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Predictors of tree damage and survival in agroforests after major cyclone disturbance in Fiji

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Abstract This study explores the resilience and damage dynamics of agroforests, a critically important yet understudied agroecological system, in the aftermath of Category-5 Cyclone Winston in Fiji. As agroforestry gains prominence globally as a versatile production system able to support agrobiodiversity and food security for climate resilience, understanding the characteristics that contribute to its resistance and resilience to disturbance becomes increasingly important. Here we examine the effects of individual and species-specific traits, and management (planted and fallow vs forest areas) on the probability of tree stem survival and damage, and discuss the resistant and resilient qualities of trees and management actions in these systems. We found that the probability of post-cyclone survival increased as a function of wood density, irrespective of management type. Damage severity increased with tree size (diameter at breast height). Some of the species with the highest wood density were native trees, emphasizing the role of native species in agroforests, and the value of agroforests to conservation. Overall, agroforest trees experienced relatively low stem mortality (12.2%), suggesting that these agroforests may resist extreme disturbances despite their potential vulnerabilities such as landscape edge effects and altered species compositions. Our study provides insight

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into the potential of agroforests as resilient agroecological systems capable of withstanding escalating cyclone intensities, and the role of effective management strategies for fostering resilience amid a rapidly changing climate.

Keywords Hurricane · Resilience · Biodiversity conservation · Food systems · Pacific

Introduction

Climate change has induced changes in storm intensity, frequency, and geographic occurrence (IPCC 2021). While the overall number of cyclones is expected to stabilize or decrease, the frequency and intensity of severe Category 4–5 storms are expected to increase, with peak windspeeds also rising (IPCC 2021). Region-specific changes project a northward shifting latitude of peak wind intensity for western North Pacific cyclones (Feng et al. 2021), and increased windspeeds in Southern Hemisphere extratropical cyclones (IPCC 2021). Despite data limitations detailing past cyclone events, it is likely that the proportion of major cyclone (Category 3–5) events has been increasing over the past forty years (IPCC 2021). While social and economic repercussions of severe cyclones have been well documented across the globe, the ecological impacts on forests and agroforests remain comparatively incomplete, necessitating concerted research efforts (Pruitt et al. 2019).

Cyclone induced tree damages typically include defoliation, branch and crown/stem snapping, and uprooting (Burslem et al. 2000; Imbert and Portecop 2008; McGroddy et al. 2013; Webb et al. 2014). Factors that determine damage resistance, such as wood density, growth rate, and architectural traits like diameter at breast height (DBH), height, and canopy characteristics, vary across storms, locations (McGroddy et al. 2013; Webb et al. 2014), and forest types (Cameron et al. 2021; Delaporte et al. 2022). Wood density has been shown to correlate negatively with all damage types in the Pacific Islands after major cyclone disturbance (Webb et al. 2014), but this relationship is inconsistent with other regions like the North Atlantic (Uriarte et al. 2019) and Australia (Metcalfe et al. 2008). Similarly, the impact of DBH on damage and mortality varies widely. For example, tree size was not a determinant of mortality in Hawai‘i post Hurricane Iniki (Herbert et al. 1999) and no relationship was observed between tree size and uprooting in Samoa post Cyclones Ofa and Val (Elmqvist et al. 1994); however, tree size was associated with different types of damage in Tonga post-Cyclone Waka (Franklin et al. 2004). Windspeed (e.g. Imbert and Portecop 2008) and topography (e.g. Tanner and Rodriguez-Sanchez 2014) have also been shown to be important determinants of damage in the Caribbean, whereas in the Pacific, the impact of topography on damage is less consistent (Burslem and Whitmore 1999; Burslem et al. 2000; Webb et al. 2011) and warrants further investigation (Delaporte et al. 2022).

Management practices can help to improve resilience to cyclones. Forests with a productivity-focused land-use history may resist and recover from cyclone damage more effectively (Philpott et al. 2008; Lazos-Chavero et al. 2018). This may proceed through a legacy of purposefully planted N_2-fixing trees facilitating higher recovery productivity (Beard et al. 2005), tree architecture modifications, like reduced height, allowing for resistance to wind damage (McGroddy et al. 2013), or long-term effects like soil stabilization from deep-rooted trees protecting against cyclone-induced landslides (Perotto-Baldiviezo et al. 2004). In Vanuatu, customary stewardship practices in native forests appear to have played a positive role in recovery and resistance post Cyclone Pam (Ticktin et al. 2024, 2018). In contrast, in heavily harvested mangrove forests in Fiji, management practices may have had severe negative impacts on cyclone resilience, where a 77% loss in mangrove area has been observed since 2008 (Cameron et al. 2021). The role of management in various forest types, alongside ecological factors, is critical yet under-researched, highlighting a need for more studies to understand and enhance forest resilience.

Agroforestry is a forest-based, human-managed agroecological system whereby crops and understory plants are cultivated with overstory trees and shrubs of food and non-food value (Kumar and Nair 2004). In the Pacific Islands, agroforestry is part of a larger social-ecological system that provides diverse food, medicinal, building, and other resources to communities, and has enabled resilience to disturbance for centuries (Thaman 2014).

In Fiji, trees within agroforests are actively managed through practices such as tree pruning or pollarding (Thaman 2008) which have been shown to help mitigate hurricane damage in Mexico (McGroddy et al. 2013). Agroforest management practices can help to improve resilience to cyclones via adaptation, such as in Honduras post Hurricane Mitch where communities relocated and re-diversified their agroforest sites conferring resilience to subsequent disturbance (McSweeney and Coomes 2011).

Given that between 25 and 33% of the global population is estimated to rely on forests, including agroforests, for subsistence (FAO and UNEP 2020; UN 2021) cyclones significantly impact livelihood and food security (Lazos-Chavero et al. 2018). However, research focused on understanding the impacts of cyclones on agroforests is scarce (but for trees on agricultural land see Uriarte et al. 2019; Philpott et al. 2008; Lazos-Chavero et al. 2018).

In the Pacific, two studies incidentally assessed the effects of cyclones on abandoned agroforest areas in the Pacific Islands. Webb and colleagues (2014) assessed tree damage in a 20-year-old abandoned agroforest in Samoa after a Category-5 cyclone which passed within 28 km of their plots. They found survival was dependent on damage type, which varied by species, and that higher wood density may allow greater resistance to wind damage, but not always greater survival. Similarly, Franklin (2007) assessed the impact of various disturbances, including cyclones, on species composition in 30–40 year-old abandoned agroforests in Tonga. To our knowledge, no studies have examined what types of damage trees sustain in active agroforests in the Pacific Islands, or their survival.

As cyclone frequency, intensity, and geographic occurrence patterns change in the Pacific, trending towards more frequent intense cyclones (IPCC 2021), the need to understand how trees in Pacific Island agroforest systems experience and recover from cyclone damage becomes great and warrants further assessment. Overall, the ecological impacts of cyclones in the Pacific are significantly under-researched compared to other regions (Lin et al. 2020). Of the studies conducted in the Pacific Islands, almost all have followed cyclones of Category-4 magnitude or lower (c.f Elmqvist et al. 1994; Franklin et al. 2004; Goulding et al. 2016 but see Webb et al. 2014), or only indirectly impacted sites (c.f Burslem et al. 2000; Webb et al. 2011). Cyclone events in the Pacific region have exhibited unprecedented behavior in trajectory, velocity, geographic occurrence in recent years, emphasizing the need to better understand their dynamics (Magee et al. 2016) and ecological impacts (Asbridge et al. 2018). The unusual magnitude and behavior of sequential South Pacific Catogory-5 cyclones Pam in Vanuatu (2015) (Magee et al. 2016) and Winston in Fiji (2016) (Sharma et al. 2021) highlight this; Winston surpassed Pam as the strongest cyclone on record in the South Pacific (WMO 2016). The extreme magnitude of these cyclones has raised questions about the need to add a Category-6 cyclone intensity classification (WMO 2016).

We studied the impacts of Cyclone Winston on tree stem survival and damage in agroforests in Fiji at 1- and 3-years post-cyclone Winston. We expected that survival would (1) decrease with increasing severity of stem damage; (2) increase with increasing wood density, and (3) be higher in actively managed agroforest plot types (i.e. in plots that were planted and recently fallow) than in forest plots. We also expected that (4) damage severity would increase with tree size (DBH) and wood density, and would be higher in unmanaged agroforest plot types (forest plots) than in actively management types (recent fallow and crop).

Materials and methods

Study site and context

Fiji is archipelago of over 300 islands, most inhabited, in the Near Oceania region of the South Pacific. The most recent census shows Fiji's population to be 884,887, with 55.9% residing in urban areas, while the remaining 44.1% reside in rural areas (Fiji Bureau of Statistics 2018). Agroforests were historically part of a larger land-sea based social-ecological system that met communities' food, medicinal, social, infrastructural, and other subsistence needs, either directly or through trade with other communities (Thaman 2014). Global change has influenced agroforestry management practices and species composition (Thaman 2008; Shah et al. 2018), but they remain an important source of food and other resources (McGuigan et al. 2022).

Similar to other Asia–Pacific agroforests (Shin et al. 2020), and more specifically, the Pacific Islands (Clarke and Thaman 1993a), agroforests in Fiji are shifting mosaics of forested, fallow, and planted areas (Clarke and Thaman 1993b; Ticktin et al. 2018; McGuigan et al. 2022). Trees are present across these areas; however, their composition and stand density varies (Thaman 2008). Rotation between fallows and planted areas is most common, though fallows may also succeed into secondary forests and forested areas may be transformed into planted areas in response to environmental and socioeconomic changes (Clarke and Thaman 1993a). When forested areas are selectively cleared for planting, farmers retain trees that are important culturally and/or ecologically (Thaman 2008; Shah et al. 2018), and often prune or pollard them to increase light availability, return organic material to the soil, or provide structural support for climbing crops (Clarke and Thaman 1993b). Trees that enhance agroforest production are also purposefully planted (Thaman 2008; Shah et al. 2018).

Cyclone Winston

On February twentieth, 2016, Cyclone Winston became the first cyclone in recorded history to make landfall in Fiji as a Category-5 storm (WMO 2016). It sustained an average 10 min windspeed of 160 knots (296.32 km/h) and gusts of up to 210 knots (388.92 km/h) (WMO 2016), and exhibited erratic track behavior (Sharma et al. 2021). Winston originated East of Vanuatu and initially traveled southeast, eventually shifting northeastward crossing Ono-i-lau, the southernmost Fiji islands, as a Category-2 cyclone on February fifteenth (WMO 2016). After crossing into Tonga, Winston turned back westward gaining intensity and entered the Northern Lau group on February twentieth as a Category-5 cyclone (WMO 2016). It continued its westward projection as it crossed the three largest islands of Fiji—Viti Levu, Vanua Levu, and Taveuni—exiting Fiji on the twenty-first (WMO 2016). It is estimated to have destroyed 30,369 homes, affected 540,400 people, and 44 fatalities were reported (Government of Fiji 2016; Nakamura and Kanemasu 2020).

Agroforest damage and survival surveys

Between January and March of 2017, we worked with farmers in 6 coastal villages in 3 districts on the 3 largest islands in Fiji—Viti Levu, Vanua Levu, and Taveuni—to establish 22 semi-permanent 5 × 20 m plots in forest, fallow, and planted agroforest areas. Villages were all located within 40 km of the estimated center of Cyclone Winston's path (Esri 2016) and all agroforest sites were within one hour's walk from the village, between 0.25 and 5.00 ha in size, and below 100 m elevation. The cyclone did not significantly change direction as it crossed the sites we assessed (WMO 2016). Agroforests within these specifications are primarily subsistence farms and not used for commercial purposes (Ticktin et al. 2018). Based on access and availability, 3 plots were established in planting areas, 13 in fallow areas, and 6 in forest areas of the agroforests. In each plot, the stems of every woody tree greater than 2 cm diameter at 1.4 m height from the base (DBH) were mapped, recorded to species, measured for DBH, and observed for damages sustained and survival (stem information was still recorded even if they did not survive the cyclone). We recorded 16 stems of 6 species in planted plots, 68 stems of 13 species in fallow plots, and 50 stems of 15 species with one unidentified species in forest plots. Planted and fallow plots were grouped as actively managed plots and forest plots were categorized as unmanaged. We refer to this as, "management type".

We assessed stem damage based on in-field observations (2017) and farmers' observations immediately post cyclone (2016). Damage types, in increasing level of severity, included none, defoliation, branch snapping, crown snapping, and uprooting. Only 2 trees were uprooted and were then removed from the statistical analysis. Farmers' observations detailed the level of defoliation and branch snapping each stem sustained, and confirmed mortality from cyclone disturbance where stems were already dead. We returned to these sites 2 years later (2019) and again recorded stem survival. In some cases, stems had been cut by the farmer because the cyclone damages it had sustained were so great that the tree was slowly senescing and the remaining individual was no longer beneficial and productive for the farmers' agroforest. We recorded this a cyclone-related mortality. This slow recovery or senescence may have been related to unobservable belowground root damage sustained in the cyclone (Herbert et al. 1999). In other cases, farmers had cleared otherwise healthy trees as part of their management practices and we considered this a non-cyclone-related fatality and did not record it as a mortality for the purposes of this study. Given their relevance to the aforementioned post-cyclone

Table 1 Results of the best fit model to test the effects of individual traits and forest management on the probability of tree stem survival

Predictors	Estimate	Std. error	*p*
(Intercept)	10.44	5.03	0.038
wood density	4.52	10.99	0.681
N_{unique_tree}	91		
N_{unique_plot}	21		
Observations	124		
AICc	42.674		

The full model included DBH, stand density, plot type (management) and wood density as predictors.The number of observations represent the number of stems. Tree and plot were included as random factors in the model and N unique tree and N unique plot represent the number of trees and plots respectively

Table 2 Results of the best fit model to test the effects of damage type on the probability of survival of agroforest trees after Cyclone Winston

Predictors	Estimate	Std. error	*p*
(Intercept)	13.29	4.24	0.002
Defoliation	14.79	757.67	0.984
Branch snapping	− 1.23	4.17	0.767
Crown snapping	4.67	7.57	0.537
N_{unique_tree}	98		
N_{unique_plot}	21		
Observations	132		
AIC	62.831		

Number of observations represents the number of stems. Tree and plot were included as random factors in the model and N unique tree and N unique plots represent the number of trees and plots respectively

recovery studies in the Pacific (Webb et al. 2014), we recorded stem DBH and collected wood density data from the TRY database (Kattge et al. 2020); where wood density information was incomplete, we used the mean of the genera.

Stem survival and damage models

We developed generalized linear mixed models (GLMMs) to assess 1) the effect of individual and species level traits and management type on stem survival (Tables 1 and 2) the effect of damage type sustained on stem survival (Table 2). For the survival models we used the package 'glmmTMB' (version 1.1.2.3) (Brooks et al. 2017) to create binomial GLMMs. For the damage sustained model, we used a multivariate generalized linear mixed model (MCMCglmm) using package 'MCMCglmm' (version 2.33) (Hadfield 2010) and created ordinal models. Model variables were examined for homogeneity of variance and multicollinearity. Multi-stemmed trees can snap or experience damage independently of each other (Webb et al. 2014) and trees located within a plot may not be independent. To account for this possible non-independence we also included individual tree nested within individual plots as a random effect within our models. We fit the full models, which included wood density, DBH, stand density, and plot type as predictors, and then performed null hypothesis significance testing using ANOVAs (Supplementary Tables 4 and 5) (Tredennick et al. 2021).

Results

We recorded 132 stems of 27 species across the agroforests. Within these agroforests, 42.6% of the species in fallow plots were native, while this value was 20.4% in forest plots and 25% in crop plots. Stem DBH in forest plots was greater than in fallow or crop plots: 26 ± 23.8, 15.9 ± 18.7, 15.3 ± 7.3 cm respectively (Supplementary Fig. 5).

Across all sites and plots, 58.2% of tree stems suffered some type of damage, either defoliation, branch or crown snapping, or uprooting. Specifically, of these tree stems that were damaged, 50% of stems experienced defoliation, 29.9% had branch snapping, 27.6% had crown snapping, and 1.5% (2 trees) were uprooted (Fig. 1.). The proportion of trees that survived for the different damage types were as follows: no damage (0.96), defoliation (1.00), branch snapping (0.82), and crown snapping (0.73) (Fig. 2). There were no significant differences in survival across damage types (Table 2). Although nearly 45% of stems sustained damage of branch snapping or greater severity, stem mortality over three years was relatively low (12.2%).

Stem survival increased with increased wood density (Fig. 3). No other predictors (DBH, stand density, or plot type) were in the best fit model (Table 2). The best fit model showed that severity of stem damage increased with increasing DBH (effect size = 0.36,

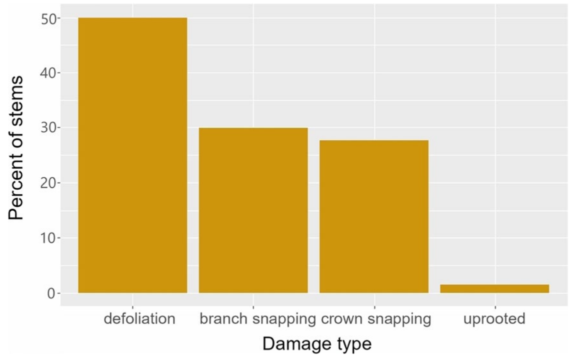

Fig. 1 Category and percent of tree damage in agroforests after Cyclone Winston. Among all stems, defoliation was the most prevalent (50%), followed by branch snapping (29.9%), crown snapping (27.6%), and uprooting (1.5% or 2 trees)

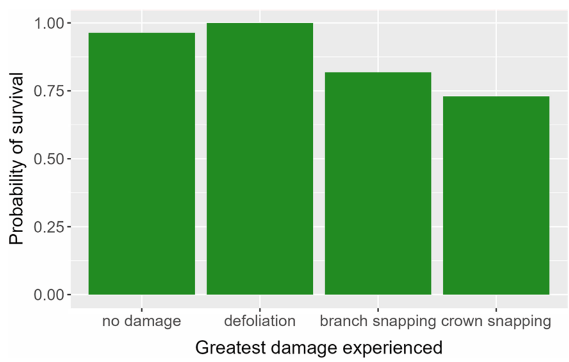

Fig. 2 Probability of stem survival for each damage category of agroforest trees after Cyclone Winston. Uprooting is not included due to small sample size. The survival rates for each damage type are as follows: "no damage" (0.96), "defoliation" (1.00), "branch snapping" (0.82), and "crown snapping" (0.73)

p MCMC = 0.11, Supplementary Table 3). No other predictors (wood density, stand density, or plot type) of damage severity were in the best fit model (Fig. 4).

In the unmanaged (forest) plots, all of the stems that did not survive were of the same species (*Storckiella vitiensis* Seem), and found within the same plot (along with other species). Additionally, all these trees experienced defoliation, or branch or crown snapping, and some experienced all three. In the managed (crop and recent fallow) plots, the stems that did not survive varied in species identity and damage type sustained, including "none", and "all." Although the two uprooted trees were removed from these analyses because of the small sample size, both were *Cocos nucifera* L. from two separate locations, and grew in different management plot types.

Discussion

Cyclones influence the structure and composition of forests (Lugo 2008; McGroddy et al. 2013), and the dynamics of the human communities that rely on them (Lazos-Chavero et al. 2018). Cyclone Winston caused catastrophic damage ecologically, economically, and societally (Government of Fiji 2016), and with extreme cyclones expected to increase with climate change (IPCC 2021), food security is threatened. Although agroforestry in Fiji has been shown to support food system resilience to cyclone disturbance at the understory crop level (McGuigan et al. 2022), there is limited understanding about how cyclones directly affect trees, and which individual, species, and landscape-level traits contribute to damage resistance and survival. Our findings demonstrate high resistance to cyclone damage in agroforests, with very low mortality rates, despite severe damage to nearly half of the stems. This aligns with observations in Samoa (Webb et al. 2014) and Mexico (McGroddy et al. 2013) and, given the critical role of agroforests in sustaining daily subsistence needs in Fiji, these results have significant implications for enhancing food system resilience.

Relationship of wood density to survival

Our best fit models suggest that species with higher wood density had higher stem survival post-cyclone. Studies assessing this relationship show mixed results across locations and storms (Lin et al. 2011), as do the few studies conducted in the Pacific Islands. A positive relationship was found between wood density and survival in American Samoa (Webb et al. 2011, 2014), while Burslem et al. (2000) found this relationship less clear, but observed that tree species with the second highest wood density suffered the greatest mortality in the Solomon Islands. An additional study in the Solomon Islands found that the least damaged forest was dominated by high wood density trees (Burslem and Whitmore 1999).

Our results have implications for agroforest composition post-cyclone, as these events can increase

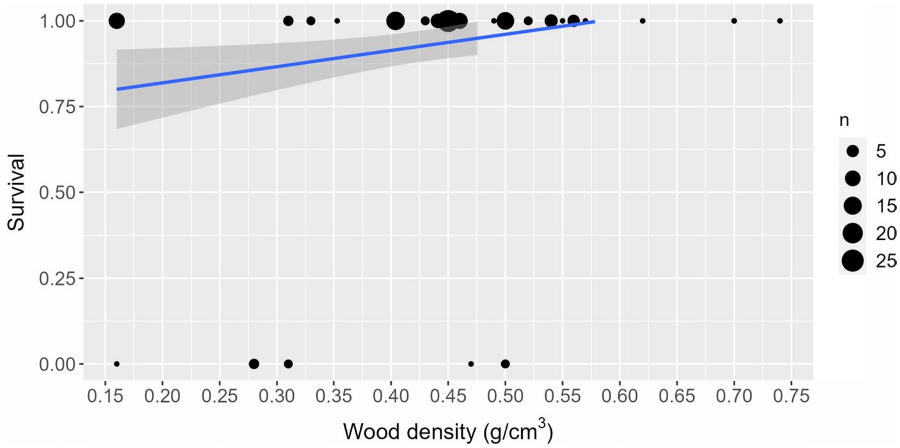

Fig. 3 Probability of survival as a function of wood density for tree stems in agroforests after Cyclone Winston. The black dots represent the observed survival (1) or mortality (0) of each individual stem. Larger black dots represent overlapping data points, with the size of the dot corresponding to the number of stems sharing the same wood density value (as indicated in the key to the right of the graph). The blue line represents the predicted relationship between wood density and tree stem survival, derived from the regression analysis. The shaded area represents the 95% confidence interval. (Color figure online)

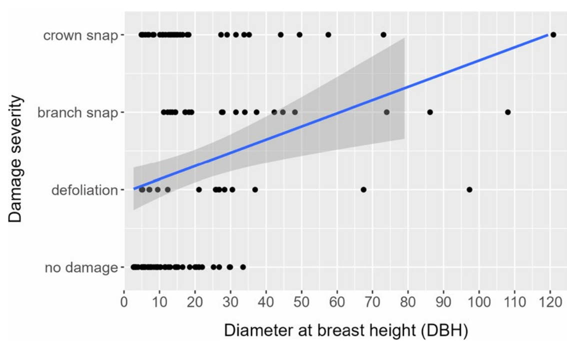

Fig. 4 Damage severity as a function of tree stem diameter at breast height (DBH) for stems of agroforest trees after Cyclone Winston. Damage types are listed in increasing level of severity from "no damage" to "crown snap". Uprooting is not included due to small sample size. The blue line represents the predicted relationship between DBH and damage severity levels, derived from the regression analysis. The black dots represent the observed damage severity levels for each individual stem. The shaded area represents the 95% confidence interval. (Color figure online)

wood density at the community level, and thus influence species composition (Lin et al. 2020). In Australia, forest communities post-cyclone were found to be composed primarily of denser species as they resisted damage more effectively (Read et al. 2011), although less dense and faster growing species may dominate initially in cases where damage is severe (Curran et al. 2008). The species with the greatest wood density in our study included *Leucaena leucocephala* (Lam.) de Wit, *Bischofia javanica* Blume, and *Citrus limon* (L.) Osbeck in managed plots, and *Intsia bijuga* (Colebr.) Kuntze, *Premna serratifolia* (L.), and *Pittosporum arborescens* Rich ex A. Gray in unmanaged plots. Notably, most of these species are native to Fiji (excluding *L. leucocephala* and *C. limon*) and all individuals of these species survived the cyclone. Although agroforest species composition is heavily influenced by human activity as compared to native forests, the impacts of cyclones on trees is still likely to affect long-term species composition. As such, resultant communities may by composed of more dense-wood native species, further highlighting the importance of agroforests to conservation in Fiji (Ticktin et al. 2018). Famers' preference for more resilient species (McGuigan et al. 2022) may also positively influence species composition towards higher wood density native trees if planted. Given predicted decreases in overall cyclone frequency, this may also allow for slower growing dense trees to re-establish their populations more effectively, despite cyclone intensity increasing (IPCC 2021). However, invasive species must still be managed.

Relationship of damage severity to survival

In contrast to other studies in the Pacific Islands (Webb et al. 2014) and the Caribbean (Tanner and

Rodriguez-Sanchez 2014) that found significant negative relationships between damage severity and survival, our results indicate that the likelihood of survival did not differ significantly between stems with no damage, defoliation, branch snapping, or crown snapping. Uprooting often has high mortality rates because roots lose access to soil resources necessary for recovery (Webb et al. 2014), as was the case in our study, where both uprooted trees died. Although our sample sizes were not large enough to assess species-specific differences in damage severity across size and forest type, we do observe that crown snapping was experienced across fifteen different species, in all plot types, including both native and non-native species (Supplementary Data 1).

Defoliation is often overlooked in its significance to recovery and resistance (Lin et al. 2020) though defoliation reduces photosynthesis and thus productivity (Yao et al. 2015), which may negatively impact long-term recovery. In the short-term, loss of foliage can increase vulnerability of trees and stems to wind damage and mortality, particularly in areas prone to higher frequency cyclone events (Lin et al. 2020). In our study more than half of the stems observed experienced defoliation. This is consistent with studies outside the region (for example, 56% defoliation in Puerto Rico) (Walker 1991). Within the region, Webb et al. (2011) found 29% total stem defoliation after a Category 4–5 cyclone in American Samoa, however this storm passed much farther away from the sites (400 km).

Our relatively small sample size (132 stems) may have influenced our findings. However, the lack of difference in survival rates may also relate to the impacts of management actions buffering against mortality. For example, Webb et al. (2014) found that trees in a 20 year-old abandoned agroforest were less likely to be uprooted, and when uprooted, had greater survival rates. This may be because humans often intentionally plant trees in agroforests areas (Thaman 2008; Shah et al. 2018), the methods of which help trees set deeper roots with better anchorage against wind disturbance (Fazio 2014). These trees may also be planted in groups to allow for more convenient harvesting, which also confers damage resistance (Gilman 2007). Finally, trees in agroforests are often pruned or pollarded in Fiji (Clarke and Thaman 1993b; Thaman 2008), dramatically reducing their height and canopy diameter, which may confer greater resistance and survival to cyclone wind disturbance (McGroddy et al. 2013). This could represent an important difference between agroforestry systems and other forest systems and warrants further research.

Predictors of damage severity

Our finding that wood density did not affect damage type differs from Webb et al. (2014)'s study in American Samoa where wood density was an important predictor of severe damage. However, in Puerto Rico wood density was also found not to be a good predictor of damage severity (Walker 1991). These contrasting results highlight the need not only for more longitudinal studies of cyclone-forest dynamics in general (Pruitt et al. 2019), but especially of agriculturally important areas (Philpott et al. 2008), including agroforests.

We found that DBH predicted the severity of damage. Although the relationship of DBH to damage type also varies across locations and storms (Webb et al. 2014), in Tonga, small-medium trees (10–15 cm DBH) had the highest frequency of snapped stems and large trees (> 20 cm DBH) were more likely to be uprooted, suffer greater branch loss, and mortality (Franklin et al. 2004). A similar result was also found in the North Atlantic basin in the continental subtropical coastal region of the U.S. post disturbance (Gresham et al. 1991). Agroforests are often composed of different species and various size-classes. Older trees with a larger DBH, or fast-growing trees with correspondingly larger DBH, are then also susceptible to cyclone damage in agroforests, similar to other forests. While Franklin et al. (2004) noted higher mortality of larger tree species in agricultural fallows, Webb et al (2014) observed higher survivability of trees after severe damage, such as uprooting, in anthropogenically disturbed (post-agroforestry) secondary forest. This suggests that in agroforests the relationships between DBH, damage, and mortality are complex, and the actively managed nature of these systems may confer greater resilience to disturbance.

Resilience of agroforests as a function of management

Management type was not found to be a significant predictor of stem survival or type of damage sustained in our models. However, in other studies, tree-related agricultural management regimes have been shown to impact multiple facets of agroecological outcomes (Philpott et al. 2008; Lazos-Chavero et al. 2018). We separated agroforest management types into planted and fallow (managed) versus forest (unmanaged) for this study because of important structural and compositional differences, however agroforests incorporate and are characterized by all three of these rotational landscape types (planted, fallow, and forest) (Ticktin et al. 2018) and associated management schemes. The spatial heterogeneity and differences in biodiversity of these agroforests improve resilience (Mijatović et al. 2013). Our finding supports the assertion that agroforestry, and its interacting social-ecological properties, may be highly resilient to cyclone disturbance. This likely proceeds through protective ecological and anthropogenic interactions which increase the resistance and resilience of both managed and unmanaged agroforest areas to cyclone disturbance.

For example, although agroforests causes habitat fragmentation via their mosaic nature, the resultant edge effects and the associated greater susceptibility of trees to wind damage (Laurance and Curran 2008) may be mediated by human activities (Darnhofer et al. 2010) that help forested agroforest areas resist damage. This includes pruning and pollarding (Thaman 2008) of edge trees producing a gradual reduction of windspeed into the forest, and purposeful planting of windbreak trees to reduce wind damage to crops seen in the Pacific Islands (SPC 2016). In Fiji, we observed *Gliricidia sepium* (Jacq.) Walp., also named bai ni cagi which translates roughly to wind fence, used often as a windbreak. Other plants used as windbreaks in the Pacific Islands include *Musa* sp L. (Nakamura and Kanemasu 2020), *Mangifera indica* L., *Bischofia javanica* Blume, and *Casuarina equisetifolia* L. (SPC 2016). The effect of windbreak trees on agroecological resilience was also observed post-cyclone in the Caribbean where pollarded citrus trees helped buffer coffee plants from wind damage (Perfecto et al. 2019). In the same way that trees in planted and fallow areas may help prevent damage in forested parts of agroforests, those forested areas may also help protect trees in planted and fallow areas; this may proceed through the reduction of windspeed as a product of forested area's structure and composition (Zhang et al. 2022).

Conclusion

Our study examined the impact of a major Category-5 cyclone on agroforest tree damage and survival in Fiji. The results revealed large scale defoliation across the agroforest sites, consistent with global forestry studies, with relatively low mortality rates after three years (12.2%). This resilience may be facilitated, in part, by management practices that provide a form of buffer against cyclone wind damage, and impact the community's ecological characteristics. The inconsistent relationships between stem size (DBH) and damage severity, as well as wood density and survival among global forest recovery assessments underscores the need for a more nuanced understanding of the interplay between individual and species level-traits, landscape characteristics including topography, windspeed, management, and cyclone damage in agroforests, and forests alike.

The resilience of agroforests depends not only on ecological factors but also on social factors, and is shaped by the interplay of management practices and the physical characteristics of the agroforest. Our findings underscore the critical role that agroforestry may play in fostering resilience to increasing cyclone intensities driven by climate change. As the climate crisis intensifies and severe cyclones become more frequent (IPCC 2021), a deeper understanding of how agroecosystems respond to and recover from disturbances is critical. Longitudinal studies on cyclone-agroforest dynamics in agroecosystems, the role of tree characteristics in damage susceptibility, and the socio-economic impacts of cyclones on agroforests should be prioritized (Perfecto et al. 2019). Additionally, assessing the effectiveness of specific management practices in enhancing agroforest resilience to cyclones is crucial. This research will contribute to the development of effective strategies to enhance the resilience of agroecosystems in the face of increasing cyclone intensity, ultimately ensuring food security and sustainable livelihoods for communities in cyclone-prone regions, and globally.

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Author contributions A.M., M.T., and T.T. conceived and designed the study. A.M., M.T., and V.T. carried out the data collection. A.M. and T.T. analyzed the data and wrote the manuscript. All authors reviewed the manuscript.

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Declarations

Conflict of interest The authors have no competing interests to declare.

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