AN OPEN-SOURCE MOBILE GEOSPATIAL PLATFORM FOR AGRICULTURAL LANDSCAPE MAPPING: A CASE STUDY OF WALL-TO-WALL FARM SYSTEMS MAPPING IN TONGA

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ABSTRACT:

Pacific Island Countries (PICs) such as Tonga rely on services provided by agricultural landscapes to support livelihoods, economic activity, and food security. At the same time these landscapes face numerous pressures and risks from factors such as environmental, climate, and market changes. Accurate, spatially explicit, and timely datasets on agricultural systems is required for an array of land and agricultural management tasks. Here, the development of an open-source ICT system providing geospatial tools for landscape monitoring, developed in collaboration between geospatial researchers and Tonga's Ministry of Agriculture, Food, and Forests (MAFF), is presented. The agile and iterative ICT for Development (ICT4D) framework used to elicit MAFF's requirements for the ICT system is presented alongside the system architecture and case studies demonstrating its impact. A key goal of the ICT4D development process was to develop an ICT system to support MAFF from transitioning from infrequent, paper-based farm surveys to coordinated, large-team, spatially explicit digital surveying augmented by tools for analysis and reporting. The mature system architecture which includes QField and QFieldCloud, and new open-source geospatial components for spatial visualisation, analysis, and reporting is presented. Case studies where the mature tool was used by MAFF's are presented and include: (1) how a large survey team captured spatial data for >11,000 farms for country-wide farm monitoring; and (2) how the tool informed MAFF's landscape decision making including recovery efforts after the 2022 Hunga Tonga–Hunga Ha'apai volcano explosion. The success of the tool demonstrates the importance of stakeholder engagement and the great potential for open-source geospatial tools for landscape management and disaster response in PICs.

1. INTRODUCTION

Pacific Island Countries (PICs) such as Tonga rely on landscape services to support livelihoods and economic activity; both smallholder and commercial operations are important. However, PICs are increasingly vulnerable to shocks and stressors such as increasing cyclone occurrence and landscape conversion (Duncan et al., 2020). Spatially explicit, timely, and accurate datasets on land-use at community scale are an important source of information for agricultural policy development, landscape management, disaster response and recovery, and climate-smart sustainable development. However, such datasets aren't available or readily accessible to stakeholders engaged in landscape management. Household surveys, participatory GIS, agricultural censuses, and remote sensing are approaches that have previously been used to capture community-scale landscape uses in PICs; however, these approaches are challenged by data collection and management burdens, mismatched scales, timely integration of data streams, aligning system requirements with local needs, and socio-technical issues associated with developing and deploying applications in new domains. Such data collection approaches often are single time-step representation of land-use and fail to capture the highly

dynamic and spatially diverse nature of PIC landscapes.

These monitoring and data collection challenges were addressed in collaboration with Tonga's Ministry of Agriculture, Food, and Forests (MAFF); a continuation of earlier work (Davies et al., 2019). MAFF's goal was to transition infrequent paper-based and non-spatial farm surveys to a spatial data infrastructure that supports coordinated, large-team farm mapping, data syncing and storage, and geospatial data analysis and reporting. An agile and iterative ICT for Development (ICT4D) framework (Bon et al., 2016) was used by MAFF and geospatial researchers and developers to co-develop the tool. Here, the development activities associated with successive phases of the project are described and reflections on the advantages (and constraints) of using the ICT4D framework for developing open-source geospatial applications in new domains with a low-resource context are discussed. The mature system architecture and case studies of the tool deployment and use by for MAFF for applications such as country-wide wall-to-wall farm system survey completed in 2021 and assisting MAFF's recovery efforts in the aftermath of the Hunga Tonga–Hunga Ha'apai volcano explosion and tsunami which impacted the main island of Tongatapu in 2022.
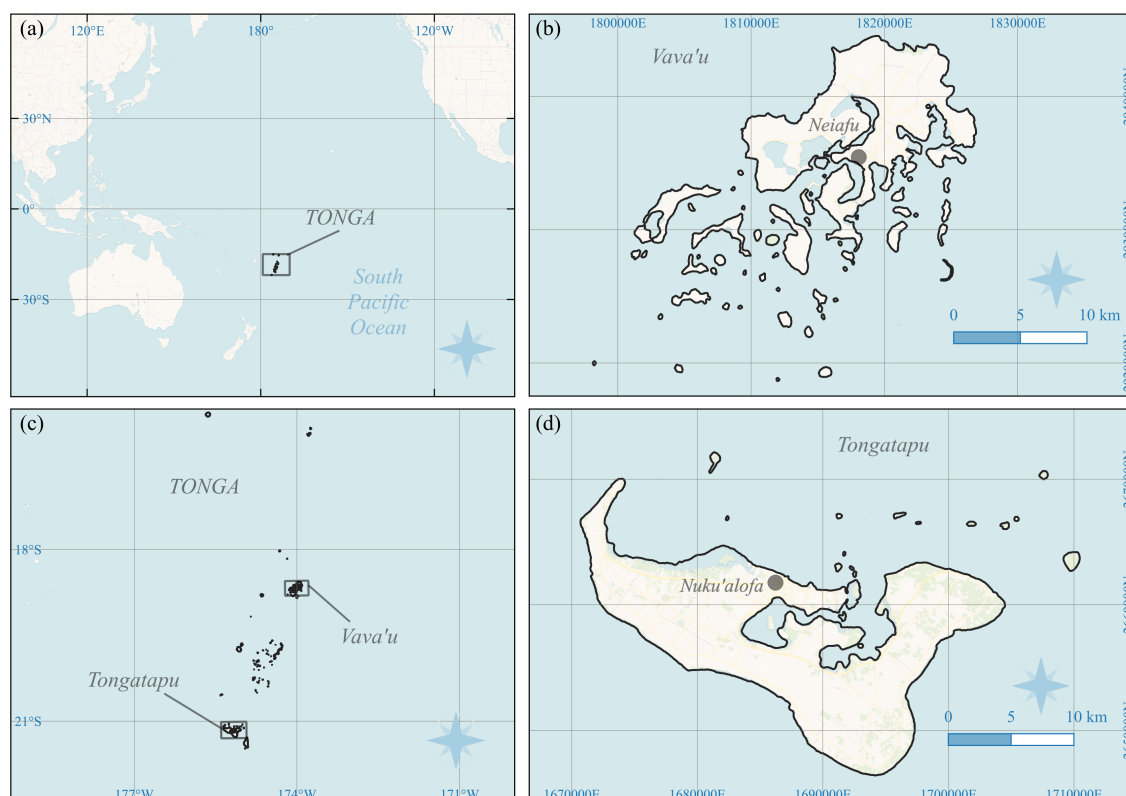
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Figure 1. Tonga (a) is an archipelago of 176 islands (b). Case studies focused on the islands of Vava'u (c) and Tongatapu (d).
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2. STUDY AREA

Tonga (Figure 1a) is an archipelago of 176 islands (Figure 1b), 36 of which are inhabited. The population of Tonga in 2016 was 100,651 with a large majority of the population (74,611) residing on the largest island of Tongatapu where the capital Nukualofa is located (Figure 1d). Agriculture is the dominant land use on Tongatapu with 42,497 acres of agricultural land. The island of Vava'u (Figure 1c) has a population of 13,738. In Vava'u there is 11,549 acres of agricultural land with 2,190 agriculturally active households, the majority of which are subsistence and semi-subsistence with only 1% of agricultural households engaging in commercial production. Households in both Tongatapu and Vava'u utilise the landscape to support a range of annual and perennial crops, livestock, fishing, and handicraft activities (MAFFF et al., 2015; TSD, 2017).

3. ICT4D OVERVIEW

The user and system requirements for the geospatial tool were identified through an ICT for Development (ICT4D) framework (Bon et al., 2016). ICT4D an iterative and agile approach to developing ICT solutions which engages stakeholders and end users at various stages of the development process. The ICT4D framework comprises five components: context analysis, needs assessment, use-case and requirements analysis, sustainability assessment, and development/testing/deployment. These components ensure that all project stakeholders and end users consider the range of technical and non-technical factors that will determine successful system implementation. In this project (UWA, 2022; Davies et al., 2019), the primary end users were MAFF; and, specifically officials within MAFF's extension di-

vision. However, the geospatial tool was designed to be generally applicable to a range of landscape mapping and (spatial) data collection tasks in different contexts. The development process started with a needs assessment to elucidate and prioritise different end users' unmet needs for geospatial data and applications. Having identified priority needs, successive phases of prototype development and in-the-field testing were conducted to elucidate key functional and non-functional requirements for the geospatial tool.

3.1 Needs Assessment

An initial needs assessment was undertaken to identify and prioritise end-user needs for geospatial applications or data that are relevant for agricultural landscape management tasks. Information for the needs assessment was sourced from focus groups and interviews with key stakeholders. Care was taken to include stakeholders operating at the national-level (e.g. MAFF's head office) and at the local-level (e.g. extension officers who work directly with farmers). Focus group discussions were structured around these guiding questions: What geospatial data do you currently collect or use?, How do you access geospatial information?, How do you collect new geospatial information?, What geospatial data needs do you have that are unmet?, and Are there any technical or organisational barriers to accessing geospatial information that you need?

The responses from the interviews and focus groups were collated. To organise this unstructured data. All needs recorded in the responses were summarised and given a thematic / descriptive label and then assigned to one of the following groups:

- **Geospatial Data**: a need for particular geospatial data such as crop types, land suitability, and land tenure.

- **Geospatial Data Collection**: a need to collect geospatial data e.g. crop type and management, market information.
- **Geospatial Analysis**: a need for spatial analysis.
- **Reference Geospatial Data**: a need for relevant geospatial reference layers at appropriate local scales.
- **Geospatial Data Sharing**: a need for sharing or communicating the geospatial data or results of analysis.

Within each of the groups, needs were prioritised using the criteria of: cost, technical feasibility, data availability, user capacity, and scalability (Table 1). This assessment provided broad scope boundaries for eliciting requirements for the ICT system.

Thematic Group	Priority Unmet Needs
Geospatial Data	Crop Type Map
Geospatial Data Collection	Crop Survey
Geospatial Analysis	Climate & Weather Analysis
Reference Geospatial Data	Land cover & Land Use
Geospatial Data Sharing	(no high priority need)

Table 1. Priority unmet needs by thematic group.

3.2 Requirements Analysis

In the ICT4D framework (Bon et al., 2016) requirements engineering, prototype development, and testing are based on agile methods. Agile approaches entail collaborative, incremental, and iterative development of ICT systems (Dijkers et al., 2018). Here, each phase of development started with end-users describing a need for geospatial data to achieve a task. Often, this narrative description of the task and identifying the data required and the necessary data collection and analysis steps were refined over several meetings. Subsequently this narrative description was converted into a brief set of functional and non-functional software requirements; a prototype application was developed to collect, process, and visualise the required geospatial data; and, the prototype was tested in-the-field by end users. Feedback was gathered and used to inform subsequent phases of development.

This approach ICT system development is collaborative and designed to engage end users, who might not have high-level technical or geospatial experience, and developers and geospatial specialists, who do not have high-levels of domain and end user context expertise (Bon et al., 2016; Dijkers et al., 2018; Bon and Akkermans, 2019). Through this approach, the requirements for the ICT system were analysed and specified incrementally. This allowed end-users to gain experience using ICT tools and to adapt their needs in-response to an increased awareness of how i) ICT systems could be deployed, ii) the data that could be generated, and iii) decision-making could be enhanced.

Initially, 10 use case diagrams that illustrated how different actors could use geospatial applications to achieve tasks were generated based on the high-priority needs. These were presented to landscape stakeholders and they were asked to comment on: the value of each task, overlaps with existing activities or applications already in-use, and potential gaps in functionality. Concurrently, a desktop review of mobile geospatial applications, which provided functionality for data collection and viewing spatial layers, was undertaken. Using feedback from stakeholders when reviewing the use case diagrams and the desktop application review, three prototype geospatial data collection projects were developed using QGIS/QField (OPEN-GIS.ch, 2022) and tested with MAFF officials : a crop and farm survey, a farm climate change vulnerability assessment, and a seed distribution survey.

Following field tests of the prototype applications, crop and farm surveying was deemed the most relevant. A crop survey is an annual data collection activity undertaken by MAFF staff whereas climate change vulnerability assessments and seed distribution surveys were not operational (despite MAFF staff and other stakeholders recognising the importance of this information). As MAFF staff had previously conducted paper-based farm and crop surveys, they had a point of reference to compare to the QField prototypes and a means to identify specific ways to improve an existing activity. This resulted in more detailed and precise feedback. End users also had a clear vision for how data generated by crop surveys and farm mapping could augment existing decision making, Ministry resource allocation, and landscape monitoring tasks. This was not the case for climate change vulnerability assessments and seed distribution surveys as they did not have experience using, or organisational processes in place to use, this data.

Further, from a user experience perspective, these initial field tests demonstrated that QField was a suitable application for spatial data collection. Users with minimal prior technical GIS or ICT expertise could interact with the QField interface to digitise features on the landscape (e.g. fields), use widgets to enter information into attribute forms, and navigate around the menus and settings. A key requirement of end-users was being able to view reference geospatial data layers in the field (e.g.datasets such as land tenure boundaries or basemap images for orientation). QField supports viewing local geospatial layers and web map services. In particular, vector tiles stored in MBTiles format and located on mobile devices can be rendered and styled in QField. This allows for large basemap datasets (e.g. entire OpenStreetMap database for a country) to be served to users without an internet connection or loss in spatial detail while keeping the application responsive.

Subsequent iterations of task description, prototype development, field testing, and software refinements included small-team mapping of vanilla plantation conditions (1-2 team members and 125 plantations), island-scale mapping of cropping systems (10 team members, 3000 farms), national-scale farm system mapping (40 team members, 11,000 farms). In between these "larger" field tests, there were frequent meetings to clarify requirements and small-scale development and test phases working on specific application functionalities. The initial phases of prototype development and testing focused on the design of spatial data collection tools using QField. Subsequent development phases focused on eliciting requirements, and developing solutions for data management, user and large-team management, tools for visualisation and analysis, and connecting data collection to decision making (Figure 2).

3.3 System Architecture and Deployment

The final architecture is comprised of open-source software components (Figure 3) that are integrated via the QFieldCloud API (OPENGIS.ch, 2022) to provide a geospatial tool for data collection, management, visualisation, and reporting tasks.

3.3.1 Data Collection QField is an open-source mobile geospatial data collection application (OPENGIS.ch, 2022) allowing users to open QGIS projects on mobile devices and interact with spatial data layers and attributes via a touch optimised interface. Spatial features can be digitised and edited using
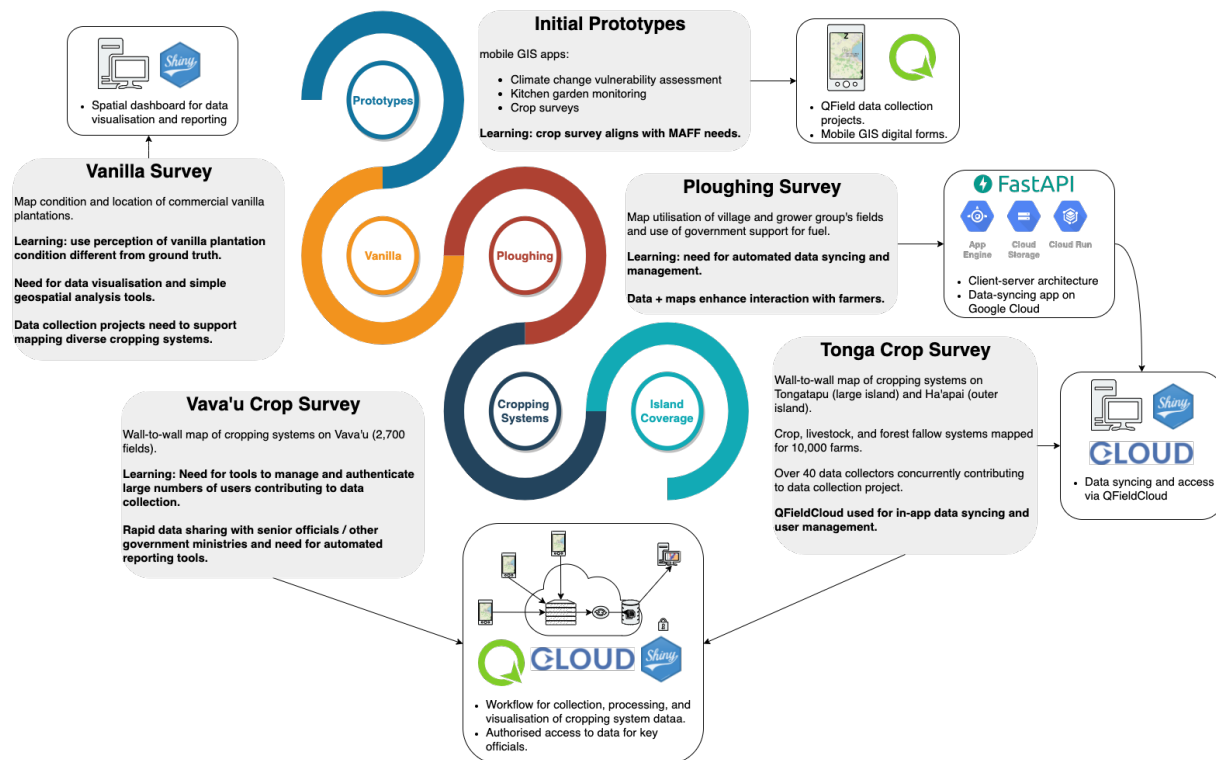
Figure 2. Main iterations of ICT system development moving from initial prototype applications, small data collection projects, to large-team data collection efforts with tools for data visualisation and reporting.

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the map interface and digital forms can be created for capturing attribute and non-spatial data.

3.3.2 Data and User Management Geospatial data management, user management, and authentication/authorisation uses QFieldCloud (OPENGIS.ch, 2022). QFieldCloud is an open-source geospatial data synchronisation application based on Django software. QFieldCloud enables syncing of data collected on (multiple) mobile devices using QField with a central project in cloud storage environments (e.g. AWS S3). QFieldCloud publishes an API to make data within the QFieldCloud system accessible to other applications and provides project management and authentication services with a range of user permission roles that are assigned on a per-project basis (admin, manager, editor, reporter, reader).

OPENGIS.ch provide a hosted version of QFieldCloud, which is actively developed and in-sync with developments to QField. However, a custom instance of QFieldCloud can be deployed on an organisation's own infrastructure; this is useful for three reasons. First, organisations might have restrictions on where their data can be stored. Second, organisations might have data collection tasks that could be completed using QField but do not have the financial resources to sustain long-term use of the hosted version of QFieldCloud. Third, the hosted version of QFieldCloud is geared towards supporting data collection projects and not long-term data and user management (i.e. costing is based on number of active users per-month which would accrue if users are requesting data from QFieldCloud for analysis tasks or to render in web maps after the data collection project has finished). However, QFieldCloud's intuitive features are well suited for managing an organisation's geospatial data and users within a single system that supports data collection, storage, analysis, and reporting. Therefore, organisation specific

deployments of QFieldCloud can support certain users with requirements beyond data collection. To this end, a guide for deploying and configuring instances of QFieldCloud has been developed along with a web application that provides a GUI interface to some of the core project and user management functionalities provided by the QFieldCloud API.

3.3.3 Analysis and Visualisation Depending on the use case and GIS expertise of the user, a range of data analysis, visualisation, and reporting options are available.

3.3.4 Desktop GIS and custom analysis For custom and complex geospatial analysis, a GIS analyst can connect to QFieldCloud via the QFieldSync plugin (OPENGIS.ch, 2022) in QGIS and download QFieldCloud project data into their local QGIS environment (QGIS Developers, 2022). The user can then use QGIS processing tools with their data. For users wishing to programmatically analyse their QFieldCloud data, data can be downloaded into their programming environment via the QFieldCloud API. For Python users, an official qfieldcloud-sdk (OPENGIS.ch, 2022) is available as a Python package to support these tasks . For R users, an R package, qfieldcloudR, has been developed providing convenience functions for QFieldCloud authentication, project management, and data download and upload from within R environments.

3.3.5 Dashboards and web maps Two dashboard and web map applications have been developed to support visualisation and querying of QFieldCloud data from web browsers.

The first application, *maplandscape-view*, is designed to allow authenticated users to view QFieldCloud data on a web map, in an interactive table, and to auto-generate reports from data collected in-the-field (Figures 4a and 4b). The goal of this application is to provide stakeholders quick access to, and views
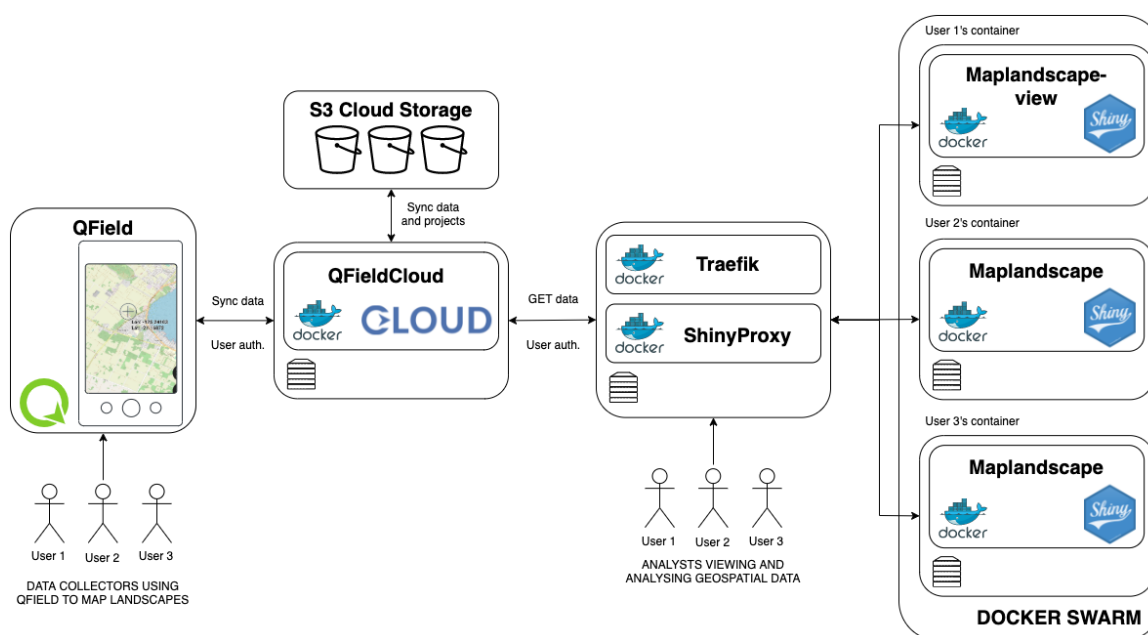
Figure 3. ICT system architecture and software components of the geospatial tool.
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of, data collected in-the-field using QField and to speed-up the process of QField data being used to inform decision making, guide landscape management, and contribute to reporting. This application address two core requirements: to provide tools for automation of key and repeated reporting tasks (e.g. generating village and district summary tables of attribute values such as crop type area); and to address a need for on-demand sharing and publishing of key datasets with authorised users.

The second application, *maplandscape*, is designed to allow users to load QFieldCloud data into their web browser, combine QFieldCloud data with local geospatial layers, and perform geospatial data querying, analysis, and visualisation tasks (Figures 4c and 4d). The application provides a simple UI and click-button interface for a range of common GIS and tabular analysis operations such as table joins, spatial joins, and group-by and summarise. It aims to support end users who don't have GIS analysis expertise but have a need for custom querying and analysis of data collected using QField. An example task could be an extension officer that needs to query paddock boundary, livestock type and number, and management practice layers to identify where and how many cattle are kept under a certain management practices within a village.

Both these applications are developed using the Shiny web framework (Chang et al., 2021); Leaflet is used for the web maps (Leaflet, 2022), DataTables is used for displaying data in interactive tables (RStudio, 2022), and ggplot2 is used for charting (Wickham et al., 2020). For large geospatial analysis operations the processing occurs in a separate PostGIS container instance (PostGIS Developers, 2022). WebGL is used to render spatial features on Leaflet web maps using the leafgl R package (leafgl, 2022). This allows users to view, style, and interact with large geospatial layers from QFieldCloud on web maps without having to deploy and maintain a web map server. This is important for end-users who might not have the resources necessary for managing web map servers yet have use cases for viewing large spatial layers (e.g. the Tongatapu Crop Survey conducted in 2021 comprises over 10,000 farm polygons).

These apps are deployed in docker containers in swarm mode via Shiny Proxy and use traefik as a load balancer and reverse proxy and Let's Encrypt for TLS (Traefiklabs, 2022; Analytics, 2022). Shiny Proxy manages user sessions and allows each user to interact with their own instance of the app running in an isolated docker container. Docker swarm allows the apps to be served across multiple nodes (hosts) enabling it to scale for multiple concurrent users (Docker, 2022).

4. CASE STUDIES

The geospatial tool has been used by MAFF staff in Tonga for a range of farm and landscape monitoring tasks. These tasks span small targeted data collection projects focusing on a single crop to large team island-scale monitoring efforts (e.g. as in figure 4d). Key features of these data collection, analysis, and reporting tasks are summarised below.

Updated knowledge of farm conditions and spatially targeted support: In May-June 2020, MAFF used the tool to map all vanilla plantations on the island group of Vava'u. Plantation attributes were recorded about vanilla variety, management, and condition. Vanilla is the main commercial crop grown on the island and condition and productivity of vanilla plantations directly affects the agricultural economy. Visualising this data on web maps provided an island-scale view of vanilla cultivation, highlighting to MAFF staff larger areas of under sub-optimal management condition than expected (Figure 5a). Further, the precise location of plantations in sub-optimal condition could be identified and targeted with support.

Field-level mapping of mixed cropping systems: Tonga's agricultural landscapes are characterised by a range of mixed cropping systems incorporating various crop types and arrangements such as intercropping, alley cropping, and agroforestry. Cropping system type varies intra-annually, inter-annually, and spatially. To reflect Tonga's cropping systems and generate useful information for agricultural and landscape management, this fine spatial detail needs to be recorded. In 2020 and 2021, MAFF mapped >2,700 crop parcels om Vava'u . Area, plant
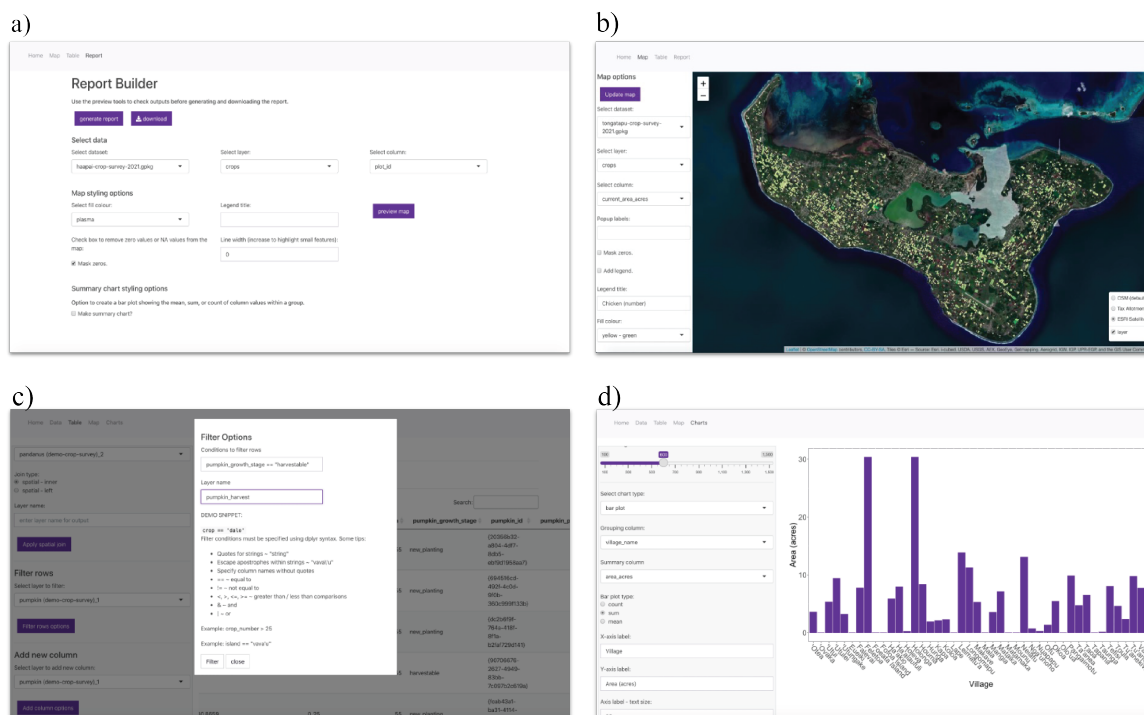
a)

b)

c)

d)

Figure 4. Report building interface (a), viewing QFieldCloud spatial layers on web maps in *maplandscape-view* (b), example performing GIS operations on QFieldCloud data in web browser in *maplandscape*, example of *maplandscape's* chart builder tools (d).
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number of each crop, and various other attributes were recorded for each parcel. The dashboards tools developed here support interrogation of cropping system data allowing analysts to specify a particular type of cropping system and generate web maps showing fields where that cropping system was present with summary tables and charts. This advances upon existing datasets (e.g. previous paper-based surveys and agricultural censuses) which aggregate crop-level statistics within geographic units (e.g. tax allotments, village). This dataset and the visualisation and reporting tools provide short-term information relevant for agricultural planning (e.g. the location and plant number of key commercial crops such as watermelons) and a better understanding of patterns of landscape and cropping system practices and changes (e.g. Figure 5b).

Data driven engagement with farmers: Datasets and visualisations generated here provided a medium for farmer engagement and stimulating discussion enabling understanding of issues affecting farmers. For example, during the early phases of the COVID-19 pandemic MAFF officials surveyed the land utilisation of fields allocated to grower groups within each village on Vava'u. The survey was done to provide information on which fallow land could be cultivated to secure food supply given pandemic-driven supply chains risks. MAFF staff were able to identify where grower groups had utilised government-provided support for tractors and fuel for ploughing to bring land under cultivation and where land was unploughed. This data was presented to town officers (village / community leaders) and prompted discussion around village-specific challenges growers faced in utilising government support to cultivate land. Similarly, after completing a survey of cropping systems in all fields in Leimatu'a village, Vava'u, MAFF officials presented the survey results to farmers in the village using web maps projected onto a big screen accompanying a report (Figures 5c and 5d). MAFF officials displayed several web map visualisations regarding the condition and land allocated to vanilla cultiva-

tion; over time less land is being cultivated with vanilla and plantations were often in sub-optimal conditions. This prompted discussion as to why potentially lucrative vanilla cultivation appeared to be in decline with farmers explaining challenges they faced in negotiating prices for their crops.

Large team data collection for national-scale farm monitoring: In October to December 2021, a survey was undertaken to map farm systems across several island groups in Tonga using QField and QFieldCloud. The goal was to generate a comprehensive spatial database of farm systems at the field-level. For example, cropping systems (mixes, area, and plant number) were recorded for all crop parcels; livestock type, population, and management (paddock, tethered, free range) were recorded for all fields with livestock present; and for various forestry or fallow land parcels attributes were recorded documenting the vegetation present. The results of this survey can be retrieved from QFieldCloud and visualised on *maplandscape* web maps and dashboards accessed via MAFF's website and the data has been used for a range of reports and to inform agricultural planning and Ministry resource allocation. On the main island of Tongatapu, QFieldCloud was used to support over 40 data collectors mapping over 10,000 crop, livestock, fallow, and forestry land parcels.

Disaster response: On the 15th January 2022 the Hunga Tonga-Hunga Ha'apai underwater volcano erupted with a tsunami and ash clouds impacting the Tongatapu and Ha'apai island groups. In parts of the main island of Tongatapu, croplands, crops growing in fields, harvested crops, and agricultural infrastructure and machinery were lost or damaged. MAFF officials conducted surveys town officers across communities affected by the disaster to ascertain loss and damage to key food security and commercial crops and agricultural machinery. Data collectors synced this data using QFieldCloud and analysts used *maplandscape* dashboards to summarise the data and prepare reports.
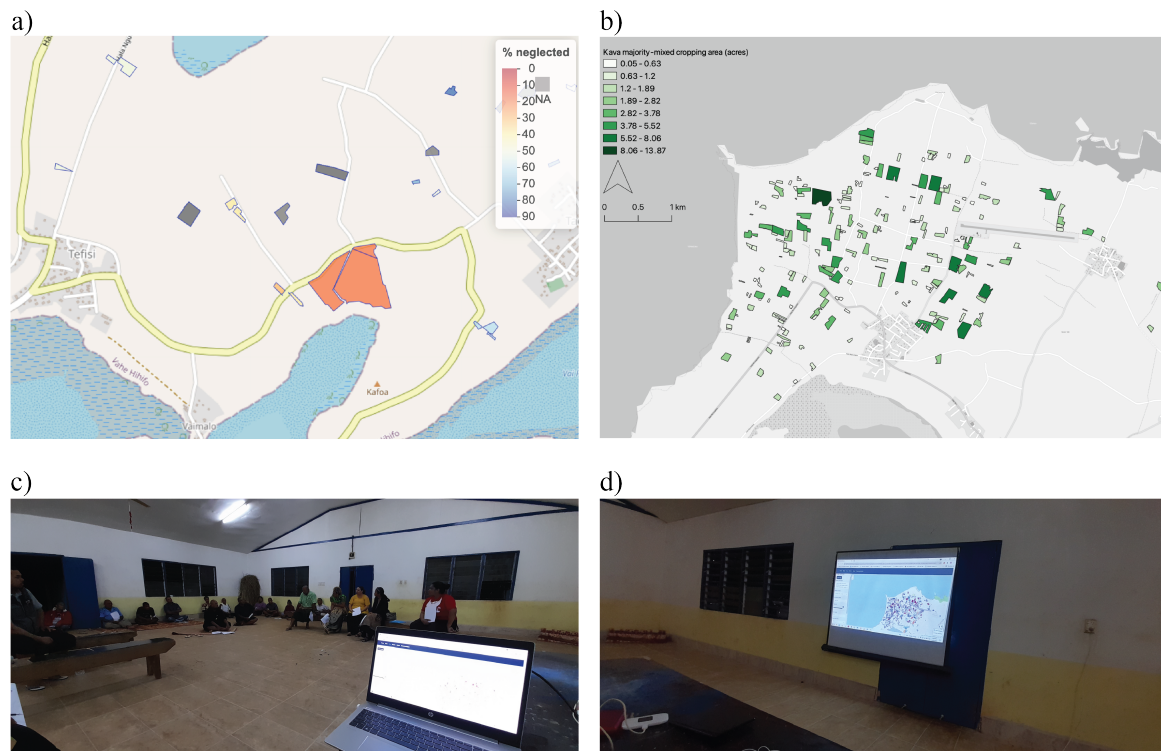
Figure 5. Web map of % of vanilla plantations in neglected condition (OpenStreetMap basemap) (a), map of the area of fields with mixed kava cropping systems (b), and photos from community feedback meetings presenting crop survey results to farmers (c),(d).

5. DISCUSSION

A well documented challenge that undermines successful development of ICT systems in contexts where end users do not have experience or a culture of using ICT is that developers do not have a good understanding of local contexts where applications will be deployed (Bon et al., 2016; Bon and Akkermans, 2019). This can result in social, cultural, political, institutional, and economic factors being overlooked, and undermines the utility of the ICT system or that the functionality does not align with end user needs(Bon et al., 2016). This was a risk for this project with GIS and developer team members not starting out with knowledge of Tonga's agricultural landscapes, food systems, or stakeholder environments. However, as demonstrated in *section 3.5*, an ICT system was developed that has been deployed by MAFF for various landscape mapping and data collection tasks. Here, the factors that enabled developers to build up sufficient awareness of the end users' contexts and end users to gain an understanding of the potential of geospatial technology and data to support their activities are discussed.

Elements of our project design and implementation provided opportunities to generate practical knowledge of end user needs, contexts, and potential for geospatial technology. The project spanned over five years with resources allocated to field work and end user training, flexibility to adapt outcomes to end user needs, and a commitment to co-design with stakeholders as part of the methodology. This enabled adoption of agile development approaches (Dijkers et al., 2018) with developers and end users going through several iterations of prototypes and testing applications in-the-field on farms in Tonga (Figure 2). This provided frequent opportunities for developers to experience contexts where applications will be deployed and gain an understanding of tasks they will be used for. Similarly, it provided end users with exposure to using geospatial tools and

data, awareness of what can and cannot be achieved with such technologies, and allows for refining of ICT system requirements to better suit their needs (Dijkers et al., 2018). This aligns with observations by Bon and Akkermans that contextual knowledge, that is critical to for successful deployment and use of ICT systems, is action-oriented and experiential and built through dialogue and action (Bon and Akkermans, 2019).

Project/end-user champions have been identified as critical to the success of ICT4D projects as they promote the project and mobilise resources (Dijkers et al., 2018). Key actors within MAFF became project champions who, early on, identified needs for geospatial data, data collection and reporting activities that would benefit from geospatial applications. The champion facilitated opportunities to test prototypes in existing activities (e.g. vanilla surveys, annual crop surveys). This generated high-quality feedback and ensured the tool was designed to align with MAFF's operational contexts, and end users testing applications could provide specific feedback on ways the technology could enhance their existing workflows. This contributed to ensuring the ICT system was end user driven and tailored to the environment in which it was deployed. Strong collaboration with a champion also helped bridge the gap between the developers' technical knowledge and end users' domain expertise. The champion was able to identify and relay key information to the development team allowing them to focus on aspects of the deployment context that were most important. As an example, the champion provided detailed information on how data collected in the field needs to be analysed and visualised to support MAFF reporting and decision making and where there were existing gaps in data management and analysis processes. This informed the design of features in the *maplandscape* dashboards (Figure 4). The position of the champion within MAFF's organisational hierarchy and stakeholder networks was also important; they operated at a senior level

and could identify how the ICT system would align with high-level Ministry priorities and programs yet had awareness of the in-the-field contexts where the technology will be deployed and used (and accompanied field teams on several occasions).

Availability of hardware and ICT system administration expertise and resources are challenges for ICT4D projects (Bon et al., 2016). Through the iterative development process used here, over time, an understanding of accessible and affordable technologies and devices and people's capacities to be trained to use and manage software applications was generated. This knowledge was then incorporated into the ICT system design. For example, to minimise on-going costs only open-source software was used. In Tonga, smartphones that can run QField are widely available, people have experience using smartphone interfaces, and the mobile phone network can support data syncing using QFieldCloud. Thus, it was feasible for QField to form the central software component of the ICT system. To reduce dependencies on local hardware for data storage and analysis, the ICT system was developed using container (docker) technologies such that it could be deployed on cloud-based services. This enabled hardware to be cost effectively rented on-demand and removes maintenance and upkeep costs. Similarly, new web applications were developed to support user and data management and analysis and reporting tasks which only require an internet connection and web browser to run (Figure 4). This removed the need for end users to install and manage local technical GIS software and moved data processing to cloud-based machines. The ICT system uses data formats that remove the need for end users manage server-databases. Data collected in-the-field using QField is stored in GeoPackages, a file-based spatial database format built on top of SQLite. This meant data can be treated as a file and stored, versioned, and retrieved using cloud storage buckets without preventing relational database-like querying and analysis operations being executed.

6. CONCLUSION

The success of our case study demonstrates the importance of stakeholder engagement in an iterative ICT 4D development framework, and the great potential that open-source geospatial tools such as QGIS, QField, and QFieldCloud can play in agricultural landscape management and disaster response in PICs.

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