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Scaling Indigenous-led natural resource management

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ABSTRACT

Rights-holders, practitioners, and researchers recognize the importance of Indigenous-led resource management for building a more ecologically just world and addressing climate change and biodiversity loss. Yet, it remains unclear how to support them in a way that increases their spatial extent and ensuring impact on equitable biodiversity conservation. We address this gap by using Diffusion of Innovations theory to explain the rapid spread of an Indigenous-led network of Locally Managed Marine Areas in Fiji. We found that 74.9 percent of adopters had a previous adopter as their nearest neighbor, and that despite contrasting patterns of adoption at the island level, such patterns could be accounted for by: perceived relative advantage, village chiefly status, distance to tourism hotspots, and presence of district-level management committees, support organizations, and trust. These insights can inform the design and implementation of Indigenous-led approaches that can scale appropriately and respond to the global environmental crisis.

1. Introduction

The unprecedented rate of global biodiversity loss and climate change threatens the future of species and ecosystems, necessitating transformative changes that build sustainable and mutually reinforcing relationships between people and the rest of nature (Mascia and Mills, 2018; Rockström et al., 2009; Westley et al., 2011). In response to these multiple threats, recent decades have witnessed a dramatic growth of societal responses that are designed to conserve biodiversity, foster sustainable development, restore ecosystems, and mitigate climate change (Bennett et al., 2016; Mills et al., 2019). These initiatives vary in spatial extent, regulatory and governance approaches, and the social and ecological contexts within which they operate. At the 15th Conference of Parties to the United Nations Convention on Biological Diversity in December 2022, governments from around the world agreed to the Kunming-Montreal Global Biodiversity Framework (GBF; Decision adopted by the Conference of the Parties to the Convention of Biological Diversity 15/4. Kunming-Montreal Global Biodiversity Framework, 2022). This Framework includes four goals and 23 conservation targets, including nearly doubling the extent of area-based conservation to 30 % of the world's land and sea surface by 2030 (Target 3).

Building on emerging scientific evidence regarding the effectiveness of Indigenous Peoples (IP) and Local Communities (LC) governed territories in reducing deforestation rate, maintaining biological diversity, reducing native vegetation conversion, and increasing regrowth (Dawson et al., 2021; Garnett et al., 2018; N. Alves-Pinto et al., 2022; Porter-Bolland et al., 2012; Shahabuddin and Rao, 2010), the GBF recognizes

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that stewardship by IP and LC is critical to global efforts to conserve, manage, and restore biodiversity. In particular, IP and LC play an important role in meeting Target 3 of the GBF, which commits to expanding "equitably governed systems of protected areas and other effective area-based conservation measures, recognizing Indigenous and traditional territories." This commitment is especially important because it acknowledges the effectiveness of IP and LC stewardship that have been historically marginalized within the environmental movement and promotes just governance of the, at least, 32 % of global land and inland waters, and 36 % of Key Biodiversity areas, owned or governed by IP and LC.

However, despite the critical importance of these Indigenous-led resource management arrangements, little is known about how and why such initiatives get adopted or "go to scale." While studies have described and explained the ecological and social impacts of these community-based resource management initiatives (Brooks et al., 2012; Cinner et al., 2012; Coppock et al., 2022; Jupiter et al., 2017), very few have investigated the factors associated with their adoption (Abernethy et al., 2014; Lewis-Brown et al., 2021; Merrie and Olsson, 2014), and fewer still have investigated the adoption factors with relation to spatial patterns and temporal trends (Fox et al., 2012). As a result, practitioners and scholars lack a comprehensive understanding of when, where, how, and why IP and LC resource management initiatives scale, and practitioners are unable to effectively support and facilitate evidence-based strategies to foster IP and LC stewardship. The resulting scientific ignorance has profound implications as humanity seeks to stay at 1.5 °C increase and reverse biodiversity loss.

To inform both science and policy, we examined the drastic growth of a network of Indigenous-led resource management arrangements in Fiji known as Locally Managed Marine Areas (LMMAs) (Mills et al., 2019). LMMAs are areas of nearshore waters and their associated coastal and marine resources that are largely or wholly managed by local coastal communities with support from partner organizations (Govan et al., 2009). Since its launch in Fiji in 2000, the LMMA Network has expanded to more than 936 communities across 15 countries and territories in the Pacific, Western Indian Ocean, and Coral Triangle. IP and LC now collectively manage more than 12,000 km^2 of inshore waters through their LMMAs (Govan, 2015; Govan et al., 2009; Mills et al., 2019). As an exemplar of rapid, widespread growth of an Indigenous-led stewardship initiative, the LMMAs of Fiji represent an excellent model system for exploring and explaining the spatial–temporal dynamics of IP and LC stewardship initiatives and for elucidating policy insights.

1.1. Theoretical framework

We used the Diffusion of Innovations theory (Rogers, 2003; Valente and Rogers, 1995) (DOI) as a framework for data collection and analysis to (a) describe the spatial–temporal patterns of LMMA adoption in Fiji and (2) to identify the characteristics of the LMMAs, the communities, and the context that influences LMMA adoption. Our goal was to provide insights into how IP and LC stewardship networks can be scaled to better combat biodiversity loss and climate change, and eventually scale other societal responses to environmental change more generally.

Within DOI, adoption is the act of deciding to partake in a new initiative, and diffusion is when "prior adoption of a trait or practice in a population alters the probability of adoption for remaining non-adopters" (Strang, 1991). Furthermore, scaling means expanding, adapting, and sustaining initiatives in various places and over time to reach more people (Hartmann and Linn, 2008). DOI posits that three main components drive the process of diffusion – characteristics of the innovation, the adopters, and the context (Figure 1). Within these components, our framework includes attributes pertinent to resource management initiatives, such as spatial proximity and ecological conditions, as proposed by Mascia and Mills (2018). We assume that spatial

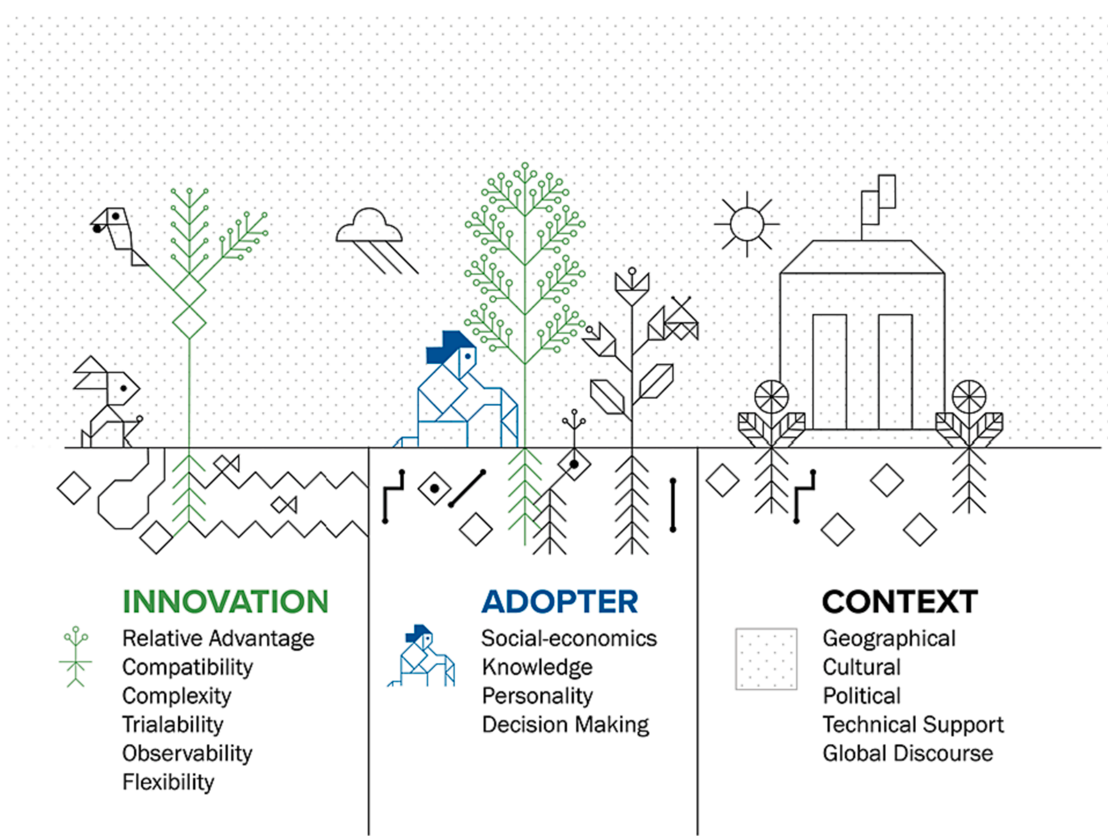

Fig. 1. Diffusion of conservation initiatives framework illustrating innovation, adopter, and context components along with the corresponding attributes. The framework is adapted from previous Diffusion frameworks by Mascia and Mills (2018), Rogers (2003), and Wejnert (2002).

proximity influences the frequency and extent of social interactions or social proximity (Burt, 1987). DOI also assumes that diffusion is a social process and that actors influence one another and their perceptions of the risks, costs, and benefits of adoption. Our framework accounts for these social influences by examining both the actor's predisposition to adopt an innovation independent of prior exposure to other adopters and how their exposure to other adopters and actors influences their propensity to adopt (Burt, 1987; Rogers, 2003).

1.2. Study context

Customary community-level governance systems have regulated natural resource use and management in the Pacific islands for centuries (Veitayaki, 1997). These systems varied widely but were important for maintaining resource availability in many communities throughout the region (Johannes, 2002). However, colonialism modified and eroded customary governance systems (Sloan and Chand, 2016), and the current extent of legal recognition for such systems and their place within the hierarchies of contemporary legal pluralism now differs greatly across Pacific Island states and territories (NZLC [New Zealand Law Commission] 2006). While customary land tenure is recognized and protected by national legislation in most Pacific Island countries (Lane, 2008), the recognition of customary marine tenure has been more uneven, reflecting a historical conflict between Pacific marine tenure systems and the 'open access' traditions of colonizing European states (Govan et al., 2009).

However, recent efforts to further recognize customary governance systems in marine resource and ecosystem management have resulted in the rapid growth in community conserved marine areas in the region (Clarke and Jupiter, 2010), such as the Locally Managed Marine Areas (LMMA). In Fiji, each village shares common principles of sustainable fisheries use but implements them differently as appropriate for their context (Jupiter et al., 2014). Fijian LMMA is bolstered by legislation that recognizes customary marine tenure over inshore areas, or qoliqolis, held solely by Indigenous iTaukei people. Qoliqolis are based on historically recognized customary fishing grounds, which loosely follow general reef geomorphology; that is, qoliqoli outer limits are often defined by the outer limits of reefs. Exemplifying Fiji's legal pluralism, the Fisheries Act protects customary fishing rights and regulates some, but not all, of how fisheries should be managed (Sloan and Chand, 2016). While the state can enforce some conservation measures, such as fishing methods and gear, spatial and seasonal closures, size and weight limits, and licensing, qoliqolis have also long exerted traditional fisheries management tools, such as tabu (periodically closed) areas for fisheries management and other spiritual and traditional intent. The Fijian Native Land and Fisheries Commission recognizes 411 registered qoliqolis extending across total 30,011.09 sq. km. Fiji LMMA (FLMMA) network was set up to support qoliqoli management both by strengthening Indigenous rights and by integrating new tools and methods. Thus, it supports Fiji's legal pluralism by seeking to integrate, and create mutual understanding between, Indigenous and Western marine management systems (Reid et al., 2021).

1.3. The adoption process

In the last 20 years, the number of LMMAs in Fiji has drastically increased, with 351 villages out of 747 coastal villages currently part of the FLMMA Network (from the Fiji LMMA 2019 database). The FLMMA Network is a formal learning network in which information and experiences with various management practices are shared, and access to external partners for support is available. To understand LMMA adoption, we identified and mapped all the villages with LMMAs (adopters) and all coastal villages without LMMAs (non-adopters) (Figure 2). We measured adoption dichotomously, based on whether the villages are formal members of the FLMMA Network or not. We chose to make this binary distinction of adoption based on membership because of the historical presence of customary marine tenure among coastal villages that support traditional management systems with diverse management regulations, including the presence of closed areas (e.g., tabus, sasi, rahui), and other norms regarding species, gears, and/or areas sometimes based on their totems and customs (Johannes, 1978; Vave, 2022). Therefore, even though most coastal fishing villages have some sort of marine resource management practice, not all are recognized as an adopter of an LMMA in our study, and we explicitly investigated formal membership in the FLMMA Network as the innovation to be adopted. Being part of the FLMMA Network requires that the village is aware and has a well-defined or designated fishing area and has substantial involvement of local interested parties in decision making. The priorities for each LMMA are based on local challenges with specific focus on marine resource use to ensure food and livelihood security. The adoption process is marked by a series of steps outlined in the LMMA guide for practitioners (Govan et al., 2008). The process starts with the community requesting LMMA establishment and engaging the FLMMA representatives through an official letter of interest endorsed by the village chief, which is then followed by more in-depth engagement across the entire community and creation of a management plan through multiple workshops (ibid). Where multiple villages share a qoliqoli, engaging the chiefly village among those is necessary to reduce conflict. Many communities establish a Resource Management or yaubula Committee to oversee the development and/or implementation of their LMMA. These yaubula committees do not play a role in the decision to adopt but facilitate implementation of LMMAs. Where these committees exist at district or provincial level, each village has a representative in the committee. The ultimate decision to set up LMMA is made by the village chief in consultation with people from the village and yaubula committee, where they exist. The support organizations, including NGOs, Ministry of Fisheries, university partners facilitate the initial engagement, but their presence is not mandated for establishing a LMMA. Many of these organizations facilitate a series of workshops to help the community identify the issues they wish to address and the solutions, which includes the rules for their LMMA or qoliqoli.

1.4. The village as the adopter

The decision to adopt or join the LMMA network is taken at the village level. While the request to set up the LMMA has to be endorsed by the village chief, the people of the village are consulted through engagement workshops. In most villages, the customary hierarchies of authority are revered though there may be exceptions. And in villages where such a conflict exists between the chief and people, LMMA engagement is paused till such conflict is resolved. After consultations with the village chief, the resource management or yaubula committee (where they exist), and people, rules of management are negotiated. These rules are a mix of customary marine management and government laws and policies. The latter are common across all villages, but the former can change depending on the particular species that is tabu to the community, seasonal bans, gear restrictions, and rotational closures. Joining the network creates opportunity for learning across the villages, helps facilitate monitoring and enforcement by training fish wardens, and formalizes customary fisheries management. These negotiations are facilitated through FLMMA representatives and support organizations (where they exist). The final decision to set up an LMMA rests with the chief. In places where qoliqolis are shared by multiple villages, the traditional hierarchy of chiefs is followed, and the chief amongst all the villages has to endorse the decision to adopt LMMA, following which individual village chiefs are approached.

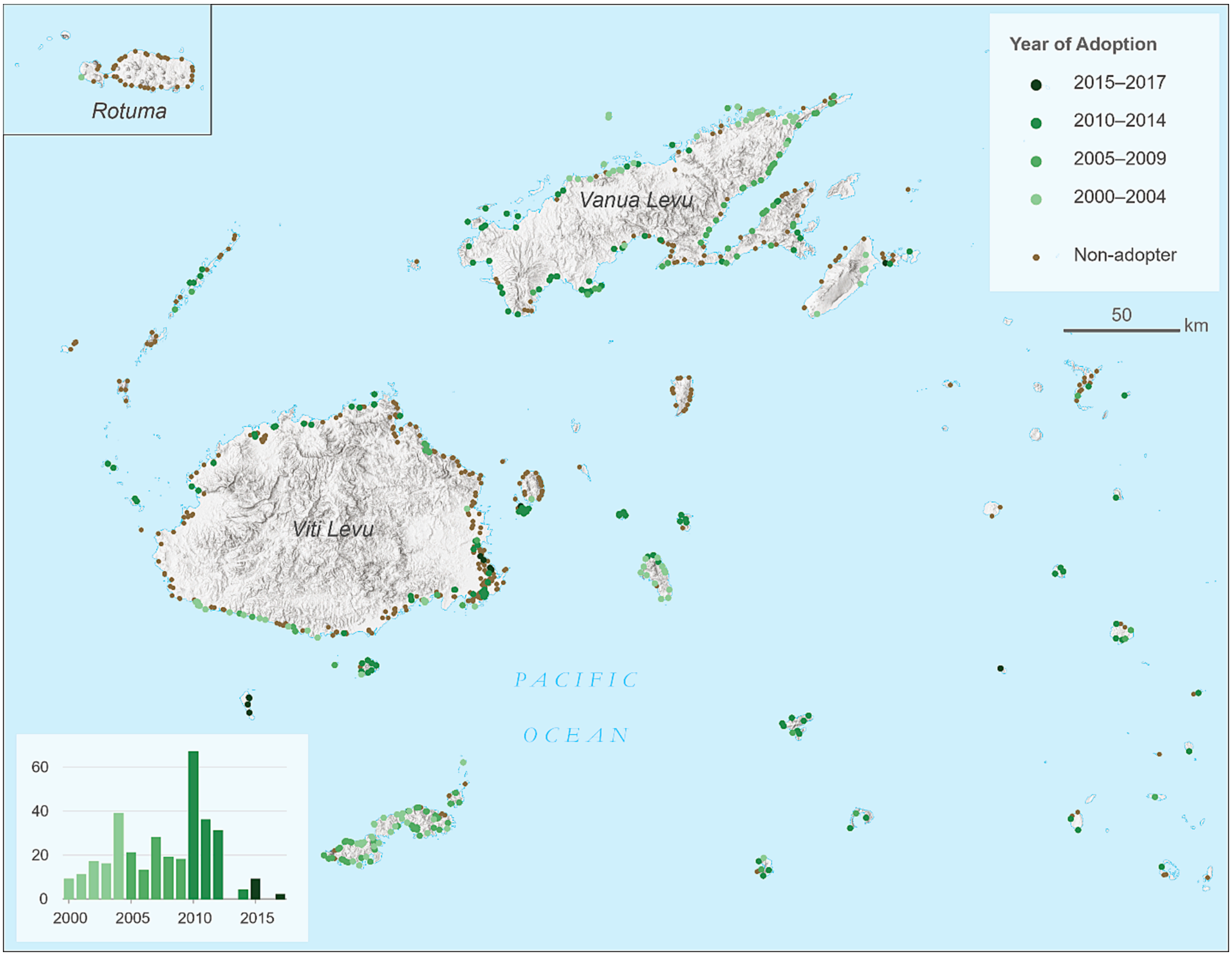

Fig. 2. Map of Fiji showing the spatial distribution of Locally Managed Marine Areas. The points are color coded based on the year of adoption, to highlight spatio-temporal proximities in adoption.

2. Methods

2.1. Describing the spatial–temporal adoption patterns

2.1.1. Sample Selection

To describe the spatial–temporal patterns of LMMA adoption, we identified all coastal villages eligible to join the LMMA Network and then used the Fiji LMMA 2019 village member database to identify those that had. These villages were coded as adopters, while the remaining eligible non-member villagers were coded as non-adopters. We noted the year of adoption, in which the village became part of the Fiji LMMA network and identified each village's spatial coordinates.

From this database (n = 747), we examined whether adoptions showed neighbor-to-neighbor effects. We then narrowed our analysis to a finer scale to identify statistically significant spatial–temporal patterns of adoption using an Inhomogeneous Space-Time K Function (Gabriel and Diggle, 2009) on a subset of villages in the two big islands of Viti Levu (n = 256) and Vanua Levu (n = 163). This narrower focus allowed us to highlight evidence of spatial–temporal clustering. We ran the analyses on the two islands because this method assumes events to occur within a spatial polygon. The other islands groups with LMMA adoptions contain several small islands, making it unfeasible for this analysis. We chose spatial search radii starting of 2 km because most villages do not have neighbors closer than 2 km. This analysis indicated whether adoption events are closer to each other in space and time than would be expected by chance.

2.1.2. Statistical analysis

We used an inhomogeneous space–time K function (Gabriel and Diggle, 2009), which measures clustering/ repulsion in a space–time point pattern after accounting for any spatial and/or temporal inhomogeneity in underlying event intensity. The inhomogeneous space–time K function is defined as follows:

$$\widehat{K}_{ST}(u,\ v) = \frac{1}{|S \times T|}\frac{n}{n_v}\sum_{i=1}^{n_v}\sum_{j=1,\, j>i}^{n_v}\frac{1}{w_{ij}}\frac{1}{\lambda(x_i)\lambda(x_j)}1_{\{u_{ij}\leq u\}}1_{\{t_j - t_i \leq v\}}\frac{1}{w_{ij}}$$

where $x_i : i = 1, \cdots, n$ and $x_j : j = 1, \cdots, n$ are adoption events in a spatial-temporal region $S \times T$, (u, v) are the spatial and temporal search radii, or the spatial-temporal difference vector between x_i and x_j, and $\lambda(x_i), \lambda(x_j)$ are the intensities at x_i,x_j, respectively. The parameters n_v, w_{ij} are used to deal with temporal and spatial edge effects (see details in SI). We defined the underlying spatial event intensity as the density of potential adopters, i.e., all the villages. We assumed the temporal intensity to be consistent across all years. After accounting for the underlying inhomogeneity in event intensity, we compared the observed inhomogeneous K statistic with a random inhomogeneous Poisson process that shares the same underlying intensity as the observed data. If no space–time clustering is occurring, we would expect $\widehat{K}_{ST}(u, v) = \pi u^2 v$. Thus, $\widehat{K}_{ST}(u, v) - \pi u^2 v$ can be used to assess the observed level of spatial-temporal aggregation vs repulsion. To test the significance of space–time interaction in the observed pattern, we employed a Monte Carlo test using 999 simulations (Diggle et al., 1995). This analysis is realized in the R package *stpp* (Gabriel et al., 2013).

2.2. Explaining the adoption patterns

2.2.1. Sampling frame

Data for this study was collected in conjunction with an evaluation study focused on impacts of LMMAs (O'Garra et al., 2023), for which we considered potential ecological spill-over effects from LMMA adopters. Specifically, the sampling frame excluded any villages that were within 1 km of adopter villages. The distance of 1 km was chosen based on a review of similar studies looking at marine spill-over effects (Halpern et al., 2009). We did not restrict LMMAs by distance from other LMMAs[1] due to sample size restrictions. Although this challenges our ability to estimate ecological spillovers from one LMMA to another for the impact evaluation, it should have no effect on the diffusion analysis because presence of previous adopter as a neighbor was covered in our descriptive analysis. This left us with a final sampling frame of 265 villages.

2.2.2. Matching

To analyze the impact and probability of villages to become part of the LMMA and the potential predictors from the Diffusion Innovation theory (innovation, adopters and context), we matched LMMA with non-LMMA villages. We identified variables expected to affect LMMA adoption and outcomes during a project workshop in June 2019 in Suva, Fiji. This workshop included representatives of the FLMMA network, partner organizations, and Fijian team members who have worked with coastal villages in Fiji for over 20 years. During the workshop, study objectives were presented along with examples of variables explored in similar studies. The workshop attendees were invited to discuss the importance of these variables to them, and any others that may have been missing. The study authors then situated these insights within the impact evaluation framing, Diffusion of Innovations theoretical framework, and marine resource management literature to decide upon the final set of variables. These variables included – 1) distance to nearest road, 2) distance to closest municipal market, 3) size of iqoliqoli (customary fishing ground), 4) coral reef cover, 5) distance to nearest previously-established LMMA village, 6) number of other villages that share iqoliqoli. The matching process resulted in a final sample of n = 160 villages (80 adopters and 80 non-adopter villages) for data collection. Of these villages, 8 were dropped (4 pairs) due to inaccessibility leading to a final sample of 152 villages (76 matches).

2.2.3. Sample Selection

For our explanatory models, we focused on the four large island groups of Viti Levu, Vanua Levu, Kadavu, and Lomaiviti for sample selection, since the density of LMMAs was higher on these and travel to more distant and isolated island groups was limited by project budget. Using the Fiji LMMA 2019 database, we focused on villages that had adopted LMMAs between 2003 and 2012. This range was chosen since this data was also used to estimate impacts of LMMAs that had been adopted either ~15 years or ~10 years earlier (O'Garra et al., 2023); furthermore, adoptions before 2003 (more than 15 years ago) were considered to have too long a time frame to collect any meaningful recall data. Other restrictions were imposed on the sampling frame to minimize spillover effects vis a vis the impact evaluation and eliminate other potential influences, including 1) excluding non-adopter villages that share an iqoliqoli with adopter villages, 2) a minimum distance of 1 km between non-adopter and adopter villages, 3) removing villages with other marine management projects. Villages were selected using matching approaches (SI), which was used specifically for the impact evaluation part of the analysis. The variables used in matching were: distance to nearest road, distance to nearest market, distance to nearest previously established LMMA village, area of customary fishing ground, coral reef cover, and number of other villages sharing the fishing ground. This was done to minimize potential confounding with respect to factors that might have influenced both adoption of LMMAs as well as LMMA impact.

All the variables for the models were chosen based on the diffusion framework (Table 1). In addition to these diffusion variables, we included a series of random effects in each model to control for potential bias in the data. These included administrative divisions of each village (province and district) as well as the island. An explicit spatial component was also included in each model.

2.2.4. Data Collection

We collected data using a structured survey to village leader groups between October 2019 and March 2020. The leaders group included the three types of leaders in Fijian communities, comprising of vanua (land, people, custom), lotu (spiritual) and matanitu (government) leadership. We tested the survey instrument in a pilot village not included in the final dataset, which resulted in some modest changes to the survey and allowed us to resolve any issues with translation in iTaukei and interpretation. Following this pilot, we conducted a first round of surveys in four villages from our selected sample, and reviewed responses. We included data from these four villages in the final sample, as no additional changes to the surveys were made. We terminated the data collection early in March 2020 due to the onset of the Covid-19 pandemic, resulting in a final sample size of 146 villages. Of the 146, 66 were LMMA villages and 80 were non-LMMA villages (Figure S1). Less than 5 % of values were missing from all variables at the end of data collection. All the necessary permissions were obtained by the provincial offices from village chiefs prior to visiting the villages and information about the project was shared according to our Institutional Review Committee.

To explain the adoption of LMMAs using the Bayesian Hierarchical models, we collected data across three components of the conservation diffusion framework– the innovation, the adopter, and the context, based on Diffusion of Innovations theory (Rogers, 2003). The complete framework along with the attributes and variables considered are provided in Table 1. The framework was operationalized, and variables selected for each attribute based on existing adoption literature (Abadi Ghadim and Pannell, 1999; Greenhalgh et al., 2004; Mascia and Mills, 2018; Rogers, 2003), their applicability in the context of Fiji, and tested with partners in Fiji.

For the innovation component, because we could not collect data on adopters' perceptions at the time of adoption, we asked them about how they presently perceived the LMMAs. We compared adopters' and non-adopters' perceptions of the innovation based on their experiences with the LMMA. We chose not to rely on recall data for perception given its unreliability. For the adopter component, we collected data on socio-economic variables such as the village infrastructure present at the time of adoption. Data on village-level infrastructure is an important indicator of economic conditions in the village, and these are hypothesized to influence adoption. Specifically, it is expected that villages with higher levels of wealth and economic development are more likely to adopt LMMAs because they are more economically secure and have the means to invest in the adoption process (Rogers, 2003). We asked the leaders key informant group to identify which of 17 types of infrastructure were present in their village. The infrastructure types were as follows: hard-top road, mobile phone, landline phone, shops/kiosk, public market, clean water for drinking, piped water service, public transportation, place to purchase fuel, mechanic/garage, banking services internet, electricity, village dispensary/doctor/nurse, electric freezers that fish is stored in, ice making facilities for storing fish and sewage treatment/septic tank. These items were reduced to a single 'village infrastructure index' using principal components analysis (PCA); the higher the index score, the more infrastructure present in the village at the time of adoption To produce this index we used an iterative

[1] An *ad hoc* justification for only controlling for spill-overs on non-LMMAs is that one of the aims of the LMMA "network" is to create a network of villages which communicate with each other (and with other stakeholders).

Table 1
Data gathering framework with innovation, adopter, and context components and their corresponding attributes and variables considered for Bayesian Hierarchical models to explain adoption of Locally Managed Marine Areas.

Component	Attribute	Definition	Variable	Recall data?
Adopter	Decision making	The capacity of individuals or groups to make decisions pertaining to adoption of the innovation	Management committee – none, village, district, provincial+	No
	Socio-economic conditions	Social-economic characteristics that influence adopter's ability to implement a new practice	Chiefly status	No
			Village infrastructure	Yes
	Knowledge	The degree to which the adopter is familiar with the innovation and innovation consequences	Knowledge of resources	No
Context	Extension & support	Public and private sector activities relating to technology transfer, education, and human resource development	Presence of champions	No
			Support organizations	Yes
	Geographical settings	Settings that affect adoption by influencing the applicability of the innovation to the ecological setting and by exerting spatial effects of geographical proximity	Shared resource grounds, Distance to tourism	No
	Political conditions	Character of political systems, along with the regulations and norms that influence the innovation	Supportive national policy	No
			Trust in government	No
	Connectedness	Modern communication systems or media effects.	Connectivity - internet, landline, phone	Yes
Innovation	Compatibility	The degree to which the practice is perceived as consistent with existing values, existing practices, and needs of potential adopters	Compatibility - culture	No
			Compatibility - needs	No
			Compatibility - practices	No
	Flexibility	The ability to transform the practice to something that aligns with the adopter's desires and constraints	Flexibility	No
	Observability	The degree to which the practice and the results of that practice are visible to others	Observability of impacts	No
			Observability of practice	No
	Relative advantage	The perceived net benefits of adopting an innovation compared to the status quo.	Comfort	No
			Economic benefit	No
			Immediacy of reward	No
			Overall relative advantage	No
			Social prestige	No
	Triability	The degree to which the practice may be experimented with on a limited basis	Triability	No

process following Gurney and Darling (2017), which suggests running PCA on the variables, removing variables that have lowest factor loading (eigenvalues), then re-running until the first principal component explains 40 % of the variance at least. The final model includes seven items, and the total variance explained by the first principal component is 46.8 % (also see O'Garra et al., 2023). We also collected data on knowledge of the fisheries management systems by asking leaders to rate their perceptions of the communities' knowledge using a scale from 1 to 5. To identify the level at which decisions regarding fisheries management are made, we asked respondents about the presence of resource management committee at four distinct levels – village, district, provincial and island. We also marked whether a village was considered a chiefly village at the district level. Our context variables included presence of civil society organizations to support LMMA adoption, connectivity infrastructure such as internet and phones, trust in government, and presence of supportive national policies. Our proximity and ecological variables such as distance to previous adopter, roads, and market were excluded from the model since they were a criterion for sample matching.

We had a few variables where we relied on recall data from the time of LMMA adoption (see Table 1). With any recall data, there are several caveats to consider that challenge recall data's reliability. To mitigate telescoping (the tendency of respondents to recall events as more recent than they were), we used checklists, closed-ended questions (Bernard et al., 1984), and used well-known cyclone events as reference points (Loftus and Marburger, 1983). Using village leaders as respondents also helped to mitigate recall bias, as they have expert knowledge of the question topics (Kimball Romney and Weller, 1984).

2.2.5. Statistical Analysis

We computed the descriptive statistics (median and inter quantile range (IQR)) for all the continuous variables and frequency for categorical variables (Table S2); we tested the independence between the outcome and the categorical variables, with Chi Square test (Table S3). We then fitted two models separately for a set of variables (adopter and context, and innovation), accounting for the spatial component.

We used a Bayesian hierarchical model to fit the data for the adopters. We defined the binary outcome for each village (1 adopters, 0 non -adopters), distributed as:

$$Y_{i(s_i)} \sim Bernoulli(p_i)$$

Where p_i is the probability of begin an adopter, for $i = 1, \ldots, 146$. We then define the model on the logit link function:

$$logit(p) = log\left(\frac{p}{1-p}\right) = \alpha + \beta X_i + z(s_i)$$

Where α indicates the log baseline probability for a village to become an adopter (intercept), β is the vector of the parameters, X_i is the covariate matrix and z_i is the spatially structured random effect. The regression coefficients – including the intercept - are normally distributed centered on zero, with a variance equal to 10ˆ-4.

We used the Stochastic Partial Differential Equations (SPDE) approach (Lindgren and Rue, 2015) for the spatial effect, which approximates a continuously indexed Gaussian Field (GF), where z is a zero-mean Gaussian Markov Random Field (GMRF) in which the correlation between locations z_i and z_j, is represented by a Matérn function. The spatial effect is a vector that links each observation to a spatial location, and thus it accounts for additional variability that cannot be explained by the available variables (Figure S4). We defined weakly informative priors for the parameters of the Matérn model. We specified a joint penalized complexity priors for the spatial range and for the standard deviation (Simpson et al., 2017). The penalized priors allowed us to shrink the spatial effect toward a base model with no spatial effect. We estimated the model and extracted credible intervals at 90 % and 95 % and opted to present the results as such and not as Odds Ratio (Table S4 and S5), as this analysis has an explorative approach and the OR for some covariates presented wide intervals and high values.

3. Results

3.1. Neighborhood effects on adoption

We found that 47 % of the of the total number of coastal villages in Fiji had adopted an LMMA (351 out of 747) and over 70 % of these had neighbors who had previously adopted LMMA. We present the graph showing neighbor-to-neighbor adoption events between the years 1997 and 2018 in Figure 3. The cumulative number of adoptions also followed the s-shaped diffusion curve showing significant uptake over time.

3.2. Spatial-temporal clustering of adoption events

Examining neighbor-to-neighbor effects across the two island groups, we found that the spatial–temporal pattern of LMMA adoption varied between Viti Levu and Vanua Levu (Figures S2, S3, Table S1). Adoption events on Viti Levu were clustered within 2–5 km and 1–3 years from each other (Figure 4). In contrast, on Vanua Levu, adoption events were spatially and temporally further from each other than would be expected at random, a pattern known as 'space–time repulsion.'

3.3. Factors influencing adoption

For the model focused on adoptere and contextual variables (Model 1), we found five variables that were positively correlated with villages joining the LMMA Network. These variables were: whether the village was considered a chiefly village according to the traditional hierarchy of Fijian villages, presence of a district-level resource management committee, presence of support organizations like non-governmental organizations, distance to tourism hubs, and trust in government agencies and external organizations. Only 18 % of the total number of villages considered for the models (n = 146) had chiefly status at the district level. We also noted that 84 % of the villages lacked a support organization, but all those with support became adopters. Non-adopters were also closer to the nearest tourist hub, represented in our models by the presence of a hotel or a resort.

The innovation variables (Model 2) suggested adopters were more inclined to perceive an overall relative advantage of joining the LMMA Network than non-adopters. We assessed several dimensions of relative advantage – economic benefit, comfort, the immediacy of reward, and social prestige – and found none individually associated with adoption (Pannell et al., 2006; Rogers, 2003). Most villages agreed that LMMAs were compatible with their needs, flexible, and triable, but not compatible with their current resource management practices (Table S2). We found no evidence of a difference in perceptions regarding the observability of the LMMA practices or impacts, the immediacy of rewards, flexibility, or triability between adopters and non-adopters.

Given our sample size, we also explored variables at the 90 % credible interval. We found that sharing fishing grounds with multiple villages was negatively associated with LMMA adoption, while compatibility with existing practices was positively correlated with adoption (Figure 5). These results are important to consider given LMMA concept in Fiji tacitly assumes that the resource users adaptively managing fisheries resources have clear and relatively undisputed rights over the fishing grounds and did not explicitly give guidance for cases where there were disputed or shared resources.

4. Discussion

Drawing on Diffusion of Innovations theory, our research reveals the spatial–temporal patterns of adoption of LMMAs, and identified

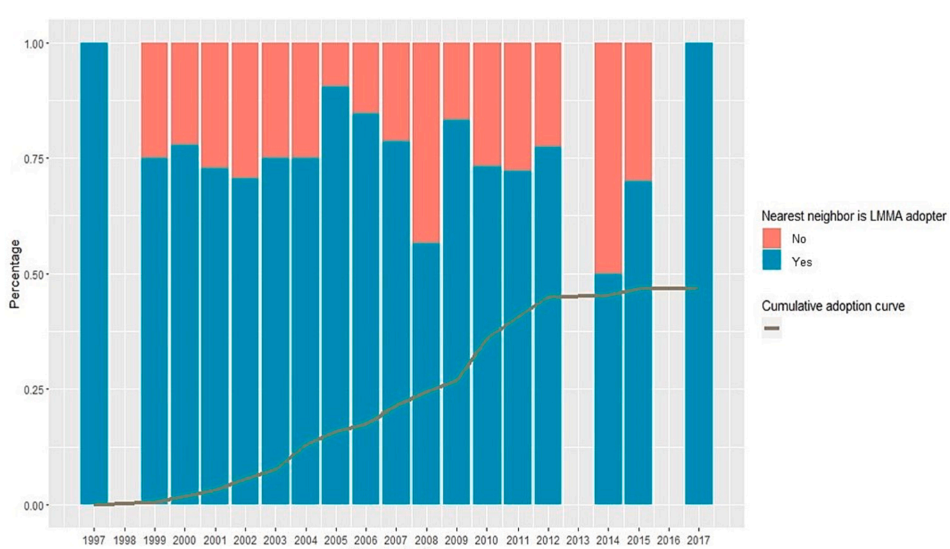

Fig. 3. Result showing the neighbor-to-neighbor adoption patterns in Fiji. The bars identify the percentage of new adoptions in a given year t. The bars show the percentage of adopters in a given year which has its nearest neighboring village as a previous adopter. The curve represents the cumulative percent of villages that are adopters in Fiji.

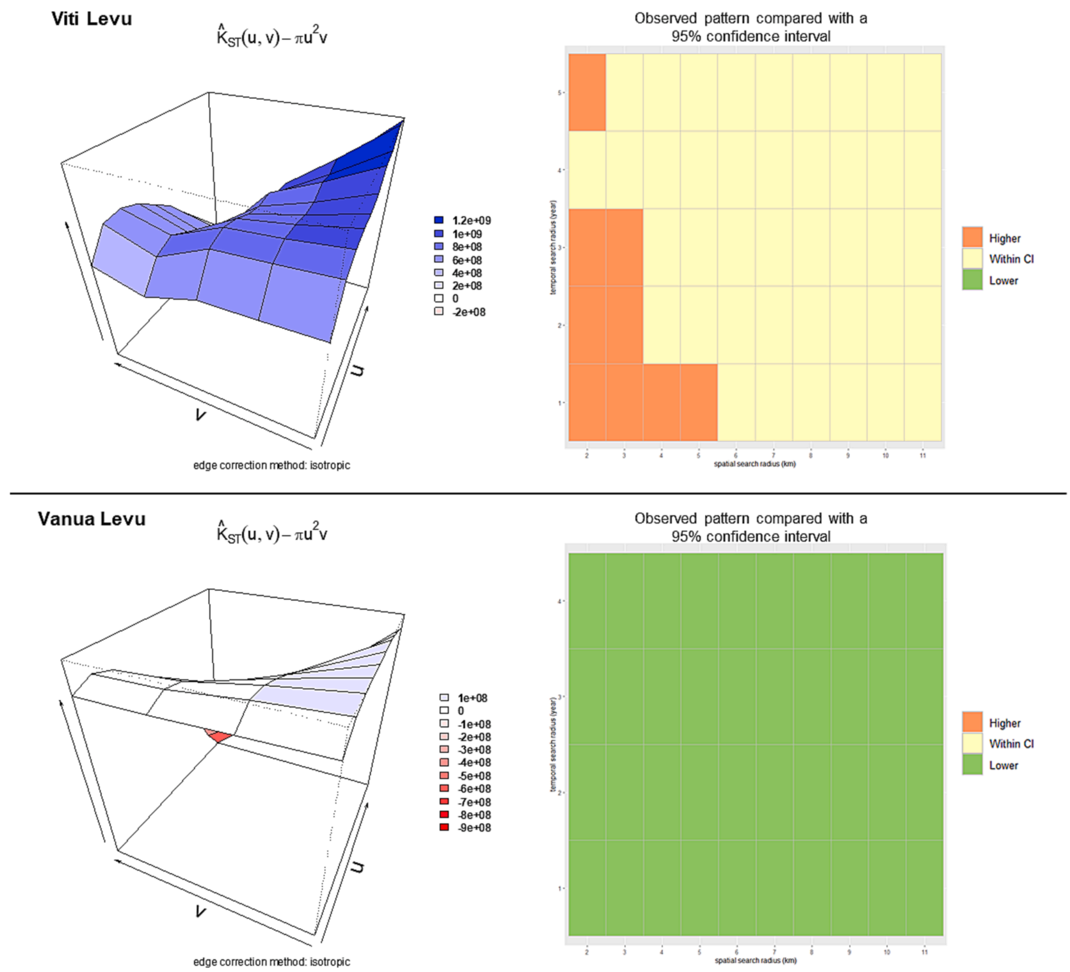

Fig. 4. Results of inhomogeneous space–time K function in Viti Levu and Vanua Levu. For Viti Levu, we used spatial search radii of $u = 2-12$ km and temporal search radii of $v = 1-4$ years. For Vanua Levu, we used spatial search radii of $u = 2-12$ km and temporal search radii of $v = 1-3$ years. The upper and lower left figures show the estimated $\widehat{K}_{ST}(u,v) - \pi u^2 v$ for the observed adoption pattern in each island; values above 0 indicates spatial-temporal clustering and values below 0 indicates spatial–temporal repulsion. The upper and lower right figures compare this statistic to the 95 % confidence interval (CI) generated from 999 simulations using an inhomogeneous Poisson process; if the observed value exceeds the upper limit of the 95 % CI at a given search radii, we say it shows significant spatial–temporal clustering; if it is below the lower limit of the CI, it shows significant spatial–temporal repulsion. If no space–time clustering is occurring, we would expect $\widehat{K}_{ST}(u,v) = \pi u^2 v$. Thus, $\widehat{K}_{ST}(u,v) - \pi u^2 v$ can be used to assess the observed level of spatial-temporal aggregation vs repulsion. To test the significance of space–time interaction in the observed pattern, we employed a Monte Carlo test using 999 simulations following Diggle et al. (1995).

innovation, adopter, and context characteristics that were strongly associated with adoption. The spatial–temporal patterns of adoption of these Indigenous-led resource management systems through neighbor-to-neighbor effects is consistent with previous studies in conservation and resource management (Aklilu and Elofsson, 2022; Conley and Udry, 2010; Romero-de-Diego et al., 2020).

Specifically, we found that a few key factors can explain much about the spread of LMMAs over time, despite the contrasting spatial patterns of adoption on Fiji's two main islands. Specifically, and consistent with previous studies of adoption, we found that the presence of support organizations explains much of why villages joined the LMMA network in clusters on Viti Levu, but not so on Vanua Levu. The first LMMA pilot occurred in Ucunivanua Village in Viti Levu, and several support organizations (non-governmental organizations, universities, and government partners) provided assistance to neighboring villages. These organizations worked simultaneously with multiple communities within districts, resulting in adoption clusters in Viti Levu. In contrast, there were fewer opportunities for learning and engagement with and among villages on Vanua Levu. This evidence for the importance of support organizations in scaling Indigenous-led marine resource management is consistent with previous studies emphasizing the importance of outreach (Romero-de-Diego et al., 2020; White et al., 2022; Wilson and MacDonald, 2018). However, Andrews and Borgerhoff Mulder (2018) found that similar spatial patterns in the adoption of community forestry institutions in Tanzania were partly explained by the fact that one village's adoption can influence the probability of a neighboring village's adoption. This influence can be positive, such as when the adoption of management institutions in one area pushes harvesters to neighboring areas, increasing the need for resource management there, or it can be negative, such as when one village's adoption leads to greater resource abundance across the region, decreasing the need for resource management elsewhere. While DOI theory suggests that peers are likely to imitate each other's adoption behaviors, we did not explicitly investigate such dynamics here and suggest that doing so may be a fruitful avenue for further research.

Similarly, and again consistent with other DOI research suggesting the importance of adoption among opinion leaders for the subsequent uptake by others (Henrich, 2001; Valente and Davis, 1999), our findings highlighted the influence of village chiefly status and district-level resource management committees on the spread of LMMAs. The Fiji LMMA Network prioritizes engaging villages with chiefly status knowing that such villages often serve as models for residents in other

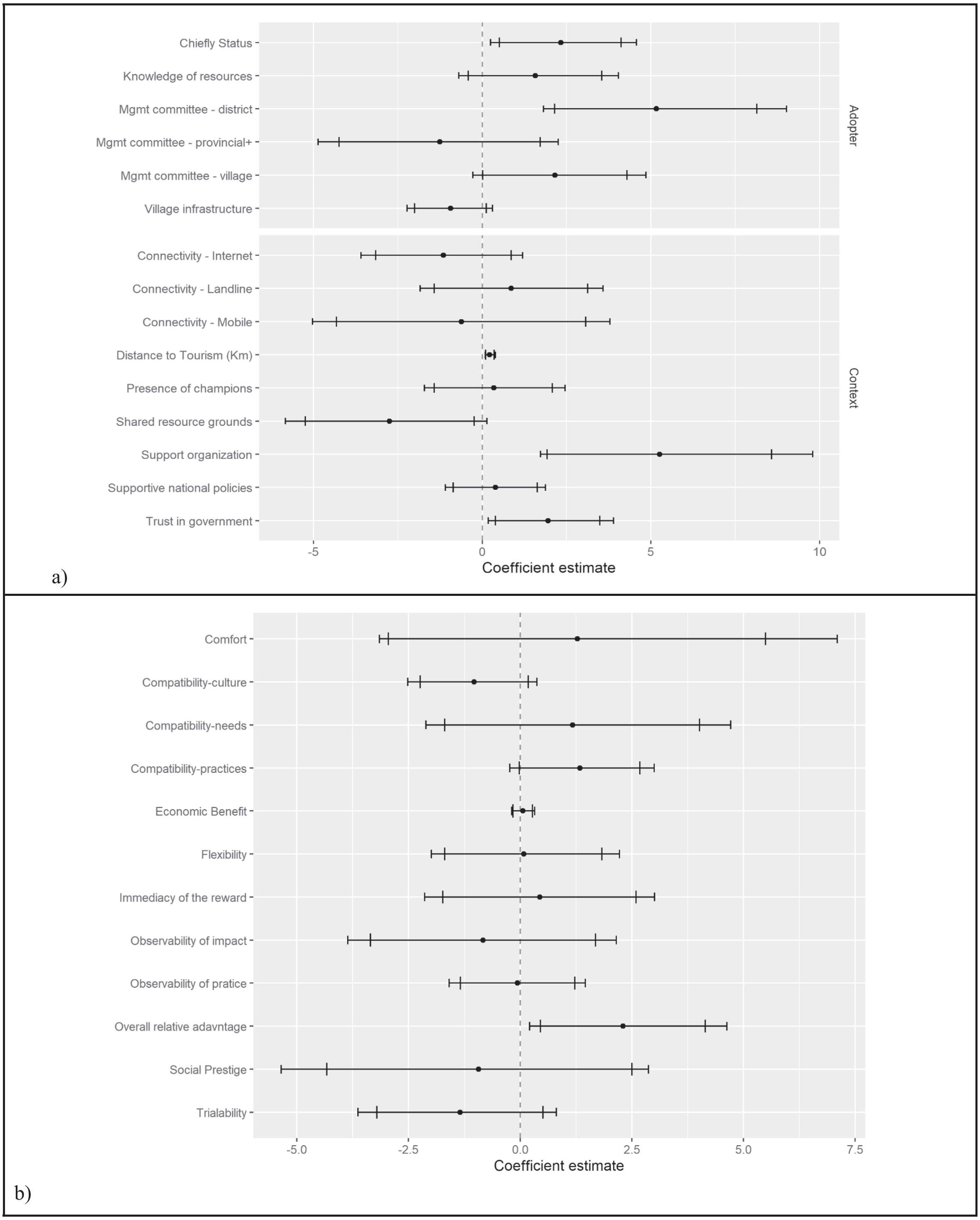

Fig. 5. Results of the Bayesian Hierarchical models a) adopter and context, b) innovation. The graphs show estimates with 95% (outside bars) and 90% (inside bars) credible intervals.

villages within the chiefs' domains. Likewise, the importance of district-level resource management committees likely reflects their function as a formal forum in which representatives from many villages discuss common governance issues, which facilitates several villages learning about and adopting LMMAs at a time. Their mid-level position between village-level and provincial-level committees – the presence of which were not found to be important for adoption – appears to give them unique influence on adoption, but knowing the reasons for why this is requires further investigation.

Our models suggested that two other contextual variables, proximity to tourist hubs and trust in government, also distinguished adopters from non-adopters. Villages closer to tourism hubs were less likely to have joined the LMMA Network, perhaps because of conflicting priorities and dependence on tourism revenue and thus saw comparatively less advantage in joining LMMA. Across Fiji, tourism hotels and resorts have diverse management arrangements, with ownership ranging from external or foreign corporations to locally owned and managed. We did not survey the hotels to identify Indigenous ownership and suggest further research on the relationship between Indigenous-led tourism and LMMA adoption. Some tourism hubs also have marine protected areas established through traditional tabus (Mangubhai et al., 2020), making entry into the LMMA Network redundant with existing management practices. Finally, trust in the government was also associated with LMMA adoption, corroborating findings from other studies on the importance of trust in information sources and government for adoption (Lubell et al., 2013; Prokopy et al., 2019; Ranjan et al., 2019; Wejnert, 2002).

The Innovation model, which analyzed respondents' perceptions of LMMAs, revealed that adopters and non-adopters differ substantially in seeing an overall relative advantage and compatibility with practices, but agreed on innovation characteristics such as compatibility with needs, flexibility, and triability. Some of this lack of variability in perceptions of LMMAs (innovation characteristics) between adopters and non-adopters may be due to a shared narrative created by an exchange of subjective evaluations among the adopters and non-adopters over time (Henrich, 2002; Jagadish and Dwivedi, 2019). For instance, while approximately 90 % of respondents believed that LMMAs had had an impact, only 38 % had observed practices that were part of LMMA implementation, emphasizing the role of information sharing in the absence of tangible and observable practices.

Within the different dimensions describing relative advantage (economic benefit, comfort, immediacy of reward, and social prestige), we found no differences between adopters and non-adopters (Pannell et al., 2006; Rogers, 2003), in contrast to the general predictions of DOI. However, the overall perceived relative advantage of the LMMA was strongly associated with the adoption. This result could be the case either because the most relevant aspect of relative advantage varies across different contexts (Lewis-Brown et al., 2021), or because we did not capture specific indicators of relative advantage relevant to LMMAs. LMMAs in Fiji are operationalized to accommodate multiple priorities and objectives, making clear distinctions in what communities perceive as important harder to ascertain (Jupiter et al., 2014).

In addition, our study highlights the need to consider all three components of diffusion - innovation, adopters, and context - to understand the scaling of initiatives. Only focusing on one component risks undermining the inter-relationships among the components.

As with all theories, there are limits to applying the DOI framework to understanding the spread of Indigenous-led marine management networks, namely 1) pro-innovation bias and 2) justice and inequality bias (Rogers, 2003). While the former can be addressed by ensuring that management networks are designed to fit adopter and context characteristics and not the other way round (as we learn from this study), the justice and inequality bias comes with a trade-off. While focusing on chiefly villages was important for the adoption of LMMAs in Fiji to build legitimacy and facilitate scaling, a similar approach elsewhere will risk increasing the inequities on who has access to initiatives and therefore needs careful consideration.

These findings have substantive implications for conservation policy and practice aimed at supporting and scaling Indigenous-led resource management. With respect to LMMAs specifically, our findings illustrate, first, that support organizations continue to be impactful in driving adoption, with the spatial–temporal clusters we observed likely the result of their strategy. Second, they provide evidence that support organizations can use to prioritize their work to make it more impactful. This includes understanding that the presence of tourism hubs may limit people's engagement with resource management efforts, and that it may be more beneficial to Indigenous-led efforts to support more directly communities that have a definitive need to engage with resource management initiatives and will be more directly impacted by its presence or absence. Third, they reveal that respecting and working with existing Indigenous and governmental institutions is particularly important, as indicated by the importance of village chiefly status and district-level resource management committees. Fourth, our finding that overall relative advantage, in contradistinction to our other variables associated with relative advantage, was important for adoption also suggests further attention to understanding the varied benefits that LMMA villages perceive from adoption, as such an understanding will be crucial to refining and framing LMMAs in ways that increase their likelihood of adoption elsewhere. Complementary work based in cultural evolution theory may provide additional insights into these dynamics (Waring et al., 2015; Andrews and Borgerhoff Mulder, 2018; Brooks et al., 2018). More generally, our findings show that trust and overall relative advantage remain crucial to scaling Indigenous-led resource management, suggesting that practitioners and policymakers continue to build long-term relationships with Indigenous partners and maintain a focus on understanding how their efforts can benefit those who are most directly impacted.

We also draw attention to the limits of scalability across contexts where national policies and legislations may not recognize or support Indigenous-led resource management. Our study's focus within one national context limits generalizability but we hope our results encourage future research to tease out the effects of national policies and legislations that support or hinder Indigenous-led resource management. We also raise questions about whether Indigenous-led resource management can sustain themselves without support from external organizations and how long more direct support is required. This could be better addressed by offering support or incentives beyond the implementation of initiatives to focus on sustaining them (recognition and facilitating stewardship by communities, formalizing management which would, in turn, formalize benefits from management such as regulation and licensing, flexibility in design of initiatives to adapt to changing priorities).

5. Conclusion

Given the urgency of global biodiversity and climate change concerns, understanding what drives the adoption and spread of resource management and conservation initiatives is imperative. Indeed, expanding equitably governed area-based conservation to meet Target 3 of the GBF necessitates scaling up measures like Fiji's LMMA Network. The results from our study can help identify characteristics of an initiative (e.g., relative advantage, compatibility with practices), adopter (e.g. social structure and decision-making), and context (e.g. presence of support organizations, trust, proximity to industries) that drives adoption. Some of these characteristics can be understood before the implementation of an initiative, helping community associations and other support organizations direct funding and support to sites where adoption is most likely, and to build a critical mass for further scaling (Jackson and López-Pintado, 2013). Further work can help identify how many years of active support is needed to ensure the durability of the initiatives. Similar studies that test the Diffusion of Innovations theory across different countries and different types of conservation initiatives can offer insights into the presence or absence of generalizable processes that facilitate the adoption and spread of initiatives. Ultimately, this better understanding may help scale up action to safeguard nature and its essential contributions to all people through socially just and equitable measures.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2024.102799.

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