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The impacts of digital transformation on fisheries policy and sustainability: Lessons from Timor-Leste

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ABSTRACT

Digital technologies are transforming how we monitor and manage natural resources, by speeding up data-driven decision-making. Still, to date, there is scant evidence of their impacts on environmental sustainability. In fisheries, a digital record of landings represents enormous potential for sustainable food production, resource management, and livelihoods, by making information about fish production and price available to all. To fill a gap in information and understanding about fisheries in Timor-Leste at the time, and to inform decision-making to renew outdated fisheries legislations and strategies, the 'Peskas' system was developed and piloted in Timor-Leste in 2017. Peskas was designed to collect, analyse and display small-scale fisheries data in near real-time to improve fisheries management through real-time data-driven policymaking. Using targeted interviews in key stakeholder groups, we assessed the progress made toward this goal through three different pathways over a six-year period: i) capacity building; ii) partnership and collaboration; and iii) sustainable resource management. Results showed that the formal Government adoption of Peskas was a tipping point that catalysed greater intragovernmental collaboration, as well as between government and communities, and brought new investment into the fisheries sector. However, Peskas has had minimal impact on the development of new regulations to date. We discuss reasons for this, such as an inadequate fisheries legal framework and wider capacity gaps and draw broader recommendations for how to leverage digital transformation for positive change in fisheries sustainability.

Synopsis

Research on how digitalisation drives more effective policies for sustainability and food production is sparse. This study shows limited impacts of digital monitoring on new legislation, but positive investments and collaboration from digital uptake.

1. Introduction

Digital technologies can enhance the efficiency, equity, and environmental sustainability of food systems and potentially increase the competitiveness of small-scale producers. By enabling the collection, storage, analysis, and dissemination of information, they can lower the transaction costs of connecting sellers and buyers (Jagun et al., 2008); reduce or remove barriers to knowledge and markets; and enable more precise and timely decision making (World Bank Group, 2019). In fisheries contexts, there is evidence that sustainable fisheries management and food and nutrition security goals can be supported by more robust data throughout the fisheries value chain (Hilborn et al., 2020). Digital technologies are used in a variety of ways in industrial fisheries from blockchain to virtual reality to improve efficiency and reduce food fraud, contamination, and waste (Cusack et al., 2023; Rowan, 2023). Some research also suggests that digital technologies can drive improved social cohesion and collective action (Nthane et al., 2020) and improve biodiversity conservation outcomes (Fulton et al., 2018). The Covid-19 pandemic and the need to transact with minimal physical contact,

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catalysed the development of digital markets and related enterprises (Ferrer et al., 2021; Stone, 2020), but innovation in small-scale fisheries is hobbled by underlying political, social and economic disparities. Sensors and automated analytics facilitate data generation, analysis, and communication, however, in small-scale fisheries, getting simple, usable data and turning that information into knowledge for decision-making has been challenging.

Inclusive digital transformation relies not on merely generating data, but rather tackling the social and economic inequities of accessing and using data and digital services. This is termed the "digital divide"(FAO and WorldFish, 2020), and it directly influences the rate at which digital development can influence fisheries production and livelihoods. This is especially true in low-income countries where there are many social, economic, and physical barriers to accessing any digital resources, such as the cost of technology and internet connectivity, literacy, and power and internet coverage in rural areas. Without addressing the digital divide and the human rights that underpin it, digital transformation can exacerbate inequalities, especially among already vulnerable communities and groups (Blythe et al., 2018). Addressing these gaps with SSF in low-income countries requires sensitivity to the limits of resources and the capacity to collect, store, analyse and respond to this data (Kolding et al., 2014).

Globally, approximately 40 % of capture fisheries are landed by small-scale fisheries (SSF) and in Africa this is as high as 66 %, yet the lack of data and information on SSF means we often have very limited scientific insight into ecological resources, as well as the social and economic dynamics of this sector (FAO, Duke University and WorldFish, 2023). As such, decisions are often made based on tradition, assumptions, or generic management knowledge. There are over 100 million people actively fishing in inland and coastal environments worldwide, yet due to the challenges involved in collecting data in dispersed, informal and diverse fisheries, the contributions of SSF to livelihoods, and also food and nutrition security, are frequently hidden and poorly accounted for (Mills et al., 2023). Consequently, fisheries solutions are underrepresented in investments and policies to address food and nutrition security (FAO, 2018). Recent research has shown that the nutrient qualities and quantities of fish already caught would be sufficient to address major micronutrient deficiencies in many countries (Short et al., 2021), and that fish-based food strategies hold untapped potential to address nutrition shortfalls (Hicks et al., 2019).

Timor-Leste is a country afflicted by malnutrition, sustaining one of the world's highest rates of stunting (low height for age), afflicting 47.1 % of children under 5 years old (Ministry of Health, GOTL, 2020). Stunted growth is multifactorial, but in Timor-Leste, a monotonous diet is likely an important factor (Provo et al., 2017). There is mounting evidence that fish is an underused resource with the potential to improve dietary quality (Mills et al., 2023, 2013), and fisheries have been a focus of national development priorities to eliminate malnutrition since 2011 (GOTL, 2011). But until recently, there was little information on the fisheries sector in Timor-Leste with which to prioritise interventions and investment.

The fisheries sector is also defined by an uncertain legal and policy landscape. The various decrees governing marine fisheries, dating from 2004, were unified and updated in 2018 into a revised fisheries law, but this remains unenacted. Numerous national fisheries strategies have been developed since independence in 2002 (Tilley et al., 2019), the most recent of which remains in draft since 2018 (Ministry of Agriculture and Fisheries, 2018). The National Biodiversity Strategy and Action Plan (2011–2020) prioritised marine biodiversity protection and sustainable use of coastal fisheries resources. The Program of the 8th Constitutional Government 2018–2023 defines fisheries objectives as improving fisheries infrastructures, increasing export and local consumption for food security purposes, and improving legislation and capacity for regulation and control of fisheries (Program of the Eighth Constitutional Government, 2018–, 2023; "SPC ReefLex," 2023).

In 2016, as part of a larger fisheries sector support program in Timor-Leste, WorldFish and the Timor-Leste General Directorate of Fisheries and Marine Resources started to co-design and develop a bespoke digital fisheries monitoring system called Peskas—meaning fisheries in the national language, Tetum. Peskas is a publicly available interactive dashboard for data exploration and decision-making processes in SSF (www.peskas.org). Peskas connects open source programs to collect, communicate, analyse and visualise SSF movement and catch data on a dashboard (Longobardi et al., 2021; Tilley et al., 2020). Using this dashboard, users can access information on total national catch, revenue, catch per unit effort, species composition and potential nutrient supply of catches at municipal and national scales. In 2019, the government of Timor-Leste formally adopted Peskas as the national fisheries monitoring system ("Timor-Leste Lansa Sistema Monitorizasaun Peska Dahuluk," 2019).

Information on the effects of digital interventions in fisheries contexts is hard to find because impact assessment is rarely incorporated into project activities, and projects or technologies that are discontinued, go mostly unreported (FAO and WorldFish, 2020). Foresight analysis has shown promise in highlighting negative externalities of digital technologies (Fleming et al., 2021) and robust evaluation methods are essential (Lioutas et al., 2021).

This study aimed to assess the impact of the Peskas digital fisheries monitoring system on three areas of fisheries: i) capacity building; ii) partnership and collaboration; and iii) sustainable resource management. Using interview responses, we draw examples and insights to guide the implementation of digital monitoring systems that improve data driven fisheries resource management and contribute to long term outcomes of improved livelihoods, increased food security, and improved capacity for digital transformation.

2. Methods

2.1. Research approach

Fisheries are complex systems with multiple subsystems interacting with each other. The three areas of influence i) capacity building; ii) partnership and collaboration; and iii) sustainable resource management were identified from the intervention Theory of Change (ToC) developed by the study authors from the framework of Timor-Leste national development priorities (Fig. 1). The integration of a ToC helped to identify the causal linkages from the intervention activities through to the desired development outcomes at the household level (Connell and Kubisch, 1998; Douthwaite et al., 2013) and helped design the sampling protocol and research tool (see Section 2.3). This study examines the perceived changes among key stakeholders across these three areas following the adoption of the Peskas system. We explore how these perceived changes subsequently affected the Timor-Leste fishery system to contribute to sustainable resource management, improved stakeholder collaboration, and enhanced capacity for broader digital transformation.

2.2. Study site and key features of the Peskas system

The Democratic Republic of Timor-Leste is a small, half-island nation of 15,410 km^2 with a population of ~1.4 million. It has a coastline of 730 km and an exclusive economic zone (EEZ) of about 72,000 km^2 (FAO, 2019). The rural population are predominantly pastoralists, with a small fishing fleet of canoes and motorboats fishing on narrow, fringing coral reefs and nearshore pelagic areas. Hence, the exploitation of ocean resources represents a substantial potential for one of the poorest and most undernourished rural populations in the world (von Grebmer et al., 2020).

Peskas enumerators are government employees based in communities who gather fisheries data at 18 landing sites across the 12 coastal municipalities and act as local community liaisons and networking agents between stakeholders. The 18 landing sites were chosen because

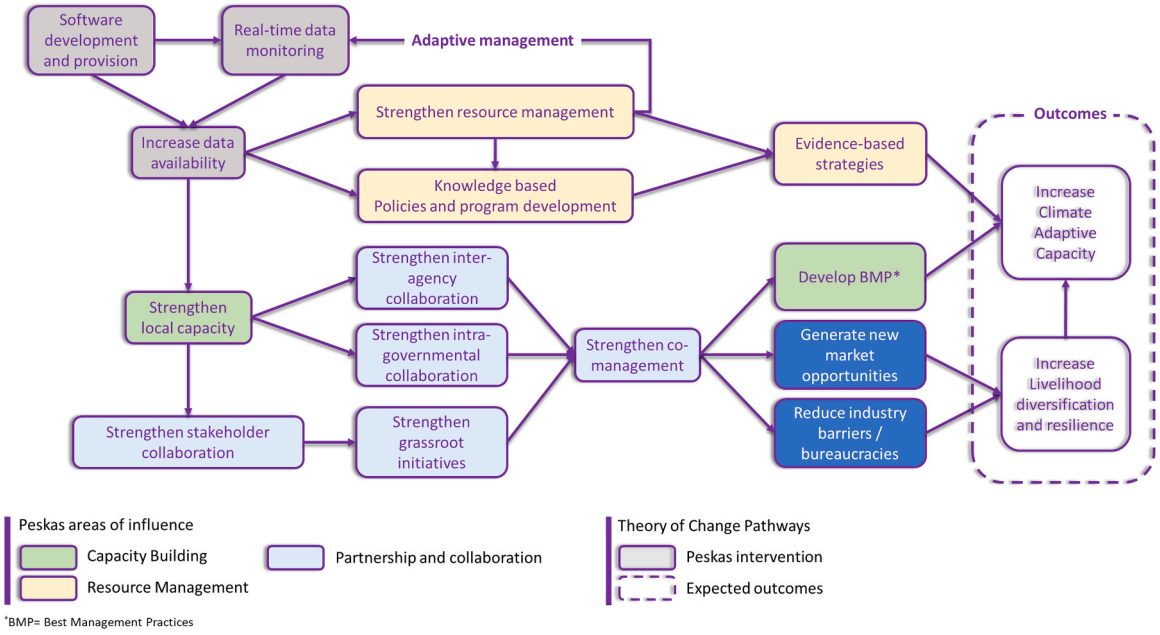

Fig. 1. Peskas theory of change pathways and outcomes according to the three areas of influence (colour coded).

of their importance and recognition as fisheries areas, rather than a stratified sampling of the national coastline. It is estimated that the 18 sites aggregate catches from approximately 20 % of the coastal fishing area of Timor-Leste. A wide range of real-time fishery variables are recorded, including total catch per species groups, size frequency information, estimated revenue, and fishing location. The landings data are ingested into the Peskas workflow, are validated using biological and fisheries thresholds based on scientific knowledge (Longobardi et al., 2021). Any flagged records are then manually validated and corrected where relevant, then added to automatic near-real-time analytics

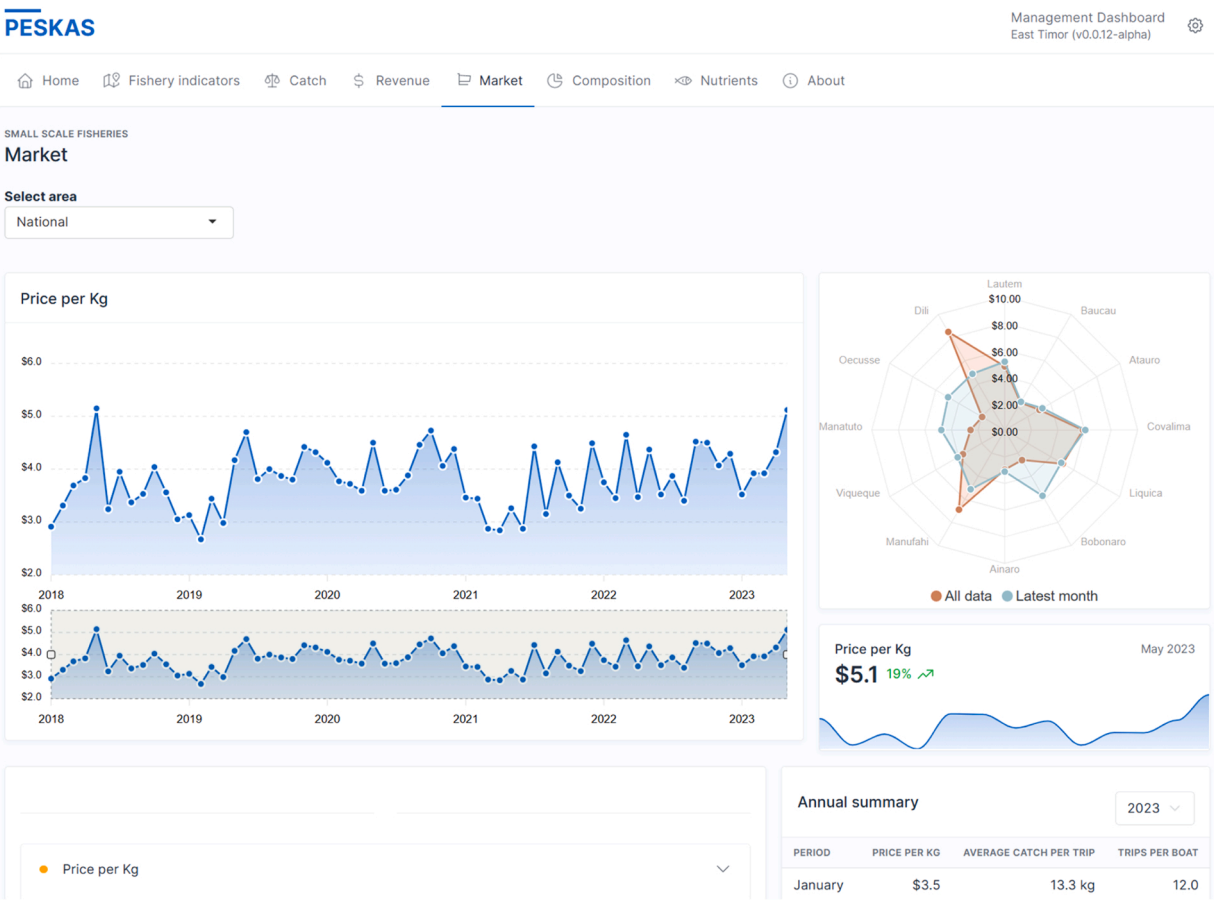

Fig. 2. An example screenshot of the dashboard of the Peskas national fisheries monitoring system of Timor-Leste. www.timor.peskas.org.

displayed on the Peskas dashboard (Fig. 2). The study survey focused on the capital Dili, where national government staff are based, and in the municipalities of Liquica, Bobonaro and Lautem, where stakeholders are familiar with Peskas since its launch in 2017.

2.3. Data collection

The primary data for the study was collected through expert interviews between August 2021 and October 2021. A total of 39 expert interviews were conducted in all but two of the coastal municipalities, covering key stakeholders that are both relevant to the development of the fishery sector and are aware of Peskas key features. The study identified the main stakeholder groups including different government levels (i.e., municipal and national governments), private sector, fisheries leaders at the community level, NGOs, and Peskas enumerators. Subsequently, interviews were conducted to cover each stakeholder group (see Table S1). The total number of interviews conducted for the study was guided by a saturation analysis (Section 2.4). The expert interviews consisted of both open and closed questions covering the topics from the study's conceptual framework (Appendix SI1) and sought to capture the expected outcomes of the Peskas ToC (Fig. 1). The design of both open-ended and closed questions drew upon multiple theoretical frameworks and help structure the scope of respondent answers. These frameworks covered subjects including capacity building (Brown et al., 2006), ecosystem services (Díaz et al., 2018; Leemans and de Groot, 2003), local institutions (Ostrom, 2011), policy analysis (Murphy, 2012), and sustainable livelihoods (Note, 2017) (see Table S2 for details). Questions were grouped according to the three areas of influence, and as such, an individual's perception of a mechanism or change, may differ according to the area. All interviews were conducted in person and followed all precautions necessary to minimize physical contact established by Timor-Leste authorities due to the Covid pandemic. Each interview lasted between 30 to 45 min and was conducted by interviewers in the Tetum language. All interviews were transcribed in English for subsequent analysis. The interview captured collaboration flows between actors through a semi-structure questionnaire and identified a) the list of actors each interviewee interacts with, b) the type of interaction (e.g. funding, capacity building, extension services, etc.) provided or received from each listed actor before and after the rollout of Peskas, and c) a Likert scale of the effectiveness and satisfaction of such interactions (1 = very dissatisfied, 2 = dissatisfied, 3 = somewhat dissatisfied, 4 = neither satisfied nor dissatisfied, 5 = somewhat satisfied, 6 = satisfied, 7 = highly satisfied).

2.4. Data analysis

Open-ended questions from the expert interviews sought to explore interviewees' perspectives on the contribution of Peskas across the expected area of influence (Section 2.1). The questions covered topics such as the role of Peskas in improving fisheries technical capacity, developing new partnerships and collaboration, strengthening fisheries resource management, opening new markets and micro-enterprise opportunities, promoting new evidence-based policies, and developing sustainable livelihoods. All responses from the open-ended questions were subsequently analysed through content analysis. The coding of the content analysis was conducted by one of the co-authors of this paper to ensure consistency in the coding. The coding was performed manually using Excel extracted from the translated interview transcripts.

Data saturation is a method used to estimate the likely number of qualitative interviews needed to reach saturation of new information for a given study (Guest et al., 2020). A saturation analysis was conducted while the interviews were ongoing to identify when new findings from the open-ended questions started to decline (Fig. S1). The results showed that by the 25th interview, the coding saturation reached 80 % of the total content analysis and by the 36th interview the saturation reached 99 % of the total content analysis. After conducting the 39th interview and considering we covered all actors of interest the authors decided that further interviews will yield no incremental benefits to the study.

Closed questions from the expert interview sought to understand the scale of the impact and relied mostly on ranking questions (1 =very ineffective, 2 =ineffective, 3 =somewhat ineffective, 4 =neither effective nor ineffective, 5 =somewhat effective, 6 =effective, 7 =highly effective). The average of the responses is presented in the results section across the Peskas area of influence. Additional to the averages, a consensus analysis is also provided for this ranking question. Both average ranking and consensus level considers only completed responses from the interviewees and the total number of responses ("n") are presented in each table. The consensus level represents the level of agreement among the respondents regarding the ranking provided. In other words, the consensus analysis provides an idea of the dispersion for any given ranking question and is measured with values ranging from one ("1") representing full consensus to a value of zero ("0") representing complete disagreement (Tastle and Wierman, 2007).

3. Results

3.1. Capacity building

Most respondents across different actor groups stated that the most relevant improvement since the rollout of Peskas has been positive policies and enhanced access to technical training (Table 1).

> "Peskas provides the fisheries data the country needs the most. With the data, [the Ministry of Agriculture and Fisheries] should be able to identify the weaknesses and abilities of the fishers and provide them with training in new technologies and techniques" (fisherman, personal communication, August 18, 2021).

Respondents suggested that new collaboration networks between fishery actors have been created thanks to Peskas. These strong collaboration flows were reported between municipal and government officials through capacity-building coordination (Fig. 3).

> "Through Peskas, the coordination network has been improved where it promotes trust and legitimacy for managers at all levels. This system has effectively provided fisheries data that directly contributes to the country's priorities and goals" (fisherman, personal communication, August 18, 2021).

However, the perceived networking progress shows a lower consensus level compared to the other contributions (Table 1). This could reflect stakeholder challenges to assign causality between Peskas and non-production related outcomes (e.g. women empowerment, co-

Table 1
List of perceived progress resulting from Peskas efforts to improve partnership and collaboration between Timor-Leste fishery actors.

Peskas contribution	(n)	Rank	Consensus
Increased capacity building and technical training	29	5.6	0.60
Positive policies (new regulations, laws, national or regional plans, etc.)	29	5.8	0.74
Resource management improvements	23	5.1	0.60
Equitable access to resources (among women and vulnerable groups)	20	4.8	0.50
Increased resources (funding, personnel)	20	5.4	0.59
Improved networking between all actors	19	5.1	0.53
Sharing resources, risks, and responsibilities between all actors	19	5.3	0.58
Gender equality (equal access to resources, credit, and benefits)	16	5.4	0.63
Increased partnership commitment	13	5.3	0.60
Increased monitoring of fish resources	1	7.0	1.00

Note: Rank measured on a 7-point Likert scale (1 = low progress; 4 = neutral; 7 = high progress); "n" = the number of unique respondents listing the observed change; consensus level (0 = full dissent and 1 = full consensus).

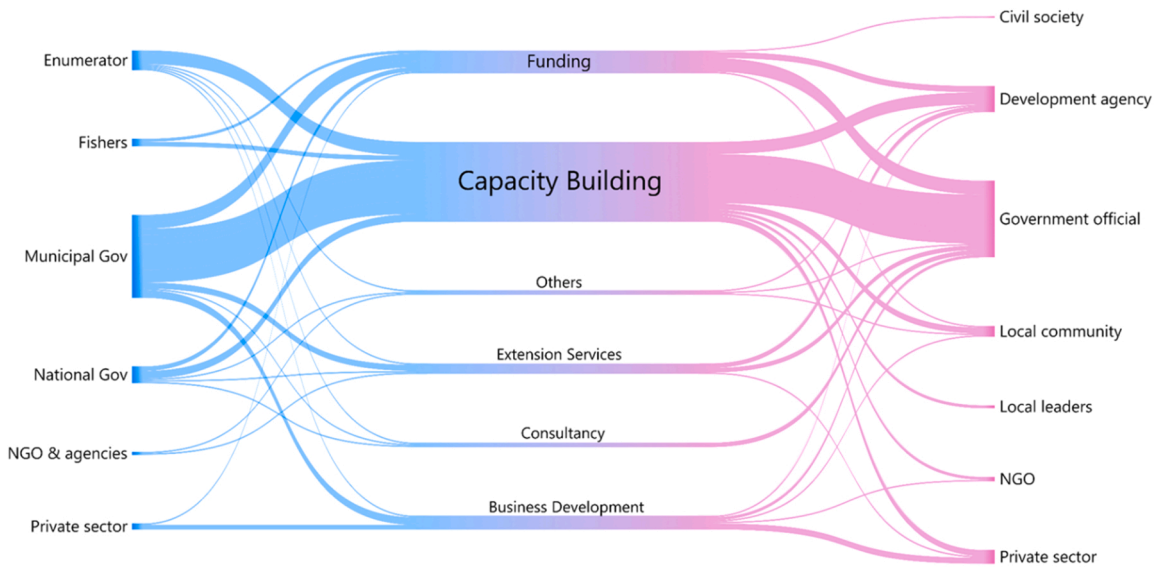

Fig. 3. New collaboration flows between fisheries sector actors in Timor-Leste due to Peskas.

management). The need for more specific training seeking to increase digital literacy and resource management was noted as a challenge to drive further changes in management practices and policy *"More training and capacity building for fishers to fully understand this digital system [is needed], but [also] more importantly, the whole [concept of] fisheries management. Also, knowledge transfer and public awareness on the fisheries laws and regulations is important, where fishers will eventually have a better understanding of the fisheries resources"* (Municipal official, personal communication, August 27, 2021).

Responses show statistically significant progress toward sustainable development of the fisheries sector in key areas since the rollout of Peskas (Table 2). Moreover, these results have the highest consensus levels across the respondents showing that Peskas contribution to a sustainable fishery sector is clearer among all stakeholders. However, key factors to incentivize the development of new markets and micro businesses are lagging. Access to extension services, credit, and inputs, such as fishing gear, have not significantly improved *"there is a real need for access to microcredit or loans for fishers and traders to support enhanced production and fish supply"* (NGOs and agencies, personal communication, September 8, 2021).

Table 2
Perceived progress to develop a sustainable fishery sector in Timor-Leste before and after the rollout of Peskas.

	Progress		Consensus		Sig	
	Before	After	Before	After		
Adoption of best management practices (n = 39)	4.1	5.2	0.6	0.7	0.001	***
Access to extension services, credit, and inputs (n = 39)	4.1	4.5	0.6	0.7	0.191	
Improved fish harvest productivity (n = 39)	4.7	5.5	0.7	0.8	0.001	***
Access to fish market and distribution infrastructure (n = 39)	4.5	5.5	0.7	0.7	0.000	***
Knowledge of fish availability by season (n = 39)	4.8	5.6	0.7	0.8	0.001	***
Livelihood diversification (n = 39)	4.5	5.5	0.6	0.8	0.000	***
Post-harvest management activities (n = 39)	3.9	4.9	0.6	0.7	0.000	***
Access to real-time fishery data (n = 39)	4.5	5.3	0.7	0.8	0.000	***
Regional management of fishery resources (n = 39)	4.3	5.5	0.6	0.8	0.000	***
Equal access to fishery resources (n = 39)	4.3	4.8	0.7	0.7	0.006	**
A shift from unsustainable practices (n = 39)	4.4	5.1	0.7	0.7	0.013	*

Note: Progress measured on a 7-point Likert scale (1 = very ineffective; 4 = neutral; 7 = highly effective); consensus level (0 = full dissent; 1 = full consensus); "n" = sample size; ***p < 0.001; **p < 0.01, *p < 0.05.

3.2. Partnership and collaboration between stakeholders

New collaboration networks have been created through the development and scaling of Peskas. Intragovernmental collaborations have expanded, most of them considered 'satisfactory' (Fig. 4): *"With the existing cooperation, [the Ministry of Agriculture and Fisheries] and WorldFish can create a strong collaboration in the fisheries and aquaculture sector in Timor-Leste"* (NGOs and agencies, personal communication, September 8, 2021). However, there is concern that without continuous efforts to sustain them, they will fall apart *"[what is needed is to] improve more coordination network between government entities and NGOs through Peskas"* (National government official, personal communication, September 3, 2021).

Results show mixed progress in improving the effectiveness of partnerships. While respondents agree that partnerships between and within different actors have significantly improved since the rollout of Peskas (particularly government and local communities), partnerships involving the private sector still feature among the lowest progress areas (non-statistically significant) (Table 3).

> "Peskas has provided really good data, yet more coordination and consultation [with local communities] are needed when it comes to design and implementation of any marine and fisheries resources management policies, regulations or customary laws" (Peskas enumerator, personal communication, August 27, 2021).

Results show that key dimensions of community integration into management have improved since the establishment of Peskas (Table 4).

3.3. Sustainable resource management

The expert interviews suggest that Peskas contributes to data-driven decision-making for effective resource management at the national/regional level: *"With Peskas, [the Ministry of Agriculture and Fisheries] can manage fisheries and marine resources by taking wise decisions"* (Peskas

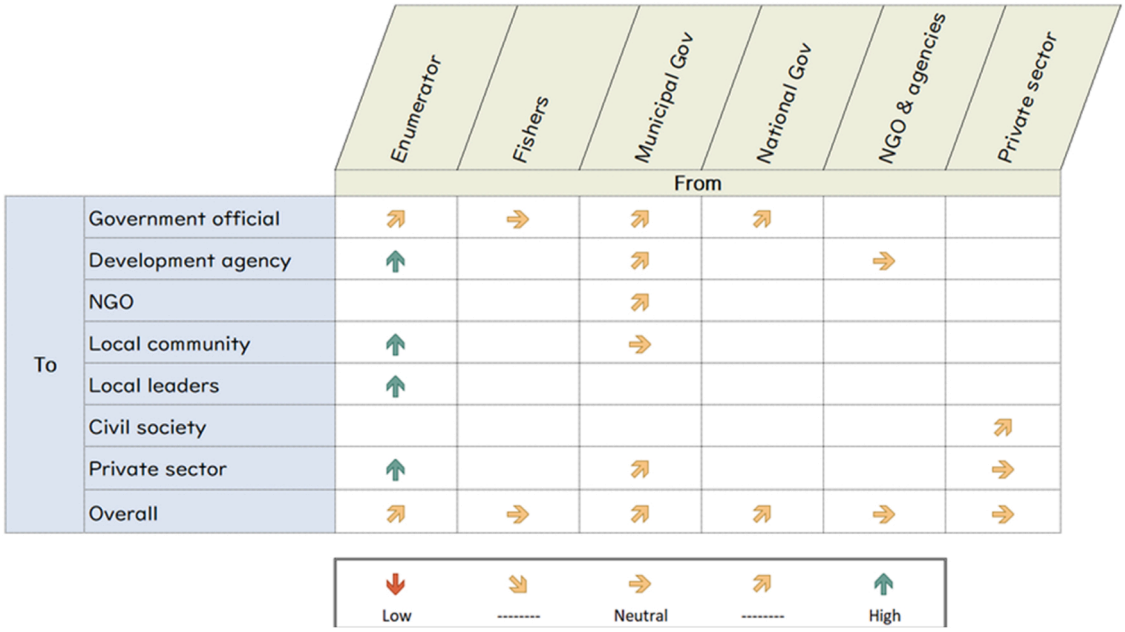

Fig. 4. Collaboration satisfaction between actors since the Peskas rollout. Satisfaction was measured on a 7-scale Likert scale (↓ = 1 to 2.2; ↘ = 2.2 to 3.4; → = 3.4 to 4.6; ↗ = 4.6 to 5.8; ↑ = 5.8 to 7).

Table 3
Progress and consensus level of partnerships effectiveness since the rollout of Peskas.

	Progress		Consensus		Sig	
	Before	After	Before	After		
Between community members (n = 37)	5.1	5.6	0.8	0.8	0.002	**
Between private actors (n = 38)	4.5	4.8	0.7	0.6	0.246	
Between government and the community (n = 38)	4.7	5.2	0.7	0.7	0.017	*
Between government and the private sector (n = 38)	4.9	5.3	0.8	0.7	0.085	
Between government departments (n = 38)	4.9	5.6	0.8	0.8	0.002	**
Between the private sector and the community (n = 38)	4.7	5.1	0.7	0.7	0.134	

Note: Progress measured on a 7-point Likert scale (1 = very ineffective; 4 = neutral; 7 = highly effective); consensus level (0 = full dissent; 1 = full consensus); ***p < 0.001; * *p < 0.01, *p < 0.05.

Table 4
Resource management progress since the rollout of Peskas.

	Progress		Consensus		Sig	
	Before	After	Before	After		
Transparency of decision-making process (n = 39)	4.5	5.3	0.6	0.7	0.000	***
Communication between govt. and communities (n = 39)	4.6	5.4	0.7	0.8	0.009	**
Monitoring and evaluation of fisheries (n = 39)	4.8	5.4	0.8	0.7	0.003	**
Access to quality data and research (n = 39)	4.7	5.4	0.8	0.8	0.002	**
Enhanced resource allocation capabilities (n = 39)	4.7	5.2	0.7	0.7	0.021	*
Sustainable fishery practices (n = 39)	4.5	5.0	0.6	0.7	0.020	*

Note: Progress measured on a 7-point Likert scale (1 =very ineffective; 4 =neutral; 7 =highly effective); consensus level (0 =full dissent; 1 =full consensus); ***p < 0.001; **p < 0.01, *p < 0.05.

enumerator, personal communication, August 31, 2021), however, the actual decisions being taken based on the data remain ambiguous. The need was stated to move beyond data generation to develop new fisheries policies and interventions based on the information collected from Peskas:

> "Since 2019 there haven't been any new regulations or policies due to Peskas, but luckily this digital platform has helped many of us to see the fisheries data in real-time" (Private sector, personal communication, September 7, 2021).

> "This work shows the importance of fisheries data to marine resource management, yet the implementation of regulations, policies and strategies should be built on this evidence" (Peskas enumerator, personal communication, August 19, 2021).

The information presented by Peskas was reported to be important to track national and international goals, and shape national-level strategies and policies (Table 5). Despite the lack of specific examples of data-driven decision-making and a slight reduction in consensus about monitoring and evaluation of fisheries before and after Peskas, the results suggest significant improvement in the *transparency* of decision-making, the effective communication between government officials and the community, and more effective monitoring of resources (Table 4).

4. Discussion

4.1. Capacity building

National government staff contributed to the iterative design of Peskas, and as such it responds to the needs and capacity level of national fisheries managers in terms of the types of data collected, the

Table 5
List of the most relevant use of the information generated by Peskas to develop the Timor-Leste fisheries sector.

Contribution type	(n)	Rank	Consensus
Development of policies and regulations for the fishery industry	34	5.9	0.63
National production and food balance information	26	6.0	0.72
Academic research	23	6.0	0.71
Monitoring national goals	22	6.0	0.76
Resources allocation (people, budget)	21	5.7	0.67
Development assistance prioritization	21	5.5	0.70
Monitoring international goals and objectives (e.g., SDGs)	19	5.5	0.63
Fishermen Training	1	4.0	1.00

Note: Rank measured on a 7-point Likert scale (1 = low progress; 4 = neutral; 7 = high progress); "n" = the number of unique respondents listing the observed change; consensus level (0 = full dissent and 1 = full consensus).

sophistication of analyses and presentation of results. To ensure the system could be maintained both financially and technically, training and outreach activities were undertaken from the local community level to national fisheries officers. This vertical flow of information was seen as an essential factor to increase engagement of, and collaboration between, fisheries stakeholders, and contributed to the Government of Timor-Leste's decision to adopt and invest in Peskas as the national fisheries monitoring system. In digital development, insufficient user-centred design and iterative adaptation in response to feedback can lead to a weak sense of ownership and legitimacy, and as such limit uptake and sustainability (FAO and WorldFish, 2020; USAID, 2017).

The slow uptake of digital technologies in fisheries has been attributed to legal and institutional barriers, along with a lack of trust between stakeholders (Bradley et al., 2019), but in Timor-Leste, respondent that Peskas increased collaboration through new and existing connections (Fig. 3). The first phase of Peskas was 'top-down', focused on designing a system to collect and visualise data with and for the Ministry of Agriculture and Fisheries. Top-down data systems with limited vertical exchange between stakeholders can discourage fishers and enumerators from submitting accurate data (Eayrs et al., 2015). Peskas is currently not designed for effective use by fishers, and to date, there has been little training focused on data literacy and digital tools at the community and fisher level, with only the community enumerator receiving directed training. Fisher training programs and the development of new Peskas elements will be needed to increase impacts on fisher livelihoods, empowerment, and gender-transformative approaches.

4.2. Partnership and collaboration between stakeholders

Digital transformation in education scenarios has been shown to reduce administrative burdens and increase collaboration (Timotheou et al., 2023). The design of Peskas to utilise community members as enumerators was intentional, incorporating learning from the expansive research on community-based resource management approaches in the Pacific (Steenbergen et al., 2021). The presence and employment of a community member in a government position is not novel, but this investment and level of engagement in coastal fishing communities by the government is an innovation in Timor-Leste. In national consultations carried out to guide the drafting of the national fisheries strategy of Timor-Leste (Ministry of Agriculture and Fisheries, 2018), the need for greater vertical communication with the department of fisheries was cited as important and aligns well with the current government objective of decentralisation (Program of the Eighth Constitutional Government, 2018–, 2023, 6.2). In a study of the effects of digital development on carbon abatement in China, it was found that promoting regional cooperation (reducing administrative divisions) had significant positive impacts on carbon abatement (Liu et al., 2022). Fisheries decentralisation will necessitate many investments at the municipal level, as stated by respondents, and these investments must be data-driven and increase the digital and financial inclusion of coastal communities, while minimising local protectionism. This initial step, of establishing community enumerators as part of Peskas development, appears to have been influential in improving collaborations within communities and between communities and government (Fig. 4). However, there must be a constant effort to go beyond using communities as information providers and research subjects, and instead to integrate their inputs and aspirations into the co-design of new digital tools and interventions (FAO and WorldFish, 2020).

Fisheries management in Timor-Leste is complex, with overlapping local, municipal, national and cultural governance institutions and jurisdictions (Tilley et al., 2019). Fishers and other community level stakeholders' interaction with the digital interface of Peskas is still limited due to the digital divide, so with appropriate training, the enumerator role is one that could be developed as an extension officer to build digital literacy, capacity, and empowerment of fisheries stakeholders. Currently, in most municipalities there is only one landing site for Peskas data collection, so aggregating data for municipal-level analysis and decision-making might be misleading. Hence, municipal-level fisheries management will also require investment to expand the number of landing sites monitored in each municipality to ensure adequate catch sampling. Currently, there are no plans for this expansion, and with Timor-Leste's reliance on dwindling oil reserves, budgets are more restrictive than ever (Novak, 2023).

4.3. Sustainable resource management

The information presented in Peskas is valuable to track national targets and resources. Moreover, Peskas has contributed to greater transparency and increased the amount of information available for decision-making. Our TOC proposed that more timely and accurate data would be used for better decision-making by fisheries officers, such as priority locations for extension services, training provisions or equipment subsidies to fishing communities, or to highlight major areas of need for new fisheries policies. There is evidence that the use of such innovations in other regions of the world has contributed to enhanced fishing sustainability (Hilborn et al., 2020). However, to date, few strategies, policies, and interventions have been developed in Timor-Leste from this information, so translation into decisions is missing.

However, the need to develop plans to guide and shape resilience and livelihood strategies at the community level was highlighted. These strategies include increasing the capacity of fishers and giving fishers agency over their businesses and lives *"we haven't seen any tangible impacts at the community level, specifically for fishers"* (Personal communication, Peskas enumerator, 19 August 2021). Aligned with the implementation of Peskas, WorldFish carried out national consultations with fishing communities in 2018 and 2019, to inform the drafting of a new national fisheries strategy (Mills et al., 2019). The focus of this draft strategy was on "Timorese fisheries for Timorese people" (López-Angarita et al., 2019), and holds great promise for a practical example of nutrition-sensitive fisheries management, where the goals of fisheries policies explicitly consider the contribution to broader societal goals such as diets, nutrition, health, and sustainability, rather than merely production and revenue (Thilsted et al., 2016). Unfortunately, the strategy remains to be formally adopted and implemented. In the absence of an approved national fisheries strategy, the development of national fisheries policies or municipal mechanisms based on new data will remain vulnerable to the agendas of external agencies and institutions.

4.4. Fundamental challenges and future directions

Timor-Leste faces substantial development challenges as one of the smallest countries in the world with a heavy reliance on dwindling fossil

fuels, imported food and external aid support (Novak, 2023). Climate change featured large as a threat to the fisheries sector (Table 6), which while very pertinent for fisheries development considerations, was beyond the focus of this study. As was the lack of a cohesive legal framework for the development of fisheries policies and strategies, which was voiced consistently: *"If [Timor-Leste] would have a strong and adaptable national law, this would help [combine the mutual strengths of] local and traditional laws in the fisheries sector"* (National government fisheries officer, personal communication, September 7, 2021).

Providing data to fishers for their businesses and livelihoods decision-making through Peskas, such as predicted fishing zones, cost vs. revenue comparisons across time, space and fishing method, or real-time market information, could catalyse new business opportunities. But first, this requires addressing systemic barriers such as literacy and the integration of rural communities into the formal economies. The evidence supporting digital tools in reducing time, costs and risks to value chain actors (Jagun et al., 2008) is irrelevant if the enabling conditions for uptake of digital tools are just not in place yet. As such, the direct investment and prioritisation of policies and activities that target digital inclusion (Mori, 2011) can have a tremendous impact on broader development objectives (Finaccess, 2019).

Infrastructure development (e.g., ports, administrative offices, marketplaces) was considered key to promoting public-private partnerships and increasing private sector investment in the fisheries sector. While this model has seen successes in Timor-Leste, such as the creation of tilapia hatcheries by the Partnership for Aquaculture Development (Pant et al., 2020), a history of interventions throughout the Pacific has shown the need to avoid the creation of more "white elephants," large infrastructures that now stand abandoned in several coastal sites (Eriksson et al., 2019). Any infrastructure development should be undertaken alongside thoroughly researched consultations with communities and levels of government and be implemented by those institutions to enhance their sustainability.

The information provided by Peskas on fish supply over time and space could be leveraged to support the development of new business opportunities and connections such as investing in cold-chain infrastructure, scaling distribution, or establishing a cooperative. However, this is unlikely to occur without substantial support from a government program or Public Private Partnership targeted towards digital transformation and growth of rural economies.

4.5. Limitations

This impact assessment was based solely upon information from interviews with key stakeholders from the fishery sector in Timor-Leste. The role of these stakeholders in the design, implementation, and maintenance of the Peskas system may have led to potential biases in their responses, namely social-desirability bias and confirmation bias. Furthermore, while response rate was high (i.e. the study was able to interview most of the selected candidates), the limited pool of candidates that satisfied the selection criteria (see Section 2.3) for each type of actors may have led to a performance bias. The limited resources and the ongoing health risk posed by the COVID-19 pandemic limited opportunities to conduct community workshops and focus group discussions to cross-validate the interview results. To minimize the impacts of these limitations we interviewed experts across each key actor type (e.g., government, NGOs, local communities, etc.) and ran a saturation analysis to define the cut-off point of interviews. This is the first structured assessment of Peskas, and part of a longitudinal series of assessments that will be used to further adapt the development of Peskas in Timor-Leste and refine ways decision-making pathways into policies.

4.6. Conclusions and recommendations

The regulatory structure and legal framework for digital transformation are paramount to its success in driving development.

Table 6
List of most relevant challenges to develop a sustainable fishery sector in Timor-Leste.

Factors	(n)	Rank	Consensus
Climate change (changes in fish stock location and distribution)	29	5.9	0.74
Lack of capacity building and technical training	28	6.1	0.79
New market (domestic or export) opportunities	23	5.7	0.73
Unsustainable or destructive fishing practices (e.g., overfishing, dynamite fishing, illegal fishing)	23	5.6	0.59
Lack of information (e.g., production, stock status)	22	6.2	0.74
Market uncertainties (e.g., market price fluctuations)	20	5.9	0.70
Poor post-harvest infrastructure (roads, electricity, cold storage)	18	6.1	0.74
Poor post-harvest processing facilities and training	18	6.0	0.80
Unequal access to resources	17	5.9	0.75
Lack of access to credit and loans	14	5.5	0.68
Increased competition (e.g., imports, alternative sources of food)	13	6.1	0.81

Note: Rank measured on a 7-point Likert scale (1 = low progress; 4 = neutral; 7 = high progress); "n" = the number of unique respondents listing the observed change; consensus level (0 = full dissent and 1 = full consensus).

However, the information on how digitalisation can make agriculture policy more effective for sustainability and food production is sparse. To contribute more to the development of the agriculture sector and boost sustainable production, Peskas must evolve to capture and disseminate market information to reduce price dispersion and make information available to value chain entrepreneurs. This is illustrative of the need for digital applications across many contexts to adapt and update iteratively in response to user needs and changing conditions.

To enable fishers to use data to improve their lives, we must address systemic barriers to equal access for poor and marginalised groups. Technology subsidies, especially for rural dwellers, and campaigns targeting digital inclusion should be prioritised. Digital development must be mindful of the enabling conditions for the uptake of digital innovations and focus on how to add value for small-scale actors in ways that are ethical and transparent.

Digital transformation offers new potential for data-driven policy design, such as spatial targeting, tailoring of instruments at higher resolution, and a move towards information-based and adaptive governance based on guidance from machine learning and cybernetics approaches. However, institutional capacity and interests constrain progress, as do the capabilities of actors (Ehlers et al., 2021). Just as in Timor-Leste, many countries are in the position of having to increase base digital inclusion and capacity to achieve longer-term development goals through digital transformation.

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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2024.103684.

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