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ORIGINAL ARTICLE

Post-cyclone resilience of an agroforest-based food system in the Pacific Islands

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Abstract

As climate change increases the probability and/or severity of major disturbances worldwide, understanding how agroecological food systems can be resilient to the effects of major disturbances becomes critical. Farm-level crop and cultivar richness are critical to food security and nutritional dietary diversity, but quantitative research of how they are impacted by major disturbances, including the dynamics of their recovery, is largely lacking. We assessed the resilience of an agroforest-based food system to a recent Category 5 cyclone. Specifically, we carried out vegetation surveys in Fijian agroforests pre-cyclone, and 1 and 3 years post-cyclone, to assess changes in staple starch crop and cultivar richness over time. Resilience, measured as robustness, redundancy, reactivity, and resourcefulness, varied with the scale of analysis. At both the crop and cultivar scale, the agroforestry systems were highly reactive to cyclone disturbance. Crop species richness increased immediately post-cyclone and 3 years later remained higher than pre-cyclone levels, largely due to the increased presence of famine food crops, indicating system robustness, redundancy, and resourcefulness as well. Farmers also planted many new starch crop cultivars post-cyclone, especially of sweet potatoes, but the total number of cultivars declined over time, indicating limited redundancy and resourcefulness. Frequent crop substitutions for cassava over taro or yams, and high cultivar dynamism that resulted in the loss of traditional varieties, can have consequences both for nutritional diversity and the maintenance of cultural traditions. This research suggests resilience is present in Fijian agroforest systems, yet a greater focus on crop cultivar diversity is needed.

Keywords Agroforestry · Food systems · Pacific Islands · Resilience · Global change · Fiji

Introduction

Global change, including environmental and socioeconomic change, impacts economies, cultures, and ecosystems worldwide. Environmentally, climate change has induced sea-level rise, ocean acidification; changes in precipitation, temperature, and seasonality; and changes in storm intensity, frequency, and geographic occurrence (IPCC 2021). Socioeconomic conditions and social-ecological systems in many countries are also changing due to rapid globalization (Janssen et al. 2007).

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Food systems are inextricably connected to such environmental and socioeconomic changes, with implications for human and environmental health and resilience. Food systems involve multiple interrelated activities, including food production, processing, distribution, and consumption (Ericksen 2008; Hodbod and Eakin 2015). Achieving food security is a primary goal of any equitable food system at every scale. The 1996 World Food Summit states that food security "exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO 2006). The FAO identifies four dimensions of food security: food availability, access, utilization, and stability (FAO 2006). Food system resilience is a function of food security and is usually conceptualized as a social-ecological system (Allen and Prosperi 2016; Herrera de Leon and Kopainsky 2019; Tendall et al. 2015).

The resilience of a food system is influenced by multiple interacting factors (Ericksen 2008; Hodbod and Eakin 2015). One factor that can enhance resilience is the level of diversity in an agroecosystem. Agroecosystems that contain high biodiversity, including agrobiodiversity, have a higher potential to adapt and recover than those of lower diversity (Mijatović et al. 2013) proffering them greater resilience. Agrobiodiversity encompasses the diversity of all biotic organisms at multiple scales in an agroecosystem (Mijatović et al. 2013) and supports increased resilience via increased diversity and redundancy of functional groups and functional traits (Hodbod and Eakin 2015; Laliberté et al. 2010; Wood et al. 2015). Specifically, a high diversity of functional groups and traits allows for non-food species, crops, and crop cultivars to employ varying levels and types of tolerances to disturbances. This buffers against shocks and disturbances to the system which might cause food insecurity.

How major disturbances impact the agrobiodiversity, and associated resilience of food systems, has been studied in various ways in different parts of the world (Altieri et al. 2015; Kundermann 2000; McSweeney and Coomes 2011; Paulson 1993). Some studies have shown that agroecosystems with greater diversity at the species and landscape level exhibit resilience to major disturbances like flooding and cyclones (Altieri et al. 2015). In systems with low agrobiodiversity, many studies have shown further immediate post-disturbance declines in agrobiodiversity, leaving these agroecosystems, and the people who rely on them, more vulnerable to future disturbance (e.g., Krishnamurthy and Reddiar 2011; Thaman 2014). In some cases, however, the disturbance has encouraged positive adaptation and fostered resilience. Flooding caused by Hurricane Mitch in Honduras (1998) triggered endogenous social reform that increased resilience to subsequent natural disasters by re-instituting more biodiverse agricultural practices, and relocating primary farming plots to areas of lesser risk and by diversifying incomes (McSweeney and Coomes 2011). Similarly, in Amazonia, Ávila et al. (2021) found that after major flood disturbance, communities reported that they selectively replanted with crops and crop cultivars that survived the event more successfully, and replanted in areas less prone to subsequent flooding. In agroecosystems that have withstood such catastrophic disturbances, it is important to identify and assess the practices that allowed for resilience for broader implementation (Altieri et al. 2015). This is especially relevant for the longer term, as models suggest that while crop losses from extreme disturbances will be generally moderate in the early twenty-first century (Adams et al. 1998), the effects will be progressively worse in the later half (Altieri et al. 2015).

Crop and cultivar richness are critical to food security and nutritional dietary diversity (Hunter et al. 2019; Kennedy et al. 2017). Despite their importance, however, quantitative research is lacking on the impacts of major disturbance events on crop and cultivar richness, including the dynamics of their recovery and the implications for food system resilience. Tendall et al. (2015) provide a framework to assess the latter. Specifically, they propose four interacting components of food system resilience that can be assessed over time: robustness, redundancy, reactivity, and resourcefulness. *Robustness* is a measure of resistance to negative change after a disturbance and is defined as the ability of a system to continue to immediately provide the same or increased level of food post-disturbance as pre-disturbance; *redundancy* is represented as the number of food items that are able to replace each other if the supply of one is compromised; *reactivity* is the rapidity with which a system returns to pre-disturbance production levels after a disturbance to reclaim food security; and *resourcefulness* refers to the ability of a system to adapt and source exogenous food supplies and/or, locally available famine foods, after a period of relative stasis.

Indigenous communities in Fiji, like in other Indigenous Pacific Island Nations, have a long history of resilience to cyclones and other sources of disturbance, conferred, in part, from their biodiverse agroecosystems, traditional marine resource management strategies, and strong social networks (Campbell 2015; McMillen et al. 2014; Veitayaki 2002). Agroforestry, described as a complex, dynamic, agroecosystem where trees and shrubs grow in tandem with crops and/or livestock (Fernandes and Nair 1986), is a main component of this resilience. However, the diversity of the Fijian agroecosystems has been declining due to socioeconomic, cultural, and environmental changes (Thaman 2014). As food systems worldwide are impacted by global change, it becomes important to understand how places with a history of food system resilience to climate variability may be successfully coping, or not, with increased disturbances.

In this study, we operationalize Tendall et al. (2015)'s food system resilience framework to assess a key component of food system resilience in Fijian villages after Cyclone Winston, which made landfall in Fiji in February 2016 and was the strongest cyclone in the recorded history of the South Pacific at the time. Tropical storms, including cyclones, are of particular importance in the Pacific Islands due to their widespread and common reoccurrence (Campbell 2015; Lin et al. 2011; Marler 2014). Various studies and projection models predict diverse changes in tropical cyclone frequency, geographic occurrence, and intensity under climate change conditions (Emanuel 2013; Kossin et al. 2013; Mendelsohn et al. 2012; Zhang and Wang 2017). Additional studies have shown a notable increase in the predicted frequency of the most intense cyclones (Emanuel 2013; Mendelsohn et al. 2012), true also in the South Pacific (Zhang and Wang 2017). The intensity of Pacific cyclones has recently increased (Kossin et al. 2013) and is likely to increase in the future (Walsh et al. 2012), with substantial effects from the El Niño-Southern Oscillation phenomenon in Fiji (Chand and Walsh 2011; Magee et al. 2017).

We build on agroforest biodiversity data collected pre-cyclone (2014) (Ticktin et al. 2018), with new biodiversity data monitored 1 year post-cyclone (2017), and 3 years post-cyclone (2019), to assess changes in the richness of starch crop species and cultivars in Fijian agroforestry systems. Previous work (Ticktin et al. 2018) demonstrated that Fiji agroforests are important conservation areas for native trees, which are important to agroecological resilience (Cabel and Oelofse 2012; Ticktin et al. 2018), but did not assess crop or crop cultivar richness. We use Tendall et al. (2015) framework to interpret food system resilience as a function of changes in starch crop and cultivar richness. We use starch crop richness as a proxy for the Indigenous Fijian agroforest food system resilience due to the foundational role starch crops, and particularly roots and tubers, play in key nutritional, cultural, economic, and ecological functions in Fiji, and across the Pacific Islands (Barrau 1958; Pollock 1985, 1986; SPC 1976; Wairiu et al. 2012; but see Hidalgo et al. 2020). Underscoring this, starch crops are often perceived as categorically different from other food plants (Barrau 1958; Pollock 1986; Ravuvu 1991). Specifically, in Fiji, root and tree starch crops are referred to as kakana dina, which roughly conceptually translates to "real food" or "true food" (Pollock 1985, 1986; Ravuvu 1991; Turner 1984). Fijian worldview places the most importance on the starch component of the meal, and if kakana dina are lacking, this is seen as a weakness in the ability of the farmers to provide food for the household (Ravuvu 1991).

Today in Fiji, the four kakana dina root crops of greatest significance are taro, or dalo (*Colocasia esculenta* (L.) Schott); cassava, or tavioka (*Manihot esculenta* Crantz); sweet potato, or kumala (*Ipomoea batatas* (L.) Lam.)*;* and yam, or uvi (*Dioscorea alata* L.), hereafter collectively referred to as the "four primary root crops" (Barrau 1958; Iese et al. 2018; SPC 1976; Wairiu et al. 2012). Because tubers are mostly protected from moderate intensity natural disasters (except flooding), they have also been important in recovery in Fiji (Benson 1997). Given their nutritional, cultural, and recovery importance, we use various metrics of starch crops (scales of species and cultivar richness) as indicators of food system resilience. We also recognize that food systems are complex, dynamic, and multifaceted, and that a full analysis of food system resilience requires consideration of all foods, including purchased and imported foods, across the entire food supply chain.

We address the following questions: (1) How do starch crop and crop cultivar richness in agroforests change across time after a major Category 5 cyclone disturbance? (2) Based on this, how resilient is the agroforest-based food system in rural Indigenous Fijian communities? Given the recorded gradual decline of agrobiodiversity in Fiji (Thaman 1982a, b, 2014), we hypothesized that the richness of the four primary root crops as well as their cultivars would decline immediately post-cyclone and not recover to pre-cyclone levels, indicating lowered robustness and reactivity. Conversely, we hypothesized that in the agroforests, the species richness of all starch crops combined would remain stable since many Fijians still hold knowledge and practices related to emergency starch food plants (Ticktin et al. 2018), indicating redundancy and resourcefulness.

Methods

Study site and context

Fiji is an archipelago of over 300 islands, most of which are inhabited. According to the 2017 census, the total population is just under 900,000; 44.1% (390,635) of which reside in rural areas while the remaining 55.9% (494,252) reside in urban areas (Fiji Bureau of Statistics 2018).

Fijian agroforests are mosaics of forested, fallow (uncultivated), and planting areas under continuous rotation (Ticktin et al. 2018). The length of time an area remains within a given management type is dependent on multiple factors, including soil health and land productivity, time since and intensity of past disturbances, and changes in land tenure and agricultural goals, among other socioeconomic or environmental circumstances. Similar to other traditional agroforest practices across the Pacific (Clarke 1994), planting areas are often composed of diverse root crop assemblages including taro, cassava, yam, and sweet potato in addition to semi-managed and lesser consumed famine foods such as Polynesian arrowroot, or yabia (*Tacca leontopetaloides* (L.) Kuntze), and two wild yams, spiny yam and aerial yam, or tivoli and kaile

(*Dioscorea nummularia* Lam. and *D. bulbifera* L.) (Thaman 1982a). Endemic, native, and introduced trees, shrubs, and herbs producing various fruits and vegetables are also cultivated or otherwise protected in these areas including Fiji sago palm trees (*Metroxylon vitiense* (H.Wendl.) Hook.f.), Fiji Longan (*Allophylus cobbe* (L.) Raeusch), mangoes *(Mangifera indica* L.), slippery cabbage (*Abelmoschus manihot* (L.) Medik), and many more (Thaman 2008; Ticktin et al. 2018). Many plants not explicitly used for food are also found in these agroforestry systems.

Of the root crops, the two foremost culturally important species are yam and taro, in that order (Ravuvu 1983, 1991), which were brought by some of the first Austronesian voyagers to the Pacific Islands (Walter and Lebot 2007) and would have been highly important in early settlers' diets. Most scholars agree that sweet potato was introduced to the Pacific Islands from South America first by early Polynesians and then again by European explorers in the 1500s (Roullier et al. 2013). Comparatively, cassava is a more recent introduction brought during European colonization (Barrau 1958). Today cassava and taro are the most consumed root/tuber crops in the country (Wairiu et al. 2012), followed by sweet potato and yam, respectively (Ministry of Agriculture 2014).

Taro may be planted at any time of year and is harvestable 6 to 18 months later, depending on the cultivar and agroecological zone it is planted in (Ministry of Agriculture 2014, 2015a; Sivan 1982). Depending on the cultivar, yam is planted between June and September and may be harvested between February and July (Ministry of Agriculture 2014; Sivan 1982). Sweet potato can be grown year-round (Ministry of Agriculture 2015b) but is typically planted in April or May and is unique in that it matures quickly, within 4 to 5 months, making it an important post-disaster crop (Ministry of Agriculture 2014). Cassava can be planted year-round and matures 8 to 12 months later (Ministry of Agriculture 2014), though some cultivar names, such as vula tolu, suggest some cultivars mature in as little as 3 months. However, planting times are shifting to accommodate climate change-induced alterations in weather patterns (Hidalgo et al. 2020).

Each species consists of many different cultivars. To our knowledge, no exhaustive list of cultivars for any of these four crops exists for Fiji, although partial lists have been compiled over time (Guarino and Jackson 1986; Lebot 1992; SPC 1976). Overall, the number of cultivars is thought to have been declining over the past several decades as farmers plant a smaller number of traditional varieties in favor of commercial varieties (Masibalavu et al. 2002 (unpublished); Thaman 2014). However, the system is dynamic and cultivars can be lost or replaced as a result of economic (e.g., market demand and affordability) (Masibalavu et al. 2002 (unpublished); Tisdell 2014), sociocultural (e.g., change in dietary preference or ceremonial practices) (Lebot and Siméoni 2015), and environmental (e.g., pests and diseases) (Lebot 1992) changes.

Agroforest surveys

In 2014, Ticktin et al. (2018) carried out a study of social-ecological resilience in Indigenous Fijian communities, which included botanical surveys of 100 agroforest sites and socioeconomic interviews with members of the associated households, in 20 coastal villages across 5 districts in Fiji. The villages support mixed subsistence economies, where agroforest and fishing harvests are used for both subsistence and sale. We carried out a participatory mapping exercise with each farmer to establish the number, size, use, and location of agroforest parcels the household manages. Then, of the parcels that were used for subsistence, actively managed, and within an hour's walk of the village, we randomly selected one parcel per farmer to survey. Farms outside of these specifications tend to be monocultural and used only for commercial purposes. Parcels were between 0.25 to 5.00 ha in size and all below 100-m elevation, save for one parcel located at 196 m asl. With each farmer, we recorded all tree and understory crop species observed in crop, forest, and fallow areas. Some agroforest areas are shared within the community, and so all adjacent areas where farmers had access to were included. We identified any unknown species at the South Pacific Regional Herbarium, Suva, Fiji. When a farmer did not know the name of a crop cultivar, it was recorded as "unidentified". If a crop was growing in the farmer's agroforest but the farmer did not purposefully plant it or report to use it, it was identified as a "wild" variety. Wild types are not included in these analyses. We assumed that cultivar names referred to the same phenotype within villages and districts. However, because synonymous and homonymous names may apply at larger scales (SPC 1976), we could not assess cultivar richness at the country level. Last, during each agroforest survey, we carried out a semi-structured interview with the farmer on their management practices including, but not limited to, questions about changes to emergency food cultivation, decisions to replant in the same area or not, and any plants now desired (Ticktin et al. 2018).

In 2017, 1-year post-Cyclone Winston (hereafter referred to as "the cyclone"), we selected a subset of 10 of the original 20 villages in the four districts of Kubulau, Nakorotubu, Suva, and Wainikeli (on the islands of Viti Levu, Vanua Levu, and Taveuni) (Online Supplement 1) to resurvey the agroforests. The subset of villages was selected based on their proximity to cyclone impact (Fig. 1) and to represent a range of pre-cyclone indicators of social-ecological resilience, including agroforest biodiversity, traditional ecological knowledge, and socioeconomic characteristics as reported by Dacks et al.

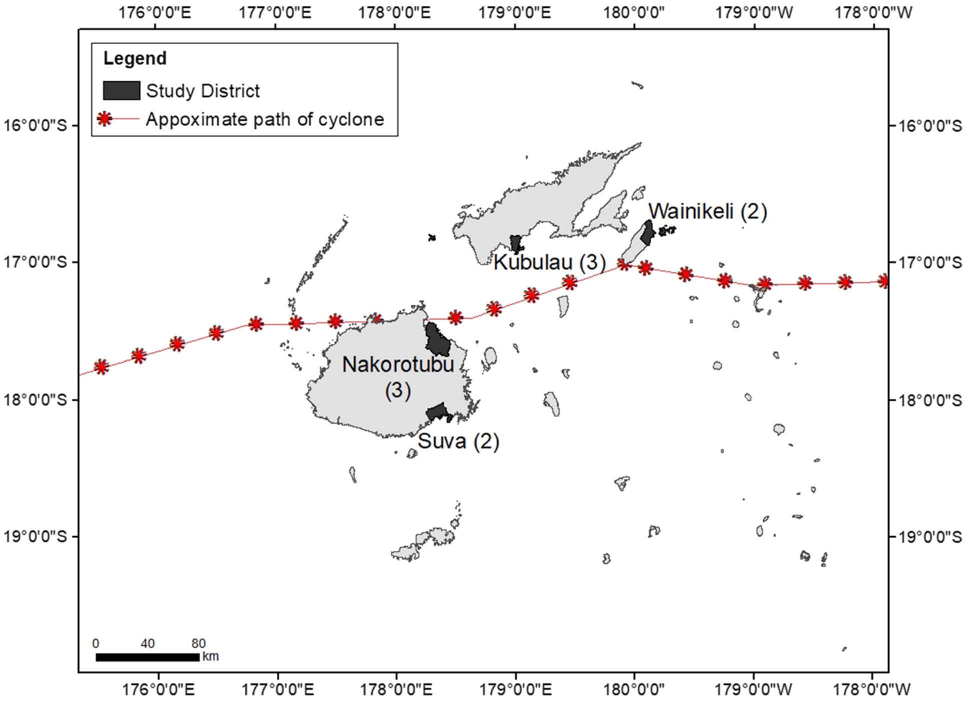


Fig. 1 Map of the Fiji Islands indicating the path of Cyclone Winston and the districts of the villages in this study

(2018). The same agroforests were then surveyed again in 2019 (3 years post-cyclone) to record all tree species and understory crops, following the 2014 protocol. In the few cases where farmers were ill, deceased, and/or had passed on their parcels to their next of kin, we worked with said relative instead (three in 2017; four in 2019).

We also conducted semi-structured interviews with farmers using the same methods as Ticktin et al. (2018), about their observations and management practices after the cyclone. Interviews included questions about how farmers replanted their agroforest areas, where they sourced their planting materials, and observations about tree and crop recovery post-cyclone. We were unable to collect data in one village, Togalevu, in 2017 and where that data is necessary for accurate analysis as described below, we exclude it from the results. In total, we surveyed 43 farms from 9 villages in 2017, and 48 farms from 10 villages in 2019.

We applied the Tendall et al. (2015) framework to our data as follows:

Robustness Starch crops, and the four primary root crops and their cultivars, exhibited robustness if species/cultivar richness 1 year post-cyclone (2017) was the same or greater than pre-cyclone (2014) richness. We calculated a robustness index as the percent increase in species/cultivar richness from pre-cyclone to 1 year post-cyclone. If the percent change was 0 or greater, we concluded robustness was present.

Redundancy We used the total number of starch species, the four primary root crops, and their cultivars present across all villages at all 3 years (2014, 2017, and 2019) as a measure of redundancy, which was classified as either "high," "moderate," or "low." We determined a threshold of redundancy based on the approximate number of species or cultivars that could sustain production over different seasons and climatic conditions (e.g., drought or wet years, dry or wet microclimates). For starches overall, a village had "high" redundancy if 6 or more species were present in a village across all 3 years; if 6 or more species were only present in 1 or 2 years, we labeled this "moderate"; if there were less than 6 species across all three years, we labeled this "low." For the four primary root crops, the threshold was 3 or more species present in a village across all 3 years for "high" redundancy; if 3 or more species were only present in 1 or 2 years, we labeled this "moderate"; if there were less than 3 species present in all three years, we labeled this "low." For the crop cultivars, we identified the two most abundant root crop species in each village and assessed the redundancy of crop cultivars for those two crops. Because each root crop has a different overall count of the number of cultivars recorded, we used different thresholds for each species when determining redundancy. We assumed "high" redundancy if there were at least 5 cultivars for taro, 4 cultivars for cassava, or 4 cultivars for yam present in a village across all 3 years. If these values were only met in one or two years, we determined the redundancy to be "moderate"; if these values were never met, we labeled this as "low."

Sweet potato was not evaluated as a primary root crop in any village. We recognize these values are approximate and context specific, and necessarily will vary across different agroecosystems.

Reactivity As a proxy for the return to potential production levels, we used the presence of a new species or cultivar in a village at either 1 year (2017) or 3 years post-cyclone (2019) when compared to pre-cyclone records (2014) as a measure of reactivity, regardless of whether species or cultivars were lost at any point post-cyclone. For the four root crop cultivars, we first assessed the cultivar reactivity of each root crop across both years. If new cultivars were recorded in either 2017 or 2019 for each of the four root crops, then that crop was considered to have cultivar reactivity in that village. Then, we assessed the composite cultivar reactivity across all four crops by determining that if at least three of the crops have cultivar reactivity in that village, then reactivity was present at the cultivar level.

Resourcefulness We determined resourcefulness was present if the species/cultivar richness levels for starch crops overall, the four root crops, and the root crop cultivars, rebounded or exceeded the pre-cyclone (2014) richness levels by 3 years post-cyclone (2019), regardless of their composition (e.g., the species/cultivar richness might rebound but with a totally different set of species or cultivars). This is expressed as percent change from pre-cyclone to 3-years post-cyclone where the change must be 0 or greater to be considered resourceful. For starches overall and the four primary root crops individually, we assessed this at the species level. For the four root crop cultivars, we first determined the two most prevalent root crops in each village and then assessed only those two crops' changes in cultivar richness to account for regional differences in microclimate, and therefore the natural variation in species presence.

Given the predominance of food-sharing across households within villages (Dacks et al. 2018), all calculations were made at the village level, rather than at the individual farmer level. For each village, we analyzed resilience at three scales: all starch species, the four primary root crops, and the cultivars of the four primary root crops.

We received permission for this research from Fiji national and district governments, village leadership (village headmen (Turaga ni Koro)), and the University of Hawai'i Institutional Review Board (2016–30418; 2018–30418). Our team consisted of one member from the University of Hawai'i at Mānoa and two Indigenous Fijian (iTaukei) research assistants each field season. These research assistants were well versed in iTaukei village protocols and ceremony, fluent in Fijian and English languages, knowledgeable about agroforest biodiversity, and at least one had assisted in the 2014 iteration of the research. The research assistants led and organized all village and field visits to the agroforests, and conducted, translated, and interpreted the interviews with the farmers. Informed consent was obtained from all farmers.

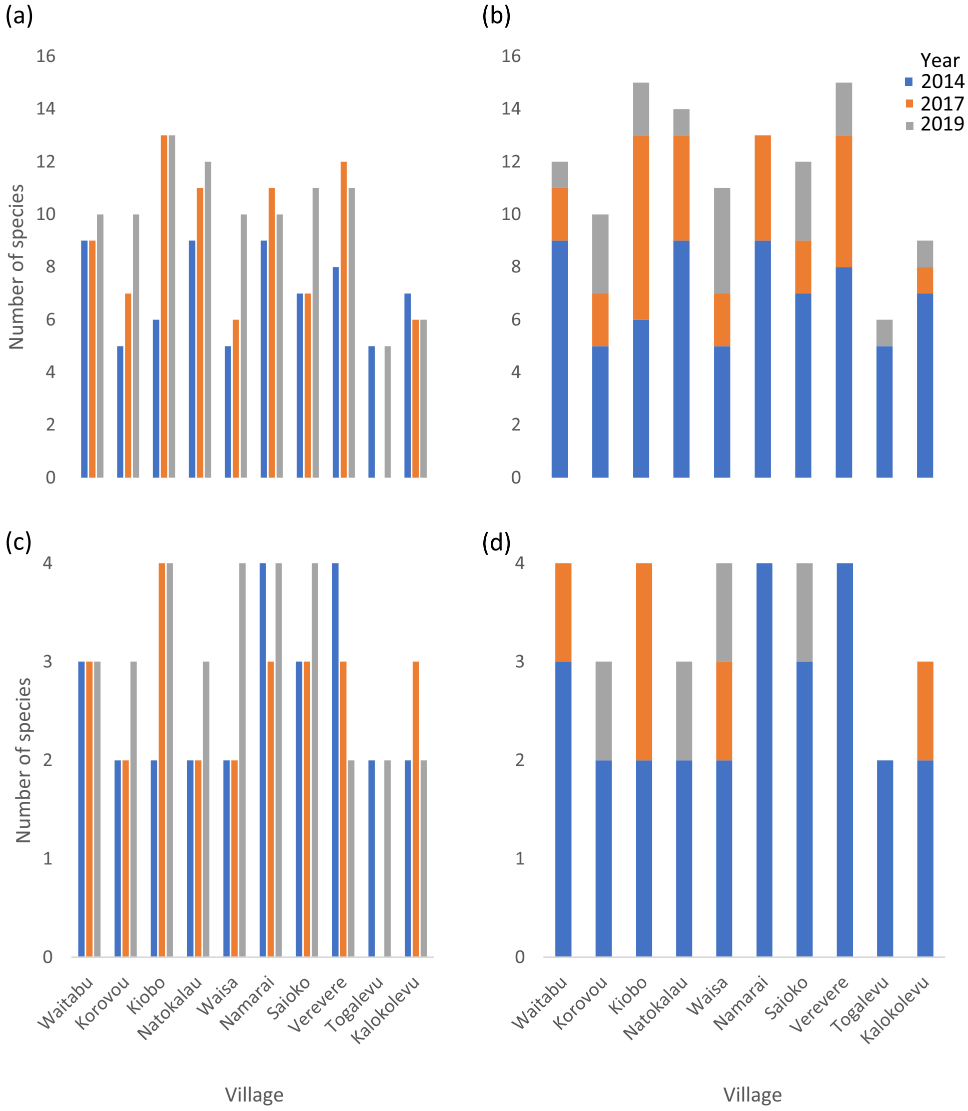
Results

Over the course of the study, we recorded a total of 16 starch species; the names of 36 cultivars of taro, 32 of yam, 30 of cassava, and 9 of sweet potato across all 10 villages (see Online Supplements 2 and 3). The average number of starch species observed per village was lowest in 2014 (7.00 ± 0.54 se) and increased through to 2019 (9.80 ± 0.79 se) (see Online Supplement 4). Of the four primary root crops, cassava had the greatest average cultivar richness per village in 2014 and 2017 (5.70 ± 0.42 and 5.22 ± 0.85 se), and similar richness to that of dalo (4.60 ± 0.92 se) in 2019 (cassava richness was 4.50 ± 0.62 se). The mean richness of yam cultivars was only 2–3 per village, though the pre-cyclone range across villages was very high (0–18). Sweet potato showed the lowest range and mean number of cultivars per village (see Online Supplement 4).

Robustness (number of starch crop species and cultivars pre- versus 1 year post-cyclone) Starch species richness 1-year post-cyclone (2017) was greater than or equal to pre-cyclone (2014) richness in 89% of the villages studied (Fig. 2a), indicating robustness to cyclone disturbance. Similarly, in 78% of the villages studied, the number of primary roots crops remained stable or increased (Fig. 2c), indicating robustness to cyclone disturbance. However, robustness varied with the scale of analysis and was most variable at the cultivar level (Fig. 3a, c, e, g). Fifty-six percent of villages increased cultivar richness by 18–86% (Table 1c). Cultivar richness decreased between 7–29% 1-year post-cyclone in the remaining villages (Table 1c).

Redundancy (presence of multiple starch crops and cultivars over time) We found that starch species overall were redundant in the agroforests we studied. In only two villages, less than 6 starch species were observed in at least 1 of the 3 years studied and were thus only moderately redundant (Fig. 2a). Redundancy in the four primary root crops, however, was much weaker, as less than 3 species were present on farms in numerous years across most villages (Fig. 2c); thus, most villages only exhibited moderate redundancy (Table 1b). The crop assemblage most commonly observed was taro, cassava, and yam. The crop cultivars varied even more greatly; some villages had high redundancy in crop cultivars, whereas some had only moderate redundancy, meaning that for the two most prevalent crops recorded in

Fig. 2 Count of (**a**) total and (**b**) newly recorded starch crop species; and (**c**) total and (**d**) newly recorded primary root crop species by village per year. Data does not exist for Togalevu in 2017



a village, the number of cultivars recorded fell below the number of cultivars needed to be present to be considered redundant for at least one of the crops selected (Table 1c). Cassava had the highest levels of cultivar redundancy across villages where the average total number of cultivars present per village across all three years ranged from 4.50 to 5.70 (Online Supplement 4). Redundancy was never low at any scale.

Reactivity (presence of newly recorded starch crops and cultivars) Overall, reactivity was present in all villages across all levels of analysis (Table 1a–c; Fig. 2b, d). In almost all of the farms, new starch crops were recorded at 1 and 3 years post-cyclone (Fig. 2b). Reactivity of the four primary root crops was also present in all villages; however, in two villages where all four root crops had been present in 2014, the number of root crops recorded declined (Fig. 2d). The reactivity in the four primary starch crop cultivars was high but varied the most across time and space. For taro and cassava, between 2014 and 2019, there was an average of 3.7 ± 0.1 se and 3.3 ± 0.1 se new cultivars added per village, respectively (Fig. 3d, b). Reactivity in cultivars of yam and sweet potato was lower with an average of 2.7 ± 0.1 se and 2.3 ± 0.1 se new cultivars appearing, respectively (Fig. 3h, f).

Resourcefulness (number of starch crop species and cultivars pre versus 3 years post-cyclone) Generally, resourcefulness was present in the agroforest systems we studied. Overall, we observed total starch crop resourcefulness across all the farms we surveyed in all villages, with starch crop richness in 2019 equal to or higher than pre-cyclone levels in all villages except one, where there was a slight decrease in the number of starch species present (Fig. 2a). Similarly, for the four primary root crops, resourcefulness was present in all villages, with the number of primary root crops present in 2019 equal to or higher than pre-cyclone levels. The one exception was a village where

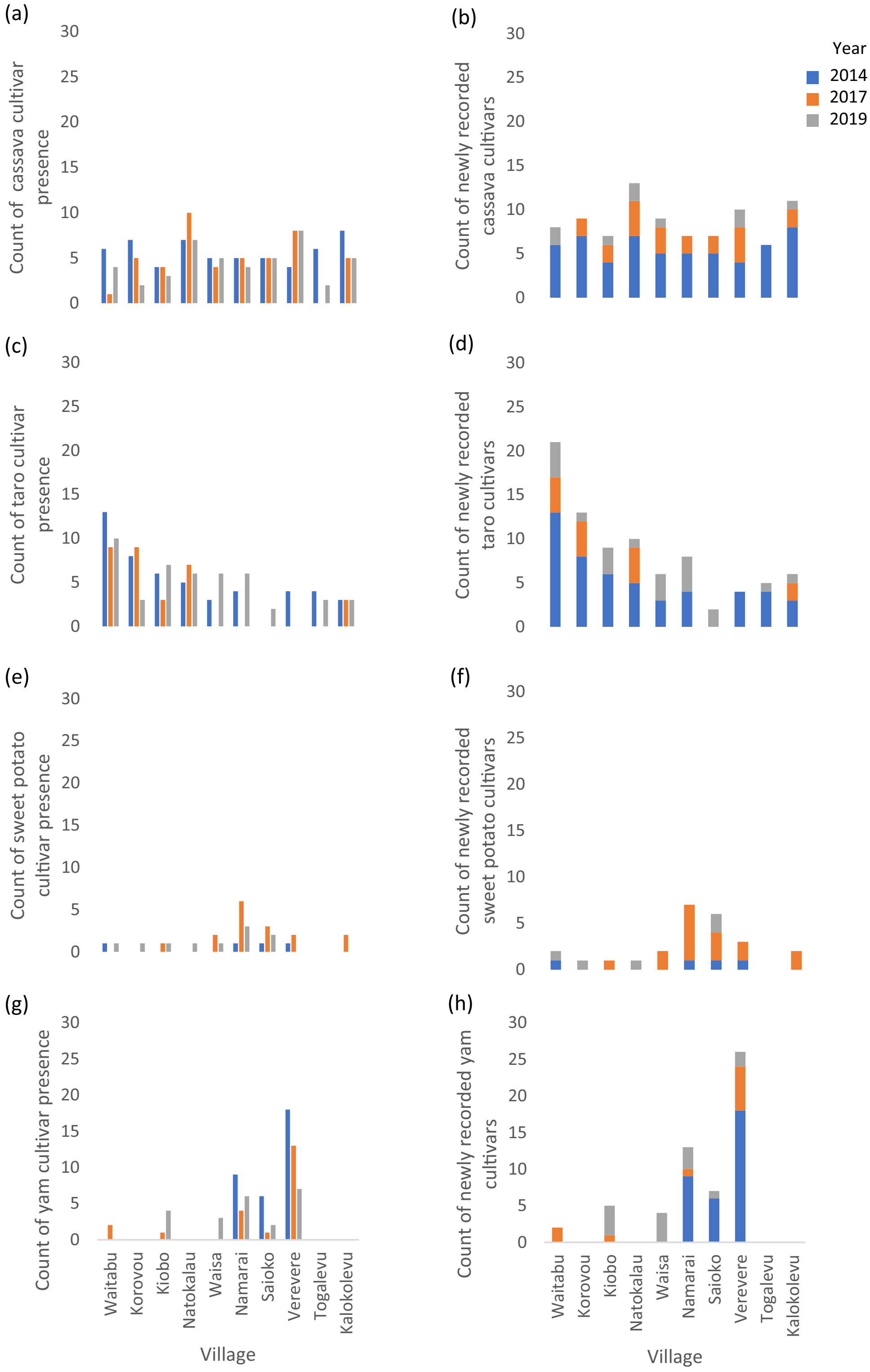


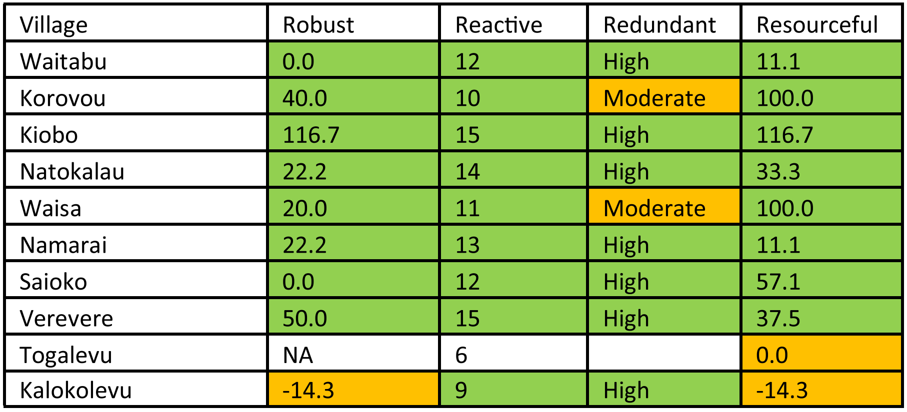
Fig. 3 Number of cassava (**a**), taro (**c**), sweet potato (**e**), and yam (**g**) cultivars recorded in each village per year. Number of newly recorded cassava (**b**), taro (**d**), sweet potato (**f**), and yam (**h**) cultivars in each village per year. Data does not exist for Togalevu in 2017

two fewer root crops, specifically taro and yam, were observed 3 years post-cyclone (2019) compared to pre-cyclone levels (Fig. 2c). However, there was a large variation in resourcefulness at the cultivar level across the villages (Table 1c). Farms of only four villages exhibited resourcefulness at the cultivar level, meaning that for the rest of the villages, by 2019 the number of cultivars had not rebounded to pre-cyclone levels. The lowest level of resourcefulness was observed for cassava which experienced declines in cultivar richness ranging from 20% to as much as 71% (Fig. 3a).

Table 1 Summary of robustness, reactivity, redundancy, and resourcefulness of starch crops and cultivars at each village. A green cell indicates that the agroforest in that village showed resilience post-cyclone, as measured respectively by robustness, reactivity, redundancy, and resourcefulness (as defined in the methods). A yellow cell indicates moderate resilience, and red indicates the aspect was not observed to contribute to resilience. Data was unavailable for Togalevu in 2017 and summary results were omitted where that data was necessary

(a)

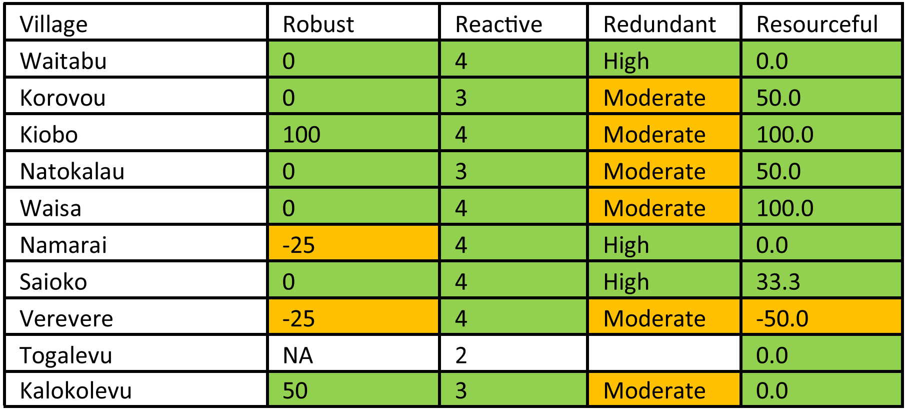
Starch Level Resilience Summary



Village	Robust	Reactive	Redundant	Resourceful
Waitabu	0.0	12	High	11.1
Korovou	40.0	10	Moderate	100.0
Kiobo	116.7	15	High	116.7
Natokalau	22.2	14	High	33.3
Waisa	20.0	11	Moderate	100.0
Namarai	22.2	13	High	11.1
Saioko	0.0	12	High	57.1
Verevere	50.0	15	High	37.5
Togalevu	NA	6		0.0
Kalokolevu	-14.3	9	High	-14.3

(b)

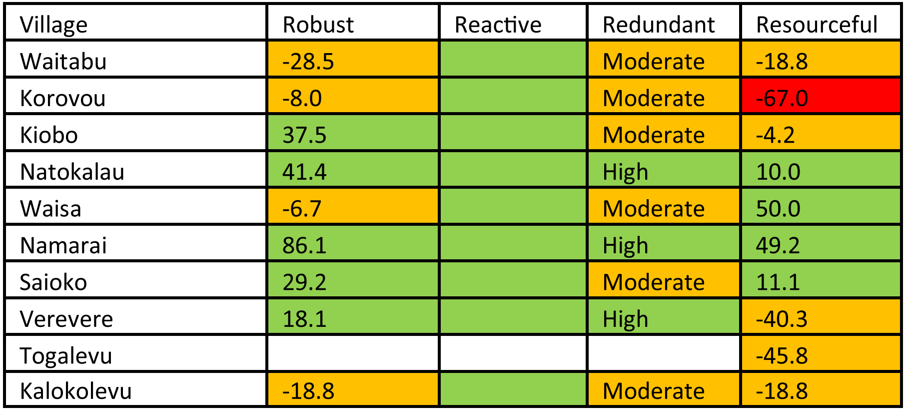
Four Primary Root Crops Resilience Summary



Village	Robust	Reactive	Redundant	Resourceful
Waitabu	0	4	High	0.0
Korovou	0	3	Moderate	50.0
Kiobo	100	4	Moderate	100.0
Natokalau	0	3	Moderate	50.0
Waisa	0	4	Moderate	100.0
Namarai	-25	4	High	0.0
Saioko	0	4	High	33.3
Verevere	-25	4	Moderate	-50.0
Togalevu	NA	2		0.0
Kalokolevu	50	3	Moderate	0.0

(c)

Cultivar Level Resilience Summary



Village	Robust	Reactive	Redundant	Resourceful
Waitabu	-28.5		Moderate	-18.8
Korovou	-8.0		Moderate	-67.0
Kiobo	37.5		Moderate	-4.2
Natokalau	41.4		High	10.0
Waisa	-6.7		Moderate	50.0
Namarai	86.1		High	49.2
Saioko	29.2		Moderate	11.1
Verevere	18.1		High	-40.3
Togalevu				-45.8
Kalokolevu	-18.8		Moderate	-18.8

Discussion

We assessed the resilience of a Fijian agroforest-based food system to a major disturbance by assessing variation in starch species and cultivar richness pre- and post-Cyclone Winston. Although most scholars contend that species and cultivar richness of Indigenous crops has declined across the Pacific (Thaman 2014; Tisdell 2014), we found that at the scale of starch crops at least, the agroforests in the Fijian villages in our study were largely resilient to Cyclone Winston, generally increasing in richness over time. This increase from the pre-cyclone levels contributed to redundancy and robustness, and the new starch crop species observed in 2017 and 2019 highlights the reactivity and resourcefulness of the system. These trends were similar for the four primary root crops. At the cultivar level, however, while many new cultivars were added, making reactivity high, the total number of cultivars present declined and remained lower three years post-cyclone, indicating limited redundancy and resourcefulness at this scale.

Contributions of famine food crops

Famine foods, or those foods that are consumed infrequently during normal times but that come into play in times of need (McMillen et al. 2014), played a critical role in the resourcefulness of the Fijian agroforest food system. The increase in the richness of starch species we recorded in 2017 and 2019 was largely due to the appearance mostly of aroid and yam species, as well as yabia. While there were also increases in tree or tree-like starch crops, such as breadfruit, or uto (*Artocarpus altilis* (Parkinson ex F.A.Zorn) Fosberg), and plantain, or vudi (*Musa* L.), these increases were much more variable by village and year.

One of the greatest increases we recorded was in the number of tannia, or dalo ni tana (*Xanthosoma sagittifolium* K.Koch). A recent introduction of the nineteenth century from the Americas, either by missionaries or whalers, tannia is a robust, prolific crop increasing in use across the Pacific Islands (Lebot 2013; Lebot and Siméoni 2015). While some scholars believe the introduction of new crops such as tannia undermine the resilience of agroforest ecosystems in the Pacific (Sardos et al. 2016), others argue it effectuates a positive impact on agroecosystems due to their ease of cultivation (Lebot 2013). Here it appears to have played a role in helping farmers withstand and recuperate from the impacts of Cyclone Winston. Our results suggest that the impact of new plant introductions on the resilience of agroforests in Fiji is context and species specific, as discussed below in our examination of cassava.

The number of aerial yam (*D. bulbifera)* plants also increased over time. Aerial yam is unique in that while it is a yam, the edible tubers of this naturalized species also form aerially on the vines of the plant; therefore, although it is not protected from the wind produced during a cyclone, the plant may actually benefit from strong winds via dispersal of the aerial tubers (Horvitz et al. 1998) and seeds (Lebot and Sam 2019), and simultaneous forest canopy disturbance (Horvitz and Koop 2001). This may account for increased observations of aerial yam post-cyclone in Fiji, as has been in recorded in hardwood forests in Florida where an increasing frequency of occurrence, as well as coverage, of aerial yam over time was recorded post-hurricane Andrew (Horvitz and Koop 2001). Although we did not observe people actively consuming aerial yam as we did with tannia, it was frequently cited by farmers as a well-known emergency food.

Famine foods are often only used in cases of emergency because they require greater input to prepare them for consumption (Campbell 1984; Martin 1974) and in some cases are not as palatable as other food options. This is the case for aerial yam where the bulbils are toxic if not properly prepared (Martin 1974). While tannia also requires special preparation methods to eliminate its acridity, these preparation methods are less intense and include baking or boiling (Sakai et al. 1972), similar to the processes required for taro and other edible aroids. While some scholars had expected tannia to gain importance as a subsistence or commercial crop in the Pacific (Lebot 1992; Sakai et al. 1972), today it is more commonly considered a wild or emergency food (McClatchey 2012), which our interviews confirmed (data not presented). Easy access and availability of imported and processed starch foods such as rice, wheat flour, and wheat noodles may have influenced this change in use and importance.

High dynamism of crops and crop cultivars

The introduction of new starch crop species on the farms we surveyed was accompanied also by the introduction of many new crop cultivars, illustrating the very high dynamism of the Fijian agroforests. Dynamic agroecosystem management is critical for resilience in that it allows for substitutions and modifications to be made that enable adaptation and recovery (Mijatović et al. 2013). Globally, crop and crop cultivar diversification or substitution is a common adaptation strategy in farming communities in response to environmental changes and disturbances (Labeyrie et al. 2021). In our study, the most commonly listed emergency food crops farmers cited for this purpose included sweet potato, tannia, and spiny yam, listed in order of overall citation frequency.

Many cultivars exist for sweet potato and while we recorded a large relative increase in the number of newly recorded cultivars in 2017 (16) as compared to 2014 (4) across 9 villages (Fig. 3f), we only recorded 9 unique cultivar names over the course of the study (Online Supplement 3). Therefore, many of these new occurrences may have been of the same cultivars. The Fiji Ministry of Agriculture promotes sweet potato as an important disaster recovery crop since it matures quickly, can be grown relatively easily in many environmental conditions, and is less affected by natural disasters (Iese et al. 2018; Veitayaki 2002). Over 49,100 sweet potato cuttings were distributed across Fiji post-Cyclone Winston (Iese V, 2021, Member of 2017 Food Security and Livelihood Cluster, FAO, Suva, Fiji, personal communication). Thus, this increase in new cultivar observations we recorded likely stems from government aid. At the same time, strong social networks within and across villages in Fiji (Dacks et al. 2020; Ravuvu 1983) also likely played a role in facilitating the exchange of planting materials of sweet potato and other emergency food crops that we observed. In China, Jianjun et al. (2015) also reported that 80% of farmers adapted to drought occurrence by planting new varieties of their crops. Interestingly, this response was much lower in Ethiopia and South Africa in response to perceived changes in temperature where only 19% and 3% of farmers in each respective country cited this adaption method (Bryan et al. 2009). In our study, we found that 79% of farmers who grew sweet potato were planting new cultivars 1 year post-cyclone as compared to pre-cyclone records.

Another clear demonstration of the high reactivity of Fijian agroforest food systems, but at the crop level, was the quick substitution of taro with sweet potato. On the farms in our study, increases in sweet potato temporarily replaced taro post-cyclone. Although taro has high cultural and culinary importance as a historically high-status crop in parts of the Pacific (Leach 2005), especially Fiji (Wairiu et al. 2012), its longer life-cycle and more specific growing conditions means it cannot be harvested for anywhere between 6 and 18 months after planting (Ministry of Agriculture 2014, 2015a; Sivan 1982).

The reliance on sweet potato when taro supply is compromised has also been observed in the Solomon Islands in response to environmental disturbances (Iese et al. 2015), and Papua New Guinea in response to pests and diseases (Bourke 2005). In the latter cases, these changes remained more permanent, transforming entire agricultural and cultural systems (Ballard 2005). In contrast, in Fiji, 3 years post-cyclone sweet potato cultivar richness had already decreased in our study. When we asked farmers why they were not growing as many sweet potato cultivars in 2019 as compared to 2017, many cited that sweet potato is less desirable as it is less filling than the other three primary root crops. This may also explain why we observed an inverse relationship in cultivar richness between taro and sweet potato; as taro began to reach or surpass pre-cyclone richness levels, sweet potato richness declined. This lower preference may be different in Fiji, as compared to other Pacific Island countries where sweet potato has played a pivotal role, and as a result, sweet potato may have a lower potential for climate change adaptation and mitigation strategies. Nonetheless, despite this relative decrease, sweet potato richness remained higher in 6 of the 10 villages despite differences in microclimatic conditions 3 years post-cyclone than the pre-cyclone richness levels, increasing redundancy. More research is needed to develop an appropriate distribution model for the Pacific Islands for sweet potato cultivars (Iese et al. 2018), and consumption preferences in Fiji should be incorporated into such an evaluation.

Cultivar decline

Despite the high dynamism of crop cultivars, the incorporation of new cultivars was accompanied by a loss of other cultivars, especially of traditional cultivars, which were often cited by village elders as hardier and more resistant to environmental disturbances. Based on our interviews, many farmers expressed a desire to plant the “old” or “traditional” cultivars, especially of yam and taro. Efforts to source and distribute these plants of cultural, culinary, and post-disaster recovery importance may not only improve resilience to natural disasters, but also aid in the passing on of cultural knowledge about these plants and their significance.

In addition, for most villages and crops, resourcefulness at the cultivar level was compromised, as cultivar richness in 2019 had still not recuperated to pre-cyclone levels. This trend has been observed in other agroecosystems; some farmers surveyed 2 to 4 years after a major flood disturbance in Amazonia actively chose not to replant varieties of cassava after a natural disaster, either to prevent further damage or loss to their current stock should another disturbance occur, because they preferred to replant with cultivars that survived better, or because planting materials were unavailable (Ávila et al. 2021). Moreover, there has been a decline in the number of cassava cultivars grown on small farms elsewhere, as seen in the Republic of Congo (Kombo et al. 2012), and crop and crop cultivar diversity is decreasing across most agricultural species worldwide (FAO 2019).

Although cultivar decline may be a result of many factors, labor requirements and yield are often cited as among the most important in planting decisions (Guarino and Jackson 1986; Hashimoto 1990; Kombo et al. 2012; Teshome et al. 2016), likely because of the importance of these variables in cash economies. The crop that showed the highest decline in cultivars across the time of our study was yam. Moreover, while 90 to 100 yam cultivars have been recorded across Fiji in the recent past (Chandra 1979; Guarino and Jackson 1986; Sivan 1982), our study only recorded 33 cultivars of yam (some of which may be synonyms or homonyms). Yam is the most prestigious root crop in Fiji (Ravuvu 1991), holds historical culinary and other cultural importance across the Pacific (Bourke 2005; Chandra 1979; Leach 2005; Sivan 1982), and has previously been promoted for disaster recovery in Fiji (Benson 1997). Although we observed new plantings on farms in three villages in the years after Cyclone Winston where none had been recorded before, the three villages where we had recorded high richness pre-cyclone experienced large losses in cultivar richness, even though climatically they are well suited for yam cultivation. While yam has superior storage capabilities compared to the other three primary root crops (Chandra 1979), it is also more labor intensive to cultivate than taro and cassava (Rothfield and Kumar 1981) and as shelf-stable processed foods increasingly replace local food production, the need for easily stored root crops decreases. For these reasons, and a lack of planting materials, yam may be the most vulnerable to cultivar richness loss of the four primary root crops. Indeed, the overall production of yam as a species has declined from an estimated 7000 tons per year in 1982 (Sivan 1982), to 4447 tons in 2018 (Ministry of Agriculture 2018), despite advances in yield success. Studies of *Dioscorea* species consumption in general in Fiji also show declines (Lako 2001).

The decline in cultivar richness we observed may be temporary, however. A study in Ethiopia found that sorghum (*Sorghum bicolor* (L.) Moench) landrace diversity in places most exposed to stress from drought or extreme heat or cold actually increased over 11 years (Teshome et al. 2016). It is possible that the cultivar richness in Fijian agroforests needs more time to recover as traditional knowledge keepers often maintain higher levels of intra- and inter-genetic species diversity (Ticktin et al. 2018) which takes time to re-distribute. Accounting for scale and time is important in assessing resilience and more long-term cultivar richness and recovery. Further research on the decline of yam cultivation and cultivar richness is needed.

Nutrition and crop introductions

Assessing the resilience of any food system also includes consideration of nutritional quality. Cassava was recorded more frequently than any other starch crop across all the farms we visited, and while the number of cultivars 3 years post-cyclone had still not recovered to pre-cyclone levels in more than half of the villages, the redundancy of cultivars was still high. The important role of cassava in Fiji has implications for human nutrition. An extremely versatile crop that can grow in many climate conditions and matures relatively quickly depending on the cultivar, cassava is now one of the most commonly grown and consumed starch crops in the South Pacific, replacing taro, yam, and sweet potato in cultivation (Aalbersberg and Limalevu 1991; but see Bourke 2005). However, cassava is also one of the least nutritious crops, with lower protein content than taro, yam, and sweet potato (Bradbury and Holloway 1988), and antinutrients that may inhibit nutrient absorption if overconsumed (Montagnac et al. 2009). Additionally, cassava contains relatively high concentrations of cyanogens and if not properly prepared, or in cases where it serves as the primary food source, the risk of cyanide toxicity and irreversible illness or death is high (Aalbersberg and Limalevu 1991; Burns et al. 2010). Of the farmers who participated in our interviews and who were actively replanting 1 year post-cyclone, 78.3% indicated they were replanting with cassava, whereas the percent of farmers who indicated they were replanting with taro, sweet potato, and/or yam was only 47.8%, 26.1%, and 8.7%, respectively. It is therefore critical to recognize that cassava does not provide true redundancy to the system in a nutritional sense. Agroforest food systems that maintain diverse starch crops as well as cultivars, especially yam and sweet potato, can help sustain redundancy at the crop level while ensuring adequate access to nutritional diversity.

Variation in resilience across villages

The variation in measures of resilience across villages may be due to a number of climatic, social, and economic factors. For example, Taveuni experiences an average yearly rainfall of 2696 mm and maintains a relatively wetter microclimate than Nakorotubu and Kubulau. These conditions facilitate taro production and may explain the comparatively higher taro richness in the villages of Waitabu and Korovou. The Ministry of Agriculture also focuses their taro farming programs for export in Taveuni, which may also contribute to increased cultivar richness. Suva experiences high average yearly rainfall as well; however, the villages in Suva are much closer to town and the lack of taro richness is likely due to a lower focus on farming, as more individuals are employed in town and therefore have a higher reliance on foods from the market. Intravillage network cohesion was high in villages in Wainikeli, Taveuni (Dacks et al. 2020), where we found resourcefulness was also often high, and thus, we pose that stronger social networks may have helped facilitate cultivar richness recovery. In addition, villages in Nakorotubu, Kubulau, and Wainikeli were among the most damaged by the cyclone (Fig. 1); however, those in Suva were comparatively unscathed. This may also explain why species/cultivar richness remained relatively static there. Finally, additional factors we did not measure could explain differences as well. For example, species and their production levels are influenced by soil conditions, but this data was not available. Similarly, the suite of species and cultivars farmers plant is often influenced by traditional knowledge, which is commonly higher in elders (Souto and Ticktin 2012), but we did not record the age of the farmers interviewed.

Future outlook

Despite changes in biodiversity and a historical decline in overall cultivar diversity for most crops across the Pacific (Lebot 1992; Lebot and Siméoni 2015; Masibalavu et al. 2002 (unpublished); Thaman 2014; Tisdell 2014), our research indicates that Fiji agroforest systems still provide important levels of food system resilience to extreme weather events, especially of energy-dense staple crops. However, even given their importance in disaster recovery, agroforests in the South Pacific remain under constant threat from agrodeforestation (Thaman 2014) and socioeconomic change catalyzing changes in land tenure and use (Nari 2000), and must be prioritized as a critical component of climate change adaptation measures and food security plans. Our research focused on measures of species and cultivar resilience, but information on productivity would provide further insight. Additional research on the resilience and nutritional content of cultivars, and the impact of access to these crops and cultivars on diet and human health would also improve our understanding of these complex food systems and the potential they have to not only provide food, but also nutritional security. Finally, in preparation for increases in climate change-induced disturbances, this framework can be applied to other systems, to assess food system resilience and identify the ways it may be improved.

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