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Tropical cyclones, derelict traps, and the future of the Florida Keys commercial spiny lobster fishery

Amy V. Uhrin [a,b,*]

[a] Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, National Centers for Coastal Ocean Science, Center for Coastal Fisheries and Habitat Research, 101 Pivers Island Road, Beaufort, NC 28516, USA
[b] University of Wisconsin, Department of Zoology, Ecosystem and Landscape Ecology Lab, 430 Lincoln Drive, Madison, WI 53706, USA

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ABSTRACT

Derelict commercial spiny lobster (*Panulirus argus*) traps may move hundreds of meters during high wind events, resulting in tissue abrasion, breakage, and often complete removal of critical habitat elements such as seagrass, sponge, and coral. Ghost traps continue to confine lobsters, often resulting in mortality. The legacy of trap debris in the Florida Keys (USA) combined with possible increased inputs of trap debris resulting from tropical cyclone intensification presents an immediate challenge for this fishery where social, economic, and ecological vulnerabilities to disturbance are intrinsically linked. Here, predictions of percent monthly trap loss in relation to maximum wind speed (km/h) under three scenarios of tropical cyclone intensification were evaluated across four levels of fishing effort (number of traps used). Across all tropical cyclone scenarios, *Historical* fishing effort (986,000 traps) produced the greatest number of lost traps, followed in decreasing order by *Existing* (479,000), *Target* (400,000), and *Maximum Economic Yield* (*MEY;* 180,000) efforts. Under a *Business-as-Usual* scenario of intensification, converting from *Existing* fishing effort to *MEY* reduced trap loss by over 62%. The scenarios suggest that were *Existing* fishing effort to be maintained in the coming decades, tropical cyclone-related trap loss could exceed 11 million over 60 years depending upon the rate of storm intensification. Existing programs for derelict trap removal cannot currently keep pace with accumulation; consequently, the proximal source of trap debris is increasing in the environment. The net increase in derelict traps and debris generated from their degradation will only be exacerbated under potential tropical cyclone intensification. This study underscores the need for using scenarios for future exploration of these issues, particularly incorporation of fisher responses to changes in climatic, economic, and management drivers (i.e., storms, market demand, gear reduction) that may affect trap deployment patterns.

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1. Introduction

Climate change may alter or interact with existing disturbance regimes in ways that exacerbate or mediate disturbance effects in ecosystems [1]. Coastal fisheries in particular are climate-sensitive systems where social, ecological, and economic vulnerabilities to disturbance are intrinsically linked [2,3,4]. Many coastal fisheries are susceptible to tropical cyclones (e.g., tropical storms, hurricanes), the impacts of which may be amplified under a changing climate where storm intensification is predicted [5,6,7,8]. Storms may affect resource population dynamics, resource availability, and the environment through changes in species distributions, seasonality of production, or habitat damage while simultaneously disrupting fisheries directly as a consequence of lost sea (fishing) days, shore-based infrastructure damage/loss, or elevated gear damage/loss [9,10]. Gear loss is recognized as a traditional stressor in coastal ecosystems. However, proposed adaptation options for fishery resilience to climate change often ignore potential interactions between increased storm activity, derelict fishing gear generation, and subsequent accumulation and impacts [11,12].

The commercial spiny lobster (*Panulirus argus*) trap fishery in the Florida Keys (Monroe County, Florida, USA) is a climate-sensitive fishery and is responsible for approximately 90% of the State's commercial lobster harvest. Fishing effort peaked at more than 900,000 traps in the early 1990s and was implicated in contributing to undue mortality of sublegal-sized lobsters, declining trap yields, navigation issues, conflict on the water, and pollution which led to the implementation of the of the Spiny Lobster Trap Certificate Program (LTC; Florida Statute 370.142) in 1993 [13,14]. The LTC is a market-based, transferable reduction

* Present address: Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Office of Response and Restoration, Marine Debris Division, 1305 East-West Highway, SSMC4 Room 10-240, Silver Spring, MD 20910, USA.

E-mail address: amy.uhrin@noaa.gov

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program, established to create stability in the fishery by reducing the total number of traps while potentially increasing yield per trap. Although annual trap reduction rates were established under the LTC, they have been repeatedly amended over the years and a target reduction goal was not established until 2005 (400,000 traps; Florida Administrative Code R. 68B-24.009). Currently, the number of traps is reduced by approximately 0.3% each year which has delayed progress toward meeting the target reduction goal. Under the current reduction rate, the target goal would not be reached until the year 2045 [T. Matthews, Florida Fish and Wildlife Conservation Commission (FWC), personal communication].

In recent years, the number of traps permitted in the Monroe County fishery has averaged 479,000 per season. Of the total traps fished, fishermen report monthly trap losses of 2-5% over the eight-month season (August 6 to March 31) in seasons without tropical cyclones, as a result of buoy line cutoffs vandalism/theft, entanglement on the bottom, the inability to find deployed traps (i.e., GPS failure), and trap degradation [FWC Commercial Lobster Fisherman Questionnaire data, http://myfwc.com/research/saltwater/crustaceans/lobster/fishery/overview/]. Gear loss is greatly exacerbated when strong winter storms or tropical cyclones occur (19–65% seasonal loss; FWC Commercial Lobster Fisherman Questionnaire data, http://myfwc.com/research/saltwater/crustaceans/lobster/fishery/overview/). Recent estimates by Uhrin and others [15] suggest a trap debris legacy upwards of one million derelict traps residing on the seafloor of the Florida Keys, within the boundaries of the Florida Keys National Marine Sanctuary, which they conclude was likely an underestimation of the number of traps lost or intentionally disposed of during the over 50-year history of this commercial trap fishery [16,17].

When derelict traps remain intact, they have the capacity to ghost fish, i.e. they can continue to confine animals, often resulting in mortality [18,19,20]. Recent estimates by Butler and Matthews [21] suggest that ghost traps kill 637,622 lobsters in the Florida Keys each year but the contribution of these losses to changes in lobster population dynamics is unknown. In addition, derelict lobster traps cause damage to benthic habitats (e.g., seagrass beds, coral reefs) by smothering or colliding with these habitats, reducing above-ground biomass, disrupting below-ground components, abrading tissue, and breaking or denuding foundation species [22,23,24,25]. When individual traps move during high winds, the area affected is often greater than the trap's immediate footprint and can encompass several square meters [23,25]. Whether these damages translate to changes in the population- and community-level dynamics of these foundation species is unknown.

Although confidence in projections of Atlantic basin tropical cyclone frequency and intensity over the coming decades remains low [5,7] there is some model consensus that hurricane intensity will increase [5,6,7,8]. Basin-wide, the number of tropical cyclones that mature into major storms (Category 3 or greater) is influenced by the Atlantic Multidecadal Oscillation (AMO; long-duration fluctuations in North Atlantic sea surface temperature) as well as variability in the strength of Atlantic thermohaline circulation [26]. More tropical cyclones advance to major storm status during warm phases of the AMO than during cool phases [26]. Major hurricane strikes in Florida also align with the observed AMO. In a warm phase, roughly three major hurricanes make landfall in Florida per decade versus just shy of one per decade (0.8) during a cool phase [27]. According to a survey of tropical cyclone activity from 1851 to 2010, 40% of all hurricanes impacting the United States strike Florida [28] with 85% of storms occurring in the three months from August through October [6] which directly coincides with the spiny lobster fishing season. In Monroe County, 26 hurricanes have made landfall since 1926, the greatest total for any county in the United States.

Scenario planning has emerged as an effective decision-making tool when faced with unpredictable and uncontrollable futures [29,30,31]. Scenario studies describe a range of possible future states often while incorporating the uncertainty inherent in social-ecological systems [31]. Scenarios have been used to describe the implications of uncertain future tropical cyclone activity in Florida but focused on economic impacts and personal property damage/loss estimates [32,33]. Overlap between peak spiny lobster fishing effort and peak hurricane season in this region [34] creates the potential for the generation of large amounts of derelict lobster traps and associated debris [23,25]. The detrimental effects of ghost traps and the damage caused by derelict trap movement presents an immediate sustainability challenge for this fishery which could be addressed using scenarios that explore plausible trap loss in the face of uncertain tropical cyclone activity.

This study asked how tropical cyclone intensification and the number of traps regulated for use in the commercial spiny lobster fishery influenced the input of derelict traps to the benthic seascape of the Florida Keys. A set of contrasting scenarios was compared that explored a range of increases in tropical cyclone intensity and a range of both increases and decreases in fishing effort. The scenarios included combinations of four fishing efforts (current number of traps in the fishery, target effort based on biologic production models, effort based on Maximum Economic Yield models, and reversion to historical effort) and three tropical cyclone regimes (past tropical cyclone trend, past trend with two separate levels of tropical cyclone intensification), yielding 12 scenarios. For each 60-year scenario the total number of traps lost was determined.

2. Materials and methods

2.1. Data compilation

Data on monthly percent trap loss for six fishing seasons (1997–98, 1999–00, 2000–01, 2001–02, 2003–04, 2005–06) were obtained from a Florida Fish and Wildlife Conservation Commission (FWC) database of annual mail-in surveys (Commercial Lobster Fisherman Questionnaire) administered to licensed commercial lobster fishermen reporting 45 kg (100 lbs) of landings in a given season. Among questions related to overall effort and location of fishing activity, fishermen are specifically asked to report the number of lobster traps lost each month of the eight-month season (August 6 through March 31). For the six seasons of available data, the number of respondents averaged 180 (range: 65–241). A monthly weighted mean percent trap loss for each of the six seasons of available data was obtained from FWC [FWC, unpublished data].

To account for variability in storm tracks and resulting differences in wind fields across the Florida Keys during the passage of storms, historical continuous wind measurements were downloaded from the NOAA National Data Buoy Center website (http://www.ndbc.noaa.gov/) for three Coastal-Marine Automated Network (C-MAN) offshore platform stations located in the Upper (MLRF1, Molasses Reef, Key Largo), Middle (SMKF1, Sombrero Key, Marathon), and Lower (SANF1, Sand Key, Key West) Keys. Continuous wind speed (m/s) measurements at each C-MAN station include six 10-min average values of wind speed each hour. Wind speeds were converted to km/h. Wind speed data were then subset to include only the eight months of the commercial spiny lobster season (August 6 through March 31 of the following year). Because the relationship between monthly trap loss rates and wind speed was critical for this study, it was important that all high wind events, tropical cyclone or otherwise, were accurately represented in the wind speed observations. This included the winter Groundhog Day storm of 1998, one of the strongest storms outside of hurricane season ever recorded in this region, which produced high trap loss. Rather than averaging the hourly continuous wind speed measurements, the maximum continuous wind speed was determined for each month within a given fishing season. The monthly maximum continuous wind speeds for the three stations were then averaged.

Due to an incomplete record from C-MAN station SANF1 in 2005, measurements from station KYWF1 (Naval Air Station, Key West) were used for September and October of this year. As a land-based station, wind speed measurements at KYWF1 are averaged over a two-minute period and reported hourly. Rather than averaging the hourly wind speed measurements, the maximum wind speed was determined for these two months and incorporated into the three-station average.

2.2. Trap loss model using piecewise regression

Lewis and others [25] reported initiation of trap movement when winter storms with sustained winds greater than 27.8 km/h persisted for more than two days with substantially increased movement when sustained winds were equal to or greater than tropical storm force (62.8 km/h). Therefore, it was anticipated that trap loss would increase linearly with increasing maximum wind speed but that a transition between lower and higher rates of trap loss may occur, marked by a breakpoint maximum wind speed where the slope of the linear function would change. Therefore, piecewise linear regression was used to estimate the location of what appeared to be breakpoints in the data and allowed multiple models to be fit for different ranges of maximum wind speed.

A piecewise regression model is effective in modeling abrupt changes in ecological processes and defining thresholds [35]. In its simplest form, piecewise regression joins two (or more) separate straight lines at breakpoints and can be written as:

$$y_i = B_0 + B_1 x_i + e_i \qquad for\ x_i \le \alpha$$
$$y_i = B_0 + B_1 x_i + B_2 (x_i - \alpha) + e_i \qquad for\ x_i \le \alpha$$

where y_i is the ith value of the dependent variable, x_i is the ith value of the independent variable, α is the breakpoint, e_i is the error term, B_0 is the intercept, B_1 is the slope of the line below the breakpoint, and $B_1 + B_2$ is the slope of the line above the breakpoint where B_2 is interpreted as the difference in the two slopes. In this form, the piecewise regression function is continuous at the breakpoint, meaning that no change in intercept occurs.

To estimate the location of the potential maximum wind speed breakpoint, scatter plots of monthly percent trap loss against maximum wind speed (km/h) were generated and a nonparametric smoothing function was applied using PROC LOESS in SAS Version 9.3 [36]. Through visual inspection of the scatter plots, the wind speed breakpoint was expected to occur somewhere between 61 and 73 km/h. Linear regressions were performed for wind speeds in this range in one km/h increments to obtain initial starting parameters to fit individual piecewise regression models using PROC NLIN in SAS Version 9.3 [36]. Of the 13 breakpoint models evaluated, the model using a maximum wind speed of 71 km/h as the breakpoint had the smallest mean square error and therefore the best fit. The extra sums of squares test was used to compare the linear and piecewise regressions [37]. Based on comparisons of the model mean square errors (linear: 0.0016; piecewise: 0.0009), the visual fit, and the significance of the extra sums of squares test ($F_{[1,45]} = 39.64$, $p < 0.0001$), the piecewise regression model was considered an improvement over the linear model (Fig. 1). The resultant regression equations were used to calculate monthly trap loss for wind events as described below (Section 2.3) where maximum wind speed was ≤ 71 km/h (Eq. (1)) and > 71 km/h (Eq. (2)), respectively:

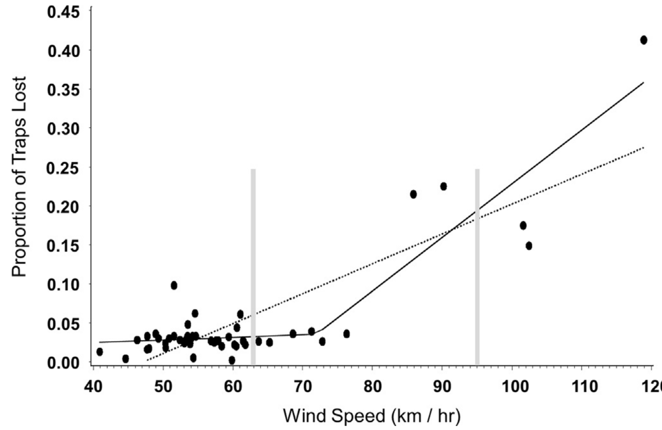

Fig. 1. Plot of the proportion of monthly trap loss versus maximum wind speed (km/h). Best-fit line for the piecewise regression is indicated by the solid line while the linear fit is indicated by the dashed line. Gray bars indicate the confidence limits on the estimate of the breakpoint (71.0 km/h) as determined through bootstrapping. The height of the gray bars is arbitrary.

$$proportionoftrapslost = 0.\ 0132 + (0.\ 00029 * windspeed) \tag{1}$$

$$proportionoftrapslost = (0.\ 0068 * windspeed) - 0.\ 44901 \tag{2}$$

Assumption tests indicated a slight departure from normality and unequal variances. Although these violations do not bias parameter estimates (e.g., B_0, B_1, B_2, and α), bias in standard errors and confidence intervals are possible. Techniques like bootstrapping, a nonparametric resampling method, can be used to estimate the accuracy in the estimation of a parameter [37,38]. In bootstrapping, a secondary dataset is generated by resampling the original dataset (with replacement) for a large number of iterations. The parameter estimates from the secondary datasets are retained and used to estimate nonparametric standard errors and confidence limits for the original piecewise model and to help characterize the reliability of the original breakpoint estimate [35,37,38,39]. Here, the original dataset was resampled with replacement for 1000 iterations. The piecewise model was then fit to each secondary dataset using the parameter estimates from the original model. The resulting secondary parameter estimates were used to estimate nonparametric standard errors and confidence limits for the original piecewise model (Table 1). The resulting 95% confidence interval for the breakpoint ranged from 63 to 95 km/h (Table 1).

2.3. Tropical cyclone scenarios

Historical tropical cyclone reports from the NOAA National Hurricane Center Data Archive (http://www.nhc.noaa.gov/data/) were accessed to determine the pattern of tropical cyclone activity for the Florida Keys over the 20-year period from 1995 to 2014. Tropical cyclones occurring in months outside of the fishing

Table 1
Piecewise regression parameter values with corresponding bootstrap estimates of the standard error and 95% confidence intervals.

Parameter	Estimate	Bootstrap	95% Confidence intervals	
		Standard error	Lower	Upper
B_0	0.0132	0.0231	-0.0196	0.0731
B_1	0.0003	0.0004	-0.0007	0.0008
B_2	0.0068	0.0028	0.0039	0.0154
c	71.0	7.7838	62.9777	94.8553

Table 2
Three future scenarios of tropical cyclone activity and four scenarios of fishing effort used in the simulations for the Florida Keys. MEY=Maximum Economic Yield.

Tropical cyclone scenarios			
Business-as-Usual Past 20-year storm and non-storm trend projected onto three successive 20-year periods	*Moderate intensification* *Business-as-Usual plus one storm per decade upgraded to Category 3+*		*High intensification* *Business-as-Usual plus 3 storms per decade upgraded to Category 3+*
Fishing effort scenarios (total number of traps in fishery each season)			
Historical	*Existing*	*Target*	*MEY*
986,000	479,000	400,000	180,000
Based on previous effort of the 1990s	Average # traps licensed annually for last 9 years	Target effort based on biologic production models	Based on Maximum Economic Yield models

season (April through July) were not included. Wind speed measurements from the aforementioned C-MAN stations (Section 2.1) were evaluated for all named tropical storms or hurricanes reported to have impacted the Florida Keys during the 20-year period. If any station recorded a maximum wind speed measurement ≥ 62.8 km/h, the minimum wind speed for tropical storm categorization, the event was included in the pattern. In this 20-year period, the Florida Keys experienced sustained tropical storm-force or greater winds from 16 tropical cyclones with multiple events occurring in eight of those years. Maximum monthly wind speeds (km/h) were also determined for those months during the fishing season when a tropical cyclone did not occur.

Three scenarios were generated to describe future tropical cyclone intensification in the Florida Keys (Table 2). The initial scenario represented a projection of an observed baseline level of tropical cyclone activity (1995–2014). The baseline projection was modified in subsequent scenarios to reflect potential changes (increases) in tropical cyclone intensity over time under both cool and warm phases of the Atlantic Multidecadal Oscillation (AMO). Because frequency of storms in the vicinity of Florida do not exhibit any upward or downward trend [6], changes in storm frequency were not considered in the scenarios.

In the "*Business-as-Usual*" scenario (Table 2), the baseline 20-year pattern (16 storms from 1995 to 2014) of tropical cyclone frequency, return interval, month of occurrence, and intensity (mean maximum wind speed) as well as the pattern for non-storm events in the Florida Keys was projected onto three successive 20-year periods yielding a 60-year scenario (2015–2074). Monthly trap loss rates for each fishing season were then calculated using the corresponding maximum wind speed and the appropriate regression model (Eq. (1) for maximum wind speeds ≤ 71 km/h; Eq. (2) for maximum wind speeds > 71 km/h).

The "*Moderate Intensification*" scenario (Table 2) was based on the average number of Category 3 or greater hurricanes per decade making landfall in Florida during a cool AMO phase (1.0/decade) [27] and assumed that these major hurricanes would specifically strike the Florida Keys. Tropical cyclone frequency, return interval, and month of occurrence as well as non-storm event months remained identical to *Business-as-Usual*. One storm per decade was randomly selected from all the storms expected to occur under *Business-as-Usual* across the 60-year scenario and this was upgraded to be a major storm (Category 3+). The intensity of the chosen storm was increased by randomly selecting a wind speed from within the range 178–213.1 km/h which spans Category 3 and partway into Category 4 on the Saffir-Simpson Hurricane Wind Scale. Wind speeds greater than 213.1 km/h could not be evaluated as 100% trap loss is achieved at this upper wind speed based on the regression model (Eq. (2)). The trap loss rate associated with the major storm was calculated using the regression model for winds greater than 71 km/h (Eq. (2)) and the corresponding wind speed.

The "*High Intensification*" scenario (Table 2) was based on the average number of Category 3 or greater hurricanes per decade making landfall in Florida during a cool AMO phase (3.0/decade) [27] and assumed that these major hurricanes would specifically strike the Florida Keys. Tropical cyclone frequency, return interval, and month of occurrence as well as non-storm event months remained identical to *Business-as-Usual*. Three storms per decade were randomly selected from all the storms expected to occur under *Business-as-Usual* across the 60-year scenario and these were upgraded to be a major storm (Category 3+). The intensity of the chosen storm was increased by randomly selecting a wind speed from within the range 178–213.1 km/h which spans Category 3 and partway into Category 4 on the Saffir-Simpson Hurricane Wind Scale. Wind speeds greater than 213.1 km/h could not be evaluated as 100% trap loss is achieved at this upper wind speed based on the regression model (Eq. (2)). The trap loss rate associated with the major storm was calculated using the regression model for winds greater than 71 km/h (Eq. (2)) and the corresponding wind speed.

2.4. Fishing effort scenarios

The three tropical cyclone scenarios were evaluated under four scenarios of fishing effort, defined as number of traps certified for use in the fishery (Table 2). These included *Existing*, *Target*, *Maximum Economic Yield (MEY)*, and *Historical* effort.

In recent seasons (2003/2004–2014/2105), the number of traps certified for use in the fishery has averaged about 479,000. Thus, in the *Existing* fishing effort scenario (Table 2), trap numbers at the beginning of each fishing season were maintained at 479,000.

Biologic production models predict modest increases in catch up to approximately 400,000 traps, at which point additional traps do not increase catch [40]. Thus, a target reduction goal of 400,000 was established in 2005 [Florida Administrative Code R. 68B-24.009]. Therefore, in the *Target* fishing effort scenario (Table 2), trap levels at the beginning of each fishing season were maintained at 400,000.

Maximum Economic Yield (MEY)is the effort level that creates the largest positive difference between (discounted) total revenues and the total costs of fishing (including labor and capital). To reach MEY, models for the Florida commercial spiny lobster fishery estimate a range of effort at 160,000–180,000 traps [40]. Thus, in the *MEY* fishing effort scenario (Table 2), the number of traps in the fishery was maintained at 180,000 at the beginning of each season.

The final fishing effort represented the potential for reversion to historical fishing effort levels in the fishery which peaked in the early 1990s at 986,000 traps [13]. At this *Historical* effort (Table 2), trap numbers were maintained at 986,000 at the beginning of each season, a near doubling of extant trap numbers.

2.5. Seasonal effort reduction

As the spiny lobster fishing season progresses, there is a steady monthly decline in the number of utilized traps, a reflection of declining lobster abundance [34]. Trap use peaks at the start of the season (August – October) and beginning in November, trap use declines by approximately 10% per month until March (end of the season) when roughly only 40% of the total number of traps that were in use at the start of the season are still being fished [34]. To reflect seasonal reductions in trap use, beginning in November of each scenario-year, the number of traps available for use was reduced by 10% increments through February; in March, the last month of the fishing season, the total traps available was reduced to 40% of the original total.

2.6. Trap loss

The total number of traps lost over 60 years for each tropical cyclone × fishing effort scenario was summed. The percent change in trap loss among the 60-year tropical cyclone × fishing effort scenarios was calculated.

3. Results

Across all tropical cyclone intensity scenarios, the number of traps available in the fishery drove the number of lost traps. *Historical* fishing effort produced the greatest number of lost traps, followed in decreasing order by *Existing*, *Target*, and *MEY* efforts (Fig. 2). Across all fishing effort scenarios, the *High Intensity* tropical cyclone scenario produced the greatest number of traps lost followed in decreasing order by *Moderate Intensity* and *Business-as-Usual* (Fig. 2).

Within the *Business-as-Usual* tropical cyclone scenario, the total number of traps lost under *Historical* fishing effort was twice that under *Existing* effort (Fig. 2). A 16.5% decrease in total traps lost over the 60-year period was observed between *Existing* and *Target* fishing effort, while a change in fishing effort from *Existing* to *MEY* reduced trap loss by over 62% (Fig. 2).

Across all levels of fishing effort, under the *High Intensity* tropical cyclone scenario, 1.7 × more traps were lost as compared to *Business-as-Usual* (Fig. 2). The *High Intensity* scenario resulted in an approximately 46% increase in the number of traps lost over the *Moderate Intensity* scenario across all levels of fishing effort (Fig. 2). Maintaining *Existing* fishing effort into a *High Intensity* tropical cyclone future resulted in a 75% increase in the number of traps lost as compared to a *Business-as-Usual* future (Fig. 2).

4. Discussion

Despite recognition of derelict fishing gear as a traditional stressor in coastal ecosystems, proposed adaptation options for fishery resilience in response to climate change often ignore potential interactions between acute events such as storm activity and derelict fishing gear inputs [11,12]. In these simulations, spiny lobster trap loss was greatly exacerbated under scenarios of increasing tropical cyclone intensity, underscoring the importance of including the potential for derelict trap generation in response to tropical cyclones in climate change adaptation planning. The finding that trap loss decreased by over 62% if *MEY* fishing effort was implemented under a *Business-as-Usual* tropical cyclone scenario suggests that limiting the number of permitted traps in the fishery to 180,000 would not only result in maximum economic yield [40] but would greatly reduce the amount of benthic habitat potentially impacted by derelict traps as well as the number of lobsters suffering mortality due to ghost fishing.

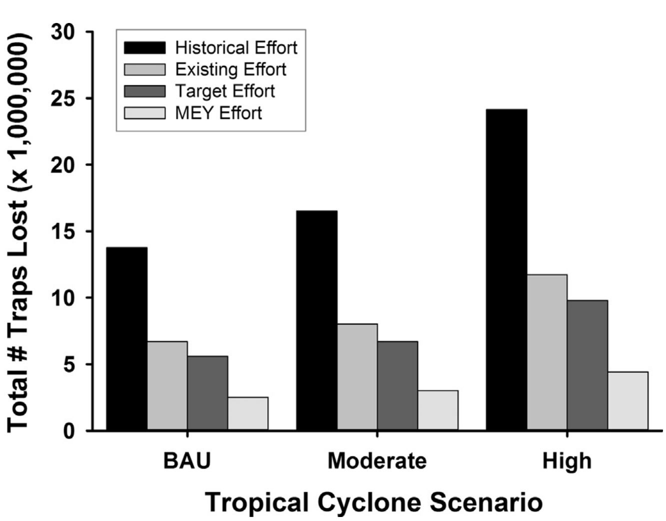

Fig. 2. Total number of traps lost across each 60-year scenario of tropical cyclone activity × fishing effort. Tropical cyclone scenarios: BAU = "*Business-as-Usual*", Moderate = "*Moderate Intensity*", High = "*High Intensity*".

Ghost fishing is well documented and can be a significant source of mortality in trap fisheries [20,21,41]. Butler and Matthews [21] estimate that the current number of ghost traps in the Florida Keys contributes to the deaths of 637,622 lobsters annually or approximately 12.5% of total statewide lobster landings for the 2014/2015 season [FWC Commercial Fisheries Landings Summaries, https://public.myfwc.com/FWRI/PFDM/ReportCreator.aspx]. If we were to assume that 637,622 lobsters perish in ghost traps in each year under any of the tropical cyclone scenarios, then upwards of 38 million lobsters could die over the 60-year period, roughly the equivalent of seven and a half years of statewide landings. Thus, increasing the number of ghost traps in Florida Keys waters could lead to reduced fishery landings (both commercial and recreational) as well as broader impacts on the lobster population at large. In fact, both spiny lobster abundance and fishery landings have been on the decline in the Florida Keys since 2000 [42,43]. Depletion of local spawning stock and reduced recruitment success due to impacted nursery habitats have been implicated [44].

However, the percentage of derelict traps that, once lost, actually become ghost fishing versus that which succumbs to movement and breakage (i.e., become nonfishing) is unknown. It is suspected that ambient trap loss occurring in months without storms results in a greater number of ghost traps as the physical forcing from high winds is reduced or lacking resulting in less initial movement and breakage [21]. Although ghost traps may remain fishing for longer than one year (observed maximum of 3 years) [21], the rate at which they degrade to a nonfishing state is unknown and depends on a number of factors [21]. The direction, intensity, and severity of subsequent storms as well as the water depth where derelict traps reside lead to varying degrees of trap movement and breakage [23,25]. Ghost trap decay is influenced by the level of trap biofouling which, incidentally is observed to be higher in Florida Bay [21]. Water depth also affects decay rates with lower rates of decay reported from deeper, offshore waters [21]. Additionally, larger marine fauna (i.e., dolphins) can disable traps and illegal tampering by divers is not uncommon [25].

Derelict lobster traps cause damage to benthic habitats (e.g., seagrass beds, hardbottom, coral reefs) by smothering or colliding with habitat elements, reducing above-ground biomass, disrupting below-ground components, abrading tissue, and breaking or denuding habitat-forming foundation species [22,23,24,25]. Maintaining *Existing* fishing effort under a *Business-as-Usual* tropical cyclone scenario could generate approximately 6,688,145 lost traps on the seafloor in 60 years. Given that lobster traps have a benthic footprint of approximately 0.49 m^2, this creates the potential for upwards of three million m^2 of injured habitat, not including additional injuries sustained during high wind events when traps move across the seafloor, multiplying the injury footprint several times over [23,25]. In scenarios with intensifying tropical cyclones, the extent of impacted area will likely increase even more due to both greater numbers of traps lost and greater numbers of traps moving. Damage to foundation species leads to reductions in ecosystem services including available habitat for commercial fishery species (including spiny lobster) and shoreline protection [45,46,47] and has implications for benthic habitat biodiversity, fishery sustainability, and potentially coastal community resilience.

The majority of ghost traps and trap debris are found in Florida Keys inshore waters [15,21] and monitoring of nearshore coral habitats in this region since 1996 indicates both a decline in coral species richness and coral cover [48] although these declines are not specifically linked to trap debris. Compared to other nearshore benthic habitats in the Florida Keys (e.g. seagrass, algae), coral-dominated habitats, including both reefs and hardbottom, appear to serve as sinks for lobster trap debris [15]. Thus, it appears that under scenarios of increasing tropical cyclone intensity, inshore coral habitats would become yet more susceptible to debris accumulation and damage.

It is recognized that interpretation of the precise derived maximum wind speed breakpoint should be approached with caution given the small sample size of wind events greater than tropical storm-force used in the model (N=8). The small sample size precludes sampling from the range of expected values for both maximum wind speed and proportion of traps lost. In addition, few historical data exist in the area around the breakpoint which precludes accurate establishment of the nature of the exact transition between 'low' and 'high' trap loss. The piecewise regression revealed a fairly sizable confidence interval around the breakpoint wind speed (63–95 km/h). Additional model runs were conducted using the upper and lower confidence interval values (63 and 95 km/h) as the breakpoints. Not surprising, the actual numbers of traps lost varied when compared with the original model using 71 km/h as the breakpoint. However, the same pattern of trap loss was observed across all tropical cyclone × fishing effort scenarios.

The scenarios presented here consider tropical cyclone intensity as the sole driver of trap loss. However, the extent of trap loss will likely be influenced by several characteristics of storms not examined here. The destructive potential of a tropical cyclone integrates storm dimension and power dissipation [49]. The size, direction, and duration of a storm will dictate which portion of the Florida Keys island chain is most impacted which has important ramifications given that trap use (trap density) varies across the Florida Keys with highest use in the Upper and Middle Keys on the Atlantic Ocean side [50]. Other factors that may influence the extent of trap loss during tropical cyclones, but not considered here, include habitat placement, depth of trap deployment, and fisher behavior [15,25]. It has been suggested that traps deployed on soft bottom habitats (e.g., seagrass) may move less and experience less breakage when movement does occur [15]. Traps in deeper water move less [25] and there is anecdotal evidence that lobstermen move traps to deeper water upon threat of an impending storm.

Understanding how fishers may respond to potential change, whether regulatory, environmental, or market-based, is critical for identifying key interactions between social, management, economic, and ecological processes which can either enhance or jeopardize fishery sustainability including social capital [51,52,53,54,55]. Recently, scenarios have been used as a research tool in other fisheries to specifically evaluate fisher responses to area closures, declines in catch, and gear conversion alternatives [56,57,58]. These highlight how social responses may amplify or dampen exploitation, bycatch, and habitat impacts and how choices made by resource users can be incorporated into adaptation planning and policy discussions [56,57,58]. Although Florida Keys lobstermen have continually been involved in the public comment portion of the regulatory process and can serve on Advisory Panels to regional Fishery Management Councils, they are not generally included in the research undertaken in support of regulations but see [23,59]. In fact, the lack of consideration of social dimensions prior to the institution of the Spiny Lobster Trap Certificate Program has been implicated in the profound and unanticipated changes observed in the cultural landscape of the commercial spiny lobster fishery and an undermining of social capital within Florida Keys commercial fishing communities [54,60].

A first step toward mitigation of derelict fishing gear impacts resulting from climate change would be incorporation of behavioral responses of fishermen to scenarios of change in the fishery (i.e., storm threats, elevated gear loss due to storm intensification, declining catch, increase/decrease in market demand, or policy mechanisms that reduce gear, control fishing mortality, or reduce catch) are solicited, documented and evaluated as feedback to scenario forecasts prior to the institution of regulations. For example, although Florida lobster fishers are required by law to retrieve their traps before the close of the season (Florida Administrative Coed R. 68B-24.005), there are no provisions for removing traps under threat of impending tropical cyclones or other extreme wind events. In fact, trap retrieval fees may be waived in areas of the Florida Keys declared to be disaster emergency areas by the Governor as a result of a hurricane or other major storm (Florida Statute 370.143). Anecdotally, fishermen report moving traps to protected (e.g., deeper) waters prior to storms. However, decision making criteria for repositioning traps likely vary among individual fishers depending upon the level of risk that is perceived and deemed reasonable. Several factors may influence these choices including, but not limited to, the number of traps the fisherman uses, the number of lobsters the fisherman has already harvested, time of year, availability of alternative sources of income, current market prices, storm intensity/size, past storm experiences, etc. Nonetheless, leaving traps in the water during storms results in the potential for continued harvest but also the risk of trap loss and incentivizing pre-storm removal could be explored beyond anecdotal observations.

Given the large number of traps in the fishery [17] and the inability to prevent trap loss, generation of trap debris will likely continue. In 1983, Florida instituted a Trap Retrieval Program (Florida Administrative Code R. 68B-55.003), administered through the Florida Fish and Wildlife Conservation Commission and funded by commercial saltwater license revenue and retrieval fees assessed to trap owners. Unfortunately, lost trap recovery is prohibitively expensive [61] and previous experience suggests that removal rates cannot keep pace with the rate that trap debris is currently accumulating [61], highlighting the importance of reducing derelict trap inputs. This is a difficult task given that future derelict trap loadings will be largely driven by the number of traps in the fishery and intensity of tropical cyclones. However, the trap loss estimates presented here under scenarios of tropical cyclone intensification and *Existing* fishing effort suggest that allowing the number of permitted traps in the fishery to exceed recommended effort levels may lead to population-level impacts both for spiny lobsters and the benthic habitat-forming species that support them.

5. Conclusions

This study draws attention to the potential for enormous increases of derelict traps into the marine environment of the Florida Keys in the face of uncertain tropical cyclone intensification. To the knowledge of the author, this is the first study to estimate the amount of derelict spiny lobster traps that may be lost under various scenarios of tropical cyclone intensification and fishing effort. The scenarios suggest that by maintaining *Existing* fishing effort in the coming decades, trap loss could exceed 11 million over 60 years depending upon the rate of tropical cyclone intensification. Although the potential for climate change, including "more destructive hurricanes", is widely recognized by decision-makers and experts in the Florida Keys, less than 5% of surveyed agencies have some form of climate change action plan in place [62]. The legacy of trap debris in the Florida Keys combined with possible increased inputs of yet more trap debris resulting from a future rise in tropical cyclone intensity presents an immediate challenge for both fisheries management and climate adaptation planning and underscores the importance of an effective process for addressing these issues. This process should consider not only the role of fishing effort and uncertain tropical cyclone activity but key social, management, economic, and ecological interactions which cannot be disregarded without unintended consequences [51,54,63].

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