DPSI model structure have been undertaken through an explorative analysis and by assessing identified pressure-state relationships using available ecological and socio-economic empirical datasets. Both participatory modeling outputs (i.e. preliminary DPSI model) and state-pressure analysis enabled us to develop a DPSI model describing major social-ecological dynamics within the coral reef social-ecological system of Moorea Island. The strength and weakness of this approach are discussed as well as the management implications according to the observed social-ecological dynamics.

2. Materials and methods

2.1. Case study

Moorea Island, located 30 km off Tahiti Island, is the second largest inhabited island in French Polynesia with more than 17,236 inhabitants [24]. The lagoon has a surface of 49 km^2 and encloses the whole island. Moorea can be characterized by a great diversity and number of resource users due to the island's proximity to the urban center and fish-market of Papeete in Tahiti. Moorea coral reefs support, among other social attributes, the livelihoods linked to fishing (i.e. recreational, subsistence and professional fishing) and tourism by providing scuba-diving, snorkeling, boating activities [25]. Recreational and commercial fishing activities are benefiting from two separate types of ecosystem services: cultural and provisioning services, respectively [26]. Tourism-based incomes, stemming mostly from tourism lodging and recreational activities generated by the coral reef ecosystem, are the main economic resource of the island. A recent economic assessment found that recreational activities stemming from Moorea coral reefs provided 27 M€/year while fishing activities provided 4 M€/year (with respectively 2.8 M€/year for subsistence value) [27]. However, these figures do not measure the fishing cultural value, which is important in the Polynesian societies (e.g. enjoyment, identity, prestige and a life style) [2]. Moorea residents, local and international visitors conduct multiple types of activities such as scuba-diving, day tours (i.e. excursion trips), beach and boating activities which exert different pressures on Moorea coral reefs and lagoon.

Moorea coral reef habitats were characterized by living coral cover of approx. 50% declining to 10% in 2006–2009 following an outbreak of the coral eater starfish *Acanthaster planci* (crown of thorns seastar, COTS) and a cyclone in 2011 [28,29]. As coral cover dropped below 10% following the severe COTS outbreak it was observed that the coral reef fish composition remained largely stable through time and space whereas compensatory changes appeared in biomass among species [28,29]. In 2015, the living coral cover partly recovered but didn't reach yet its level of 2006 (i.e. before the COTS outbreak and the cyclone Oli).

In order to manage human activities such as recreational, commercial fishing and tourism development in Moorea, a spatially explicit management plan, called Plan de Gestion de l'Espace Maritime (PGEM), was established in 2004, after a stakeholder consultation process. The PGEM covers the lagoon and fore reef until 70 m depth. The management plan can be seen as a marine spatial plan that comprises a network of 8 permanent marine protected areas implemented to conserve biodiversity and manage fisheries. The marine protected areas are monitored yearly since their implementation, but the monitoring focuses only on the assessment of ecological benefits. After ten years of protection the ecological benefits of the network of marine protected areas are limited [30,31]. There is still a lack of compliance by many stakeholders, including the fishermen since they partly question the legitimacy of what is still perceived as a top-down management. For example, it is being argued by some fishermen that the PGEM might have been implemented to enhance tourism and exclude fishing activities, as some of the marine protected areas are sited close to hotel resorts [32]. After 10 years of management and given the perceived lack of legitimacy of the PGEM [33], a reviewing process of the management plan has been launched and will continue until a consensus is reached. Our study fits in this complex social and political period with the aim to provide a first snapshot of the social-ecological dynamics occurring within Moorea coral reefs.

2.2. Workshops and expert knowledge elicitation

The Moorea coral reef social-ecological dynamics was investigated using participatory modeling workshops to gather expert knowledge on key driver-pressure relationships and derive a preliminary Driver-Pressure-State-Impact conceptual model. On May 13–14th 2013 and on February 12th, 2014 in Moorea, French Polynesia, two participatory modeling workshops with key stakeholders were conducted.

Since governance and resource management is still very top-down in Moorea (although there is now the aim to develop specific community-based and/or co-management frameworks), care was given on the selection of experts that could provide an enhanced understanding of the social-ecological dynamics according to the current management scheme. Moreover, according to the social and political context with pro- and anti-management plan around Moorea, a part of the civil society (including fishermen) refused to take part in this modeling endeavor. However, the identification and selection of experts have been made to ensure the diversity of expertise and opinion. The selection criteria helped (1) to minimize the redundancy of opinions and (2) to have a balanced and broad spectrum of scientific and technical expertise and organizational representation [15,34]. The participants were representatives from governmental agencies, research institutes, management bodies, environmental and cultural organizations, local administrations, members of the civil society and tourism operators. Researchers from the fields of ecology, fisheries science, law, environmental economics and anthropology accounted for a fourth of the participants, reflecting the growing interest of the research community in social-ecological research and management [35]. To enlarge the expert group in the workshops, experts could recommend peers who could also contribute to the participatory approaches and provide more insights on the social-ecological system [36]. Workshops were limited to 25 participants to allow a fruitful discussion and avoid an impersonal mass event.

The overall aims of the workshops were (1) to identify the main social and ecological components of the coral reef resource system of Moorea Island and (2) to elicit the main relationships between the social-ecological system components. Components and their interactions of the Moorea social-ecological system defined during the first workshop were exhaustively listed and categorized into drivers, pressures, states and impacts [16,17,37]. This allowed us to develop a draft model based on this first stakeholders input. The model was then presented at the second workshop where stakeholders interactively discussed and commented on the model to produce a preliminary DPSI model (Fig. 1). Hence the methodology used during the workshop combined the use of the DPSI model and the participatory approach to build a preliminary representation of the complex coral reef resource system of Moorea [14,38,39]. This work greatly benefitted from this two-step process. Workshop attendees' involvement was largely increased in the second workshop (i.e. when the draft model was presented) as they understood better than during the first event how their knowledge would be used and how the conceptual model could be used to reach the stated objectives.

Participants were provided with a workshop reader synthesizing the necessary background information prior to the first workshop to prepare for the discussions. The document contained the workshop agenda, a summary of the project and a brief overview of the workshop's aims and key research questions. The workshops were organized in several successive sessions. Opportunities for discussion were used widely throughout the different sessions of the workshops. The first session of the first workshop presented the INTHENSE project and the modeling approach that was originally proposed. All the others sessions were dedicated to define and link the different components of the modelled social-ecological system. The components and the links of the preliminary DPSI model were defined entirely by participants with no help from available data. Potential disagreements about relationships were resolved by negotiation. In the last session, participants, depending on their central interest, background and skills, were grouped into thematic working groups. Thematic working groups explored scenarios of the social-ecological system according to specific management objectives and related management actions. [40].

2.3. Exploring key pressure-state relationships: data preparation and exploratory analysis

The pressure state analysis enabled us to test the preliminary DPSI model interactions and develop DPSI models. Ecological data used in this study were taken from a biannual ecological monitoring program, started in 2004, at 117 stations around Moorea. This monitoring was set up specifically for the ecological monitoring of the PGEM management plan. In total, data from 13 sites monitored around Moorea (eight marine protected areas and five control areas). At each site three reef habitats (stations) were sampled: (a) on the border of the fringing reef close to the channel, or when there is no channel at the boundary of the barrier reef and the fringing reef; (b) on the barrier reef at 200 m shoreward from the reef crest; and (c) on the fore reef at 10 m depth. At each station, three replicates were randomly sited on the bottom, and fishes, invertebrates, and benthic substrates (including coral cover) were identified and counted (three 25 m-long and 2 m-wide transects). Ecological variables were standardized by surface area (biomass, abundance and percent cover per m^2, respectively).

Environmental data were retrieved from sensors that monitor silicium, phosphate and temperature at three different habitats (the fringing reef, the barrier reef, and the fore reef) in the north of Moorea Island.

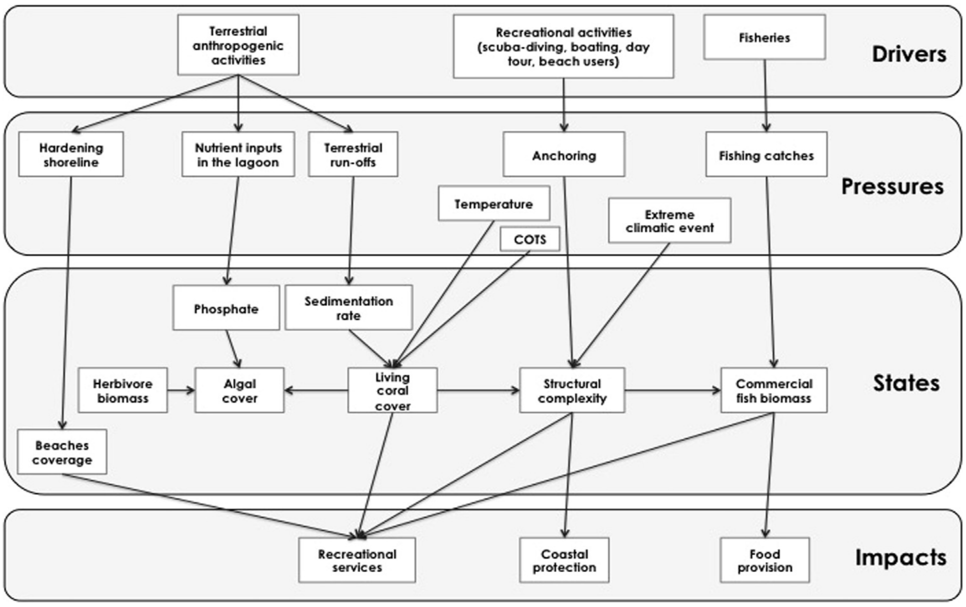

Fig. 1. Preliminary Driver-Pressure-State-Impact (DPSI) model of the coral reef social-ecological system of Moorea based on participatory workshop outputs. Human Drivers are exerting Pressures on the States of key environmental components. Ecosystem changes due to both anthropogenic and natural Pressures have an Impact on ecosystem services. COTS means Crown Of Thorns Seastar.

Socio-economic data were extracted by French Polynesia Statistical Institute (ISPF) surveys and census or collected for this present study. The 2007 and the 2012 Polynesian Census were used. ISPF Surveys were tourism frequentation surveys collected in every Moorea hotels from 2007 to 2012 on a monthly basis. Surveys focusing on recreational activities were conducted in 2014 specifically for this project. An overview of the available data and their respective temporal coverage can be found in Appendix Element A.

Based on discussions during the second workshop it became clear that a spatially resolved understanding of the interactions between drivers, pressures, states and impacts in the lagoon and the fore reef was required. Each ecosystem has key ecosystem processes and functions that are impacted to various extent by different human and natural pressures [41]. As described by Adam et al., Moorea coral reefs comprise distinct ecosystems that have been roughly categorized into lagoon and fore reef [7]. Besides, some uses are specific to one of those two sub-systems. Therefore ecological and socio-economic data for the lagoon and fore reef were separated and pressure-state relationships were respectively assessed. Key pressure-state relationships and links between the preliminary DPSI model components were identified using time series data (spatially averaged), correlation and regression analyses defining the structure of the DPSI model for the fore reef and lagoon. Building on this revision process and the results of the explorative analyses, the DPSI model has been further specified comprising the key drivers, pressures, states and impacts of the Moorea lagoon and fore reef. Key indicators were defined at the island level using the scientific literature: structural complexity of coral reefs, commercial fish biomass (kg m^{-2}), and income and expenses related to tourism, Associated incomes and Tourism operator incomes, respectively.

3. Results

3.1. Preliminary Driver-Pressure-State-Impact model

Workshops output provided a preliminary DPSI model (Fig. 1) where three main drivers influencing Moorea coral reef and lagoon social-ecological dynamics were perceived as terrestrial anthropogenic activities, lagoon recreational activities and fishing activities. Terrestrial activities such as tourism, housing and agriculture were predicted to cause direct and indirect pressures on the lagoon ecosystems such as the increase in hardening of the shoreline (i.e. embankment buildings along the shoreline), terrestrial run-offs and nutrient inputs [42,43]. These pressures affected the state of some ecosystem components such as beach coverage and algal and coral covers. These modifications might impact the provision of recreational services such as scuba diving. Recreational activities caused direct pressures such as the destruction of habitat complexity due to anchoring, thus impacting supporting ecosystem service of coastal protection [44].

3.2. Pressure-states analysis and Driver-Pressure-State-Impact sub-models

Both in the lagoon and fore reef, three types of actors were distinguished in the social-ecological system of Moorea: Moorea residents, local visitors (hereafter called Tahitian tourists), and international tourists. These actors were directly linked to the drivers detailed in the preliminary DPSI model (Fig. 1) such as Recreational activities, Fisheries and Terrestrial anthropogenic activities.

On the fore reef, these three types of actors performed various recreational activities. Using a pressure state-analysis, results showed that the number of international tourists had an impact on commercial fish biomass, which could have subsequently had an impact on food provision (i.e. the node Fishing catches) (Fig. 2). The model showed that the number of Moorea residents and Tahitian tourists had an negative effect on coral cover and subsequently on coastal protection through the node Structural complexity (Fig. 2) [45].

For the lagoon no clear interaction between the three actor groups and the ecosystem components were identified. Nevertheless, the state of the lagoon ecosystem was clearly influenced by terrestrial activities, especially by nutrient inputs (i.e. phosphate) (Fig. 2).

On the fore reef, no significant relationships were found between temperature and coral cover over the years, herbivore fish biomass and algal cover, COTS density and coral cover. However, these relationships are well described in the literature and have been considered. Indeed, although there was scientific evidence of the negative effects of COTS outbreak on the living coral cover [6,7], this pattern didn't came out from the analysis, most probably because none of the data used was specifically dedicated at monitoring COTS densities (which have thus been largely underestimated).

Significant relationships were between coral cover and algal cover, between coral cover and the number of Tahitian tourists, and between coral cover and the number of Moorea residents (see Appendix B and D). International tourists number can have a greater (negative) effect on commercial fish biomass than Moorea inhabitants. The number of Moorea inhabitants increased roughly around 1000 people yearly over the last 10 years while a larger magnitude was observed for international tourists. This means that a potential increase of fishing pressure on the fore reef might be directly associated to the numbers of international tourists. This relationship together with an increasing local employment rate resulted in a significant fit of a linear regression model (see Appendix B and D).

For the lagoon we observed a significant positive linear relationship between phosphate and coral cover (see Appendix C). No significant linear relationships were found between coral cover and algal cover, algal cover and herbivore fish biomass or phosphate rates and algal cover. Commercial fish biomass is correlated with structural complexity (See Appendix C).

4. Discussion

4.1. Expert elicitation and Driver-Pressure-State-Impact model

Engaging participatory modeling workshops with a broad range of scientific disciplines and stakeholder groups with diverging interests can be challenging and time-consuming [46,47]. However it improves interactions between groups of people, provides a common language and a mutual identification of the different dynamics (including conflicts) occurring in the social-ecological system of interest, and enables discussion of multiple management perspectives, hopefully leading to more consensus and adaptability in decision-making [48]. Some of the crucial questions associated to such workshops remain “who participates? " and "who are the experts?” [34,49,50]. Here, workshop participants were representatives from governmental agencies, management bodies, environmental and cultural organizations, local administrations, lagoon users and tourism operators, and researchers from the fields of ecology, fisheries science, law, environmental economics and anthropology. Unfortunately, due to the social and political context stated above, most fishermen did not engage in the process. Integrating fishermen's local ecological knowledge was thus not possible in the model despite the fact that the relevance of using such knowledge in resource management is increasingly recognized [51,52].

While gathering expert knowledge to develop the DPSI model there can be a conflict or a gap between model complexity and expert input [16] and it was thus essential to have flexibility in terms of organization during the workshop. At the beginning of each workshop, we stressed the type of expected outcomes and the modeling framework that we intended to use. It helped minimizing misunderstanding and maximizing the amount and quality of information received. We had to remain flexible in the workshop program due to an unanticipated demand from

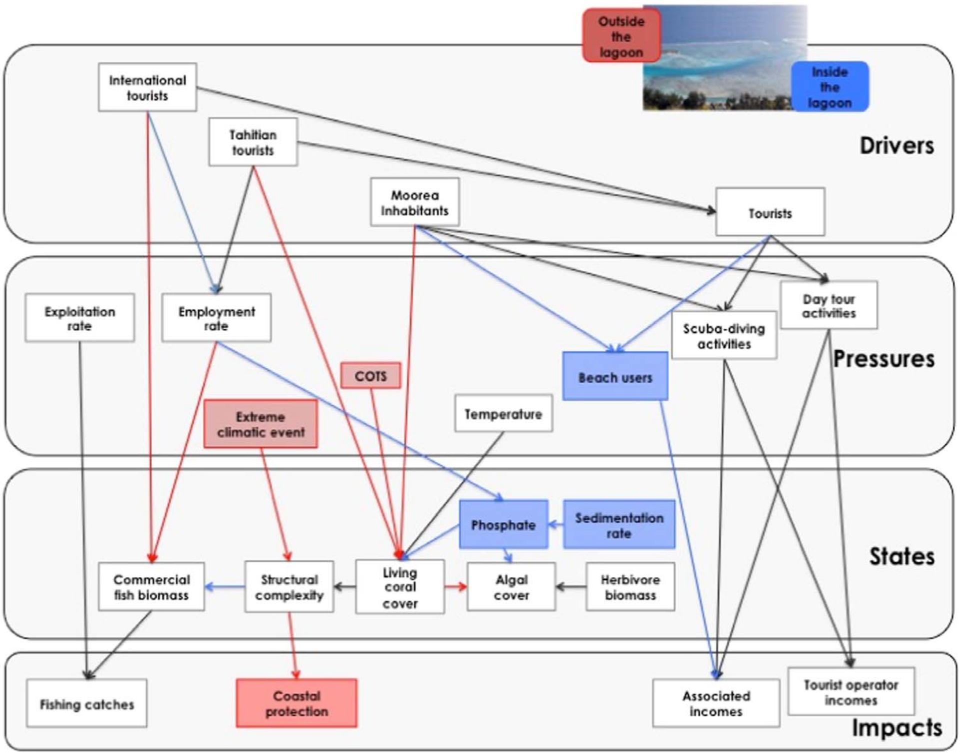

Fig. 2. Driver-Pressure-State-Impact (DPSI) model once validated through a pressure state analysis using empirical social-ecological data. There are two sub-system DPSIs embedded within this general model, with model components that are specific to the lagoon (in blue) or the fore reef (in red), while the other components apply to the two sub-systems (in white).

some workshop participants to have a technical briefing on the modeling methodology adopted for the project (i.e. participatory modeling and DPSI framework). Flexibility can also give the experts a sense of ownership and further engage them in the project [36]. As model components and interactions become more complex, more effort may be needed to frame issues, questions, and processes for experts. Many stakeholders do not think in terms of parameterization, number of components, or probabilistic relationships and outputs. Therefore, model transparency is crucial. From our experience, it was worth our time to explain modeling basis, to produce schematics and visuals of our modeling concept [36] even if we could have used also the fuzzy cognitive mapping approach [53]. All experts greatly benefited from the development of the DPSI models since it facilitated the critical process of making explicit the differing mental constructs of stakeholders and it also illuminated the existing social-ecological dynamics and the possible management perspectives associated to them, as also showed in other contexts [54].

One advantage of the DPSI models is that they can be converted into influence diagrams, which can in turn be further transformed into Bayesian Belief Networks [55,56]. Those graphical and probabilistic models enable to represent correlative and causal relationships among variables and can account for uncertainty (McCann et al., 2006). Moreover, combined with geographic information system tools those type of models may enable to conduct a spatial explicit assessment of potential impacts of spatial management options [57,58]. Indeed, these types of modeling tools have been successfully applied to natural resource management to address environmental management problems and to assess the impact of alternative management measures [56,59–61].

Participatory approaches have multiple benefits but remain challenging and have some limitations [62,63]. As many other approaches, it is time-consuming. While trust is needed to establish appropriate relationships for knowledge sharing, the analyses and interpretation are often led by an expert external to the studied system, hence raising issues of legitimacy and making the impact of the endeavor challenging. Also, as in the current case with fishermen, it is difficult to be fully representative, and when it is the case, power relationships might prevent some group to fully express their thoughts.

4.2. Social-ecological dynamics

The DPSI model revealed different types of social-ecological interactions for the fore reef and the lagoon of Moorea (Fig. 2). The main differences found were that terrestrial anthropogenic pressures seemed disconnected from ecosystem states on the fore reef, while there was a clear link between terrestrial anthropogenic activities and lagoon system states. For instance commercial fish biomass in the lagoon is linked to habitat quality (i.e. it correlated to structural complexity) that is in turn influenced by anthropogenic activities. In contrast, for the fore reef, the state of the commercial fish biomass is correlated with the fishing intensity.

On the fore reef, the observed relationship between Tahitian tourists and corals (“the more Tahitian tourists the less coral cover“) can be related to direct impacts of Tahitian tourists on reefs through, e.g., anchoring. However, the causal relationships might be more complex. The economic crisis that hit Moorea (peaked in 2008), the crown-of-thorns seastar (COTS) outbreak that started at the end of 2006 and the cyclone Oli in 2010 all happened in the same time window [6,7]. The COTS outbreak and cyclone impacted corals [Lamy's ref]. The economic crisis impacted international tourism (French Polynesia being an expensive destination) [ISP ref], which resulted in great discounts for Tahitian tourists in hotels in Moorea in order to compensate the loss of income due to the drop in international tourists. This dynamic could explain the observed negative correlation between Tahitian tourists and coral cover (Fig. 3).

The pressure-states analysis also suggested that the number of international tourists could have a greater negative effect on the fore reef commercial fish biomass than Moorea inhabitants. However,

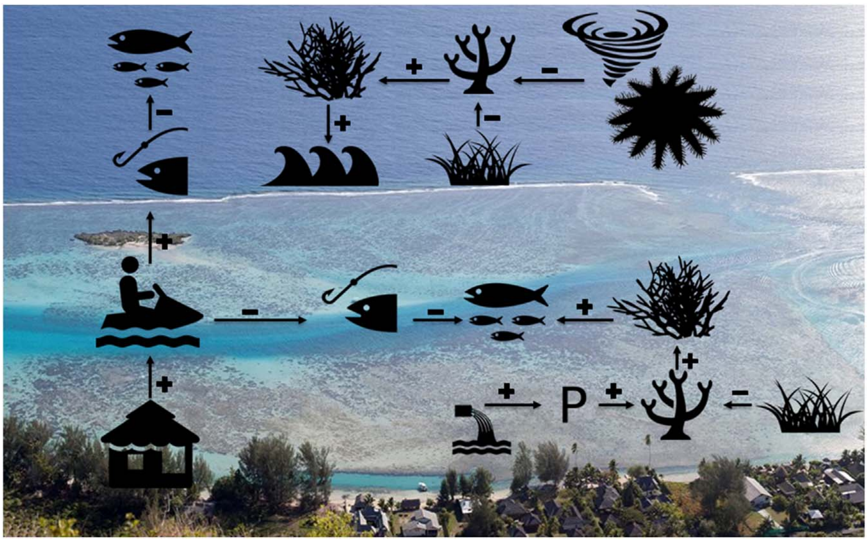

Fig. 3. Synthesis of the possible social-ecological interactions occurring within Moorea coral reefs. It shows the potential links existing between the (1) phosphate enrichment and effect on coral cover; (2) the fishing effort displacement from the lagoon to the fore reef enhanced by international tourists frequentation; (3) and the coral-algal competition and crown of thorns seastar and cyclone effects on the fore reef.

international tourists do not consume reef fishes in Moorea (they are not available in restaurants due to risks of ciguatera), while Moorea residents do. While the increase in international tourists is positively correlated with the economic activity of Moorea (e.g. the employment rate), it also leads to an increase in recreational activities, which are mostly based in the lagoon (being based on day-tour activities and ray feeding activities). Thus, many conflicts for space between uses such as recreational and fishing activities appeared recently. For instance, non-regulated feeding practices resulted in both an increase in shark numbers and a change in sharks behavior that modified local interactions with spear-fishermen [64]. Hence, the causal relationships might be that more international visitors leads to more recreational activities that in turn conflict with local fishermen activity in the lagoon. More international tourists would therefore lead to a displaced fishing effort from inside to outside the lagoon (Fig. 3).

In the lagoon, the positive effect of phosphate on corals is in line with several studies in Moorea [65,66] which described a first enhancement of coral growth due to increase phosphate concentrations followed by decreasing skeletal density. Nutrient enrichment has been shown to have dose-dependent positive effects on coral growth [67]. Moreover a recent six-month factorial field experiment in the lagoon of Moorea suggests that the early recovery of disturbed areas of reef, which can be system-wide if disturbance is severe enough, depends on the combination of sediment, nutrient and fishing pressures on the system [66] (Fig. 3).

More continuous and integrated surveys would help to lower the uncertainties attached to this study, Time series used to explore key relationships between ecological and socio-economic components were here rather short (less than 11 years), not necessarily collected at the same time steps, and don't account for within-year variability. In addition, although the developed models accounted for inside/outside lagoon differences, they were not spatialized further. It has previously been showed in Moorea that the effects of the cyclone and COTS outbreak were largely similar around the island and that the effects of the marine protected areas were very limited [29–31] but fishermen behavior can vary around the island [25,68].

4.3. Towards a Polynesian-based resource stewardship?

This study clearly shows that Moorea coral reef management should account for different reef zones for spatial planning. Thus, following the concept of an ecosystem-based approach to spatial management, the lagoon and the fore reef may require different types of management measures since they are not driven by the same social-ecological dynamics. On the fore reef, fishing is the most important anthropogenic pressure on ecosystem state. Since fishing activities outside the lagoon might be linked with intensity of recreational activities within the lagoon, the management measures on the fore reef should be framed in this context. In the lagoon, pressures resulting from terrestrial anthropogenic activities appear to be the main drivers for living coral cover. This makes a strong case for a coherent spatial planning approach accounting for the interconnection of land-based activities and their impacts on the marine environment. Observed social-ecological dynamics reveals that these two systems are strongly interconnected. The Polynesian culture has a strong centuries-old cultural heritage in the forms of resource stewardship, integrated management, and sustainable use of fisheries [69]. This culture is largely reef-oriented in terms of knowledge, traditions and resources. Moreover the Polynesian people have always viewed a continuous relationship between the sea and the land considering their natural resources from ridge to reef as a whole [69]. In this context, the management plan of Moorea coral reefs, with separate terrestrial and marine management, has yielded 20 years of mismatches between state governance priorities and processes with traditional Polynesian environmental and resource management styles. Such mismatches coupled with intensified human impacts on the marine environments due to increase in fishing pressures and recreational activities have resulted in environmental decline. From a broader perspective and in the context of the revision process of the management plan of Moorea coral reef resource system, considering how traditional cultural heritage and marine tenure systems could be integrated within contemporary structures of governance should become a priority.

5. Conclusion

Participatory modeling has enabled stakeholders and scientists to capture the complexity of a coral reef social-ecological system. Results suggest that, on the fore reef, fishing pressures (that may be influenced by the intensity of recreational activities in the lagoon) are the main driver affecting food provisioning, while the provision of specific ecosystem services provided by the lagoon is more impacted by terrestrial activities than by activities occurring in the lagoon. Within the 11 year-long time window of this study, the system registered some important natural and anthropogenic pressures affecting the social-ecological system of Moorea. Local contextual information must be carefully analyzed in order not to forget the cross-correlation in time of drivers affecting the social-ecological system. According to these patterns, we stressed that local management should be further adapted and in particular: (1) account more specifically to the existing typology of actors; (2) be more spatially-explicit to better distinguish management objectives and actions for the lagoon and the fore reef; and (3) be more coordinated with terrestrial agencies for a coherent land-sea connection that would both (i) account for existing land-sea interaction and (ii) better reflect the Polynesian cultural heritage that consider nature from ridge to reef as a whole. Our approach is an essential step towards providing scenarios to inform policy and support management.

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Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version at doi: http://dx.doi.org/10.1016/j.marpol.2017.01.014.

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Appendix A : Metadata in relation to selected indicators. All ecological variables were spatially averaged for both the lagoon and the fore reef at the scale of Moorea Island.

Variable	Description	Metric	Sources
Employment rate	% of Moorea inhabitants between 15 and 64 years old who have a job divided by the total population of 15-64 years old. We assumed that this rate evolve such as the salaried employee rate of Moorea island	Ratio of people working	ISPF Census 2007-2012 + combined with the salaried employee rate of Moorea island from 2004 to 2013
Moorea inhabitants	Number of Moorea Inhabitants. we assumed that this variable has a linear evolution	Number of people	ISPF Census 2007-2012.
International tourists	Number of nights by international tourists in Moorea hotels (not include guesthouses)	Number of nights	ISPF Survey of tourist frequentation from 2006 to 2013
Tahitian tourists	Number of nights by local tourists in Moorea hotels (not include guesthouses)	Number of nights	ISPF Survey of tourist frequentation from 2006 to 2013
Tourists	Equal number of nights by local tourists + Number of Nights by international tourists	Number of nights	ISPF Survey of tourist frequentation from 2006 to 2013
Coastal protection	Relative weight of Coral Reefs in coastal protection	%	(Pascal and LePort 2015)
Hardening shoreline	% of embankment building, concrete walls and peers along the shoreline. We assumed a linear evolution between 2001 and 2009 / Moratorium on embankment buiding in 2012	Percentage (%)	Progem report 2009 + 2001
Beaches coverage	% of white sand beaches along the shoreline.	Percentage (%)	Progem report 2009 + 2001. We assumed a linear evolution between 2001 and 2009
Water quality	Annual water quality	Factor (qualitative)	Monitored by the local ministry of health
Extreme climatic event	Cyclone Oli heated Moorea in 2010	yes=1/no=0	Expert knowedge
Exploitation rate	% of catches from the comfish_biomass	%	expert opinion + functional relationship. p (Exploitation_rate |) = NormalDist(Exploitation_rate, 0.05,0.05)
Catches	Depends on the available commercial fish biomass (affected by Moorea and tourists fishermen), the exploitation rate (affected by the employment rate) and the surface of exploitation	T	functional relationship.p (Catches | Comfish_biomass, Exploitation_rate) =

			NormalDist(Catches,(Comfish_biomass*20)*Exploitation_rate, Exploitation_rate)
Scuba diving operator gross income	Income = Nb of dive* Dive cost + Nb of trip * trip cost (80€ for scuba, 50€ for boat trip)	€	CRIOBE surveys (2014)
Associate expenses	Associate expenses (= Hotel + food) of actors that had a scuba-diving or/and boat tour activities and/or went to the beach	€	CRIOBE surveys (2014)
Scuba-diving	Frequentation	Nb of dive	CRIOBE surveys (2014)
Day tour activities	Frequentation	Nb of trips	CRIOBE surveys (2014)
Beach users	Nb of beach users observed	Nb of beach users	CRIOBE surveys (2014)
Boating	Nb of sail boats observed	Nb of boat	CRIOBE surveys (2014)
Commmercial fish biomass	Commercial fish biomass (the list of targeted species has been adapted from Madimoussa, 2009)	g/m2	Moorea MPA monitoring (2004-2014)
Herbivore biomass	Herbivore Biomass (include browser, grazer and scrapers fishes). We applied the following normal probability distribution: p (Herbivore_biomass |) = NormalDist(Herbivore_biomass, 174.39 , 57.78)	Average biomass density by m2	Moorea MPA monitoring
Giant clam abundance	Giant Clam abundance	Abundance by m2	Moorea MPA monitoring (2004-2014)
Acanthaster planci	Acanthaster planci abundance. (Underestimated because it is a cryptic animal).	Abundance by m2	Moorea MPA monitoring (2004-2014)
Coral cover	Living coral cover. Include: *Montipora,Porites,Acropora, Leptastrea, Pocillopora, Pavona, Millepora, Montastrea, Psammocora, Astreopora, Herpolitha, Fungia, Acanthastrea, Synarea, Favia, Gardineroseris"Lopophylia, Coral_UnID, Coscinaraea*	Percentage of cover by m2	Moorea MPA monitoring (2004-2014)
Structural complexity	Living + dead coral cover	Percentage of cover by m2	Moorea MPA monitoring (2004-2014)
Algal cover	Algal cover. Include: *Dictyota, Halimeda, Cyanophycea, Turbinaria,Boodlea, Padina, Sargassum, Caulerpa*	Percentage of cover by m2	Moorea MPA monitoring (2004-2014)
Phosphate	PO4 concentration	µM	CRIOBE monitoring
Sedimentation rate	proxy of SiO3 concentration	µM	CRIOBE monitoring
Temperature	temperature	°C	CRIOBE monitoring

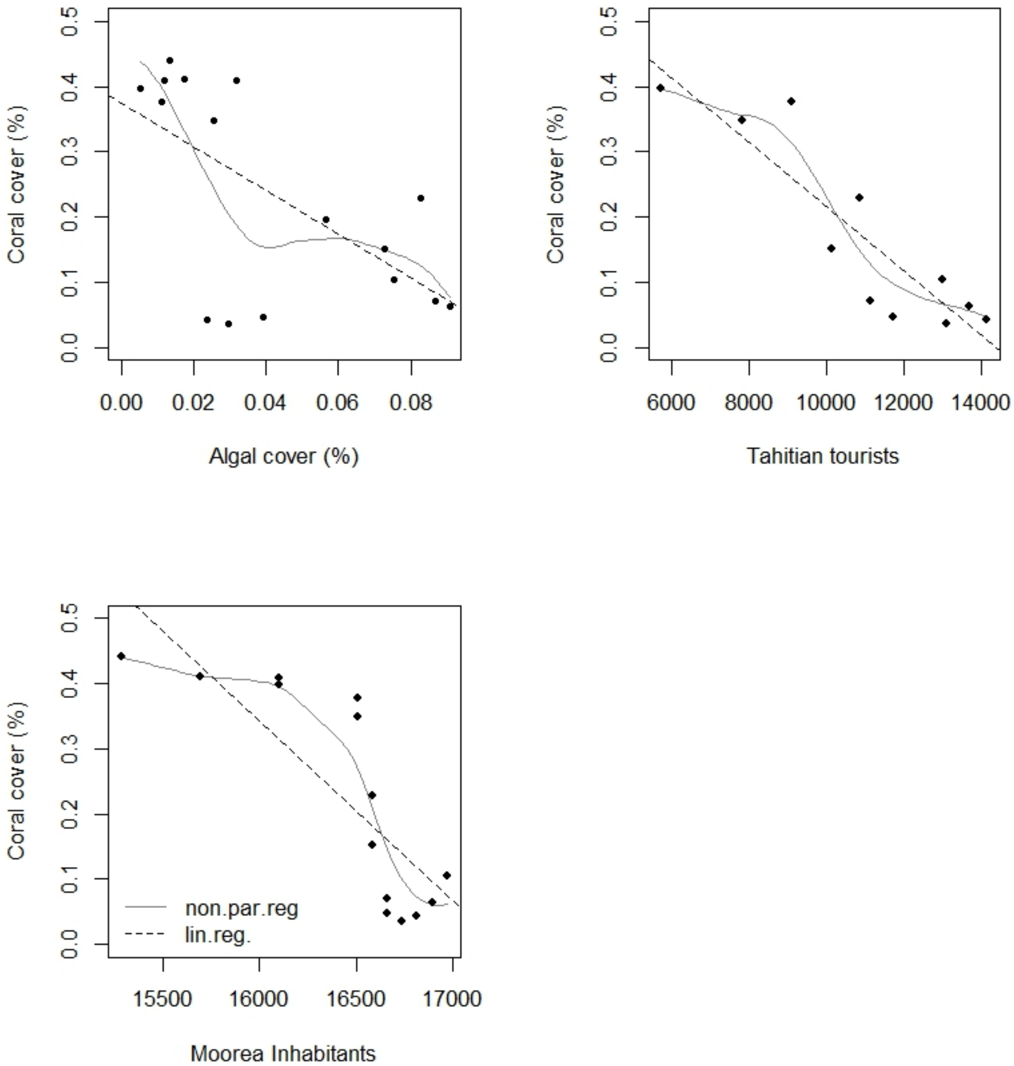
Appendix B : Results of significant linear regression models calculated with fore reef time series data (2004-2014).

Response	Intercept	Exploratory	Coefficient	F	df	Adjusted R-squared	p-value
coral cover (%)	0.37	algal cover	-3.35891	9.41	14	0.359	0.008
coral cover (%)	4.5	Number of Papetee tourists	-0.467	33.61	9	0.765	0.00026
coral cover (%)	43.24	Number of Moorea inhabitants	-4.43	27.91	13	0.657	0.00014
commercial fish biomass (kgm^{-2})	13.69	Number of int. tourists	-1.20	4.61	8	0.419	0.046
		employment rate	11.1				
Employment rate	0.867	Number of Papetee tourists	-0.046	15.45	12	0.526	0.001998

Appendix C : Results of significant linear regression models calculated with lagoon time series data (2004-2014).

Response	Intercept	Exploratory	Coefficient	F	df	Adjusted R-squared	p-value
coral cover (%)	1.5307	Phosphate	0.2715	6.779	14	0.278	0.02083
Commercial fish biomass	3.93	Structural complexity	2.3419	6.598	29	0.265	0.004348

Appendix D : Examples of identified significant linear relationships between time series data sampled at the fore reef (OS) on coral cover (%) and algal cover (%), numbers of Polynesian tourists and numbers of Moorea inhabitants



Transition

Nous venons de mettre en évidence, dans le chapitre précédent, que dans le cas du système socio-écologique du lagon de Moorea, la modélisation participative ainsi que l'analyse de données empiriques permettent de capturer la complexité du système. Les résultats de cette étude se traduisent par la construction d'un modèle DPSI (Driver-Pressure-State-Impact) soulignant certaines dynamiques socio-écologiques intervenant au sein du lagon et de la pente externe de Moorea. L'utilisation de la connaissance experte dans la construction de ce modèle s'est avérée décisive afin de pouvoir interpréter correctement les données et les corrélations croisées entre certaines variables d'intérêt. Parallèlement, ce type d'initiative a également permis de construire une meilleure représentation commune du système socio-écologique corallien de Moorea, facilitant ainsi une perception plus claire des principaux enjeux de gestion du lagon et de la pente externe.

L'étape suivante de notre réflexion consiste à adapter le modèle développé à une modélisation par réseaux Bayésiens. Ce type d'approche a pour objectif de nous permettre d'identifier des scénarios exploratoires d'évolution des principaux services écosystémiques du lagon et de la pente externe de Moorea en fonction de différents forçages naturels et anthropiques. En effet, comprendre ces dynamiques d'adaptation sera fondamental pour comprendre la résilience et la durabilité à long terme des systèmes socio-écologiques.

Chapitre 4 : Scénarios d’évolution du système socio-écologique du lagon de Moorea : modélisation par réseaux bayésiens

Identifying social-ecological trade-offs of multiple drivers of change for coral reef ecosystem services using Bayesian Belief Networks

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KEYWORKS

Social-ecological system, coral reefs, Bayesian belief network, scenarios, coastal management

ABSTRACT

Coral reef resource systems are complex adaptive social-ecological systems. They experience effects of multiple social and environmental drivers that cause social-ecological trade-offs and potentially affect the provision of vital and valuable ecosystems services such as food provision, coastal protection or recreational activities. From a management perspective, there is a crucial need to develop scenarios of multiples drivers on coral reef social-ecological systems to anticipate, mitigate or adapt to these drivers. Here we developed spatially explicit Bayesian belief network models to explore the social-ecological trade-offs revealed by a set of multiple driver's scenarios in the coral reef resource system of Moorea Island, French Polynesia. For each spatial entity of the resource system (i.e. the lagoon and the fore reef), two types of BN models were developed, one that was top-down based on a participatory modeling process and one that was bottom-up driven by available time series data from the lagoon and fore reef. Exploratory scenarios tested with both the

fore reef and lagoon models disclosed fairly surprising social-ecological trade-offs occurring within the Moorea coral reef resource system. In the case of the fore reef, fishing activities have been influencing the ecosystem state the most, acknowledging that an increase in commercial fishing in the fore reef might be linked to the increase in recreational activities within the lagoon. In the lagoon, social-ecological trade-offs are less clear but drivers resulting from terrestrial anthropogenic activities (i.e phosphate inputs) appeared to be the main drivers for state changes of living coral and algal cover. Based on our trade-off analysis we suggest that Moorea coral reef management should account for different spatial entities in their management system, thus, following the concept of an integrated and ecosystem-based management with linked management objectives and control measures for the lagoon and the fore reef to maintain the provision of vital ecosystem services and allow for a sustainable resources use of the coral reef system. Further our results strengthen the need for an ecosystem based management approach that explicitly considers existing land-sea interactions and better reflects the Polynesian cultural heritage considering nature from ridge to reef as a whole.

1.Introduction

Coral reefs are prominent examples of complex adaptive social-ecological systems [1]. They are among the most biologically diverse marine ecosystems in the world providing vital and valuable ecosystem services to the social and economic welfare of local communities such as food provision, coastal protection and recreational activities [2–5]. The combined effects of major chronic anthropogenic stressors and environmental disturbances are severely eroding the functioning of these social-ecological systems worldwide [6,7]. Anthropogenic stressors such as overfishing, land-based water pollution or coastal development strongly contribute to modifying the provision flow of vital ecosystem services [8]. These anthropogenic stressors interact with other environmental disturbances such as extreme climatic events and Crown Of Thorns Seastar (COTS) outbreaks [7,9], further impacting the delivery of ecosystem services [10]. Multiple stressors favor the emergence of new trajectories and dynamics forcing the social-ecological system to regenerate, re-organize, or both [11–13]. Feedbacks on human uses and on human wellbeing can lead to trade-offs between the provision and use of ecosystem services [14–17].

Predicting feedbacks and trade-offs is key for sustainable management of coral reefs [7,18].

Models provide a powerful tool to enable an understanding of complex system dynamics and may help to investigate social-ecological trade-offs and inform management. [19–21]. Most models applied to coral reefs typically represent computationally complex approaches such as trophic mass balance or spatially explicit models [22,23]. However, their application as management tools is very limited due to relatively high resources needed to collect the data to feed into the models. Bayesian belief networks (BNs) are being increasingly used to both analyse complex relationships between marine ecosystem components but also to inform management[24–29]. BNs are powerful probabilistic and graphical modeling tools using causal graphs and conditional probability distributions in the graph [28,30], able to deal with small and incomplete data sets combining different sources of knowledge (e.g. from empirical data or expert knowledge) while accounting for uncertainty [24,31,32]. BNs have been successfully used in the operationalization of environmental risk assessments or the assessment of the impact of alternative management measures [29,33–36]. BNs are also used to explore different stressor scenarios on resource systems [30,37,38]. The use of exploratory scenarios allows investigating management risks [39–42] as well as to explore logical consequences of management actions on ecosystem services provisions [43]. Building on clearly defined management objectives, the risk of failing to achieve those can be assessed by exploring the social-ecological trade-offs under different scenarios of multiple stressors [44,45].

In Moorea Island, French Polynesia, multiple environmental and social drivers (e.g. COTS outbreaks, cyclones, coastal development, fishing) affect the coral reef resource system [46–48]. Much uncertainty remains around the social-ecological impacts emerging from interacting effects of those multiple drivers. Managers and decision-makers clearly identified the need to understand how multiple drivers affect the social-ecological dynamics of the system and more precisely the provision of crucial ecosystem services such as food provision and recreational services [49]. To this end, a transdisciplinary approach stemming from participatory modelling and empirical data has been used to develop a Driver-Pressure-State-Impact (DPSI) model to depict interactions within the social-ecological system of Moorea [49]. Here, we built on the DPSI conceptual model and developed a BN to identify feedbacks and trade-offs under a range of scenarios defined by managers and decision-makers, under various environmental and social drivers. This approach is an essential step towards an informed decision-making process for a sustainable management of coral reef goods and services in Moorea.

2. Materials and methods

2.1. Case study area and data

Moorea Island, located 30 km off Tahiti Island, is the second largest inhabited island in French Polynesia with more than 17,236 inhabitants [50]. The lagoon has a surface of 49 km² and encloses the whole island (Fig. 1). Moorea can be characterized by a great diversity and number of resource users due to the island proximity to a urban center and fish-market (Papeete in Tahiti). Moorea coral reefs support, among other social attributes, the livelihoods linked to fishing (recreational, subsistence and professional fishing) and tourism (scuba-diving, snorkeling, boating activities) [47]. Recreational and commercial fishing activities are benefiting from two separate types of ecosystem services: cultural services and provisioning services, respectively [43]. Tourism-based income, stemming mostly from tourism lodging and recreational activities generated by the coral reef ecosystem, is the main economic resource of the island. A recent economic assessment found that recreational activities in Moorea provided 27M€/year while fishing activities provided only 4M€/year [51]. However, these figures do not measure the fishing activities in the context of a subsistence economy, the latter having an important cultural role in the Polynesian society (e.g. enjoyment, identity, prestige and a life style) [3,52]. Moorea residents, local and international visitors conduct multiple types of activities such as scuba-diving, day tours (i.e. excursion trips), beach and boating activities which exert different drivers on Moorea coral reefs and lagoon.

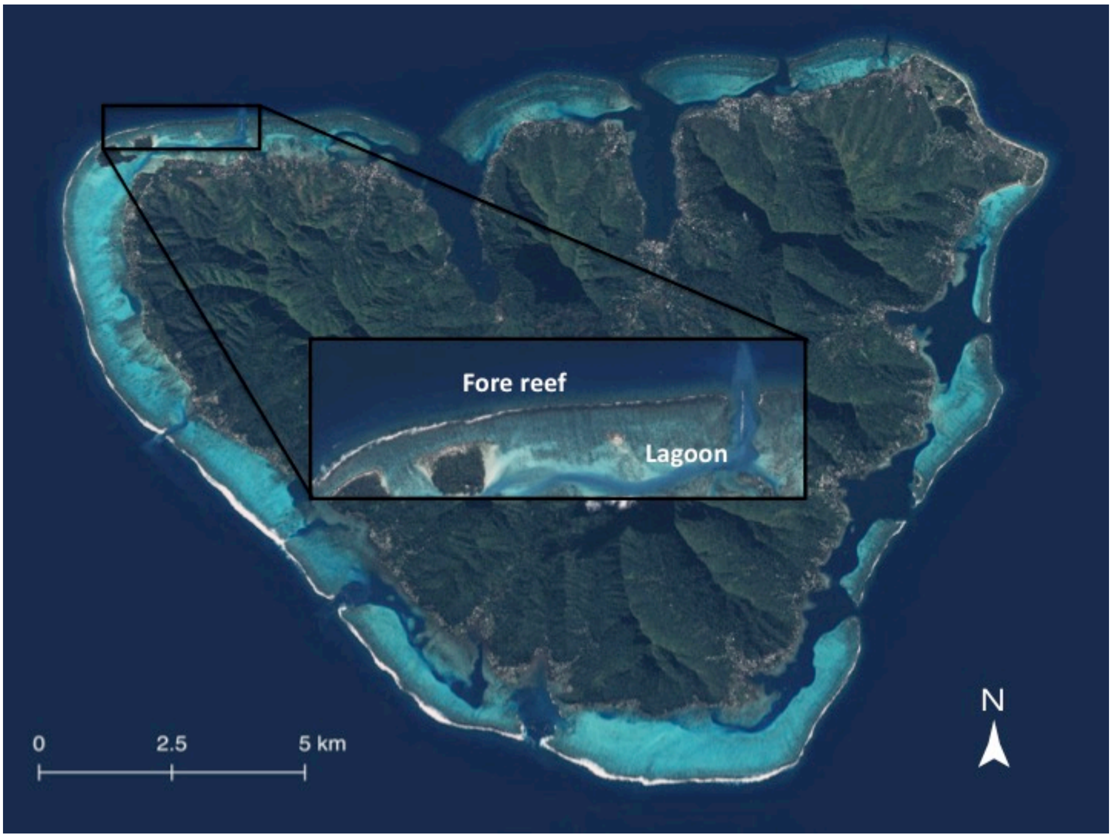

Figure 1: Moorea Island with the study area of the lagoon and fore reef

In the past Moorea coral cover fluctuated between 5% and 50% depending on the occurrence of the coral eater starfish *Acanthaster planci* (crown of thorns seastar, COTS) outbreaks and cyclones [48,53–55]. The last major events occurred between late 2006 (beginning of a COTS outbreak) and 2010 (cyclone Oli). A spatial management plan was established in 2004 after 10 years of stakeholder consultations. This management plan (PGEM; Plan de Gestion de l'Espace Marin) covers the lagoon and fore reef up to the 70 m isobath and is made of, among other attributes, a network of permanent marine protected areas (MPAs) or areas of restricted use (e.g. catch limitations). The MPAs are monitored annualy since their implementation, with respect to their ecological benefits. After ten years of protection the ecological effects of the network of marine protected areas are limited [46,48,56]. Ten years after the implementation, given the perceived lack of legitimacy of the PGEM [57], a reviewing process of the management plan has been launched and will continue for the next two years. In this context and as described in Leenhardt et al. 2017 stakeholders were consulted to frame explorative scenarios of the social-ecological system according to specific management objectives and related management actions

[49]. From this process, a general list of desired and existing management objectives with associated management actions has been produced (Table 1).

Table 1: Management options to reach desirable states of ecosystem services, associated to actions available to reach those states, derived from workshops with the stakeholders.

Management objectives	Managements actions
Reduce terrestrial run-offs	Forests restoration Eradication of invasive plant species Eradication of fires Decrease in cultivated surfaces Modification of agricultural practices Decrease in river diggings and earthwork Ecological restoration of rivers shores
Increase water quality	Control illegal waste water release Participatory monitoring of water quality
Sustainable management of lagoon resources	Keep fishing activities below the MSY Define the carrying capacity of the lagoon for recreational activities (for specific sites) Secure perennial management funding Enhance co-management and self-enforcement
Hardening shoreline	Increase enforcement efficiency

We gathered data for the BN modelling from different sources. Ecological data (corals, fishes, algae, and mobile invertebrates) were extracted from an ongoing biannual monitoring program with 117 stations around Moorea Island, both in the lagoon and fore reef (see CRIOBE: observatoire.criobe.pf/ for details). Further environmental data were retrieved from sensor deployments measuring silicium, phosphate and temperature in the lagoon and fore reef (CRIOBE). Socio-economic data on hotel frequentation surveys were extracted from Polynesian Census. Surveys on recreational activities were conducted in 2014 specifically for this study. An overview of the available data and their respective temporal coverage can be found in Table 2.

Table 2: Description of lagoon and fore reef Bayesian belief network (BN) model nodes and states. For each node and each area, the ranges of low and how values (around the time series median) are provided.

BN nodes	Description	Coral reef areas	Median values	Node States
Moorea inhabitants	Number of Moorea Inhabitants. Taken from the ISPF census of 2007 and 2012. We assumed that this variable had a linear evolution from 2007 to 2014. Source: ISPF	Fore reef	16 661	[1000 – 16661];]16661 – 20000]
		Lagoon	16 661	[1000 – 16661];]16661 – 20000]
International tourists	Number of Night by international tourists in Moorea hotel (decrease with the economic crisis) from 2006 to 2013. Source: ISPF	Fore reef	53 217	[1000 – 53217];]53217 – 80000]
		Lagoon	44 469	[1000 – 44469];]44469 – 80000]
Tahitian tourists	Number of Night by Tahitian tourists in Moorea hotel (increase with the economic crisis) from 2006 to 2013. Source: ISPF	Fore reef	11 172	[500 – 11172];]11172 – 15000]
		Lagoon	12 975	[500 – 12975];]12975 – 15000]
Tourists	Number of Nights by Tahitian tourists + Number of Nights by international tourists from 2006 to 2013. Source: ISPF	Fore reef	63 625	[1000 – 63625];]63625 – 80000]
		Lagoon	57 791	]1000 – 57791];]57791 – 80000]
Employment rate	Percentage of Moorea inhabitant between 15 and 64 years old who have a job divided by the total population of 15-64 years old. Taken from the ISPF census of 2007 and 2012. We assumed that this rate was correlated with the salaried employee rate of Moorea island. Source: ISPF	Fore reef	0.44	]0.4 - 0,44];]0.44 - 0.47]
		Lagoon	0.44	]0.4 - 0,44];]0.44 - 0.47]

Commercial fish biomass	Average biomass in g/m2. Commercial fish biomass (the list of targeted species is taken from Madi Moussa, 2009).	Fore reef	220.29	[0 – 220.29];]220.29-868.993]
		Lagoon	28.72	[0 – 28.72];]28.72 - 868.993]
Associated expenses	In euros (€). Associate expenses (= Hotel + food) of users that had a scuba-diving or/and boat tour activities and/or went to the beach IN 2014. Source: Criobe	Fore reef	2 053 855	[0 – 2053855];]2053855 - 10000000]
		Lagoon	1 601 780	]0 – 1601780];]1601780 - 10000000]
Coral cover	Percentage of cover by square meter. Living coral cover (% of cover). Include: Montipora,orites,Acropora, Leptastrea, Pocillopora, Pavona, Millepora, Montastrea, Psammocora, Astreopora, Herpolitha, Fungia, Acanthastrea, Synarea, Favia, Gardineroseris"Lopophylia, Coral_UnID, Coscinaraea. Source: Criobe	Fore reef	0,21	[0 - 0.21];]0.21 - 0.5733]
		Lagoon	0,16	[0 - 0.16];]0.16 -0.5733]
Algal cover	Percentage of cover by square meter. Algal cover (% of cover). Include: Dictyota, Halimeda, "Cyanophycea, Turbinaria,Boodlea, Padina, Sargassum, Caulerpa. Source: Criobe	Fore reef	0.04	[0 - 0.04];]0.04 - 0.393]
		Lagoon	0.03	[0 - 0.03];]0.03 - 0.393]
Herbivore fish biomass	Average biomass in g/m2. Herbivore Biomass (include browser, grazer and scrapers fishes). We applied the following normal probability distribution: p (Herbivore_biomass |) =	Fore reef	169.16	[0 - 169.16];]169.16 - 635.093]
		Lagoon	33.39	[0 – 33.39];]33.39 - 635.093]

Acanthaster abundance	Acanthaster planci abundance by square meter. Underestimated due because it is a cryptic animal. Source: Criobe	Fore reef	0.0013	[0 - 0.0013];]0.0013 - 0.5]
		Lagoon	-	-
Extreme climatic event	Cyclone Oli heated Moorea in 2010	Fore reef	-	0 ; 1
		Lagoon	-	-
Structural complexity	Percentage of cover by square meter. Structural complexity = Living coral cover + dead coral cover	Fore reef	0.28	[0 – 0.28];]0.28 – 0.65]
		Lagoon	0.17	[0 – 0.17];]0.17 – 0.65]
Giant Clams abundance	Abundance by m2. Source: Criobe	Fore reef	-	-
		Lagoon	0.08	[0 – 0.08];]0.08 – 3]
Temperature	Temperature in °C	Fore reef	27.74	[26.5 – 27.74];]27.74 – 30]
		Lagoon	27.59	]26.5 – 27.59];]27.59 – 30]
Phosphate	Phosphate concentration (P2O5) (in µM), from 2008 to 2013 monitored in Tiahura frangeant reef	Fore reef	-	-
		Lagoon	0.32	[0-0.32];]0.32 – 0.7]
Sedimentation rate	Silicium concentration (SiO3) (in µM), from 2008 to 2013 monitored in Tiahura frangeant reef	Fore reef	-	-
		Lagoon	1.96	[0 – 1.96];]1.96 - 5]

2.2. Bayesian belief network model development

In general, Bayesian Belief networks (BNs) are based on two structural model components: (1) a directed acyclic graph (DAG) that denotes dependencies and independencies between the model's variables (referred to as nodes); and (2) conditional probability tables (CPTs) denoting the strengths of the links in the graph [58]. The DAG consists of a structured set of variables or nodes that represent the modeled system. Directed arrows that represent cause effect relations between the system's variables indicate the statistical dependencies between the different nodes. Each arrow starts in a parent node and ends in a child node. The absence of a link between two variables indicates independence between them. The graph is acyclic and therefore no feedback arrows from child nodes to parent nodes exist. The DAG can be developed by experts and based on system understanding or can be learned by empirical observation. The resulting BN structure forms the bases for developing operational BNs. Individual BN nodes are constrained to contain a finite number of states (e.g. high, medium, low) that describe the probability distribution of the system variables. Each node contains a CPT and each given state of one variable is associated with a probability between 0 and 1, so that the sum of state values makes a total of 1.

Here we followed the good practice in BN modeling in a management context and each node was therefore assumed to affect the final output and was either manageable, predictable or observable on the respective scale of the model [59]. Each variable was assigned two states (low and high; transformed from continuous to discrete data). (A detailed description of the nodes and corresponding data sets can be found below (Table 2).

We developed for each spatial entity (fore reef and lagoon) two BNs, one where the DAGs were derived from expert knowledge (BN_{DPSI}) and one where the respective DAG structures have been learned with the help of transformed (dichotomous) empirical data (BN_{fitted}). For the BN_{DPSI} we modified the DPSI frameworks of [49] by removing all nodes without direct observations and transformed those into DAGs. For the BN_{fitted} models we fitted a fully saturated log-linear graphical model to the data allowing for a maximum of three factor interactions in the model [60]. We conducted a stepwise backward elimination with a significance test (gRim library for R) as selection criteria to determine the DAG of the respective BN_{fitted}. Fitted structures should not only base on conditional independence statements and probabilistic properties, moreover they should represent cause-effect relationships. In other words, a BN should represent the causal structure of the data it is describing; this is also referred to as Pearl's causality [61]. We therefore constrained the structure learning process with a number of well-known key relationships such as e.g. temperature and coral cover. For both models of the two spatial entities the conditional probability tables were populated with the categorised empirical data.

For the BN models of the fore reef the nodes describing the key ecological components comprised *Algal cover*, *Coral cover*, *Structural complexity*, *Herbivore biomass* and *Commercial fish biomass* (Table 2 and Fig. 2). For the BN models of the lagoon the node *Giant clams abundance* replaced the node *structural complexity* because it better represented complex coral structures not damaged by the destructive clams fishing practices (Fig. 3). The response nodes for the fore reef are *Commercial fish biomass* and *Structural complexity* since those reflect ecosystem services of food provisioning and coastal protection. While for the lagoon the response nodes are *Commercial fish biomass* and *Giant clam abundance*. Four other nodes – *Temperature*, *Phosphate*, *Acanthaster abundance*, and *Extreme climatic events* - represented environmental drivers influencing the variables of the ecological nodes. The nodes *Acanthaster abundance* and *Extreme climatic events* were only considered in the fore reef BN models while the node *Phosphate* was only included in the lagoon BN models and were linked to *Sedimentation rate*. The node *Temperature* influenced the *Coral cover* both in the fore reef and in the lagoon.

The socio-economic nodes of the BNs for both the lagoon and the fore reef comprised *Associated expenses*, *Employment rate* and three different groups of people using or depending on the different ecosystem services: *Moorea residents*, *Tahitian tourists* and *International tourists.* The *Associated expanses* reflect the economic returns from various recreational activities such as boating and diving.

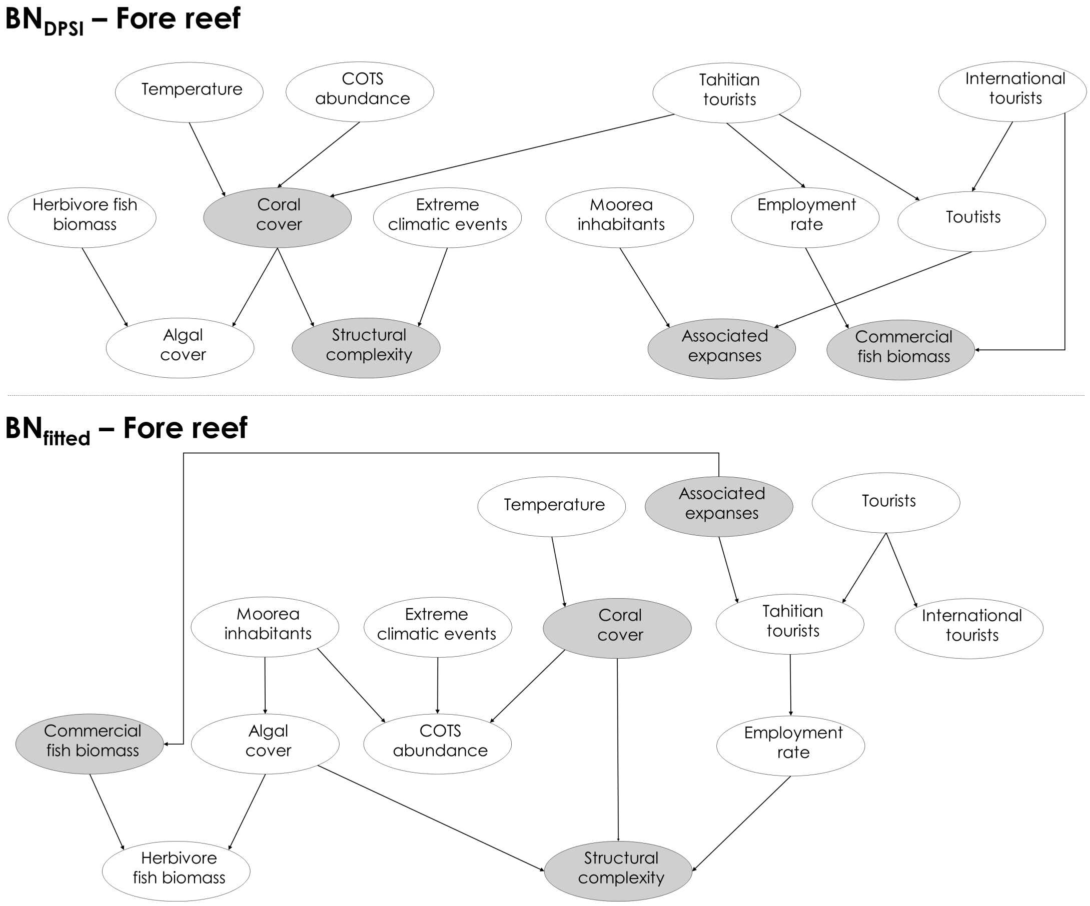

Figure 2: Bayesian belief network models describing the key interactions of the social-ecological system of the fore reef. BN_{DPSI} (upper panel) based essentially on the driver-pressure-state-impact relationships as perceived by stakeholders; BN_{fitted} (lower panel) based on graphical non-linear models fitted to dichotomous (low, high) monitoring data. The response nodes commercial fish biomass, structural complexity, associated expanses and percentage coverage of living coral are highlighted.

2.3. Models sensitivity and performance assessment

We performed a sensitivity analysis of selected BN nodes to identify to which degree variability in posterior probability distributions is explained by other variables (i.e. rank order) [62]. For the BNs of the fore reef we calculated the entropy reduction for the nodes *Structural complexity*, *Coral cover* and *Commercial fish biomass*. While for the BNs of the lagoon the entropy reduction was calculated for the nodes *Giant clam abundance* (that is used as a proxy for *Structural complexity), Commercial fish* *biomass* and *Associated expanses*. Those nodes have been selected since they are the response nodes reflecting ecosystem services. We further assessed the prediction performance of the BN models of the fore reef and lagoon (BN_{DPSI} vs. BN_{fitted}) by removing the observations of selected nodes and calculating the maximum-likelihood state [63]. This allowed us to estimate the Type I error rate (referred to as confusion error) by comparing the predicted most likely states of the unobserved tested nodes with the true states for the tested nodes. We computed also the confusion error weighted by the total number of conditional probabilities of the respective BN [63] and evaluated the classification success rate also with the spherical payoff index [62].

2.4. Exploratory scenarios

A total number of 30 exploratory scenarios were defined and we inferred the behaviour of the response nodes under those scenarios (Table 3). Those exploratory scenarios were defined by varying the intensity of multiple social and ecological drivers to explore the potential social-ecological trade-offs occurring within the modelled systems. In accordance with local stakeholders those scenarios addressed the potential management of anthropogenic drivers under varying environmental conditions (Table 1). Those scenarios aimed to inform the management of recreational services and food provisioning of the Moorea lagoon and fore reef resource systems.

For the fore reef we defined exploratory scenarios in order to inform management objective that particularly targeted the sustainable use of resources to safeguard the provision of food and recreational services such as fishing or diving. Thus, the scenarios addressed the potential consequences for the response nodes *Commercial fish biomass*, *Structural complexity*, and *Associated expenses*. The fore reef scenarios focused on the influence and interplay between the numbers of *Tahitian tourists* (reflecting the number of local tourists), number of *International tourists*, changes of the *Employment rate* (reflects the state of the overall economic situation) and environmental drivers: scenarios 1 and 2 described changes of one manageable driver (number of *Tahitian tourists*); scenarios 3 to 6 explored the interplay between an environmental driver (Algal coverage) and one social driver that could be managed (*Tahitian tourists*); scenarios 7 to 10 reflect the interaction between one social driver that could be managed (*Tahitian tourists*) and socio-economic conditions that cannot be directly managed (*Employment rate*); scenarios 11 to 14 simulated varying conditions of three social and ecological drivers (*Temperature*, *Algal coverage*, *Tahitian tourists*) and explored therefore the responses to combined drivers.

As outlined in Leenhardt et al 2017 the Moorea lagoon is much stronger linked to terrestrial drivers. The defined scenarios focused therefore on the responses of *Commercial fish biomass*, *Giant clam abundance* (that is a proxy for structural complexity) and Associated expenses to changes of manageable social and ecological drivers such as number of *Tahitian tourists* (reflecting local tourists coming from Tahiti) or number of *International tourists* and environmental change (Phosphate, Temperature, Sedimentation rate). The Moorea lagoon scenarios 1 and 2 described changes of one manageable driver (number of Tahitian tourists); scenarios 3 and 4 described varying states of phosphate concentration; scenarios 5 to 8 reflected the interaction between one driver that could be managed (Tahitian tourists) and changes of sedimentation rates; scenarios 9 to 12 explored the interdependencies between two environmental drivers (Temperature and Phosphate); scenarios 13 to 16 explored the responses to varying conditions of three drivers (Temperature, Phosphate, Tahitian tourists).

All computations were done within the programming environment of the free statistical software R [64], using the libraries gRain and gRim [60] and the commercial software Netica (version 4.16).

Table 3: Summary of explorative scenarios defined for the fore reef and lagoon describing changes of states of a single social driver and multiple social and ecological drivers; n.c. = no change from baseline (average past conditions), n.a.= not applicable.

	Fore reef Scenarios													
Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Herbivore biomass	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Commercial fish biomass	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Acanthaster abundance	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Structural complexity	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Coral_cover	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Algal cover	n.c.	n.c.	**high**	**low**	**high**	**low**	n.c.	n.c.	n.c.	n.c.	**high**	**low**	**high**	**low**
Temperature	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	**high**	**high**	**high**	**high**
Employment rate	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	**high**	**low**	**high**	**low**	n.c.	n.c.	n.c.	n.c.
Moorea inhabitants	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
International tourists	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	**high**	**high**	**low**	**low**	n.c.	n.c.	n.c.	n.c.
Tahitian tourists	**high**	**low**	**high**	**high**	**low**	**low**	n.c.	n.c.	n.c.	n.c.	**high**	**high**	**low**	**low**
Tourists	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Associate expenses	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Extreme climatic event	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Sedimentation rate	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Giant Clams abundance	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Phosphate	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

	Lagoon Scenarios															
Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Herbivore biomass	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Commercial fish biomass	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Acanthaster abundance	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Structural complexity	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Coral_cover	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Algal cover	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Temperature	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	**high**	**low**	**high**	**low**	**high**	**high**	**high**	**high**
Employment rate	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Moorea inhabitants	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
International tourists	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Tahitian tourists	**high**	**low**	n.c.	n.c.	**high**	**high**	**low**	**low**	n.c.	n.c.	n.c.	n.c.	**high**	**high**	**low**	low
Tourists	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Associate expenses	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Extreme climatic event	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sedimentation rate	n.c.	n.c.	n.c.	n.c.	high	low	high	low	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Giant Clams abundance	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Phosphate	n.c.	n.c.	high	low	n.c.	n.c.	n.c.	n.c.	high	high	low	low	high	low	high	low

Table 4: Bayesian belief network models sensitivity analysis of the response nodes *structural complexity* (fore reef models), *giant clam abundance* (lagoon models), *commercial fish biomass* and *associated expanses*. Model sensitivity is expressed as percent entropy reduction whereby the two most influential variables are indicated in bold.

Model	BN_{fitted} fore reef			BN_{DPSI} fore reef			BNf_{fitted} lagoon			BN_{DPSI} lagoon		
Nodes	**Structural complexity**	**Commercial fish biomass**	**Associate expenses**	**Structural complexity**	**Commercial fish biomass**	**Associate expenses**	**Giant Clams abundance**	**Commercial fish biomass**	**Associate expenses**	**Giant Clams abundance**	**Commercial fish biomass**	**Associate expenses**
Coral_cover	**29.6**	0	0	**39.8**	0.01	<<0.01	**1.35**	<<0.01	0	**8.46**	**0.02**	<<0.01
Structural complexity	-	<<0.01	<<0.01	-	<<0.01	<<0.01	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Commercial fish biomass	<<0.01	-	**20.3**	<<0.01	-	0.25	<<0.01	-	**5.99**	0.22	-	0
Giant Clams abundance	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	-	<<0.01	0	-	**0.22**	0
Algal cover	0	0	0	**4.25**	<<0.01	<<0.01	0.82	0	0	<<0.01	<<0.01	0
Herbivore biomass	<<0.01	**34.3**	**8.15**	0	0	0	<<0.01	0.76	**9.36**	0	0	0
Acanthaster abundance	0.29	0	0	<<0.01	0	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Temperature	0.91	0	0	0.281	0	0	<<0.01	<<0.01	0	**0.62**	<<0.01	0
Extreme climatic event	0	0	0	0.0881	0	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Phosphate	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	<<0.01	0	0	0.62	<<0.01	<<0.01
Sedimentation rate	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.83**	0	0	<<0.01	0	0
Associate expenses	<<0.01	**21.9**	-	0	0.26	-	0	**6.08**	-	0	0	-
Employment rate	**1.12**	0.14	0.50	0.348	**1.06**	<<0.01	0	<<0.01	0	<<0.01	0	0.02
Tourists	<<0.01	0	0	<<0.01	0.96	**21.1**	0	0	0	<<0.01	0	**1.23**
International tourists	<<0.01	0	0	0	**2.31**	**8.18**	0	0	0	0	0	0.48
Tahitian tourists	0.37	0.44	1.54	1.07	0.35	0.02	0	0	0	<<0.01	0	0.07
Moorea inhabitants	0	0	0	0	0	0.32	0	**0.49**	5.97	0	0	**6.2**

3. Results

3.1. Comparison of model structure, sensitivity and prediction performance

The derived BN models (BN_{DPSI} and BN_{fitted}), describing key social-ecological dynamics of the fore reef and lagoon, are presented in Figures 2 and 3. For both spatial entities the model structures (DAGs) between the DPSI derived BN models (BN_{DPSI}) and with constraints fitted BN models (BN_{fitted}) varied. An obvious difference in both cases was the hierarchical position of the node *Associated expenses*, being in the fitted BN models rather a predictor than a response node as in the DPSI BNs. Interestingly, in both cases the node was linked to *Commercial fish biomass*.

For the fore reef BN_{fitted} model the link between *Employment rate* and *Commercial fish biomass* was removed and replaced by a link to *Structural complexity*. The structure of the BN_{fitted} models contained also some causal links that could be questioned such as the ones between *Climatic events* and *Acanthaster abundance*. Also, *Coral coverage* being a parent node of *Acanthaster abundance* could be questioned in relation to its causality. However, due to the statistical properties of a BN inferring the probabilities of states of *Coral cover* or *Structural complexity,* this link was still robust and valid.

Overall the fitting procedure for the lagoon BN_{fitted} had more constraints. Next to the changes of the hierarchical position of the node *Associated expenses*, the nodes *Phosphate* and *Sedimentation rate* changed their order. Further, those predictor nodes had a more direct influence on the response node *Giant clam abundance*.

The comparison of sensitivity of the response variables of the four BN models to changes of states of other nodes is shown in Table 4. The response nodes of the fore reef models were in general more influenced by the social nodes such as the *Tahitian tourists* or *International tourists*, while this was not obvious for the lagoon models. Thus it seems, that social-ecological links between nodes were clearer for the fore reef than for the lagoon. The lagoon models showed maximum values of 8 % and 9 % for the most influential variables, while the maximum entropy reduction values varied between 20% and 34% for the fore reef models.

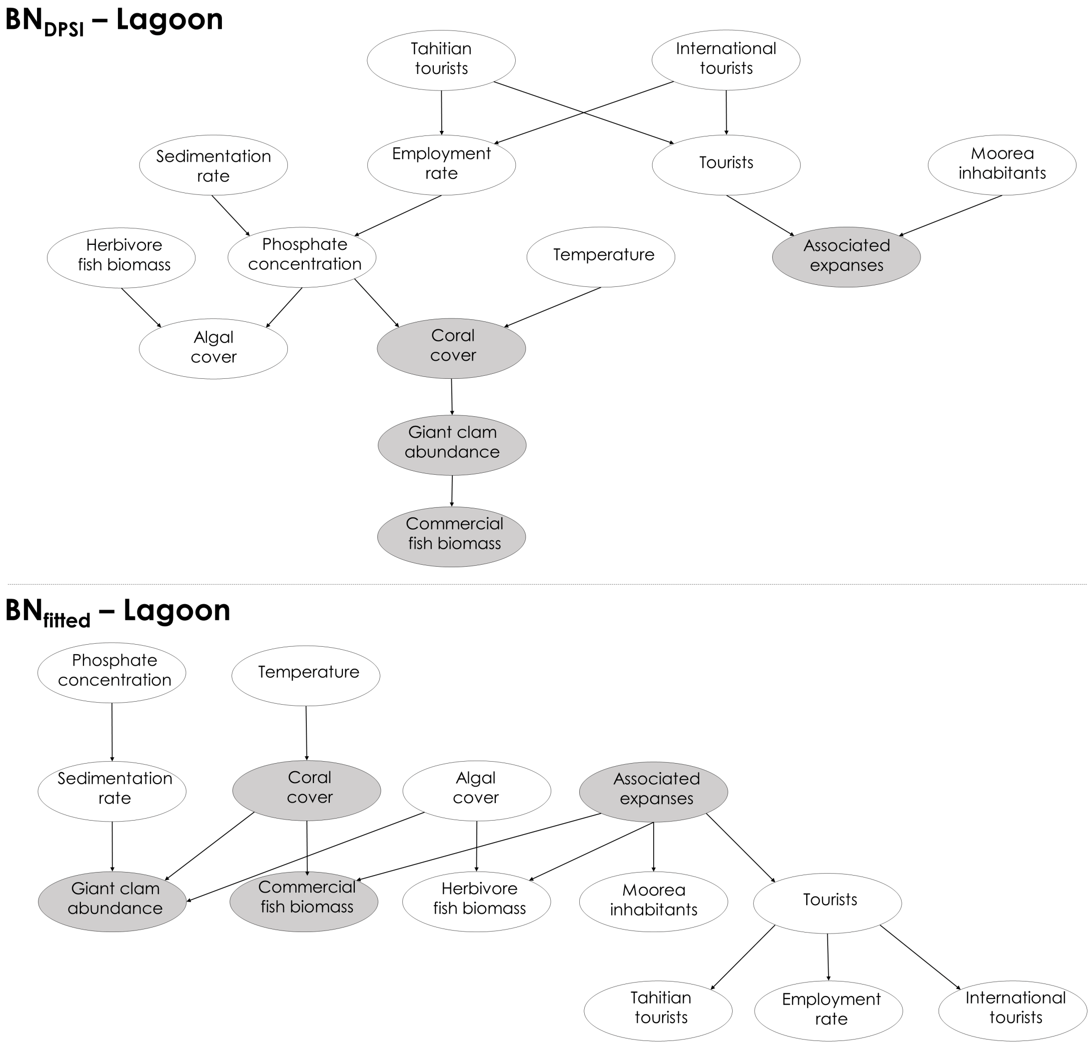

Figure 3: Bayesian belief network models describing the key interactions of the social-ecological system of the lagoon. BN_{DPSI} (upper panel) based essentially on the driver-pressure-state relationships as perceived by stakeholders; BN_{fitted} (lower panel) based on graphical non-linear models fitted to dichotomous (low, high) monitoring data. The response nodes commercial fish biomass, abundance of giant clams, associated expanses and percentage coverage of living coral are highlighted.

Further we observed that *Commercial fish biomass* of the BN_{fitted} models of the fore reef and lagoon was most influenced by *Associated Expenses* and *Herbivores fish biomass*. The *Commercial fish biomass* node of BN_{DPSI} fore reef model was most influenced by *International tourists* and the *Employment rate* while in the lagoon BN_{DPSI} it was most influenced by *Giant clam abundance* (reflecting structural complexity) and *Coral coverage*. Despite structural differences of the fitted BN models for both spatial entities, the models predicted a strong link between *Associated* *expenses* and *Commercial fish* biomass. The sensitivity analysis revealed also that *Associated expenses* for the BN_{fitted} model were most influenced by *Commercial* and *Herbivore fish biomass*, while in the case of the BN_{DPSI} models it was most influenced by number of *Tourists* or *Moorea inhabitants*.

Table 5: Complexity and prediction performance of the Bayesian belief network models (BNDPSI and BNfitted) developed for the Moorea fore reef and the lagoon. Prediction performance is described by the confusion error (%), conditional probability weighted confusion error and spherical pay off value (ranging from 0 to 1 see [63])

Model	***BN_{DPSI} fore reef***	***BN_{fitted} fore reef***	***BN_{DPSI} lagoon***	***BN_{fitted} lagoon***
Model complexity				
Number of nodes	14	14	14	14
Number of covariates (=number of node links)	14	14	13	14
Number of conditional probabilities	74	70	64	68
Number of node states	28	28	28	28
Model prediction performance: Confusion error (%)				
Coral cover	0	0.6	28.1	37.5
Structural complexity	0	0	n.a.	n.a.
Commercial fish biomass	43.7	0	37.5	31.2
Giant Clams abundance	n.a.	n.a.	31.2	34.3
Associate expenses	7.6	15.3	42.3	46.15
Conditional probability weighted confusion error				
Coral cover	0	16.8	1798.4	2550
Structural complexity	0	0	n.a.	n.a.
Commercial fish biomass	3233.8	0	2400	2121.6
Giant Clams abundance	n.a.	n.a.	1996.8	2332.4
Associate expenses	562.4	428.4	2707.2	3138.2
Spherical payoff				
Coral cover	0.982	0.958	0.786	0.767
Structural complexity	0.987	0.977	n.a.	n.a.
Commercial fish biomass	0.712	0.969	0.708	0.751
Giant Clams abundance	n.a.	n.a.	0.758	0.789
Associate expenses	0.912	0.837	0.772	0.821

The complexity and prediction performance of the four models is compared in Table 5. The most complex model was the BN_{DPSI} of the fore reef and the less complex the BN_{DPSI} of the lagoon. The confusion error rates showed that for the fore reef the predictions of the BN_{fitted} were overall better than the predictions of the response nodes of BN_{DPSI} (e.g. 43.6 % vs. 0% error rate for commercial biomass). Across the four models the conditional probability weighted confusion error and spherical pay off values showed highest values for BN_{fitted} for the fore reef, compared to the poorest prediction performance of BN_{fitted} for the lagoon. For the fore reef the BN_{fitted} model should therefore be preferred for scenario evaluations and supporting of a decision-making process, while for the lagoon the BN_{DPSI} should be selected.

The posterior probability distributions of the four compiled BN models are presented in Figure 4, which reflects the average past conditions of the states of the nodes, being inferior than or equal to, or superior than median values of the time series of the monitoring data. The average condition is referred to as the baseline or 'business as usual' scenario (scenario 0). Greatest differences between the posterior probability distributions of the compiled fore reef models were found for the nodes *structural complexity*, *commercial fish biomass*, *coral coverage*, and *algal coverage* (Fig. 4; left panel). The differences between the posterior probability distributions of the lagoon BN models were in general less pronounced. Also, the probabilities for most nodes being in state low or high (values inferior than or equal to, or superior than median values of the time series data) were around 0.5, with the exception of the total *number of tourists*, number of *international tourists, employment rate*, and *algal coverage*.

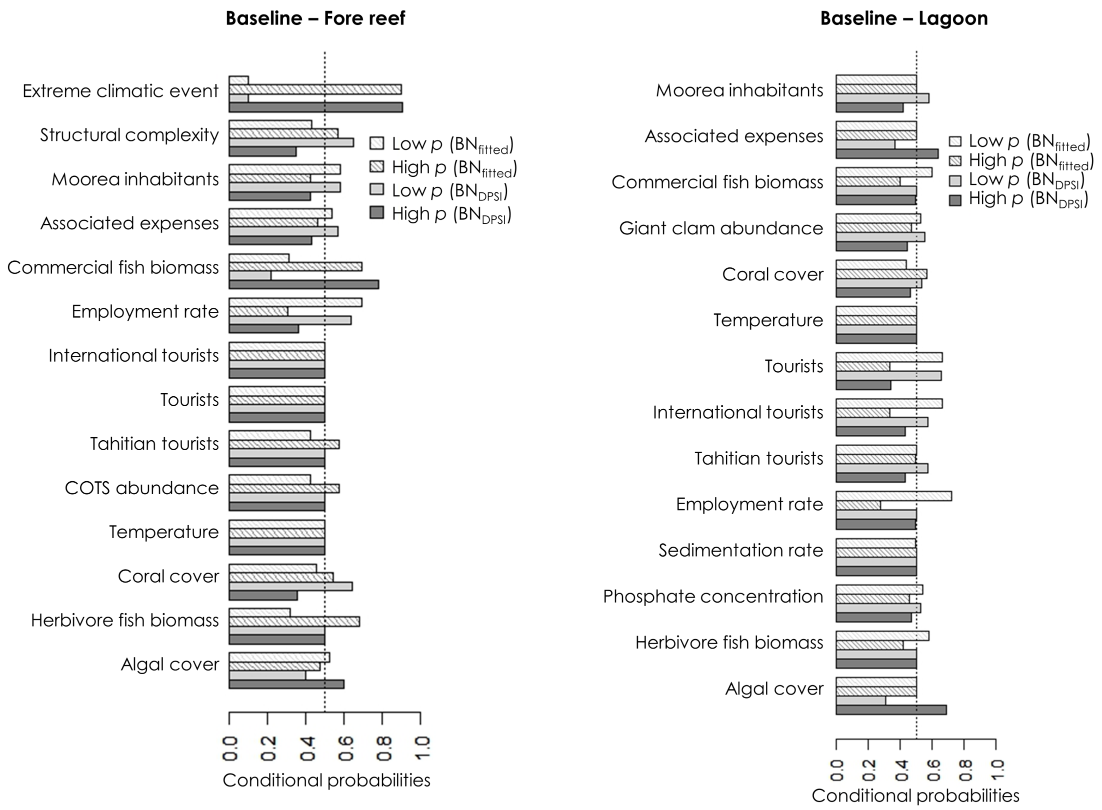

Figure 4: Summary of the posterior probability distributions of the compiled Bayesian belief network models (BNDPSI and BNfitted) for the fore reef (left panel) and lagoon (right panel). The 0.5 probability level is indicated by a dashed line.

3.2. Exploratory scenarios

Analysing the influence of exploratory scenarios on the response nodes in the fore reef and lagoon BN models can reveal potential social-ecological trade-offs between management options. We defined scenarios where the probabilities of "high" values (P(high); likelihood of values being superior than median value of time series) were highest for the three response nodes and identified scenarios causing the widest spread in probabilities. A comparison of the development of the posterior probability distributions of P (high) of the three response nodes of the four models can be found in Figure 5. Scenario 0 is referred to as the baseline scenario, against which the relative changes of the probabilities are compared.

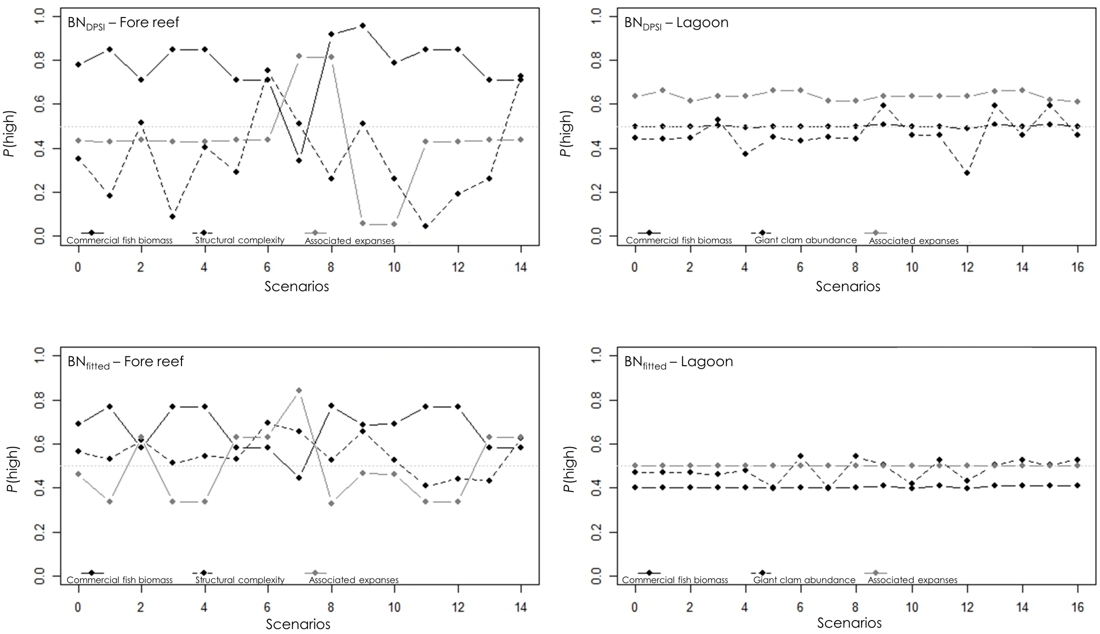

Figure 5: Comparison of behaviors of response nodes of the Bayesian belief network models (BNDPSI and BNfitted) under the defined explorative scenarios for the fore reef and lagoon (see Table 3). Scenario 0 reflects the baseline scenario (average past conditions); scenario numbers correspond to Table 3.

The scenario results for both fore reef models showed a similar pattern, while the BN_{fitted} model results revealed a lesser degree of variation in the changes of the probabilities of a single node. Due to the results of the prediction performance we focused here on the results of the model BN_{fitted}. Scenarios 2, 5, 6 and 14 forced P(high) to values between 0.6 and 0.7 for the three response nodes. Those scenarios share the threshold of regulation in number of *Tahitian tourists*. The widest spread of P(high) values across all response nodes was found for scenarios 1, 3, 4, 8, 11 and 12. Only scenarios 11, 12, and 13 pushed P(high) of structural complexity to values inferior to 0.5. Scenario 7 had the same effect on *Commercial fish biomass*, which described high *Employment rates* and high number of *Tahitian tourists*. Thus, caution should be taken regarding the interaction of those two social components of the Moorea coral fore reef resource system when dealing with the management of fisheries of commercial fishspecies.

The scenario results for both lagoon models showed distinct pattern, while the BN_{fitted} model results showed almost no deviation from P(high) values around 0.5 for *Giant clam abundance* and *Associated expenses*. Based on the prediction performance of the lagoon models we focused here on the scenario analysis of the BN_{DPSI} model for the lagoon. Scenarios 3, 9, 13, and 15 caused P (high) to values superior or equal to 0.5 for all three response nodes. All four scenarios simulated phosphate values superior to 0.32 and scenarios 13 and 15 assumed temperatures superior to 27.59°C. The number of *Tahitian tourists* being high or low did not influence the scenario results. The positive relationship between *Giant clams abundance* and *Phosphate* concentration triggered also the predicted drop of P(high) for scenarios 4 (0.35) and 12 (0.3). The likelihood of *Commercial fish biomass* of being greater than 28.72 kg remained for all scenarios around 50 %. Also, P (high) values for the *Associated expenses* varied only marginally around 0.6.

4. Discussions

Here we developed spatially explicit Bayesian belief network (BN) models to explore the social-ecological trade-offs revealed by a set of multiple driver's scenarios in the coral reef resource system of Moorea Island, French Polynesia. For each spatial entity of the resource system (i.e. the lagoon and the fore reef), two types of BN models were developed, one that was derived from an expert elicitation process in the lagoon and one that was fitted to the available monitoring data in the fore reef. We identified trade-offs among ecosystem services occurring in the lagoon or on the fore reef.

In general, uncertainties in a BN model can relate to uncertainties of the input data and defined relationships, and therefore in system understanding [65]. The latter refers to the structural uncertainty, which is very likely for complex ecological models. Various model structures exist that can describe the system adequately [59]. We therefore developed for each spatial entity two BN models, one which was derived from an expert elicitation process (top-down) and one that was fitted to the available monitoring data (bottom-up). Our models and scenario results do not provide an absolute representation of the system, but form a strong basis for future applications at any spatial scale and with other types of social-ecological interactions when respective data become available. This is in line with the view that BN modeling is an ongoing process, since beliefs could be easily updated once new data becomes available, individual CPTs or parts of the model can also be rebuild without redoing the whole modeling exercise [62]. Given the conditional probability weighted confusion error and spherical pay off values (Table 5), the fitted fore reef model (BN_{fitted}) was preferred for scenario evaluations and support of a decision-making process, while for the lagoon the BN_{DPSI} was selected. This is a clear example for a case of weak relationships between empirical data (i.e. for the lagoon model), here a top down model using local expert knowledge, is to be preferred for the exploration of scenarios. Building on a data driven process or local expert knowledge, our BN modelling approach provided a common language and a mutual identification of the different conflicts emerging in the SES [49,66].The graphical nature of the networks and the rapid calculation of running scenarios with the BN models make them ideal for use during discussions with stakeholders where the impact of changes in management can be quickly and easily demonstrated on the live model [67].

If the BN_{fitted} fore reef model better resembled relationships in the available monitoring data, then the "social" nodes such as the *Tahitian tourists* or *International tourists* had a greater influence, while this was not obvious for the BN_{DPSI} lagoon model. The BN_{fitted} fore reef model structure driven by the data showed clearer social-ecological links between nodes than for the lagoon. Indeed, scenarios 3,4 and 8 of the BN_{fitted} fore reef model addressed trade-offs between *Commercial fish biomass* and the number of *International tourist* (or with the *Employment rate* that is linked to the intensity of recreational activity). The reason for those social-ecological links was not directly explicit. Since *International tourists* don't fish on the fore reef and they don't buy any fish for private consumption. Moreover none of Moorea restaurants sell reef fishes [68]. Reef fishes can lead to intoxication due to ciguatera and restaurants sell rather pelagic fishes (e.g. tuna) [69]. But, an increased number of *International tourists* visiting Moorea could lead to a high number of recreational activities in the lagoon. Some recreational activities such as day tour activities providing ray (and indirectly shark) feeding experience or jet ski excursion often lead to conflict of use with the fishermen community. One possible consequence of those spatial use conflicts may result in a fishing effort displacement from the lagoon to the fore reef. In the case of the fore reef, fishing activities have been influencing the ecosystem state the most, acknowledging that an increase in commercial fishing in the fore reef might be linked to the increase in recreational activities within the lagoon. Thus, a fishing effort displacement may take place from the lagoon to the fore reef, increasing also the conflict potential between tourist operators and fishermen. Although, an MPA network of eight MPAs (including 5 no-take-areas and 3 multi-use MPAs) has been implemented ten years ago to foster a separation of recreational and fishing activities, it seems that there still exists an overlap between those activities. Since MPAs often fail to achieve management objectives such as the reduction of conflicts [70], additional management measures should be considered to solve potential conflicts between different human uses. Thus, underlining the need for an ecosystem approach to spatial management which aims to integrate management measures related to social and ecological targets [44]

Another interesting trade-off in the fore reef model was revealed with scenarios 2, 5, 6, 14. Indeed, the probabilities of high *Commercial fish biomass, Structural complexity* and *Associate expenses* appeared when the number of *Tahitian tourists* was low. Again causal links between those social-ecological trade-offs did not appear very explicit. However, the observed cause-effect relationship between high number of *Tahitian tourists* and low probabilities of high *Commercial fish biomass*, *Structural complexity* and *Associate expenses* coincides with the time period after the economic crises (peaked in 2008) and multiple environmental drivers such as a COTS (from 2006 to 2009) outbreak and the Cyclone Oli (in 2010). COTS outbreak and the Cyclone Oli effects were correlated in time with the economic crisis [49]. While COTS and cyclone effects resulted in a drop of living *Coral cover* and *Structural complexity*, the economic crisis resulted in a drop of *International tourists*. At the same time, many hotels in Moorea offered great discounts for *Tahitian tourists* in order to compensate the loss of income due to the decrease in *International tourists*. This dynamic could explain why we found that the decrease in *Coral cover* had a positive impact on *Tahitian tourists*. From a management perspective those social-ecological trade offs enable to identify some scenarios where the *Commercial fish biomass*, *Structural complexity* and *Associated expanses* generated by recreational activities could improve in comparison to the baseline with probabilities ranging between 50-70 %. Those scenarios simulated a regulation of number of Tahitian tourists. Such a regulation seemed to have the potential to buffer against the impact of combined environmental drivers. This example illustrates how it is possible to misinterpret results or allow for specific directions of cause-effect relationship in BN modeling. For the fore reef model data and commonly accepted relationships were driving our model first. Thus, those results should be always interpreted with care since in the latter fore reef scenarios (i.e. scenarios 2, 5, 6, 14) both good ecological (i.e. high probability of *Commercial fish biomass* and *Structural complexity)* and economic (i.e. high probability of *Associated expanses)* conditions seemed to be influenced by a regulation number of *Tahitian tourists*. Indeed, these good ecological and economic conditions are in reality associated with no economic crisis and no extreme climatic.

In the lagoon, the BN_{DPSI} model doesn't provide any direct social-ecological trade offs. However, *Phosphate* can be considered as an indirect social driver since *Phosphate* inputs in the lagoon are probably linked to terrestrial anthropogenic activities. Our BN_{DPSI} model reflected a positive cause-effect relationship between phosphate concentration and giant clam abundance (reflecting structural complexity). During the participatory modeling workshops consensus has been reached that water enrichment due to terrestrial run offs and non-operational water treatment play a strong role in coral bleaching/mortality [49]. This pattern is also well described in the literature even if it remains an area of active research [71,72]. In the lagoon, social-ecological trade-offs are less clear but drivers resulting from terrestrial anthropogenic activities (i.e phosphate inputs) appeared to be the main drivers for state changes of living coral and algal cover. While the Polynesian culture has always viewed a continuous relationship between the lagoon and the land considering their natural resources from ridge on the mountain to reef as a whole, terrestrial and marine management has always been disconnected [52]. Thus, this makes a strong case for a coherent and integrated spatial planning approach accounting for the interconnection of land-based activities and their impacts on the marine environment. The lagoon management system should not be disconnected from terrestrial activities. Moreover, additional research and monitoring should be launched to increase our understanding of cumulative impacts especially coming from terrestrial anthropogenic activities focusing on the concentration levels of other nutrients, such as nitrate and phosphate, their terrestrial sources and their potential impact on the living coral cover.

5. Conclusions

The aim of this study was to develop spatially explicit models to assess coral reef social-ecological trade-offs and explore potential state changes under different scenarios to inform management. We limited the focus of the scenarios to ecosystem components directly linked to the provision of crucial ecosystems services such as food provision (i.e. the commercial fish biomass) or the coastal protection (i.e. the structural complexity). Exploratory scenarios tested with both the fore reef and lagoon models disclosed fairly surprising social-ecological trade-offs occurring within the Moorea coral reef resource system. On the fore reef the number of international tourists seemed to be a direct driver of an effort displacement of commercial fishing while the effect of numbers of Tahitian tourists inherited adverse effects of the economic crisis and of cyclone Oli. In the lagoon, social-ecological trade-offs were less clear but drivers resulting from terrestrial anthropogenic activities appeared to be the main drivers for the states of living coral and algal cover. The management of coral reef resource systems has to consider the complexity of social-ecological interactions that often mask the potential trade-offs existing between the provision of ecosystem services. Hence, this study showed that Moorea coral reef management should account for different spatial entities in their management process, thus, following the concept of an integrated a and ecosystem-based management. The lagoon and the fore reef require different – but linked – types of management targets and respective measures in order to both maintain the provision of vital ecosystem services and allow for a sustainable use of resource provided by the coral reef resource system.

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Discussion Générale

1. Synthèse des résultats

Une approche transdisciplinaire des systèmes socio-écologiques côtiers intégrant les sciences de la complexité doit permettre de caractériser les dynamiques socio-écologiques et les propriétés émergentes qui structurent l'évolution incertaine de ces systèmes. Il est nécessaire pour cela d'adopter une méthodologie de recherche qui intègre l'écologie, la sociologie, l'anthropologie, et les sciences économiques de par l'apport de données empiriques ou de la connaissance experte. Une étude préalable du système socio-écologique récifo-lagonaire de l'île de Moorea nous a permis d'explorer sa complexité ainsi que les manques de connaissances limitant la compréhension des dynamiques socio-écologiques de ce système. Comme pour de nombreuses pêcheries récifo-lagonaires du Pacifique, les activités de pêche dans le lagon de Moorea sont très difficiles à surveiller et à quantifier, car elles varient énormément et sont très dispersées. La complexité de la pêcherie récifo-lagonaire de Moorea, à bien des égards, est ainsi représentative d'autres pêcheries récifo-lagonaires insulaires du Pacifique. Une grande diversité de poissons est capturée avec au moins cinq grands types d'engins et la pêche se produit pendant la journée ou la nuit sans aucun horaire régulier ou protocoles formalisés. La pêcherie de Moorea est cependant assez spécifique lorsque l'on considère le contexte socio-économique et les motivations d'accès à cette ressource naturelle. Contrairement à de nombreuses autres pêcheries récifo-lagoanire dans le Pacifique et dans le monde, la Polynésie française est un pays relativement riche. Ainsi, la grande majorité des habitants de Moorea ne dépendent pas des ressources marines lagonaires pour leurs subsistances. Seul un faible pourcentage des ménages de Moorea identifient la pêche comme leur principale source de revenus ou de moyens de subsistance (Leenhardt et al. 2016). Les activités de pêche sont en revanche d'une très grande importance pour leurs avantages non matériels. Pour les habitants de Moorea, la consommation de poissons de récif frais est aussi fondamentale pour leur identité que de parler la langue tahitienne. Ainsi pour mieux comprendre les dynamiques socio-écologiques liées à cette activité, il faut tenir compte des avantages non matériels liés au style de vie et à l'identité polynésienne.

Étant donné la complexité sociale et écologique des activités de pêche récifo-lagonaire à Moorea, toute tentative de comprendre leur dynamique exige une méthode intégrée qui tient compte des deux systèmes simultanément. A ce titre, notre approche de modélisation participative a permis aux acteurs et aux scientifiques de saisir la complexité de ce système socio-écologique récifo-lagonaire. Des modèles conceptuels « Force motrice-Pression-État-Impact » furent construits à l'aide d'ateliers de travaux de modélisation participative et l'évaluation d'interactions pression-états en exploitant des données empiriques. Des modèles de réseaux bayésiens furent ensuite développés en utilisant une base de données socio-écologiques longue de 11 années ainsi que de la connaissance experte afin de produire des scénarios exploratoires, définit par des groupes de porteurs d'intérêts, pour tester les effets de différents forçages sur le système et ainsi révéler les dynamiques complexes du système socio-écologique récifo-lagonaire de l'île de Moorea. Les scénarios exploratoires montrent (1) l'impact majeur des activités humaines terrestres sur les écosystèmes récifo-lagonaires, (2) la possible existence d'un report d'effort de pêche du lagon vers la pente externe due à l'augmentation des activités récréatives au sein du lagon et (3) la compétition algue-corail sur la pente externe qui est directement influencée par la fréquentation de cet espace. Nous avons souligné que la gestion locale devait être davantage adaptée et notamment: 1) tenir compte plus spécifiquement de la typologie existante des acteurs; (2) être plus spatialement explicite afin de mieux distinguer les objectifs et les actions de gestion pour le lagon et la pente externe; (3) être plus coordonnées avec les agences terrestres pour une liaison terre-mer cohérente qui (i) tienne compte des interactions terre-mer existantes et (ii) reflète mieux le patrimoine culturel polynésien qui considère la nature du sommet de la montagne à la crête récifale comme un ensemble continu. Le lagon et la pente externe exigent des objectifs de gestion différents mais liés entre eux afin de maintenir la provision de services écosystémiques vitaux et de permettre une utilisation durable des ressources fournies par ce système récifo-lagonaire. Enfin, ce travail souligne aussi que les perceptions culturelles des systèmes socio-écologiques côtiers doivent être mieux intégrées dans les schémas de gestion afin d'éviter les déséquilibres entre les priorités de gouvernance de l'État et les systèmes traditionnels de gestion des ressources naturelles.

2. Apport de la science de la complexité à l'étude des systèmes socio-écologiques

Les systèmes socio-écologiques côtiers sont des systèmes complexes possédant des interactions multi-échelles, des propriétés émergents ainsi que des dynamiques d'évolution non linéaires renforçant une incertitude quant à leur évolution (Gallopín et al. 2001, Levin et al. 2012).

Les dynamiques socio-écologiques se produisent sur une large gamme d'échelles spatiales et temporelles. Ce paradigme implique que les dynamiques locales des systèmes côtiers sont imbriquées et donc influencées par des dynamiques plus globales expliquant le rôle de phénomènes cumulatifs locaux sur des processus globaux (Bodin et al. 2006, Kininmonth et al. 2011). Gunderson et Holling (2002) ont résumé ce concept des interactions croisées en soulignant que «de plus en plus, les problèmes locaux du moment peuvent avoir une partie de leur cause située à une demi-planète et avoir des causes dont la source provient de changements lents accumulés au cours des siècles». Dans le cadre d'étude du système socio-écologique récifo-lagonaire de Moorea, l'impact local d'une crise économique mondiale nous a permis de mesure à quel point ce système était ouvert et pouvait potentiellement être influencé par des dynamiques extérieures de bien plus grandes échelles (Leenhardt et al. 2017).

Les systèmes socio-écologiques côtiers possèdent des propriétés émergentes uniques. Ces propriétés n'appartiennent pas aux systèmes sociaux ou naturels séparément, mais émergent de leur interaction (Liu et al. 2007, Graham et al. 2013). Le terme émergence est utilisé pour décrire des phénomènes spatiaux et/ou temporels inattendus ou imprévisibles de la structure et de la dynamique d'un système, telle que sa résilience (Parrott 2002, Parrott et al. 2012). L'observation et la compréhension des propriétés émergentes des socio-écosystèmes côtiers sont cruciales pour comprendre la dynamique du système (Folke et al. 2010). La résilience du système socio-écologique récifo-lagonaire de Moorea est sans conteste une propriété émergente de ce système qu'il nous est pour le moment difficile de parfaitement appréhender. Cette résilience est à l'origine de phénomènes de rétroaction au sein du système qu'il nous a été impossible à modéliser du fait des limites techniques imposées par l'utilisation des modèles par réseaux bayésiens (qui excluent la prise en compte des phénomènes de rétroactions). Afin d'appréhender la résilience du système socio-écologique récifo-lagonaire de Moorea et des possibles rétroactions complexes, une utilisation des modèles multi-agents pourrait s'avérer pertinente.

Une caractéristique importante des systèmes socio-écologiques est qu'ils possèdent une dynamique non linéaire, par définition difficile à prévoir et anticiper (Folke 2006, Koch et al. 2009). La non-linéarité génère des interactions qui peuvent changer à mesure que le système évolue (Folke 2006). Par exemple, Koch et al. (2009) ont démontré que le service écosystémique de la protection côtière était non linéaire et dynamique. Ils ont montré qu'il existe de nombreux facteurs importants, tels que la densité et l'emplacement des habitats, les espèces, le régime des marées, les saisons et la latitude, qui peuvent également influer sur les modèles de non-linéarité de ces services écosystémiques (Granek et al. 2010). À Moorea, le service de protection côtière est largement influencé par le taux de couverture corallienne de la pente externe et de la crête récifale. Si notre étude a confirmé que certains facteurs environnementaux tels que la prédation du corail par *Acanthaster planci* ou les phénomènes météorologiques extrêmes (comme le cyclone Oli en 2010) pouvaient impacter ce service, il reste cependant très compliqué de pouvoir prédire l'évolution et la pérennité de ce service écosystémique crucial au bon développement économique du littoral lagonaire. La gestion des services écosystémiques côtiers est de ce fait étroitement liée à la gestion de l'incertitude, en particulier dans le contexte des changements globaux climatiques. À ce titre l'utilisation des modèles par réseaux bayésiens s'avère particulièrement intéressante car ce type d'outil intègre et quantifie l'incertitude quant à l'évolution du système.

3. L'approche socio-écologique : une approche limitée par les données ?

L'un des défis majeurs de l'étude et de la gestion des systèmes socio-écologiques est le manque de données normalisées et rigoureuses qui relient les changements dans les processus écologiques aux réponses dans les dynamiques sociales ainsi qu’aux rétroactions ultérieures entre elles (Le Cornu et al. 2014, Leenhardt et al. 2015). La surveillance et le suivi des systèmes socio-écologiques marins côtiers est par conséquent indispensables à la bonne gestion de ces derniers (Forst 2009, Pastres et Solidoro 2011). Par exemple, Cinner et al. (2013) ont étudié la vulnérabilité socio-écologique des pêcheries récifo-lagonaires au Kenya vis-à-vis du changement climatique à l'aide d'indicateurs d’exposition au climat, de la résilience biologique, de la sensibilité sociale au changement et de la capacité d'adaptation et de réorganisation sociales (Cinner et al. 2013, Cinner et McClanahan 2015). Cette approche a été la première à quantifier la vulnérabilité écologique des récifs coralliens au changement climatique ainsi que la vulnérabilité sociale des communautés de pêcheurs aux changements du système écologique, telles que la dépendance à la pêche et la capacité d'apprendre des chocs climatiques et de s'y adapter. En identifiant les communautés côtières vulnérables aux changements climatiques, cette approche a évalué les mesures de gestion socio-économiques et de gouvernance pour réduire la vulnérabilité future de ces populations. Il s'agit là d'un exemple d’utilisation de données de suivi sociales et écologiques empiriques rigoureuses pour informer les pratiques de conservation et de gestion.

Traditionnellement, la gestion des zones côtières s’est appuyée sur des suivis biologiques, écologiques et physiques des milieux délaissant le suivi des données socio-économiques. Cependant, il est désormais indiscutable que l’intégration de composantes sociales dans les processus de gestion et la prise de décision permettent d’avoir des structures de gouvernance plus robustes et durables (Kittinger et al. 2012, 2013). L'absence de données sociales dans un contexte de gestion côtière est maintenant perçue comme une omission qui peut souvent éroder l'efficacité de toute action de gestion ou de conservation des ressources naturelles marines. Par exemple, de nombreuses études ont montré que lorsque les données sociales ne sont pas intégrées dans les décisions de planification, les initiatives ont souvent un succès limité et parfois des résultats négatifs inattendus (Christie 2004, Fulton et al. 2011, Kittinger et al. 2013). Cela a conduit au développement d'indicateurs sociaux relatif à la sécurité alimentaire, de la réduction de la pauvreté et du bien-être humain dans le cas de la gestion des ressources marines et de la planification de la conservation (Ban et al. 2013, Mills et al. 2013, Milner-Gulland et al. 2014, Stephanson et Mascia 2014). L'intégration de cette composante sociale nécessite un effort concerté des scientifiques pour concevoir, financer et mener des études socio-économiques et/ou anthropologiques conjointes afin d'évaluer les compromis pratiques en matière de gestion des ressources naturelles marines et de conservation (Ban et Klein 2009, Kittinger et al. 2014).

Si dans l'étude du système socio-écologique récifo-lagonaire de Moorea nous avons utilisé des données écologiques et sociales, la plus faible quantité de données sociales sur Moorea a très certainement limité le potentiel de l'étude. En effet, le suivi des activités socio-économiques directement dépendantes de services écosystémiques majeurs tels que les activités récréatives ou la pêche sont encore trop limité voir inexistant. Comme pour de nombreuses petites pêcheries de récifs coralliens, les activités de pêche dans le lagon de Moorea sont très difficiles à surveiller et à quantifier, car elles varient énormément et sont très dispersées. Bien que les estimations de la production réelle soient incertaines, la productivité potentielle durable des pêcheries de la lagune de Moorea est totalement inconnue. En Polynésie française, il est extrêmement difficile, compte tenu de l'aspect diffus des activités de pêche d'avoir des chiffres précis des captures. Les données statistiques actuelles sont peu fiables, car les chiffres concernant le transport aérien inter-îles et les pêches de subsistance et de loisir ne sont pas connus. Bien qu'il n'existe que très peu de statistiques des produits lagonaires, il est possible d'estimer la production totale de Polynésie française aux environs de 4 300 tonnes par an (SPE 2006).

Étant donné la complexité sociale et écologique du système socio-écologique récifo-lagonaire de Moorea, toute tentative de comprendre sa dynamique complexe exigera probablement des méthodes intégrées qui tiennent compte des deux sous-systèmes écologique et social simultanément. Ainsi un travail de suivi annuel plus intégré est nécessaire pour mieux évaluer la complexité des dynamiques socio-écologiques.

4. Une science transdisciplinaire, mais une gestion interdisciplinaire ?

La transdisciplinarité – une stratégie de recherche qui traverse les frontières disciplinaires pour créer une approche holistique – est une condition préalable aux recherches sur les propriétés et la dynamique des systèmes socio-écologiques (Deppisch et Hasibovic 2011, Hummel et al. 2012). La multiplicité des termes se référant à l'interaction des systèmes sociaux et écologiques reflète les différents champs disciplinaires et les traditions intellectuelles au sein desquelles le concept de système socio-écologique a été développé. Ainsi, les termes «systèmes socio-écologiques liés» (Hughes et al. 2005), «systèmes couplés homme-environnement» (Holling 2001, Young et al. 2006), les «systèmes humains et naturels couplés» (Liu et al. 2007) ou les «systèmes socio-environnementaux» (Diaz et al. 2011) sont également utilisés. Depuis de nombreuses années, le besoin de collaborations transdisciplinaires dans la gestion des ressources naturelles et surtout dans les sciences de la conservation marine a été sous-estimé (Christie 2011, Fisher 2012). Les enjeux et problématiques complexes de gestion côtières se sont révélés difficiles à explorer sous l'angle monodisciplinaire et il est aujourd'hui largement reconnu que nous avons besoin d'approches intégratives impliquant à la fois les sciences sociales et les sciences naturelles afin de saisir la complexité des dynamiques socio-écologiques (Liu et al. 2007, Ostrom 2009, Carpenter et al. 2009). Ainsi, les collaborations transdisciplinaires entre la biologie, l'écologie, l'économie, la géographie, l'histoire, le droit, les sciences politiques, l'anthropologie, la psychologie, la sociologie et l'informatique peuvent apporter un soutien fondamental aux connaissances relatives à la gestion des ressources naturelles marines. Cependant, bien que la transdisciplinarité doit être un effort académique, il est clair que l'interdisciplinarité est beaucoup plus réalisable dans un contexte de gestion côtière dans lequel les gestionnaires font appel de façon pragmatique à des expertises disciplinaires diverses en fonction des problématiques rencontrées (Leenhardt et al. 2015).

5. L'approche socio-écologique : un complément essentiel de la gestion écosystémique ?

La gestion écosystémique est une approche relativement nouvelle en matière de gestion des ressources naturelles qui vise à assurer la pérennité des services écosystémiques et des bénéfices qu'ils procurent pour les communautés humaines tout en maintenant des écosystèmes sains et productifs (Sievanen et al. 2012). Ce type de gestion adopte une approche holistique qui évite de concentrer la gestion sur une seule espèce, proposant une approche complexe qui tient compte des impacts cumulés et des interactions entre les composantes des écosystèmes (Norse et al. 2005). La mise en œuvre réussie de la gestion écosystémique nécessite cependant une connaissance approfondie des interactions entre les systèmes sociaux et écologiques ainsi que des effets de seuils dans les dynamiques de ces systèmes couplés qui conduisent à des changements d'état de l'écosystème (Leslie 2011). Par conséquent, la gestion écosystémique est une approche axée sur la compréhension des liens existant entre les ressources naturelles et les communautés qui en dépendent (Bousquet et al. 2015). C'est une réponse pratique à la recherche théorique sur les interactions socio-écologiques dans les systèmes marins. Le succès de la gestion écosystémique repose donc sur les enseignements de l'approche socio-écologique qui identifient les interactions, les dynamiques socio-écologiques et les effets des impacts cumulés des pressions environnementales et anthropiques au sein des systèmes socio-écologiques (van Poorten et al. 2011). D'un point de vue conceptuel, la gestion écosystémique consiste à gérer les comportements sociaux au sein des écosystèmes plutôt que les écosystèmes eux-mêmes et exige un examen holistique de la manière dont les activités humaines affectent toutes les fonctions de l'écosystème. Comme évoqué précédemment, la gestion écosystémique est encore difficilement mise en œuvre dans le cadre de la gestion des ressources naturelles marines côtières du fait notamment du manque de données pertinentes pouvant éclairer la gestion. Néanmoins, l'apport théorique de l'approche socio-écologique doit permettre dans certains cas d'étude, comme celui du système socio-écologique récifo-lagonaire de Moorea, de proposer des pistes de réflexion pertinente pour mettre en œuvre de la gestion écosystémique intégrée des ressources naturelles marines. De plus, l'approche socio-écologique a généré l'émergence d'un fort intérêt pour la compréhension des phénomènes de résilience et des mesures de gestion pertinente pour garantir/maintenir cette capacité de résilience des systèmes.

6. Perspectives

Comprendre les dynamiques socio-écologiques récifo-lagonaires de Moorea est un défi majeur, mais aussi une opportunité, car cela pourrait permettre de tirer des enseignements sur l'avenir de beaucoup d'autres îles dans le Pacifique. Bien que l'influence de la mondialisation et du développement économique varie inévitablement d'un océan à l'autre, de nombreuses nations insulaires du Pacifique subissent des changements socioculturels et économiques semblables à Moorea, en raison de l'augmentation de leur densité de population, de leur modernisation et de leur lien avec les flux mondiaux. Leurs pêcheries artisanales ressemblent de plus en plus à celles de Moorea, où les pêcheurs sont moins dépendants du milieu marin (pour leur subsistance ou leur revenu), mais plus liés à des facteurs non matériels de revendication de leur identité et leur culture. En dépit des multiples pressions environnementales et anthropiques, les récifs coralliens de Moorea sont encore majoritairement sains avec une couverture corallienne élevée. Ainsi, même si la situation de Moorea est unique de par sa situation économique et géopolitique liée à la France, l'étude de ce système socio-écologique récifo-lagonaire permet d'avoir un aperçu de la façon dont les effets de la mondialisation et/ou de phénomènes globaux peuvent être intégrés pour une gestion socio-écologique durable.

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Résumé

L'approche socio-écologique appliquée à la gestion côtière : concepts et application

Pierre LEENHARDT

Résumé

Les zones côtières à travers le monde sont soumises à de fortes pressions dues aux changements climatiques globaux, à la destruction d'habitats ou encore à la surexploitation des ressources marines. Ces différentes pressions peuvent induire des changements rapides d'état des écosystèmes caractérisés par de fortes modifications de la biodiversité, avec des écosystèmes entiers cessant de fonctionner dans leur forme courante. En conséquence, la pérennité des biens et des services écosystémiques produits par les zones côtières n'est plus assurée. Il en résulte des perturbations économiques et sociales évidentes pour les populations dont le mode de vie dépend de manière directe ou indirecte de la biodiversité côtière. Afin d'appréhender ces interactions homme-environnement, l'approche socio-écologique est de plus en plus utilisée pour illustrer le rôle de l'Homme sur la dynamique des écosystèmes marins côtiers ainsi que les bénéfices qu'il tire de ces derniers. Cependant, la majorité des recherches actuelles reste théorique et peu de cas d'étude appliqués à la gestion des zones côtières mettent à l'épreuve ce concept dans une démarche transdisciplinaire. Cette thèse a donc pour objectif principal de combler ce manque en explorant les concepts de l'approche socio-écologique appliquée à la gestion côtière. Ainsi, dans le premier chapitre de cette thèse nous résumons les spécificités, les défis et les enjeux de l'approche socio-écologique appliquée à la gestion côtière. Les chapitres 2, 3 et 4 s'intéressent à l'analyse du système socio-écologique du lagon de Moorea en Polynésie française. Le chapitre 2 est consacré à un état de l'art des études s'intéressant à la pêcherie récifo-lagonaire de cette île permettant de faire émerger la complexité du système socio-écologique étudié. Le chapitre 3 propose ensuite d'explorer les dynamiques socio-écologiques de ce système à l'aide d'un processus de modélisation participative et de l'analyse de données empiriques. Enfin le dernier chapitre (4) nous permet d'identifier, à l'aide d'une modélisation par réseaux bayésiens, des scénarios exploratoires d'évolution des principaux services écosystémiques du lagon de Moorea en fonction de différents forçages naturels et anthropiques. Enfin, nous discutons des avantages et des faiblesses de notre approche ainsi que des potentiels d'applicabilité en tant qu'outil de gestion des zones côtières.

Mots-clés : système socio-écologique, ressources naturelles marines, service écosystémique, transdisciplinaire, modélisation, connaissance experte, système récifo-lagonaire, gestion.

Application of the social ecological approach to coastal management: concepts and application

Abstract

Coastal areas around the world are under intense pressures from climate change, habitat destruction, and over-exploitation of marine resources. These different pressures can induce rapid changes in the state of ecosystems characterized by strong changes in biodiversity, with whole ecosystems ceasing to function in their current form. As a result, the sustainability of goods and services produced by coastal areas is no longer assured. This results in economic and social disruptions for populations whose livelihood depends directly or indirectly on coastal biodiversity. In order to understand these linked social and environmental interactions, the socio-ecological approach is increasingly used to illustrate the role of humans in the dynamics of coastal marine ecosystems and the benefits it derives from them. However, the majority of current research remains theoretical and few case studies applied to the management of coastal areas test this concept in a transdisciplinary approach. The main objective of this thesis is to fill this gap by exploring the concepts of the socio-ecological approach applied to coastal management. Thus, in the first chapter of this thesis, we summarize the challenges insights and perspectives of the socio-ecological approach applied to coastal management. Chapters 2, 3 and 4 focus on the analysis of the coral reef resource system of Moorea island in French Polynesia. Chapter 2 is devoted to a state-of-the-art study of the coral reef fisheries of this island, revealing the complexity of this social ecological system. Chapter 3 then proposes to explore the social ecological dynamics of this system through a participatory modeling approach and the analysis of empirical data. Finally, in the last chapter (4) we developed spatially explicit Bayesian belief network models to explore the social-ecological trade-offs revealed by a set of multiple driver's scenarios in the coral reef resource system in order to explore the potential evolution of the main ecosystem services of the Moorea lagoon. Finally, we discuss the advantages and weaknesses of our approach as well as potential applicability as a tool for coastal zone management.

Keywords: social-ecological system, marine natural resources, ecosystem service, transdisciplinary, modelling, expert knowledge, coral reef system, management.

Annexe 1

Chapter 9

The Role of Marine Protected Areas in Providing Ecosystem Services

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INTRODUCTION

Marine ecosystems experience constant change and adaptation processes because they are under the influences of a suite of pressures (Hooper et al., 2012). Human impacts can affect the ecosystem functioning of marine ecosystems and reduce the associated production of goods and services required for human well-being (Cardinale et al., 2012; Mora et al., 2011). For example, major concerns are rising over observed declines in the abundance of particular species as well as reductions in functional diversity and changes in food web structure due to the intensity of some anthropogenic activities (De'ath et al., 2012; Hughes et al., 2010). These changes induce strong modifications of whole ecosystems or some of their components, resulting in loss of function (Graham et al., 2013). Such ecosystem disruptions may affect the flow of ecosystem services (such as food provision) that are vital for human well-being (Carpenter et al., 2006; Chapin et al., 2000; Díaz et al., 2006). As a result, the conservation and/or restoration of marine biodiversity and its derived ecosystem goods and services are major concerns. To this end, marine protected areas (MPAs) are being established worldwide to maintain biodiversity, ecosystem functions, and the flow of ecosystem services (Gaines et al., 2010). MPAs are a specific type of management zone—they may allow some uses, including scuba diving and some types of fishing; may be strictly no-take such as marine reserves; or they may be completely no-access zones where neither extractive nor nonextractive uses are allowed (Day and Dobbs, 2013). Most MPAs include another layer of complexity by combining different levels

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of protection within a spatially zoned management scheme. Zones may be dedicated to strict conservation, act as buffer zones that can be used for research, education, or traditional uses, and/or allow nonconsumptive and limited-consumptive uses (Agardy et al., 2003).

Today, MPAs are commonly used around the world as management tools to promote the sustainable use of marine resources (Hargreaves-Allen et al., 2011). In this chapter, we will review the different impacts of MPAs on ecosystem functioning and service production. We will focus especially on the relationship between the effects of MPAs on ecosystem functioning and the benefits provided to people. The livelihoods and well-being of coastal communities rely on ecosystem services produced by marine ecosystems. Thus, it is assumed that MPAs secure human livelihoods and well-being by protecting marine ecosystems and ecosystem services. However, the links between ecological effects of MPAs and services have rarely been explored.

The aims of this synthesis are to (1) identify relationships between the effects of MPAs on ecosystem functioning and service provision; (2) identify knowledge gaps on which future research efforts could focus; and (3) empower marine resource managers to make more informed decisions and maximize the value derived from their natural resource base. We propose that quantification and monitoring of species' functional trait distribution and assemblages' functional diversity are promising approaches for assessing the effects of MPAs on ecosystem functioning and services.

INTRODUCTION TO MARINE PROTECTED AREAS

MPAs are globally important management tools that are expected to (1) control and manage human activities and marine uses; (2) promote the recovery of exploited marine populations; (3) conserve or restore habitats, biodiversity, and food webs; and (4) manage and enhance ecosystem services such as food production, water purification, or recreational activities (Halpern, 2014; Liquete et al., 2013). Most MPAs are implemented to mitigate some of the human-induced modifying forces on marine ecosystems, especially by reducing or removing fishing mortality (Claudet, 2012). Originally, MPAs and especially "no-take" marine reserves were conceived as pragmatic means to eliminate harvest pressure and thereby protect marine depleted and endangered species, habitats, fisheries, and ecosystems, and to provide public enjoyment of the oceans (Mora et al., 2011). Today they are also used as management tools regulating fishing, tourism, and industrial activities. Thanks to different types of zoning, each established according to specific management goals, MPAs can reduce conflict and allow coexistence of different resource uses. Establishment of different-use zones must be combined with the establishment of: easily identifiable borders to reduce possible impacts of incidental intrusions; public information about uses permitted in different zones; and the participation of local communities and diverse users who contribute to the process (Hargreaves-Allen et al., 2011). Compliance with spatial zoning regulations, such as those within an MPA, depends on whether users understand the regulations designed to ensure the orderly and sustainable use of marine resources. If compliance is good, additional management costs to ensure zoning enforcement will be reduced.

In recent years, MPA research has made several advances. First, empirical data and analyses have shown how MPA effects are driven by different factors such as MPA age, size, fish life history traits, and the level of enforcement (Claudet et al., 2008, 2010; Guidetti et al., 2008). These findings have important implications for MPA design and management. For example, if even young and small MPAs can be effective in increasing fish population density, then old, large, and isolated MPAs may show even greater positive responses (e.g., Edgar et al., 2014). Meanwhile, no positive responses should be expected from MPAs with low levels of enforcement (Guidetti et al., 2008). Second, major advances were made on the numerous indirect ecological effects of protection such as functional diversity and delivery of ecosystem services, which are also time-dependent (Fletcher et al., 2011). Third, the potential socioeconomic benefits of MPAs are now becoming clearer. Studies show, for example, that MPAs can enhance food security, empower local communities (Mascia et al., 2010), and lead to jobs and/or revenue increases in activities linked to MPAs such as fishing and tourism, as well as to the maintenance of traditional activities (McCook et al., 2010; Pascal, 2014), although negative impacts on some users have also been documented (Mascia et al., 2010). Fourth, the general agreement among scientists that MPA networks can optimize conservation and fishery benefits has led to significant advances in network design and evaluation.

Considering these recent findings, it is clear that MPAs can provide different types of benefits. They can ensure the protection and/or the restoration of marine biodiversity that provide multiple ecosystem functions and human benefits. Below we provide a definition and overview of ecosystem services, then review the expected and documented effects of MPAs on the delivery of selected ecosystem services vital for human activities (e.g., fishing and recreational activities) and well-being.

INTRODUCTION TO ECOSYSTEM SERVICES AND THE LINK TO HUMAN WELL-BEING

Ecosystem services are the benefits people derive from nature (Liquete et al., 2013). They are the cornerstones of marine resource systems and are widely used to describe human–nature interactions (Diaz et al., 2011). Thus, ecosystem services support natural ecosystems, livelihoods, and human well-being through direct and indirect processes (Liquete et al., 2013). A conceptual model that represents those different interactions is a cascade linking the

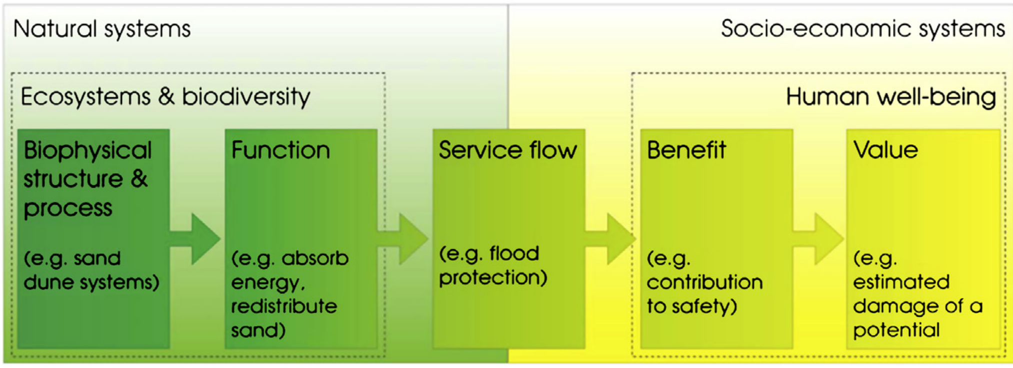

FIGURE 1 The cascade framework showing how natural provision of ecosystem services contributes to human well-being. *From Liquete et al. (2013).*

biophysical structure and processes with the benefit that people eventually derive (Figure 1). It highlights not only that ecosystems provide services but also that services do not exist in isolation from people's needs (Haines-young and Potschin, 2010).

The Millennium Ecosystem Assessment of 2005 (MA, 2005) classified ecosystem services into four categories: *provisioning services* such as food, water, timber, fiber, genetic resources, and pharmaceuticals; *regulating services* controlling climate, air and water quality, erosion, disease, pests, wastes, and natural hazards; *cultural services* providing recreational, aesthetic, and spiritual benefits; and *supporting services* such as nutrient and water cycling, soil formation, and primary production. According to the MA, approximately 60% of ES are degraded, including capture fisheries.

MPAs are key management tools established to secure the delivery of marine ecosystem services and thus contribute to human well-being (Fletcher et al., 2011). Indeed, improvement in the quality of the natural environment provided by MPAs is expected to strengthen the capacity of coastal ecosystems to produce goods and services for local people, local and nonlocal entrepreneurs, and the global community (TEEB, 2010). From a socioeconomic perspective, MPAs may be seen as public investments in marine ecosystems conservation (Laurans et al., 2013). As such, a basic question is the magnitude of MPAs' contributions to individual and societal well-being. This question has been tackled by cost–benefit analysis.

Alban et al. (2011) synthesized assessments of income and jobs related to the presence of 12 Mediterranean MPAs. A distinction was made between users obtaining commodities (commercial fishers) and recreational users (recreational fishers and scuba divers). Income generated by MPAs was generally high, particularly for commercial fishing and recreational scuba diving. The average yearly money incomes locally generated by uses in MPAs amounted to 710,000 € per MPA (between 48,000 € in Medes Islands and 1,573,000 € in Columbretes) in the case of professional fishing, 551,000 € per MPA (between 16,000 € in Tabarca and 1,099,000 € in Medes Island) in the case of scuba diving, and 88,000 € per MPA (between 35,000 € in La Graciosa and 211,000 € in Monte da Guia) in the case of recreational fishing (Roncin et al., 2008). These figures should be compared with yearly MPA management costs, which amounted on average to 588,000 € per year per MPA. However, the contribution to different economic sectors varied greatly from place to place. On a relatively remote MPA (Columbretes, Spain), the economic contribution of commercial fishing was dominant. This activity generated nearly 90% of all income provided by the ecosystem use. On an MPA closer to densely populated areas (Medes), incomes generated by commercial fishing amount to only 5% of those generated by scuba diving (Alban et al., 2011). In the Great Barrier Reef Marine Park in Australia, the estimated distribution of economic value between recreational uses and commercial fishing is approximately 4:1 (Stoeckl et al., 2011). However, despite significant improvements in recent years, this type of assessment faces substantial difficulties. First, the limited availability of economic data at a relevant scale frequently hinders a complete assessment of the influence of MPAs on the economy of the neighboring zone (Laurans et al., 2013). Moreover, total value is always underestimated because the measurement of nonmarket values, including nonuse values such as the value of marine biodiversity, is a difficult task. Even assessing the impact of an MPA using some specific market values (e.g., fishery rent) may be problematic due to limited quantitative information on underlying ecological processes (e.g., larval and juvenile spillover from MPAs to fishing grounds) (Pascal and Seidl, 2013); the use of CPUE was suggested as a way to bypass this issue. As a result, the application of cost—benefit analysis to MPAs is generally incomplete (François et al., 2012), providing an assessment of only a part of the net benefits MPAs provide. Below we review the expectations and evidence for MPAs' contributions to a selected group of ecosystem services.

MARINE PROTECTED AREA EFFECTS ON INDIVIDUAL ECOSYSTEM SERVICES

Review of the literature reveals that MPA establishment is expected to support a suite of services. Here, we provide an overview of the conceptual or empirical basis for such effects (Table 1). As a first step toward establishing a link between ecological change in MPAs and service provision, we also discuss what functional traits of species, functional groups, and/or ecological community attributes underlie MPAs' effects on services.

Marine Protected Area Effects on Provisioning Services: The Example of Fisheries

MPAs support provisioning services through their effects on fisheries and diversity (Worm et al., 2006). The first anticipated effects of establishing

TABLE 1 Examples of the Effects of MPAs on Ecosystem Services, the Mechanism Underlying Service Provision, and the Functional Traits, Functional Groups, and/or Community Attributes Driving These Effects

Ecosystem Service Category (MA, 2005)	Ecosystem Service	Mechanism by which MPAs Provide Service	Species, Community Attribute, Functional Trait, or Functional Group Underlying Effect	References
Provisioning services	Food	Increased production/ stabilization of target species biomass	Large size of target species, recovery of top predators and food web complexity	Goñi et al. (2010)
	Ornamental resources	Increased production/ stabilization of ornamental fish biomass	Species diversity	Williams et al. (2009)
	Raw materials	Algal and sand production	Predators controlling herbivory, bioeroders, corallivores	Karnauskas and Babcock (2014)
	Genetic resources	Protection of genetic diversity, adaptation to climate change	Response diversity, genetic diversity	Miller and Ayre (2008)
	Medicinal resources	Protection of molecular diversity	Chemically defended species, biological diversity	Schroder et al. (2004)
Regulating services	Carbon sequestration and climate regulation	Protection of plants and calcifying organisms (e.g., mangroves, sea grass, corals)	Species that have high C sequestration capacity (primary producers, calcifying species, bioconstructors)	Gonzalez-Correa et al. (2007)

Cultural services	Cultural heritage	Maintenance of traditional community-based natural resource management	Charismatic species (e.g., sharks, sea turtles, large mollusks)	Clarke and Jupiter (2010)
	Spiritual and historical heritage	Maintenance of traditional community-based natural resource management	Charismatic habitat (e.g., coral reef, kelp forests)	NA
	Recreational activities	Creation of nature-based eco-tourism opportunities (scenic beauty and emblematic species)	Charismatic species, large species, and habitat-forming species	Rios-Jara et al. (2013)
	Science and education	Creation of opportunities for research and education in placed of reduced human impacts	Biological diversity, complex food webs	Galzin et al. (2004)
Supporting services	Primary production	Protection of primary producers	Primary producers, habitat-forming species	Milazzo et al. (2002)
	Coastal protection	Protection of habitat formers (e.g., corals, sea grasses, mangroves) providing attenuation of wave intensity nature-based	Habitat-forming species	Mumby and Hardone (2010)

Babcock et al. (2010), Clarke and Jupiter (2010), Galzin et al. (2004), Goñi et al. (2010), González-Correa et al. (2007), Milazzo et al. (2002), Mumby and Harborne (2010), Ríos-Jara et al. (2013), Schroder et al. (2004), and Williams et al. (2009).

no-take or limited-take regulations through MPAs can be summarized as follows. First, mortality from fishing is immediately eliminated so that targeted individuals can live longer and attain larger sizes. In the short term, the increase in fish and invertebrate densities and sizes can lead to increases in reproductive output and recruitment (Claudet et al., 2010; Micheli et al., 2012). Possible negative habitat impacts associated with the use of destructive fishing methods also cease, allowing for the recovery of biogenic habitat that in turn positively affects fish recruitment and survival (Mumby and Harborne, 2010). Thus, in the medium to long term, habitat quality is improved, the preharvesting population age and size structure is re-established, and food web complexity increases due to increased diversity and recovery of top predators, which are often major fishery targets (Babcock et al., 2010; McCook et al., 2010; Micheli and Halpern, 2005). Consequently, one of the most commonly described indirect effects of marine reserves involves a trophic cascade, which is classically defined as the indirect effects of apical species in the food web (e.g., carnivores) on basal species (e.g., primary producers), mediated by intermediate consumers (e.g., herbivores) (Babcock et al., 2010).

Fishery effects of protection can only take place if an export of fish individuals occurs over the boundaries of the MPA ("spillover"; McClanahan and Mangi, 2000), and/or if eggs and larvae are exported from the MPA outwards ("seeding"; e.g., Planes et al., 2009). In MPAs with permeable boundaries, spillover can induce increases in catch per unit of effort (CPUE) of target species in surrounding fisheries' grounds. These increases constitute a yield surplus and fishers' CPUEs tend to be higher, although often more variable due to seasonal processes underlying spillover (Goñi et al., 2006; McClanahan and Kaunda-Arara, 1996). Spillover can also induce increases in total catch, catch per unit of area, species mean size in catch, and species diversity in catch (Goñi et al., 2010). These increases in turn can lead to increases in fishing effort along the MPA boundaries. For fishers, catch of adult spillover focuses in most cases on the borders of the reserve. The fishers' behavior in response to the MPA establishment is usually the concentration of effort at the boundaries of the reservation to take advantage of export adults. This mechanism known as "fishing the line" (Roberts et al., 2001) can be interpreted as evidence of a spillover mechanism and becomes so severe in some cases that it may be affecting densities inside the reserve (Halpern et al., 2008). Figure 2 describes the CPUE decreases for lobster fishery from the border of the reserve and thus shows the concentration of effort in this area.

Although this effect has been poorly quantified (Sale et al., 2005), experience shows that the profit generated by the spillover generally has an impact limited to the local fishery and does not seem to significantly increase the densities for large fishing areas. It also has been debated whether the catch from spillover offsets harvest losses due to closure. A recent synthesis by

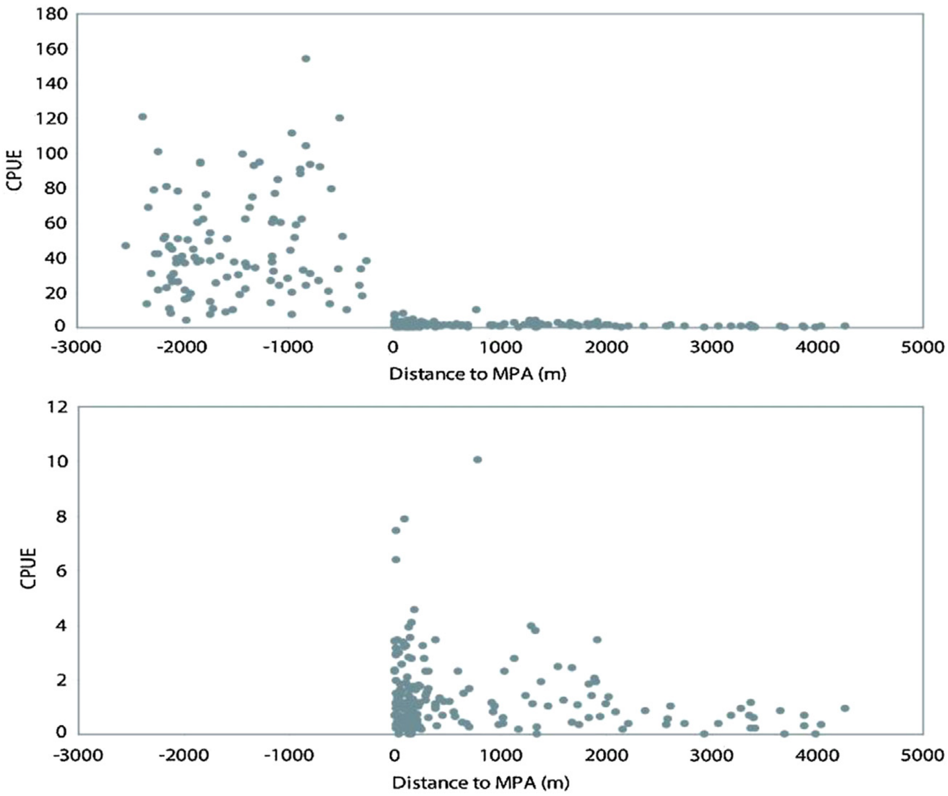

FIGURE 2 Lobster catch per unit effort (CPUE—number of lobsters caught per 600 m of net per day) versus distance from fishing set to the Columbretes Islands Marine Reserve boundary. Positive values are outward the MPA boundaries. Negative values are inward the MPA boundaries. (Upper panel—commercial and experimental data combined; lower panel—commercial fishery data on expanded y-axis scale.) *Adapted from Goñi et al. (2006, 2011).*

Halpern et al. (2010) concluded that even though the spatial extent of the contribution from the MPAs to fisheries is limited (600−1500 m from the MPA edge), in a majority of studies this contribution compensated for the loss of fishing grounds in MPAs. The average magnitude of these effects, however, should be considered with caution because (1) this study pooled very different species—e.g., with different mobility; and (2) studies on spillover focus primarily on species for which some form of spillover is expected.

Studies comparing effects of MPAs on surrounding CPUEs are scarce (Halpern et al., 2010; Harrison et al., 2012; Roberts et al., 2001). Gell et al. (2003) conducted a study selection of nine reserves in several locations with different designs and tested a significant improvement on different species' CPUEs. In their review, the authors quoted two cases of reserves in St Lucia—in Bermuda (Roberts et al., 2003) CPUE for large traps had improved by 46% after five years, and in Nabq (Egypt) the improvement was 66% for the net fishery. It also referred to reserves in Apo (Philippines) with

10-fold increases in longline CPUE after 20 years of protection, with the largest and most stable total catch in the Philippines over a 15-year span. In Tabarca, fishers benefited from a 50%−85% higher CPUE for key species, compared with before closing. Other cases in Mombasa (Kenya) (McClanahan and Mangi, 2000) have the highest catch in the region even with a major effort. However this does not increase the CPUE but only slows its decline. Also in South Africa, Tunley (2009) shows that the reserve has "only" stabilized catch. Other reserves in Chile showed that fishers are benefiting from a CPUE that is 4−10 times superior for a specific bivalve fishery, and in Columbretes (Spain) from a CPUE that is between 6 and 58 times higher for the lobster (Goñi et al., 2006).

Marine Protected Area Effects on Cultural Service: The Example of Recreational Activities

MPAs enhance the development of nonextractive activities, making recreational users perhaps the main beneficiaries of marine conservation (Christie and White, 2007). MPAs provide critical recreational services through nature-based tourism revenue (Balmford et al., 2009). The effects of MPAs stem directly from the fact that the marine environment within an MPA (particularly within a no-take zone) is granted a high level of protection against anthropogenic pressures. Protection in turn is likely to improve the quality of some attributes, such as large charismatic species and/or habitat-forming species that are valuable to visitors (Graham and Nash, 2012). For example, coral reefs are valued as cultural heritage (Hicks et al., 2009). Charismatic habitats (e.g., corals) and species (e.g., reef sharks) serve as focal points for local tourism and ecotourism, thereby enabling residents and visitors to enjoy aesthetic and spiritual values of coral reef ecosystems and seascapes. There are several species, such as the sicklefin lemon shark in French Polynesia and the dusky grouper in the Mediterranean Sea, that increase the recreation/tourism value of tropical and temperate reefs (Clua, 2011; Vandewalle et al., 2007; Guidetti and Micheli, 2011).

Even if, MPAs are expected to be powerful attractors for tourism, quantitative evidence for this benefit remains scarce (Andersson, 2007; Asafu-Adjaye and Tapsuwan, 2008; Depondt and Green, 2006; Harrison, 2007). For example, the relationship between underwater tourism and MPA impacts on some ecological attributes is not well known (Andersson, 2007). There are scientific knowledge gaps and technical difficulties in separating MPA effects on tourism from other context variables such as access and local infrastructure. High costs of studies, late participation by social sciences in MPA science, and effects too weak to be statistically significant have been proposed as reasons for the scarcity of studies of MPA social benefits (Christie et al., 2012; Cinner et al., 2009; Pollnac and Seara, 2010; Sale et al., 2005).

Marine Protected Area Effects on Supporting Services: The Example of Coastal Protection

MPAs provide protection to foundation species such as coral reefs, sea grass, kelps, and mangroves. These species produce physical structures that are natural barriers to waves, hurricanes, typhoons, and elevated sea levels, thereby providing coastal protection to people and critical coastal habitats. Thus, MPAs can contribute to maintaining the ecosystem service of coastal protection through the protection of habitat-forming species and communities (Graham and Nash, 2012). These habitats, when under good ecological conditions, limit the phenomenon of coastal erosion by absorbing high amounts of wave energy and lessening damage from severe weather events (hurricanes, tropical storms, and typhoons) (UNEP-WCMC, 2006) (Kench and Brander, 2006). Coral reefs and mangroves protect against waves by forming barriers along the coastline. Similarly, lagoon areas protected by barrier reefs are generally quiet areas that promote the multiple uses described previously. Several studies show that the reefs act similarly to wave breakers or shallow coasts—this includes a recent meta-analysis of 27 studies conducted in the Atlantic, Pacific, and Indian Oceans revealing that coral reefs provide substantial protection against natural hazards by reducing wave energy by an average of 97% (Ferrario et al., 2014). Reef crests alone dissipate most of this energy (86%). A comparison with artificial structures indicated that coral reefs can provide comparable wave attenuation benefits to artificial defenses, but at lower costs. The median costs of reef restoration projects are in fact an order of magnitude lower than the costs of building artificial breakwaters, indicating that reef conservation and restoration are cost-effective strategies for reducing risk from natural hazards. Finally, an estimated 200 million people receive risk reduction benefits from reefs, or bear hazard mitigation and adaptation costs if reefs are degraded (Ferrario et al., 2014) (it might also be important to highlight the importance of physical processes and low impact of ecological ones for coral reefs).

MARINE PROTECTED AREA EFFECTS ON LONG-TERM ECOSYSTEM FUNCTION AND THE PROVISION OF MULTIPLE SERVICES

Several studies have highlighted the positive effects of MPAs on some aspects of ecosystem function, such as functional diversity and redundancy. MPAs can have positive effects on maintaining specific functional traits, such as large body size, as well as the diversity of functional traits within communities (Micheli and Halpern, 2005; Mouillot et al., 2008). However, few studies have addressed relationships between functional diversity and composition and ecosystem services (Micheli et al., 2014; Raffaelli, 2006). Additional future work directly quantifying ecosystem function and services and investigating relationships between ecological attributes and service provisioning will be critical for understanding the role of biodiversity protection in maintaining the suite of functions and services provided by marine ecosystems (Menzel et al., 2013; Micheli et al., 2014).

In the next sections, we review work to date exploring these relationships and defining and quantifying functional traits and attributes of marine communities. We propose that broader application of functional frameworks is a key step in linking MPAs and their ecological effects to ecosystem service provision.

The Role of Biodiversity: Expectations from Functional Diversity and Redundancy

The goals of MPAs are increasingly expanding beyond the protection and restoration of a few to the restoration of ecosystem functions and services (e.g., herbivory and maintenance of corals, predatory control of invasive species, recruitment and recovery potential, coastal protection, fisheries, and opportunities for recreation and education). MPAs also aim to maintain long-term ecosystem health and sustain multiple ecosystem functions and services within the context of changing environmental conditions (e.g., UNEP-WCMC, 2008). One suggested approach for tackling this extremely complex and multifaceted sets of goals is to use biodiversity as a target for management and a proxy for the full range of functions and services within an ecosystem (Duffy, 2009; Palumbi et al., 2009). Indeed, a majority of MPAs include biodiversity protection among their goals or anticipated benefits (Pomeroy et al., 2005). Biodiversity conservation goals stem both from a recognition of the existence and option values of species and a growing recognition that biodiversity—the degree of variation in living organisms, at the genetic, population, community, and ecosystem or landscape levels—contributes to the many important ecosystem processes that underlie marine ecosystem health and ecosystem service provision. Therefore, the global trend of declining biodiversity may lead to a similar decline in ecosystem services and human well-being—both in terms of immediate losses in ecosystem services and also in the loss of an ecosystem's capacity to adapt to environmental changes and sustain the provision of services into the future (Daily, 1997; MA, 2005; Tilman et al., 2006). For example, a study of local experiments, long-term time series, and global fisheries data by Worm et al. (2006) showed that declines in genetic and species diversity in marine systems were associated with decreases in not just the productivity of fisheries, but also in their stability and recovery across different temporal scales.

Most assessments of biodiversity effects on ecosystems have focused on species or genetic diversity and have generally reported positive relationships between biodiversity and ecosystem processes from a range of ecosystems including mudflats (Emmerson et al., 2001), sea grasses (Duffy, 2006), salt marshes (Griffin and Silliman, 2011), kelp forests (Byrnes et al., 2006), and rocky shores (O'Connor and Crowe, 2005). However, there is an increasing awareness that the nature of the relationship between species diversity and ecosystem processes is highly dependent on the link between species diversity and functional diversity (Micheli and Halpern, 2005). Functional diversity is the variation in functional characteristics represented by the diversity of living organisms, and it is these characteristics that determine the range of ecological roles and species interactions that are present, and thus mediate the relationship between biodiversity, ecosystem functioning, and service provision (Cadotte, 2011; Díaz and Cabido, 2001; Loreau, 1998; McGill et al., 2006). Specifically, biodiversity is expected to promote immediate and long-term ecosystem functioning through patterns of complementarity and redundancy in the functional characteristics it encompasses (Maestre et al., 2012; Walker et al., 1999). Therefore, the protection and restoration of functional diversity is increasingly highlighted as an important principle for management of both marine and terrestrial ecosystems (Chapin et al., 2010; Foley et al., 2010).

Two key reasons underlie the expectation that functional diversity promotes long-term ecosystem health and service provisioning. First, maintaining high levels of functional diversity in an ecosystem allows for the full range of species' ecological roles and interactions to persist and thus for maintenance of multiple ecosystem functions. Both empirical and modeling studies have found that as more ecosystem functions are considered, higher levels of biodiversity are required to sustain all functions simultaneously (Gamfeldt et al., 2008; Hector and Bagchi, 2007; Hensel and Silliman, 2013; Maestre et al., 2012; Zavaleta et al., 2010). Furthermore, in some cases functional diversity, rather than species diversity, may be more important in maintaining ecosystem multifunctionality, since it is the complementarity of species' functional contributions that allows for multiple ecosystem functions to persist (Mouillot et al., 2011). Because many ecosystem services valued by people depend on multiple ecosystem functions (Palumbi et al., 2009), and different ecosystem functions and services may trade off with each other (Bennett et al., 2009; Carpenter et al., 2009), the protection of biodiversity, particularly functional diversity, can serve as a tractable proxy for an ecosystem state that sustains a balance between a range of ecosystem functions, especially when the key drivers and interactions of those functions are not yet well known (Duffy, 2009; Palumbi et al., 2009).

Second, functional diversity may act as a form of insurance for ecosystem functions and services in the face of environmental fluctuations and global environmental change (Bernhardt and Leslie, 2013; Elmqvist et al., 2003; Naeem and Li, 1997). Specifically, functional diversity is expected to promote ecosystem resilience, defined as the ecosystem's capacity to absorb disturbance, reorganize, and maintain its functioning, structure, and feedbacks such that it does not undergo an undesirable phase shift involving the loss of key ecosystem services (Folke et al., 2004). Two aspects of functional diversity underlie this expected link resilience: functional redundancy and response diversity.

Functional redundancy occurs when multiple species contribute similarly to ecosystem functions, such that redundant species may be able to functionally compensate for the decline or loss of one or more species (Naeem and Li, 1997; Walker, 1992, 1995). Therefore, loss of species would not significantly impact the functioning of the ecosystem until the last member of a functionally redundant group is lost. However, the loss of that last member could lead to the complete loss of important ecosystem feedbacks and a complete transformation or shift of the ecosystem to an alternate state (Hughes, 1994). Because of high uncertainty and variability of species' ecological roles, the extent of redundancy, and the vulnerability of functions to environmental changes and human pressures, maintaining high levels of functional diversity and redundancy in natural communities should be a key management goal.

Quantifying and Protecting Functional Diversity and Redundancy in Marine Protected Areas

Quantifying Functional Diversity

Recent reviews of strategies for sustainable management of terrestrial and marine ecosystems have specifically highlighted functional diversity and redundancy as targets for protection or restoration (Chapin et al., 2010; Foley et al., 2010). In order to successfully manage and maintain functional diversity and redundancy in ecosystems, a first step is to develop practical ways to measure and monitor these attributes in the field.

Two approaches have generally been used to quantify functional diversity in ecological communities. The most common method is to assign species to discrete functional groups based on knowledge of species' resource use and life history strategies (Micheli and Halpern, 2005; Simberloff and Dayan, 1991), or by using a hierarchical clustering analysis on a set of measured species traits (Jaksić and Medel, 1990). Functional diversity can then be measured at the level of functional groups: functional-group richness is simply the number of functional groups, while functional-group diversity is usually assessed using the Shannon–Wiener index (H') and incorporates a measure of the relative abundance, or evenness, of the functional groups. Functional redundancy is assessed by calculating species richness or Shannon–Wiener diversity within each functional group. Functional group approaches have a long history in ecology and have provided many insights into species interactions and community structure (Dethier et al., 2003; Simberloff and Dayan, 1991; Steneck and Watling, 1982). However, this method suffers from several problems, arising from the use of discrete groupings to model functional differences that are generally continuous in nature. Most importantly, the threshold for considering functional differences as significant is an arbitrary one, and it is assumed that all pairwise differences between species from different groups are equal in magnitude (Mouchet et al., 2010; Petchey and Gaston, 2002). In some cases, these problems may compromise the usefulness of functional groups in assessing functional diversity–ecosystem functioning relationships (Wright et al., 2006). On the other hand, particularly in applications of a functional framework to diverse communities, a lack of detailed data on functional traits for all species makes categorical functional classifications, or the use of a mix of categorical and continuous trait values, the only possible approach (Micheli et al., 2014; Stuart-Smith et al., 2013).

To address some of the weaknesses identified in the functional group classification approach and increase the explanatory power of functional diversity for ecosystem function, various trait-based multivariate measures of functional diversity have been developed (Botta-Dukát, 2005; Laliberté and Legendre, 2010; Mason et al., 2005; Mouillot et al., 2013; Petchey and Gaston, 2002; Villéger et al., 2008; Walker et al., 1999). Many of these measures are calculated by first representing species within the community as points in a multivariate functional trait space, and then assessing various aspects of the distribution of species and their relative abundances within this space (Mouillot et al., 2013; Villéger et al., 2008). Unlike the functional group approach, these measures may account for various degrees of functional difference between species. They also allow for different, complementary measures of functional diversity to be assessed, such as the relative abundances of functionally redundant and functionally unique species in the community, or community-wide shifts in specific traits (Mouillot et al., 2008). However, the use of this approach has generally been limited to low-diversity assemblages or subsets of taxa within a community, such as higher taxa that have directly comparable morphological traits (e.g., terrestrial plants, insect families, and fish).

Compared with measures of species diversity, all methods of quantifying functional diversity and redundancy are more data-intensive; they require additional information about each species' functional characteristics in the form of either knowledge about species' basic ecologies or quantitatively measured trait values for each species. The latter is especially time-consuming to obtain and may not be tractable in some species-rich ecosystems such as coral reefs (Micheli et al., 2014). As a result, incorporating functional diversity into assessments of ecosystem health, MPA performance, or MPA design still presents a challenge and has not been widely implemented. Nevertheless, the few studies that have measured functional diversity in the context of MPAs have provided some useful insights into how effective MPAs have been in protecting different aspects of functional diversity.

Spatial Protection of Functional Diversity

Functional diversity has generally not been considered explicitly in the design and location of MPAs. In siting MPAs and MPA networks, areas of high taxonomic diversity (particularly species richness) have usually been targeted as a way to achieve the protection of biodiversity. Because empirical studies have demonstrated a generally positive relationship between species richness and functional richness, it is often assumed that species richness adequately proxies functional richness for the purposes of management (Foley et al., 2010).

However, the few studies that have examined spatial variation in marine functional diversity have reported spatial mismatches between MPAs and areas of high functional diversity. This incongruence corresponds to a mismatch between hotspots of taxonomic diversity and hotspots of functional diversity that occurs at multiple spatial scales. Regionally, Mouillot et al. (2011) found that existing networks of MPAs in the Mediterranean Sea were spatially congruent with fish species diversity, but failed to cover areas of high functional diversity. At a global scale, Stuart-Smith (2013) reported that areas of high reef fish functional diversity were concentrated in temperate latitudes, in contrast with well-known patterns of species richness that peak in the Tropics. They suggest that the tropical bias for MPA formation may result in failure to protect the functional aspects of biodiversity on a global scale.

Similar mismatches in functional diversity with species diversity and protection efforts have been reported in terrestrial systems (Devictor et al., 2010) and could reflect a more general need to integrate functional diversity into management. One such integrative framework has been developed to prioritize areas for conservation within a series of floodplain water bodies in France. Maire et al. (2013) assessed a combination of fish functional diversity, taxonomic diversity and the diversity of the species' natural heritage and social-economic importance and concluded that downstream areas with high lateral connectivity to the main river channel should be prioritized for protection. A similar integration of spatial patterns of marine functional diversity with other management goals could be useful in improving spatial protection of functional diversity.

Effects of Marine Protected Areas on Functional Diversity

While the limited evidence available suggests that current MPAs fail to provide adequate coverage of areas with high functional diversity, studies addressing the direct effects of MPAs on functional diversity, and in some cases redundancy, have generally found positive effects. Most direct assessments of MPA effects on functional diversity have used functional group approaches to compare functional richness and functional redundancy between MPAs and reference areas, but the emerging use of trait-based multivariate approaches has begun to provide some more detailed insights into the effects of reserves.

In the most spatially extensive assessment of MPA effects on functional diversity, Micheli and Halpern (2005) analyzed a global dataset of reef fishes from 31 different no-take reserve sites, including both temperate and tropical reefs. They reported that in comparison with reference sites, no-take reserves generally contained more functional groups (higher functional richness) and increased functional redundancy within some groups. Studies of individual MPA systems have reported similarly positive effects of MPAs on functional diversity. In the Bahamas, fish assemblages within a no-take marine reserve contained more functional groups and greater functional redundancy within each group, compared with nearby fished areas (Micheli et al., 2014). In the Mediterranean Sea, MPAs were also associated with higher functional diversity (Villamor and Becerro, 2012) and greater functional redundancy (Stelzenmüller et al., 2009).

Across most of the studied areas, greater functional diversity within MPAs was associated with higher species diversity (Micheli and Halpern, 2005; Micheli et al., 2014; Stelzenmüller et al., 2009). This pattern is often observed at least at low levels of species richness because functional richness is positively related to species richness, although the exact shape of the relationship can vary (Micheli and Halpern, 2005; Petchey and Gaston, 2002). However, opposing or uncorrelated effects of MPAs on species diversity may also be observed when different species increase and decline simultaneously, which is relatively common due to indirect effects of protection on species through competitive and predatory interactions (Micheli and Halpern, 2005). Several reserves from the Micheli and Halpern (2005) analysis were associated with positive effects on functional diversity but negative effects on species diversity, while the Spanish MPA system studied by Villamor and Becerro (2012) reported positive effects on functional diversity but no significant effect on species diversity. Collectively, these studies suggest that though species and functional diversity are generally correlated, functional diversity is more likely to respond positively to protection, and measuring species diversity alone may lead to failure to detect reserve effects on functional diversity.

Trait-based multivariate measures of functional diversity have not yet been widely used to assess the effects of protection measures in either aquatic or terrestrial ecosystems, potentially because they are a newer set of tools that also require a fairly large amount of information. In the context of management, they have generally been applied in assessing ecosystem responses to large-scale environmental and anthropogenic impacts, especially the anthropogenic modification of terrestrial and aquatic habitats (Barragán et al., 2011; Edwards et al., 2014; Helsen et al., 2013; Magnan et al., 2010; Mouchet et al., 2010; Pakeman, 2011). These trait-based approaches are expected to be particularly suitable for assessing shifts in ecological communities for two key reasons. First, trait-based measures of functional diversity are more likely to show predictable shifts with environmental change because each individual species' response to environmental drivers is ultimately determined by its functional traits (i.e., response traits). Second, these trait-based measures are based on species abundances rather than presences or absences, so they are more sensitive to changes in species assemblages, and could provide advance signals of disturbance in ecosystems ahead of the actual loss of species (Mouillot et al., 2013). Indeed, most of the studies that have applied these measures to assess ecosystem change have reported systematic losses in functional diversity and/or shifts in trait composition consistent with some degree of environmental filtering.

Because global climate change impacts essentially all marine ecosystems (Bernhardt and Leslie, 2013; Halpern et al., 2008), local-scale impacts (e.g., fishing) and management efforts (e.g., MPAs) inevitably co-occur with global-scale environmental changes such as warming and ocean acidification (Crain et al., 2008; Halpern et al., 2008). Therefore, trait-based measures of functional diversity may become increasingly useful for assessing the performance of MPAs in the context of environmental change. The potential value of this approach is illustrated by a recent study of fish functional diversity within a global warming hotspot. Bates et al. (2013) compared species richness and multivariate functional diversity measures between a Tasmanian marine reserve and nearby reference sites over 20 years. They found no significant differences in species richness or overall functional richness between the reserve and reference sites; functional richness increased in both over the study period. However, by comparing the functional trait composition of the fish assemblages, they found that the increase in functional richness within the reserve was partly driven by an increase in large-bodied, carnivorous species that are targeted by fisheries, whereas the increase in functional richness outside the reserve was driven by the colonization of species with warmer affinities. In fact, the degree of invasion of warm-water species was significantly less within the reserve, suggesting that fish communities within the MPA were more resilient to the effects of climate change. In this case, a trait-based multivariate approach was able to detect the interaction between an MPA and a large-scale climate driver, and identify the effect of the MPA on a key function: resilience to climate change. In contrast, a traditional species diversity or functional group classification approach failed to highlight this effect of protection on ecosystem function.

Trait-based functional diversity indices may also be able to provide more specific information about important reserve effects on functional diversity. For example, the integrity and functioning of ecosystems are disproportionately impacted by the contributions of functionally unique species (O'Gorman et al., 2011; Petchey et al., 2008) because functionally unique species, by definition, perform functions with low redundancy. Mouillot et al. (2008) developed and used a trait-based index, the Conservation of Biological Originality (CBO), to examine changes in the prevalence and abundance of functionally unique fish species before and after the establishment of a French MPA. They concluded that the MPA was successful in protecting the most functionally unique members of the fish community: these species were more widely distributed and more abundant after MPA establishment. Unique combinations of functional traits may be crucially important for maintaining ecosystem functioning, as demonstrated by studies of large parrotfishes in coral reefs of the Great Barrier Reef and Pacific Line Islands (Bellwood et al., 2003).

Results of the studies by Bates et al. and Mouillot et al. suggest that: (1) MPAs can have positive effects on maintaining the diversity of functional traits within communities; and (2) trait-based multivariate measures of functional diversity are a promising approach for assessing reserve effects on functional diversity. More MPA assessments using trait-based multivariate metrics will be needed to determine if these metrics generally provide better insights into ecosystem health and functioning than the less data-intensive traditional approaches based on taxonomic diversity and other community properties such as total abundance, size structure, or species composition, and if any additional information gained is worth allocating more resources for obtaining trait data.

KEY DIRECTIONS AND OPEN QUESTIONS

Our review highlights that empirical evidence for positive effects of MPAs on ecosystem service provision by coastal marine ecosystems is accumulating. However, gaps in knowledge clearly remain. Existing studies are still largely focused on a subset of services, namely provisioning services and to a lesser extent some regulating services. Studies on some regulating, supporting, and even nonmonetary provisioning services (e.g., subsistence fishing), as well as most cultural services (e.g., aesthetic and spiritual values), are still very scarce.

We argue that a possible productive way forward is to apply functional frameworks to assessing the broader effects of MPAs on services, through the links that exist between functional diversity, redundancy, and trait composition and service flows. Developing this research program will require efforts to (1) better link functional trait or functional group assignments to actual ecosystem functioning and service provision, (2) scale up analyses to whole assemblages, and (3) assess the drivers and consequences of temporal variability in functional diversity and trait composition. Such programs would allow better identification of how MPAs can protect existing and/or provide new ecosystem services, as well as identifying which ones are the drivers and correlates. An important point to identify is the extent toward MPA borders at which MPAs still have an effect. It would also enable the clearing out of those ecosystem benefits not affected by MPAs.

A key practical aspect, particularly if the main application aim is to inform management, is to enable and facilitate the acquisition of the additional data needed for functional analyses. Acquisition of morphological and behavioral data through direct collaboration between scientists, MPA managers, and fishers, and through the development of cost-effective monitoring—e.g., through low-cost video systems, publicly available databases, and involvement of diverse users (e.g., through citizen science projects)—are promising avenues for allowing the broader application and testing of functional frameworks to MPA assessments.

To successfully develop scientific frameworks and datasets needed to address the links between MPAs, ecosystem functioning, and ecosystem services, closer collaboration is needed between natural and social scientists on the one hand, and among academics, MPA managers, and users on the other.

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Annexe 2

Reef and lagoon fisheries yields in Moorea: A summary of data collected

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Introduction

Due to their diversity of animal and plant species, coral reefs are among of the most productive and complex marine ecosystems in the world (Birkeland 1997; Grigg et al. 1984; Letourneur and Chabanet 1994). Covering a surface area of 255,000 km^2 (Spalding and Grenfell 1997), coral reefs support the development of local and national economies and provide a large number of goods and services to island communities through fisheries and tourism (Moberg and Folke 1999).

Exploiting reef ecosystems and their resources, including fisheries, is of major importance to many Pacific Island countries and peoples, especially those in the South Pacific (Ferraris and Cayré 2003; Kronen 2007). These largely small-scale fisheries call on a variety of fishing strategies (e.g. commercial fishing, recreational fishing, subsistence fishing). These multi-species and multi-gear fisheries and their widely scattered landing sites, do not facilitate the task of collecting reliable data to quantify such activities (Ferraris and Cayré 2003). Total artisanal fishery production[4] in the South Pacific has been estimated at 100,000 t, with significant disparities between islands. In addition, some 80% of these landings come from subsistence fisheries activities (Dalzell et al. 1996). The absence of any large single-species stock, the difficulty that fishing vessels have in gaining access to coral reefs, and the possibility of ciguatera on certain islands explain why reef fisheries are mainly artisanal or traditional.

Given that fishing activities in French Polynesia are widely dispersed, it is extremely difficult to get accurate catch figures. Current statistical data are not reliable because these figures cover inter-island air transport but do not include subsistence and recreational fisheries. While only limited statistics exist on lagoon products, French Polynesia's total production can be estimated at about 4,300 t annually (SPE 2006). Production is thought to be distributed as follows: 3,400 t of lagoon fish, 700 t of small pelagic fish, and 200 t of other types of catch (e.g. molluscs, crustaceans, echinoderms).

Artisanal fisheries are an integral part of the French Polynesian lifestyle. They are roughly divided into three categories: oceanic fisheries, coastal fisheries and lagoon fisheries. Lagoon and/or reef fisheries, which are the focus of this article, can be described as "all the activities that are involved in exploiting biological resources and are carried out on the fringing and barrier reefs, channels, passes and *hoa* (or lagoon in the widest sense) and on the first few metres of the outer slope (depths <80 to 100 m) to the very limits of coral growth" (Galzin et al. 1989; SPE 2006).

Fishing activities on Moorea are important socio-economically because they provide income from fish sales as well as food security[5] (home consumption) (Aubanel 1993). Moorea has experienced very high population growth over the past 36 years. Population census figures for Moorea went from 5,058 to 16,490 between 1971 and 2007 (ISPF 2007) — an annual population growth rate of 2.39%, which is higher than the rate for French Polynesia as a whole (1.57%). In addition, elsewhere in the Pacific Islands, fishing pressure is directly linked to the number of inhabitants (Jennings and Kaiser 1998; Russ and Alcala 1989). Given these demographics and growing urbanisation, it is vital to get a precise picture of Moorea's fisheries activities. A large number of studies since 1985 have attempted to assess fish production[6] (Galzin 1985) or reef and lagoon fisheries yields[7] (Aubanel 1993; Brenier 2009; Vieux 2002; Yonger 2002) on Moorea. As in other coral island settings, quantifying lagoon fisheries here has proven to be a particularly difficult exercise for many reasons. Fishing is often done at night (with or without a boat), is widely dispersed, uses many different types of gear, and landings and sales do not take place at specific sites but rather anywhere along the coast and often even on private stretches of coastline on family properties (Fig. 1).

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[4] Total catches by a fishery over a year (given in tonnes).
[5] Part of the fishery catches are destined for home consumption within the family.
[6] Fish biomass (in tonnes).
[7] Reef and lagoon fisheries yield corresponds to the fishery production of all lagoon fishing activities, which is expressed in the form of yield (i.e. catches in tonnes per surface area unit, or km^2, over a period of time, generally one year). It is also called fisheries performance.

Figure 1. Lagoon fish sold along the roadside on Moorea (Images: R. Madi Moussa).

Research methodologies used between the times of Galzin (1985) and Brenier (2009) have also evolved considerably. Over the space of 25 years, five different studies attempted to evaluate Moorea's lagoon fishery production (in the form of yield), and only two studies (Aubanel 1993 and Vieux 2002) used the same methodology. Fishery production estimates for Moorea's lagoon vary widely from one study to the next — even more so depending on the methodology used. The goal of this study is to review studies conducted over the past 25 years that describe lagoon fishing activities in Moorea. Special attention is paid to examining the limits of the various estimation methods used in each study so as to decide which lagoon fishery production estimate seems to be the most realistic.

Materials and methods: Characterising lagoon fisheries activities on Moorea and reviewing the various methods used for estimating fishery production

Study site

Moorea lies 25 km northwest of Tahiti (17°30' S, 149°50' W). Triangular in shape, the island covers a surface area of 134 km^2, with a maximum elevation of 1,207 m (Mount Tohivea), and has a 61-km-long coastline (Fig. 2).

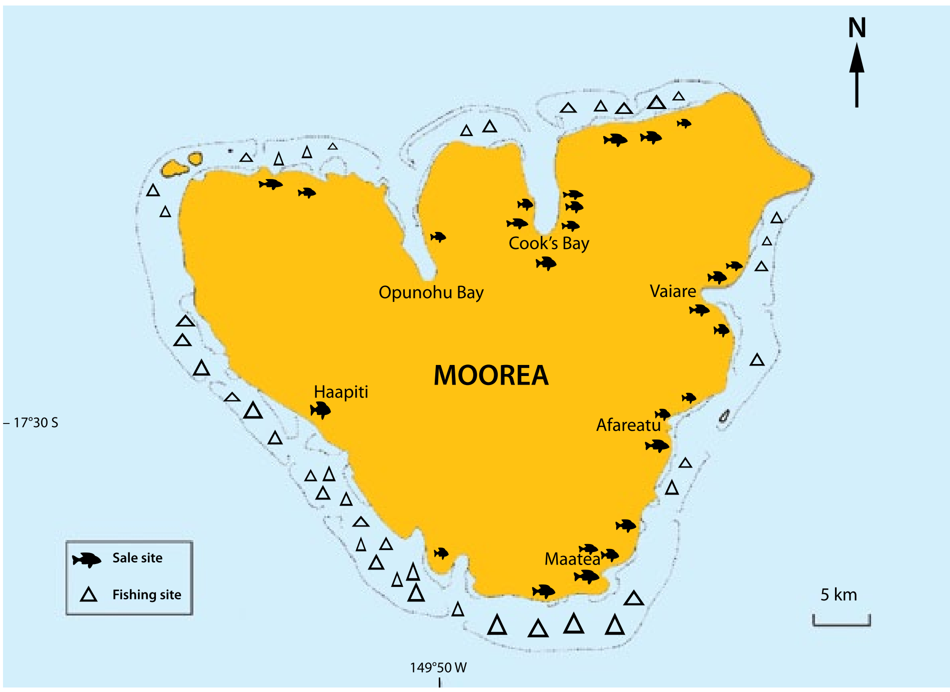

Figure 2. Moorea's fishing and landing sites.

The island is surrounded by a barrier reef that encloses a 49 km^2 lagoon, whose width varies from 500 m to 1,500 m, with depths of 0.5–30 m. The barrier reef has 11 passes that vary in depth (Galzin 1985). The entire coral ecosystem remains submerged at low tide and the tidal range is only about 40 cm. Moorea has a moist tropical climate with two distinct seasons — a hot rainy season from November to April and a cool, less rainy season from May to October. Moorea has a marine area management plan (PGEM), the first in French Polynesia, which applies to the township of Moorea by Order no. 410/CM dated 21 October 2004. The PGEM has four objectives: 1) rational use and development of resources and the area; 2) managing conflicts regarding lagoon use; 3) controlling pollution and damage to marine environments; and 4) protecting marine ecosystems and endangered species.

Moorea's lagoon fisher population

According to Yonger (2002), Brenier (2009) and Leenhardt (2009), there are three categories of fishers on Moorea: commercial fisher, subsistence fisher and recreational fisher (Table 1).

In all, 23.2% of Moorea's population is involved in fishing: 16% for recreational purposes, 4.6% for supplementary income (subsistence) and 2.6% are commercial fishers (Brenier 2009; Leenhardt 2009; Yonger 2002). While commercial and subsistence fishers are all Moorea residents, a certain number of recreational fishers come from the nearby Society Islands, mainly Tahiti (Leenhardt 2009). It should be noted that more than 70% of the people who fish on Moorea are recreational fishers. None of the catches from this category of fisher appear in the fisheries data collected at landings or at sales sites. Moreover, according to Yonger (2002), subsistence fishing may account for 58% of the catches in the lagoon. Also, a percentage of those catches are never recorded because they are directly destined for home consumption.

Lagoon fisheries techniques

The extremely wide diversity of lagoon catches explains why there are so many fishing techniques, each adapted to very specific organisms. Given the many different techniques, fishers often use a multidisciplinary approach, using several techniques depending on their preferences and resources, season, weather conditions, target species, and time of day. The main gear types used in the lagoon are spearguns, nets (gillnets or nets with pot traps), lines (handlines, hook-and-line, trolling, bottom longlines), harpoons, beach seines, cast nets or scoop nets (Leenhardt 2009; Yonger 2002). Fish traps, which are widely used in the Tuamotu and Leeward Islands, and account for 90% of catches in those areas (Galzin et al. 1989), are not used in Moorea's lagoon.

a. Net fishing

Net fishing is commonly used on Moorea and takes a wide variety of forms: gillnet fishing; beach seine net fishing (used seasonally on bay floors to catch *ature*, or *Selar crumenophthalmus)*; funnel net fishing (*haapua*), which includes a wire net that targets parrotfish, trevallies, surgeonfish and goatfish; cast nets and scoop nets, which are used to catch flyingfish.

b. Speargun fishing

This technique is widely used on Moorea, both during the day and at night with a powerful electric torch. When this type of fishing is done at night, it is very effective, providing high yields per fishing trip. This technique accounts for about 29% of lagoon fish production in the Windward Islands as compared with 18% in the Leeward Islands (SPE 2006). This type of fishing is very selective but can lead to local overexploitation of stocks because so many species (80%) are non-migratory and tend to be confined to a specific habitat (Lecaillon et al. 2000).

c. Line fishing

Line fishing is done directly from the coastline or from vessels powered by oars or 2–25 hp outboard motors. The different techniques include trolling, bottom longlining, fishing with artificial lures, using lines with one or more hooks, and fishing with natural and live bait.

d. Pot and trap fishing

This technique mainly targets fish but also crabs and other crustaceans.

Table 1. Classification and characteristics of fishers on Moorea.

Commercial fisher	Subsistence fisher	Recreational fisher
Two to five fishing trips per week	One to three trips per week	One to four trips per month
Sells catch	Some of the catch is sold and some is kept for home consumption	Catch is for home consumption
Fishing is the main source of income for the year	Fishing is a supplementary form of income	Fishing is primarily a recreational activity

An overexploited lagoon?

Results of perception surveys by Brenier in 2009 clearly indicate that Moorea has experienced a decline in the abundance and size of food fish species, increased scarcity of giant clams, decreased live coral cover, and increased macroalgae cover. By extrapolating these data, he also estimated the fisher population at 77 fishers km^{-2}, with 1,916 ± 530 motor boats and 481 ± 68 fishing trips km^{-2} each month. The latter figures show the intensity of fishing pressure on Moorea's coral ecosystems and are potential indicators of overexploitation. Fishing pressure can be considered high with 5 fishers km^{-2} (McClanahan et al. 2002).[8] These observations by the local population are potential signals of the overexploitation of lagoon resources.

In addition, in 2005, using underwater surveys Lison de Loma noted a decrease in the size of herbivores. In 2008, several photo identification campaigns involving lagoon fish catches sold along the roadside clearly confirmed a decrease in the size of all marketable fish (Madi Moussa 2010). In addition, most catches are taken with spearguns, a type of gear that is very selective. It would be reasonable to think that each fisher tries to maximise the sizes of catches so as to optimise profits. So the size ranges of the marketable species sold on the roadside represent the maximum size values for fish that can be caught by spearfishing. They are, therefore, good indicators of the maximum fish sizes found in the lagoon. Also, while over the past decade, most fishers say that they are still catching as many fish, they all agree that their fishing effort has increased (Leenhardt 2009). All of these perception indicators and field data tend to confirm the idea that Moorea's lagoon is overexploited.

Women gillnet fishing in Moorea's lagoon
(Image: R. Madi Moussa).

Estimation methodologies

The maximum sustainable yield[9] (MSY) calculations that Galzin (1985) used were based on fish production data obtained by monitoring the three main species in Moorea's lagoon — the herbivorous fish *Ctenochaetus striatus*, the omnivorous fish *Stegastes nigricans* and the carnivorous fish *Sargocentron microstoma* — and extrapolated to total biomass along with the reef and lagoon fisheries production estimate that Munro made in 1984. Even though this MSY figure is more than 25 years old, it is worth using it because it is the only estimate done on Moorea. It served as a comparison for the orders of magnitude of fishery production estimates from the many studies that followed, and allowed comparisons between regions (Labrosse et al. 2000).

In order to assess lagoon fisheries yields, several estimating methods were used on Moorea, including such indicators as catches, tax on fish sold at the Paopao market, counting the number of fish sold on the roadside, and even house consumption data for the island. The results differed from one method to the next, often with very high ranges. However, the data from these methods provided information on fishers' catches and helped discern fishing pressure.

[8] It should be pointed out that the fishers listed were not all commercial fishers, who account for only 1% of the population, as the others were semi-commercial (6% of Moorea's population) and recreational fishers (17% of Moorea's population) (Brenier 2009).

[9] Maximum sustainable yield (MSY) is the largest quantity of biomass that can be removed from a fishery stock on average over the long-term under existing environmental conditions without affecting the reproduction process.

a. Estimating biomass and MSY

In 1985, Galzin studied the population dynamics (biology, biometry, stock, biomass, growth, production) of the three species and the different trophic levels in order to assess fish production in a reef and lagoon sector in northwest Moorea. These three species account for 74% of the total fish biomass of the fringing reef at the edge of the channel. The total biomass and the biomass for those three species were estimated at 103.4 g m^{-2} and 74.2 g m^{-2} year^{-1}. Those figures made it possible to calculate MSY (Y_{MAX}).

$Y_{MAX} = X(Y + MB)$

Y_{MAX} = maximum sustainable yield (MSY)

X	=	correction factor = 0.3	(Galzin 1985)
Y	=	annual fisheries yield = 10 t km^{-2}	(Munro 1985)[10]
M	=	natural mortality	
B	=	mean biomass	
F	=	fisheries-related mortality = Y/B	(Munro 1985)
Z	=	total mortality = $M + F = P/B$	(Munro 1985)
P	=	biological production	

$Z = P/B = 74.2 / 103.4 = 0.72$

$F = Y/B = 10/103.4 = 0.09$

$M = Z - F = 0.72 - 0.09 = 0.63$

$Y_{MAX} = 0.3\,(10 + (0.63 \times 103.4)) = 23$

$$\mathbf{Y_{MAX} = 23\ t\ km^{-2}\ year^{-1}}$$

b. Galzin's initial approach in 1985: the PaoPao market tax

Built in 1987, the Paopao market was the single official point of sales where, theoretically, all fishers from the north side of the island had to sell their fish, following an order that no longer authorised the sale of fish from along the roadside[11] (Aubanel 1993). According to observations and studies by Galzin et al. in 1989, total catches were roughly estimated at 7 t during November. This estimate was based on the fact that the township levied a tax of XPF 10 per kilo sold. Based on total catches for November, excluding pelagic fish, a figure for tonnage per production year was obtained.

c. Survey of roadside fish sales

In 1993 Aubanel, estimated Moorea's fishery production by inventorying *tui*[12] (Fig. 1) sold along the roadside and at the Paopao market. The weight was estimated by extrapolating the number of *tui* sold each year and multiplying the number of *tui* by 3 kg (the average weight of a *tui*). In 2002, Vieux repeated the same protocol to characterise lagoon fisheries and measure quantitative changes in this activity.

d. Consumption survey

In 2002, Yonger proposed a study based on a household lagoon-fish consumption survey to assess fishery production. An analysis of seafood consumption can be a good alternative for indirectly assessing fishery production (Gilbert 2006; Labrosse and Letourneur 1998; Labrosse et al. 2000; Loubens 1975; Paddon 1997). To be valid, this method requires that the case study be a well-defined system with low quantities of imported or exported reef and lagoon fish. On Moorea, it can be seen that catch exports are limited to recreational fishers who come over from Tahiti on the weekends. Fish imports are also relatively low and correspond to the sales of some pelagic fish (*ature*) from Tahiti or coolers sent from the Tuamotu Islands (Leenhardt 2009). In general, Moorea can be considered to be a virtually closed system because lagoon fish imports and exports have been deemed negligible (Brenier 2009). In all, 136 households were sampled (i.e. 4.9% of Moorea's household population).

As a comparison, a survey had just been carried on a village on Moorea. In 2006 Kronen conducted a socioeconomic survey in the township of Maatea in southern Moorea for the PROCFish project[13]. Of the 235 households in the township, 28 households (12%) with 112 people were surveyed and interviewed. This sample provided socioeconomic data on 25 fishers in the township (i.e. nearly 8.5% of the total presumed number of fishers in the township). Kronen precisely described the fisher population, particularly its composition (i.e. 18% commercial fishers, 11% subsistence fishers and 71% recreational fishers).

[10] Munro (1985) gave a figure of 15 t km^{-2} year^{-1} for all fish, crustaceans and molluscs, and Russ and Alcala (1989) gave yields of 0.4 to 40 t km^{-2} year^{-1} for fish in small areas of active coral growth (Yonger 2002).

[11] Since 1989, because the order is no longer applied several sales sites have reappeared around the island.

[12] A wreath of fish consisting of one or more species, tied together with plant fibre drawn through their gills and then suspended on a metal holder, which forms the sales unit.

[13] The Pacific Regional Oceanic and Coastal Fisheries (PROCFish) project was funded by the European Development Fund (EDF) and implemented by the Secretariat of the Pacific Community (SPC). The project was initiated in March 2002. The coastal component of PROCFish was designed to enhance management of reef fisheries in the Pacific Islands by providing Pacific Island governments and communities with accurate, unbiased scientific information about the status and prospects of reef fisheries. Seventeen countries and territories were targetted by the project.

e. Participatory method

Brenier carried out the most recent survey designed to estimate (indirectly) the fishery production of Moorea lagoon in 2009. It was based on participatory monitoring of reef fisheries through household surveys that were designed to collect data on consumption and fishing activity from large sample groups. Fishery production was estimated using surveys by schoolchildren, which provided detailed information on the fishing trips of one fisher in the household over a two-week period.

There were three or four parts to the questionnaire distributed to schoolchildren. The first part was designed to gather general information on the household's fishing activities and fish consumption (e.g. address and size of household, how often fish was eaten, origin of the fish eaten, number of boats, number of fishers). The second part included questions on the number of fishing trips of one fisher in the household over a two-week period (so as to cover one spring tide period and one neap tide period) along with the names, sizes and number of fish eaten at meals over the previous three days. These surveys involved 137 participants (i.e. 4.4% of household population), and the questionnaire return rate was 68%. The schoolchildren received training in how to carry out the survey in their homes using one questionnaire each.

Results: Overview of various fishery production estimates for Moorea

Reef and lagoon fisheries yield estimates for Moorea vary greatly from one estimation methodology to another (Table 2), and there is considerable differences in their approaches. Yield estimates based on catch data give us relatively low figures for the island's fisheries yields (from 0.7–2.2 t km^{-2} $year^{-1}$). On the other hand, data from consumption surveys or participatory surveys estimate fishing yields at between 20 t km^{-2} $year^{-1}$ and 25 t km^{-2} $year^{-1}$.

Discussion

The significant differences noted between catch monitoring methods and those for socioeconomic surveys incite us to discuss the various limitations of each study so as to give our views on which lagoon fishery production estimate seems to be the most realistic.

Monitoring catches, landings and sales

An analysis of the methods used by Galzin, Aubanel and Vieux indicate that fishery production was underestimated, mainly because catches from recreational fishing and the quantities commercial and subsistence fishers ate themselves were not counted. In general, these studies demonstrated the difficulty in monitoring fishing activities in peri-urban island settings. The increase in population, the emergence of new markets (e.g. direct sales based on advance orders), and the discontinued use of the Paopao central market make it increasing difficult to monitor fish landings and estimate fishing production using the catch observation method. In fact, the dispersed nature of landings and the importance of lagoon fishing from a socioeconomic point of view do not facilitate the task of quantifying fish catches. On the other hand, monitoring roadside sales can be an excellent way of discerning fishing pressure by noting the sizes of the fish sold (Madi Moussa 2010). The assessment of fishery production that resulted from monitoring the municipal tax (Galzin et al. 1989) was an underestimate because it only took into account the percentage of fish that were sold, whereas, according to Vieux (2002), such catches only account for 40% of the overall quantity caught in the lagoon. In the same way, Aubanel (1993) and Vieux's (2002) studies — two observations a decade apart that used the same methodology — gave yields that were once again underestimated. However, the three studies gave similar yield figures, which is normal because the sample concerned fishers who sold their catches on the roadside and did not take into account home consumption. The entire coastline of Moorea is a potential landing

Table 2. Yield estimates per surface area unit by type of survey.

Yield (t km^{-2} $year^{-1}$)	Type of data	Source
24.5	Participatory surveys carried out by schoolchildren on Moorea	Brenier 2007
28.14*	Socioeconomic surveys in the village of Maatea on Moorea	PROCFish 2006
22.9	Direct consumption surveys	Yonger 2002
1.01 to 2.2	Quantities sold on the roadside	Vieux 2002
0.7 to 1.4	Quantities sold on the roadside	Aubanel 1993
1.2 to 1.4	Extrapolation of fishing data	Galzin et al. 1989

* Reef fishery yield for the township of Maatea only.

area for fishers so it is very difficult, if not impossible, to monitor catches that do not go through conventional sales channels. In addition, this technique ignores recreational fishing catches, which are not counted despite their high levels (Brenier 2009).

Consumption surveys and bias

When you look at the average annual, per capita consumption of fish, French Polynesia is considered to be one of the countries with the highest levels of consumption (Kronen et al. 2006). On Moorea, annual consumption is nearly 110 kg per inhabitant (Yonger 2002), whereas the mean annual per capita figures for the Pacific Islands region are between 4.8 kg and 40 kg, with an average of 23 kg (Labrosse et al. 2006). Even if it is difficult to compare the results of consumption surveys carried out under different circumstances and using different methodologies, the gap between the estimates in French Polynesia and the maximum values for other Pacific Islands countries is intriguing and encourages consideration of possible biases of these methodologies and the context of each survey.

In regards to survey methodology, it can be seen that of the four variables used to collect data during a consumption survey — fish family, origin of fish eaten, quantity eaten at each meal, and weekly frequency of meals — only "weekly frequency of meals" appears to be slightly overestimated (Gilbert 2006). This slight overestimate may be due to a poor interpretation of the term "meal". It may be that eating leftovers was reported as a meal, thereby artificially raising the number of meals .

In terms of the context, the "one-off" nature of the surveys was a source of bias for the average annual estimates made. In fact, annual figures were extrapolated from average weekly estimates. This relationship was based on a presumption that eating habits and fishery production remain stable over time (Gilbert 2006). In the same way, quantities eaten were assessed based on the number of fish eaten by species, their sizes or, more rarely (for oceanic species), their weights. Fish sizes were generally estimated with gauges and size and weight conversions used biometric ratios. Size and weight ratios were not always calculated in a precise manner. In fact, when no species ratio existed, the studies used ratios for similar species (Gilbert 2006). So, the information collected from households was more qualitative than quantitative because it was based on perceptions. It called on the short-term memory of the person interviewed and his or her ability to convert an image or a memory into a physical size (Gilbert 2006).

However, indirect studies based on household seafood consumption surveys do offer a good alternative for studying fishery production in these settings. Among other things, they take into account the catches of all types of fishers, including recreational fishers. They have also been subjected to a larger number of studies over the past few years (Kuster et al. 2006; Lagadec 2003; Léopold et al. 2004; Yonger 2002). Léopold et al.

In Moorea, Brenier trained schoolchildren in how to carry out household fish consumption surveys in their homes. Average per capita consumption of lagoon fish calculated from data collected by these schoolchildren was almost the same as that calculated from data collected by scientists in previous household surveys (Image: A. Brenier).

(2004) calculated the prediction error for production based on consumption surveys to be 4.5%. Kuster et al. (2006) showed that catch estimates, fishing effort and fish consumption data (using household surveys) were coherent and did not differ statistically from those resulting from direct surveys. As with participatory surveys, there were no differences between average per capita consumption of lagoon fish calculated from the data collected by schoolchildren or from data collected by scientists (Brenier 2009). Other studies where schoolchildren were involved in the collection of scientific data have shown that they can produce reliable data (Au et al. 2000; Delaney et al. 2008; Nicholson et al. 2002).

Which fishery production estimate is the most reliable?

Based on the obvious signs of overexploitation noted in Moorea's lagoon and the MSY figure of 23 t km^{-2} $year^{-1}$ calculated by Gazin in 1987, it is reasonable to think that Moorea's current reef and lagoon fisheries yield is higher than that figure, and is probably closer to 25 t km^{-2} $year^{-1}$. This would tend to confirm that indirect estimate studies based on consumption and perception surveys are the most relevant for estimating fishery production and yields in Moorea's lagoon.

Conclusion

Fishery activities in Moorea's lagoon are quite difficult to monitor and assess because they vary greatly and are quite dispersed. Several categories of fishers (commercial, subsistence and recreational) use a wide range of fishing techniques for sales, exchange, and home consumption purposes. Over a period of 25 years, several studies have tried to assess fishery production in Moorea's lagoon, with each study using a specific methodology. There is a wide gap in the estimates of fishery production when using catch monitoring methods (0.7–2.2 t km^{-2} $year^{-1}$) and when using consumption or participatory socioeconomic consumer surveys (22.9–24.5 t km^{-2} $year^{-1}$). Taking into account the bias found in each estimating method, it seems that methods involving socioeconomic surveys give the most realistic fishery production estimates. In fact, those methods are better at taking into account catches by all fishers in contrast to catch monitoring methods that only consider catches that are sold but not those from recreational fishing. Finally, signs of overexploitation in this lagoon have lead us to think that current fishery production is probably higher than the MSY of 23 t km^{-2} $year^{-1}$ calculated by Galzin, and this would confirm that Moorea's current reef and lagoon fisheries yield is likely closer to the values estimated by socioeconomic surveys, about 25 t km^{-2} $year^{-1}$.

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Résumé

L'approche socio-écologique appliquée à la gestion côtière : concepts et application

Pierre LEENHARDT

Résumé

Les zones côtières à travers le monde sont soumises à de fortes pressions dues aux changements climatiques globaux, à la destruction d'habitats ou encore à la surexploitation des ressources marines. Ces différentes pressions peuvent induire des changements rapides d'état des écosystèmes caractérisés par de fortes modifications de la biodiversité, avec des écosystèmes entiers cessant de fonctionner dans leur forme courante. En conséquence, la pérennité des biens et des services écosystémiques produits par les zones côtières n'est plus assurée. Il en résulte des perturbations économiques et sociales évidentes pour les populations dont le mode de vie dépend de manière directe ou indirecte de la biodiversité côtière. Afin d'appréhender ces interactions homme-environnement, l'approche socio-écologique est de plus en plus utilisée pour illustrer le rôle de l'Homme sur la dynamique des écosystèmes marins côtiers ainsi que les bénéfices qu'il tire de ces derniers. Cependant, la majorité des recherches actuelles reste théorique et peu de cas d'étude appliqués à la gestion des zones côtières mettent à l'épreuve ce concept dans une démarche transdisciplinaire. Cette thèse a donc pour objectif principal de combler ce manque en explorant les concepts de l'approche socio-écologique appliquée à la gestion côtière. Ainsi, dans le premier chapitre de cette thèse nous résumons les spécificités, les défis et les enjeux de l'approche socio-écologique appliquée à la gestion côtière. Les chapitres 2, 3 et 4 s'intéressent à l'analyse du système socio-écologique du lagon de Moorea en Polynésie française. Le chapitre 2 est consacré à un état de l'art des études s'intéressant à la pêcherie récifo-lagonaire de cette île

permettant de faire émerger la complexité du système socio-écologique étudié. Le chapitre 3 propose ensuite d'explorer les dynamiques socio-écologiques de ce système à l'aide d'un processus de modélisation participative et de l'analyse de données empiriques. Enfin le dernier chapitre (4) nous permet d'identifier, à l'aide d'une modélisation par réseaux bayésiens, des scénarios exploratoires d'évolution des principaux services écosystémiques du lagon de Moorea en fonction de différents forçages naturels et anthropiques. Enfin, nous discutons des avantages et des faiblesses de notre approche ainsi que des potentiels d'applicabilité en tant qu'outil de gestion des zones côtières.

Mots-clés : système socio-écologique, ressources naturelles marines, service écosystémique, transdisciplinaire, modélisation, connaissance experte, système récifo-lagonaire, gestion.

Application of the social ecological approach to coastal management: concepts and application

Abstract

Coastal areas around the world are under intense pressures from climate change, habitat destruction, and over-exploitation of marine resources. These different pressures can induce rapid changes in the state of ecosystems characterized by strong changes in biodiversity, with whole ecosystems ceasing to function in their current form. As a result, the sustainability of goods and services produced by coastal areas is no longer assured. This results in economic and social disruptions for populations whose livelihood depends directly or indirectly on coastal biodiversity. In order to understand these linked social and environmental interactions, the socio-ecological approach is increasingly used to illustrate the role of humans in the dynamics of coastal marine ecosystems and the benefits it derives from them. However, the majority of current research remains theoretical and few case studies applied to the management of coastal areas test this concept in a transdisciplinary approach. The main objective of this thesis is to fill this gap by exploring the concepts of the socio-ecological approach applied to coastal management. Thus, in the first chapter of this thesis, we summarize the challenges insights and perspectives of the socio-ecological approach applied to coastal management. Chapters 2, 3 and 4 focus on the analysis of the coral reef resource system of Moorea island in French Polynesia. Chapter 2 is devoted to a state-of-the-art study of the coral reef fisheries of this island, revealing the complexity of this social ecological system. Chapter 3 then proposes to explore the social ecological dynamics of this system through a participatory modeling approach and the analysis of empirical data. Finally, in the last chapter (4) we developed spatially explicit Bayesian belief network models to explore the social-ecological trade-offs revealed by a set of multiple driver's scenarios in the coral reef resource system in order to explore the potential evolution of the main ecosystem services of the Moorea lagoon. Finally, we discuss the advantages and weaknesses of our approach as well as potential applicability as a tool for coastal zone management.

Keywords: social-ecological system, marine natural resources, ecosystem service, transdisciplinary, modelling, expert knowledge, coral reef system, management.