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# Space and time matter in social-ecological vulnerability assessments

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ABSTRACT

Fostering sustainable local social–ecological interactions playing out against a backdrop of larger-scale dynamics are ubiquitous challenges to natural resource management and biodiversity conservation. Social-ecological vulnerability assessments are highly relevant for place-based management and can help target and prioritize management actions. However, an understanding of how linked social-ecological vulnerabilities respond to external drivers is still lacking. This paper presents an approach that integrates the spatial and temporal dimensions into social-ecological vulnerability assessments, where social and ecological vulnerabilities are linked by a feedback loop. The approach is applied to the Moorea coral reef social-ecological system, which has been significantly influenced by major environmental and social drivers over the last decade. Temporal changes in linked social-ecological vulnerabilities are mapped *before* and *after* exposure to the multiple drivers. Nearly 23% of households and 13% of the reef area show low and decreasing vulnerability despite exposure. However, high and increasing levels of vulnerability were detected in 6% of households and associated reefs after exposure to the drivers, providing early warnings of potentially unsustainable situations. Importantly, changes in ecological vulnerability did not propagate linearly to changes in social vulnerability. Similarly, hot spots of social vulnerability were not necessarily associated with hot spots of ecological vulnerability, highlighting the need to specifically adapt management interventions to local social-ecological settings. Mapping social-ecological dependencies in space and time provides communities and decision-makers with the information required to identify and prioritize management interventions while accounting for the effects of large-scale or external drivers.

## 1. Introduction

Natural resource management and conservation aim to influence the way people interact with their environment to achieve a range of objectives related to the condition of an ecosystem or a subset of its components (species, habitats, functioning), often while increasing or maintaining human well-being. Reaching such objectives involves navigating complex social-ecological systems by accounting for human-nature interactions and inter-dependencies, and the influence on these of external drivers [1,2]. Drivers can be social (e.g., shifting socio-economic settings, governance and tenure) or biophysical (e.g., extreme climatic events or spatiotemporal shifts in species distributions) [2–4]. Understanding how internal social-ecological linkages play out against external drivers is critical to effectively inform decision-making. Yet, too often, conservation strategies and management decisions are based on overly simplistic, fully internalized or overly vague representations of social-ecological systems [5].

The concept of vulnerability –which is a function of the sensitivity and adaptive capacity of a system to exposure (or risk of exposure) to a stressor – has emerged as a valuable approach to inform structured decision making in climate change policies [6]. Its application has provided the foundation for characterizing interactions between

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internal system processes (e.g., resource use, ecological resilience, etc.), and indirect drivers (e.g., demography, climate change) [7]. The vulnerability framework has also been instrumental in designing mitigation interventions (focusing on exposure) or adaptation strategies (focusing on sensitivity and adaptive capacity) [8,9]. The utility of the vulnerability concept has prompted recommendations that it be used in a nested model to capture key features of the dynamics of linked social-ecological systems [6,10], but there remains the need to develop a "social-ecological vulnerability framework" for application at local scales.

In order to capture complex realities and effectively guide place-based management, the development of an applicable social-ecological vulnerability framework faces several challenges [11–13] that can be summarized as follows. First, although human-nature interdependencies are widely acknowledged, their quantitative integration remains elusive. Second, vulnerability can be heterogeneous across landscapes and segments of communities and societies [14]. Third, external drivers that shape vulnerability operate at different spatial and temporal scales [1,2], making it difficult to represent vulnerability with a single snapshot. Fourth, similar magnitudes of vulnerability (or changes in vulnerability) can be caused by different drivers [4], so that assessments of vulnerability can obscure underlying mechanisms and limit the appropriateness or effectiveness of interventions aiming to reduce vulnerability.

In an attempt to address those four challenges, this paper presents an approach that captures temporal dynamics and spatial heterogeneity of linked social-ecological vulnerability. This approach is applied in the context of the small-scale coral reef fishery of Moorea, French Polynesia, by mapping spatial patterns of linked social and ecological vulnerabilities and tracking temporal changes in response to multiple socioeconomic, institutional and biophysical drivers. The resulting framework enables decision makers to develop a dynamic representation of social-ecological vulnerability, laying the foundations for deriving insights about interactions between local and large-scale drivers that can ultimately help identify and prioritize management interventions for reducing vulnerability of an ecosystem and the people who depend upon it.

## 2. Material and methods

### 2.1. Study site

This study examines the response of local social-ecological interactions and interdependencies to direct and indirect external drivers of change using the coral reef fishery of Moorea, French Polynesia, as a case study. Fishing is the main form of natural resource use in Moorea. Key features include (i) the use of different gear types (mainly speargun, net and line); (ii) a wide range of target species (mostly soldierfishes, parrotfishes and surgonfishes); (iii) multiple overlapping motivations for fishing (e.g., for food, recreation and income); (iv) an absence of market and conventional sale channels (i.e., catches mostly destined for self-consumption or shared among family or other community members); and (v) temporal variability in catch that varies a several scales [15]. Social-ecological interdependencies here refer to the interdependencies between resource (locally targetted reef species) and resource users (fishing households).

The island of Moorea and its associated coral reef fishery present an interesting case study to examine the response of local social-ecological interdependencies to global drivers of changes. First, Moorea's progressive urban integration to its sister-island Tahiti since the 1970's has led to a shift from a subsistence to a cash economy, accompanied by a 298% increase in population (from 5788 inhabitants in 1977 to 17,234 in 2012), increased development of residential (houses), tourism (hotels, golf, harbor) and public (port, airport, routes) infrastructure and emergence of a salaried sector [16,17]. This rapid change in lifestyle has resulted in an increased proportion of the population at least partly dependent on the cash economy, especially through growth in tourism. Nevertheless, subsistence economy –and particularly fishing, on which 25% of the active population relies for food or income– still remains highly important for many households to reduce food-related expenses, providing a safety net against failure from income in the salaried sector, and decreasing cumulative risks of poverty traps [18]. This direct dependence on reef-associated provisioning services was of particular importance during the 2008 economic crisis that contributed to a sharp decline in tourism (from 225,000 visits in 2007 to 161,000 in 2012 [19]). This was accompanied by a general slowdown of economic activity throughout French Polynesia, leading to a significant decrease in employment in the salaried sector in Moorea which resulted in a drop from 2253 active people in 2007 to 1711 in 2016 [20,21].

Second, growing population and urbanization combined with continued or increased dependence on ecosystem services has amplified pressures on the reef ecosystem, leading to the introduction of new policies and a centralized system of marine spatial planning over the period 2007–2017 [22,23]. These new measures included eight permanent Marine Protected Areas (MPAs) as well as a variety of spatially explicit fishing regulations on size, species, gear and fishing seasons, which are currently under revision. While formally designated, the various rules brought in under the new management regime have not been widely accepted by local communities, with frequent reports of non-compliance, especially illegal fishing [24–26].

Third, during the recent period of socioeconomic and cultural changes, the coral reefs of Moorea have also been exposed to major biophysical drivers, including cyclones, outbreaks of the coral predator starfish (*Acanthaster planci*) and coral bleaching events [27,28]. While the first two only struck the fore reef, the latter impacted the entire reef ecosystem (lagoon and fore reef). These drivers manifest as recurrent stresses [27–31]: three bleaching events (2002, 2003 and 2007), an *A. planci* outbreak (between 2007 and 2009) and a cyclone (2010) have affected Moorea's reefs over the last two decades.

### 2.2. Mapping social-ecological vulnerability

Building from previous conceptual developments (see review in [32]), the Intergovernmental Panel on Climate Change (IPCC) defined vulnerability as the function of a system's exposure to a driver, its sensitivity to such driver and its capacity to adapt to changes caused by exposure to the driver it. In this generic conceptual model, the key elements of vulnerability are interpreted as follows:

1) **Exposure** designates the magnitude, frequency, duration and/or extent in which an entity (social or ecological) is in contact with, or subject to, a driver of change [33].
2) **Sensitivity** describes the set of conditions and/or characteristics mediating its short-term propensity to be influenced following the exposure [34].
3) Exposure and sensitivity create **potential impact** of a stressor, which is fully experienced in the long-term depending on the entity's **adaptive capacity**. This last component includes present and future ability to implement effective and long-lasting responses to changes by minimizing, coping with, and recovering from the potential impact of a stressor (modified from [10,34]).
4) **Vulnerability** thus is determined by the combination of potential impact and adaptive capacity.

Linkages between the ecological and the social sub-systems are here viewed through the lens of resource dependency (flow from social sub-system to ecological sub-system) and fishing opportunity (flow from ecological sub-system to social sub-system) [35–37]. Ecological vulnerability is here considered at the scale of the targeted fish assemblages and results from the combination of exposure and resilience to fishing (where resilience is here the combination of adaptive capacity and sensitivity). Social vulnerability originates from exposure,