

Stock enhancement to address multiple recreational fisheries objectives: an integrated model applied to red drum *Sciaenops ocellatus* in Florida

E. V. CAMP*, K. LORENZEN, R. N. M. AHRENS AND M. S. ALLEN

*School of Forest Resources and Conservation, Fisheries and Aquatic Sciences Program,
University of Florida, 7922 NW 71st Street, Gainesville, FL 32605, U.S.A.*

An integrated socioecological model was developed to evaluate the potential for stock enhancement with hatchery fishes to achieve socioeconomic and conservation objectives in recreational fisheries. As a case study, this model was applied to the red drum *Sciaenops ocellatus* recreational fishery in the Tampa Bay estuary, Florida, U.S.A. The results suggest that stocking of juvenile fish larger than the size at which the strongest density dependence in mortality occurs can help increase angler satisfaction and total fishing effort (socioeconomic objectives) but are likely to result in decreases to the abundance of wild fishes (a conservation objective). Stocking of small juveniles that are susceptible to density-dependent mortality after release does not achieve socioeconomic objectives (or only at excessive cost) but still leads to a reduction of wild fish abundance. The intensity and type of socioeconomic gains depended on assumptions of dynamic angler-effort responses and importance of catch-related satisfaction, with greatest gains possible if aggregate effort is responsive to increases in abundance and satisfaction that are greatly related to catch rates. These results emphasize the view of stock enhancement, not as a panacea but rather as a management tool with inherent costs that is best applied to recreational fisheries under certain conditions.

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Key words: hatchery; socioecological system; sport fishing; stocking.

INTRODUCTION

A primary goal of fisheries scientists is to evaluate what outcomes are possible under various management strategies and to identify key uncertainties that affect the consequences of policy decisions (Walters & Martell, 2004). Assessing outcomes of recreational fisheries requires consideration of both this sector's unique complexities as well as those common to most natural resources (Cowx *et al.*, 2010). Recreational fisheries are increasingly recognized for both their potential negative ecological effects and socioeconomic importance (Post *et al.*, 2002; Lewin *et al.*, 2006; Fenichel *et al.*, 2013). The economic activity (*e.g.* revenue and jobs) related to recreational fisheries is substantial in many areas (Arlinghaus & Cooke, 2009) and is widely considered as directly related to the aggregate number of fishing trips (Cox *et al.*, 2003), as it results from expenditures that fishers incur attempting to attain some social utility from fishing (Propst & Gavrilis, 1987; Edwards, 1991; Weithman, 1999). Anglers may

*Author to whom correspondence should be addressed. Tel.: +1 401 862 7702; email: edvcamp@ufl.edu

attain this utility (consumer surplus) in different ways owing to heterogeneous motivations for fishing, including enjoyment of nature, solitude and most notably, high catch rates (Hunt, 2005; Arlinghaus, 2006; Johnston *et al.*, 2010). Together, objectives of increased economic activity and stakeholder utility potentially conflict in the short term with ecological conservation-oriented objectives (Hilborn, 2007; Arlinghaus & Cooke, 2009), as high fishing effort or catch rates potentially deplete fish abundance (Cox *et al.*, 2003), sometimes leading to collapsed fish populations (Post *et al.*, 2008). To deal with such potentially conflicting objectives, alternatives to traditional management tools (*e.g.* effort or harvest control) are sought, including stock enhancement (Lorenzen, 2005; Naish *et al.*, 2007; Camp *et al.*, 2013).

Stock enhancement, defined as regular release of hatchery-raised fishes to augment existing, naturally recruiting populations (Bell *et al.*, 2008; Lorenzen *et al.*, 2012), is sometimes considered a means to improve or maintain socioeconomic objectives (market activity from fishing trips and angler satisfaction from fishing) without depleting fish populations (Camp *et al.*, 2013). Stock enhancement is ingrained in some fisheries (Engstrom-Heg, 1971; Halverson, 2008), perhaps due to its apparent popularity with stakeholders (McEacheron & Daniels, 1995; Walters & Martell, 2004) and its related entrenchment in management (Washington & Koziol, 1993; Naish *et al.*, 2007). Enhancements incur substantial financial investment and operating costs for collecting or maintaining brood stock, raising and stocking out juveniles (Hilborn, 1998; Lorenzen *et al.*, 2012), such that enhancement programmes often comprise a substantial share of management budgets (Johnson & Martinez, 2000). In addition to financial costs, enhancement may have unintended and potentially adverse consequences to wild fish populations (Washington & Koziol, 1993; Cowx, 1994; Naish *et al.*, 2007). Stocked fishes may negatively interact with wild fishes through predation or competition, which at the population level may lead to partial replacement of wild fishes by hatchery-raised fishes (Kennedy & Strange, 1986; Petrosky & Bjornn, 1988; Washington & Koziol, 1993; Lorenzen, 2005). Widespread concern also exists over potential deleterious effects of stocking on the genetic structure, diversity and fitness of fish populations (Araki *et al.*, 2007; Tringali *et al.*, 2008; Lorenzen *et al.*, 2012). It is also possible that enhancement can lead to increases in fishing effort which in turn may exert additional pressure on the wild population component (Baer *et al.*, 2007).

Many studies have considered enhanced recreational fisheries but very few of them have actually evaluated how enhancement could affect these fisheries' economic, social and ecological outcomes (Larkin, 1974; Cowx, 1994; Camp *et al.*, 2013). Among studies that have investigated broader outcomes, most actually consider entirely culture-based fisheries (where no stock of the same species exists) rather than enhancements, or are generally focused on ecological consequences (Flecker & Townsend, 1994; Ham & Pearsons, 2001), although some consider economic effects (Loomis & Fix, 1998; Johnson & Martinez, 2000). The paucity of quantitative assessments of enhancement in an integrated socioeconomic and ecological framework provides little information to decision makers (Rogers *et al.*, 2010; van Poorten *et al.*, 2011).

This work aims to provide a generalized framework for evaluating potential recreational stock enhancement in terms of multiple and sometimes conflicting management goals. This framework was applied to describe possible outcomes of a specific enhancement and promote realistic expectations from stakeholders and managers. Here, the potential enhancement of red drum *Sciaenops ocellatus* (L. 1766)

in Florida's coastal recreational fishery was considered. Likely outcomes of this enhancement were assessed in terms of four response metrics: conservation of wild fishes, aggregate effort, social satisfaction (*i.e.* utility) per trip and total socioeconomic value of the fishery, and outcomes were evaluated with respect to uncertain attributes, such as angler effort dynamics and relationships between catch rates and angler satisfaction. The costs (in terms of resources and finances) of achieving proposed enhancement objectives were also assessed. Finally, the applicability of these findings to other fisheries where enhancement might be considered is discussed.

MATERIALS AND METHODS

STUDY SYSTEM

The recreational *S. ocellatus* fishery in Florida is extremely popular, with generally more angler trips targeting this species than any other marine species in the state in recent years (U.S. National Marine Fisheries Service, Fisheries Statistics Division, pers. comm.). This high aggregate effort supports substantial economic activity as part of Florida's U.S.\$ 7.5×10^9 in 2009 marine recreational fishery (NMFS, 2010). While the most recent stock assessments consider Florida's *S. ocellatus* fishery neither overfished nor to be undergoing overfishing, fishing effort is increasing and there is concern that the fishing mortality (from both harvest and discard mortality) may soon drive the stocks below the target level of 40% of 'virgin' escapement (Murphy & Muyandorero, 2009). In the management of this fishery, escapement is used as a proxy for spawning potential ratio, and is defined as the ratio of *S. ocellatus* survivorship at 5 years of age under current conditions to that expected under unfished conditions. While overfishing is a conservation concern (both ecologically and for long-term socioeconomic value), the current popularity of this fishery causes any effort restriction to have a (perceived) high economic and social cost, in terms of potentially lost fishing trips and angler satisfaction. In this context, enhancement is currently being considered as a means to avoid such effort restriction without further depleting the wild-fish populations. Such enhancements would initially probably be relegated to relatively small discrete areas (*e.g.* Tampa Bay, a large estuary popular with recreational anglers). In a recent pilot study, enhancement goals were stated as increasing *S. ocellatus* abundance in Tampa Bay by 25% (Tringali *et al.*, 2008), although it is possible that smaller increases would be satisfactory.

INTEGRATED QUANTITATIVE MODEL

The potential enhancement of this system was modelled by integrating fish population dynamics (represented with a biological sub-model), socioeconomic dynamics (represented with a sub-model including satisfaction, aggregate effort and value calculations) and management actions (represented by simulating different stocking scenarios). All parameters and equations used for the integrated model are fully specified in Tables I and II, respectively, to allow replication of the modelling approach. The sub-components of the model, model tuning procedure and sensitivity analysis are described below and reference for the full model description is given in Tables I and II. The general approach followed was to first represent the recreational *S. ocellatus* fishery in Florida, requiring an integrated model. This model was then scaled to a specific region, Tampa Bay. This allowed the assessment of outcomes of various stock enhancement scenarios, in terms of conservation and socioeconomic-oriented metrics.

FISH POPULATION MODEL

The biological sub-model was constructed as a discrete annual time-step, age-structured, number dynamic population model (equations 1–6 and 30–36 in Table II), similar to those

TABLE I. Parameters and associated values used in integrated quantitative model. Subscript w, wild fish; subscript s, stocked fish; subscript h, hatchery fish; subscript m, minimum.

Symbol	Description	Units	Value
R_0^*	Recruitment at unfished conditions	fish	450 371
L_∞	Asymptotic length	mm	934
K	Von Bertalanffy metabolic parameter	year ⁻¹	0.46
t_0	Age at length = 0	years	-0.26
w_a	Mass-length constant	g	0.00000617
w_b	Mass-length exponent	g	3.09
W_m	Mass at maturity	kg	10.084
M	Instantaneous mortality at L_m	year ⁻¹	0.113
L_m	Reference length for mortality	mm	730
C_1	Allometric exponent of length-mortality relationship	constant	0.9
A_m	Maximum age	years	40
Ω	Recruitment compensation parameter	ratio	11
L_0	Length at entering recruitment period	mm	20
L_s	Length at stocking	mm	25-175
L_r	Length at leaving recruitment period	mm	180
d_1	Duration of density-dependent mortality recruitment phase, from size L_0 to L_r	years	0.75
d_2	Duration of the second stage of the density-dependent mortality recruitment stage	Proportion	Calculated
M_1	Natural instantaneous mortality year ⁻¹ of a 10 mm total length fish	year	15
S_r	Cumulative base survival for the recruitment period	rate	Calculated
ρ_h	Fitness (or survival) of hatchery relative to wild, stage 1	rate	1.0
ρ_s	Fitness (survival) of stocked relative to wild, stage 2	rate	0.8
γ_h	Share of hatchery eggs inheriting wild characteristics	%	0.2
T_t	Number of fish stocked each year	fish	0-4.5 m
$S_{0.5}$	Back-scaled mortality to fish size midway between 0.75 and 1.00 years	year ⁻¹	0.86
L_l^c, L_u^c	Fish length, standard deviation of length for vulnerability to capture (c): low (l), high (u)	mm	400, 850
σ_l^c, σ_u^c			$0.1 \times L_l^c, 0.1 \times L_u^c$
L_l^h, L_u^h	Fish length, standard deviation of length for vulnerability to harvest (h): low, high	mm	457, 686
σ_l^h, σ_u^h			$0.01 \times L_l^h, 0.01 \times L_u^h$
k^*	Per cent harvestable fish killed	%	0.27
σ	S.D. of logistic	constant	0.05-2000
F_{\min}, F_0	Minimum effort and effort at unfished stock size	trips	200 000; 600 000
q^*	Catchability coefficient	rate	0.0000051
D	Discard mortality	rate	0.08

TABLE I. Continued

Symbol	Description	Units	Value
A_c	Satisfaction (A) from catch (c)	rate	Calculated
A_n	Magnitude similar to average satisfaction from catch (n , non-catch)	constant	6.5
μ	CPUE where $A_c = 0$	rate	0.05
δ	Ratio of catch to non-catch-related satisfaction	ratio	0–1
θ^{-1}	Slope of the relationship between catch-related satisfaction and CPUE	constant	3

CPUE, catch per unit of effort.

*Values were estimated.

commonly employed in fisheries assessments (Haddon, 2001; Walters & Martell, 2004). The model was then extended to allow analysis of fisheries enhancements following the approach of Lorenzen (2005). The enhanced stock is differentiated into components according to genotype and origin (Fig. 1). The three components of the total stock (subscript t) considered are wild (wild genotype, naturally recruited, subscript w), hatchery (hatchery genotype, naturally recruited, subscript h) and stocked (hatchery genotype, stocked, subscript s). This differentiation allows a range of questions to be addressed, including the contributions of stocking and natural recruitment to yield. It is expected that sub-stocks may differ in life-history traits such as survival (Stunz & Minello, 2001). In this study, stocked fishes are assumed to have slightly lower survival relative to wild fishes during stage 2, density-dependent mortality part of recruitment as described by ρ_s (Table I and equations 12 and 13 in Table II). It is assumed that post-recruitment, stocked, wild and hatchery fishes experience the same age-dependent survival (S_a , equation 5; Table II). Interactions between wild, stocked and hatchery fishes are limited to these fitness-modified survival rates and density-modified survival in the pre-recruit phase of the life cycle, *i.e.* no explicit predation or competition between sub-population components is assumed, such that the components are affected symmetrically by density-dependent processes (Lorenzen, 2005). Once released, stocked hatchery fishes and their offspring are subject to natural selection which can be expected to result in the fitness of hatchery-type fishes increasing over generations in the wild and eventually approaching the fitness of wild fishes (Fig. 1). The model mimics this effect of natural selection by allowing some hatchery-type fishes to change into the wild-type component at a rate equivalent to the heritability of fitness traits (γ_h ; Table I) (Lorenzen, 2005).

RECRUITMENT

In line with the normal convention used in fisheries models, recruitment is defined as the number of late juveniles entering the fishable stock following a period of highly density-dependent (compensatory) mortality. Explicit consideration of the processes that affect mortality rates during the juvenile (pre-recruit) stages is critically important to outcomes of enhanced fisheries, as most fishes are stocked at a life stage and size when survival is density dependent and size dependent (Lorenzen, 1996, 2000, 2005; Hazlerigg *et al.*, 2012). Both density and size dependence in survival of stocked fishes was accounted for by ‘disaggregating’ early life, pre-recruitment mortality into multiple stages (Lorenzen, 2005). This allowed the representation of stocked fishes experiencing some density dependence in survival during the pre-recruit period following release (such that the amount of density-dependent survival depended on the size of stocking), and importantly allowed consideration of stocked, hatchery and wild fishes in the same recruitment process but with modified survival for each (as it may be that stocked fishes experience greater mortality than wild fishes). Methods accounting for specific

TABLE II. Model components and equations are described. For all equations, subscript *t* represents time dynamics (years), subscript *a* represents age dynamics (years), subscript *w* represents wild fish, subscript *s* represents stocked fish and subscript *h* represents hatchery fish and subscript *t* represents total combined fish

Component	Equation
Life-history characteristics of stock:	
1 Length (mm) <i>L</i> at age <i>a</i>	$L_a = L_\infty (1 - e^{-K(a-t_0)})$
2 Mass (kg) <i>W</i> at age <i>a</i>	$W_a = w_a L_a^{w_b}$
3 Fecundity <i>f</i> at age <i>a</i>	$f_a = \max(0, (W_a - W_m))$
4 Survival (year ⁻¹) <i>S</i> at age <i>a</i>	$S_a = e^{-(ML_m L_a^c)^{c_1}}$
5 Survivorship <i>l</i> at age <i>a</i>	$l_a = 1 \quad \left \begin{array}{l} a=1 \\ a=2:A_{max} \end{array} \right.$ $l_a = l_{a-1} S_{a-1}$
6 Eggs per recruit φ	$\varphi = \sum_a f_a l_a$
Disaggregated recruitment dynamics:	
7 Beverton–Holt <i>a</i> , <i>b</i> and re-parameterized <i>b_n</i>	$a = \Omega/\varphi_c, b = (\Omega - 1)(R_0\varphi_c)^{-1},$ $b_n = ab^{-1}$
8 Duration of phase 1 of recruitment stage 2, <i>d₁</i>	$d_1 = (L_s - L_0)(L_r - L_0)^{-1}$
9 Linear growth rate (year ⁻¹) for recruitment stage 2, <i>V</i>	$V = (L_r - L_0) d_1^{-1}$
10 Base survival of phases 1 and 2, respectively, of recruitment stage 2, <i>S₁</i> and <i>S₂</i>	$S_1 = (L_0 L_s^{-1})^{M_1 V^{-1}}, S_2 = (L_s L_r^{-1})^{M_1 V^{-1}}$
11 Survival rate of larvae for entire recruitment, ω	$\omega = a S_r^{-1} S_r = S_1 S_2$
12 Survival <i>a₁</i> for phase 1 of recruitment stage 2, modified by relative fitness of wild (<i>w</i>) and hatchery (<i>h</i>) sub-populations	$a_{1_w} = S_1, a_{1_h} = S_1 \rho_h$
13 Survival <i>a₂</i> for phase 2 of recruitment stage 2, modified by relative fitness of wild (<i>w</i>) and hatchery (<i>h</i>) and stocked (<i>s</i>) sub-populations	$a_{2_w} = S_2, a_{2_h} = S_2 \rho_h, a_{2_s} = S_2 \rho_s$
14 Density-dependent component of survival for phases 1 and 2, respectively, of recruitment stage 2, <i>b₁</i> and <i>b₂</i>	$b_1 = d_1 a b_n^{-1}, b_2 = a(b_n - b_1)^{-1}$ $(S_1 \omega)^{-1}$
15 Total eggs <i>E_t</i> in the beginning year <i>t</i> , the sum of wild (<i>E_w</i>) and hatchery eggs (<i>E_h</i>)	$E_t = E_{t-1_w} + E_{t-1_h}$, where $E_{t-1_w} = \sum_a f_a N_{t_w}, E_{t-1_h} = \sum_a f_a N_{t_h}$
Number of fish <i>N^t</i> surviving recruitment stage 1 and phase 1 of recruitment stage 2 in year <i>t</i> :	
16 Wild (<i>w</i>)	$N_{t_w}^1 = (E_{t-1_w} + \gamma_h E_{t-1_h}) \omega a_1$ $(1 + b_1 E_t)^{-1}$
17 Hatchery (<i>h</i>)	$N_{t_h}^1 = E_{t-1_h} (1 - \gamma_h) \omega a_{1_h}$ $(1 + b_1 E_t)^{-1}$

TABLE II. Continued

Component	Equation
18 Total fish N'' entering phase 2 of recruitment stage 2 in year t	$N_t^2 = N_{t_w}^1 + N_{t_h}^1 + T_t$
Number of fish R surviving phase 2 of phase 2 and thus leaving recruitment period in year t	
19 Wild (w)	$R_{t_w} = N_{t_w}^1 a_{2_w} \left(1 + bN_t^2\right)^{-1}$
20 Hatchery (h)	$R_{t_h} = N_{t_h}^1 a_{2_h} \left(1 + bN_t^2\right)^{-1}$
21 Stocked (s)	$R_{t_s} = T_t a_{2_s} \left(1 + bN_t^2\right)^{-1}$
Number N fish entering age 1, modified by back-calculated survival from 0.75 to 1 year of age $S_{0.5}$ in year t :	
22 Wild (w) at age a	$N_{a=1,t_w} = R_{t_w} S_{0.5}$
23 Hatchery (h) at age a	$N_{a=1,t_h} = R_{t_h} S_{0.5}$
24 Stocked (s) at age a	$N_{a=1,t_s} = R_{t_s} S_{0.5}$
Fishery characteristics:	
25 Vulnerability v at age a to capture (c)	$v_a^c = g_a^c - p_a^c$, where
upper – lower	$g_a^c = \left(1 + e^{-(L_a - L_u^c)} \sigma_u^{c-1}\right)^{-1}$, $p_a^c = \left(1 + e^{-(L_a - L_l^c)} \sigma_l^{c-1}\right)^{-1}$
27 Vulnerability v at age a to harvest (h)	$v_a^h = g_a^h - p_a^h$, where
upper – lower	$g_a^h = \left(1 + e^{-(L_a - L_u^h)} \sigma_u^{h-1}\right)^{-1}$, $p_a^h = \left(1 + e^{-(L_a - L_l^h)} \sigma_l^{h-1}\right)^{-1}$
29 Effort F in year t	$F_t = \frac{F_m + 2(F_0 - F_m)}{1 + e^{\frac{\left(\sum_a N_{t-1_w} v_a^c + \sum_a N_{t-1_s} v_a^c + \sum_a N_{t-1_h} v_a^c - \sum_a N_{t=1_h} v_a^c\right)}{\sigma \sum_a N_{t=1_w} v_a^c}}}$
Time dynamics:	
30 Wild spawning biomass B in year t	$B_t = E_{t_w} E_{t=1_w}^{-1}$
31 Exploitation rate U in year t	$U_t = 1 - e^{qF_t}$
32 Numbers N at age a and year t	$N_{a,t} = N_{a-1,t-1} S_{a-1} S_{tV} S_{tR} S_{tK}$

TABLE II. Continued

Component	Equation
33 Survival S of all types from in year t :	
34 Harvest (v)	$S_{t_v} = 1 - v_{a-1}^h U_{t-1}$
35 Discard of non-legal catch (d)	$S_{t_d} = (v_{a-1}^c U_{t-1} - v_{a-1}^h U_{t-1}) D$
36 Voluntary discard of legal catch (k)	$S_{t_k} = (v_{a-1}^h U_{t-1} k^{-1} - v_{a-1}^h U_{t-1}) D$
Socioeconomic dynamics:	
37 Total catch C_t in year t	$C_t = U_t \times [N_{t_w} (v_a^c) + N_{t_h} (v_a^c) + N_{t_s} (v_a^c)]$
38 Catch per unit effort y in year t	$y_t = C_t F_t^{-1}$
39 Total satisfaction per trip A_t in year t	$A_t = \delta A_{t_c} + A_n$, where
Satisfaction from catch A_c in year t	$A_{t_c} = (y_t - \mu) \vartheta^{-1}$
40 Overall socioeconomic value in year t	$V_t = A_t F_t$

components of juvenile mortality prior to recruitment to sub-adult stages are described in detail in Lorenzen (2005), and so are summarized in the text and included in tables (equations 7–21 in Table II). It is assumed that the entire early life-history period, from eggs to recruits (sub-adults), is composed of two stages (Fig. 1). Recruitment stage 1 represents the larval life-history stage, from hatching until settlement, where mortality is assumed to be density independent, following Lorenzen (2005). This assumption is particularly reasonable given the offshore, pelagic spawning behaviour of *S. ocellatus* (Murphy & Muyladorero, 2009). Recruitment stage 2 represents the juvenile life-history stage, from settlement until recruitment

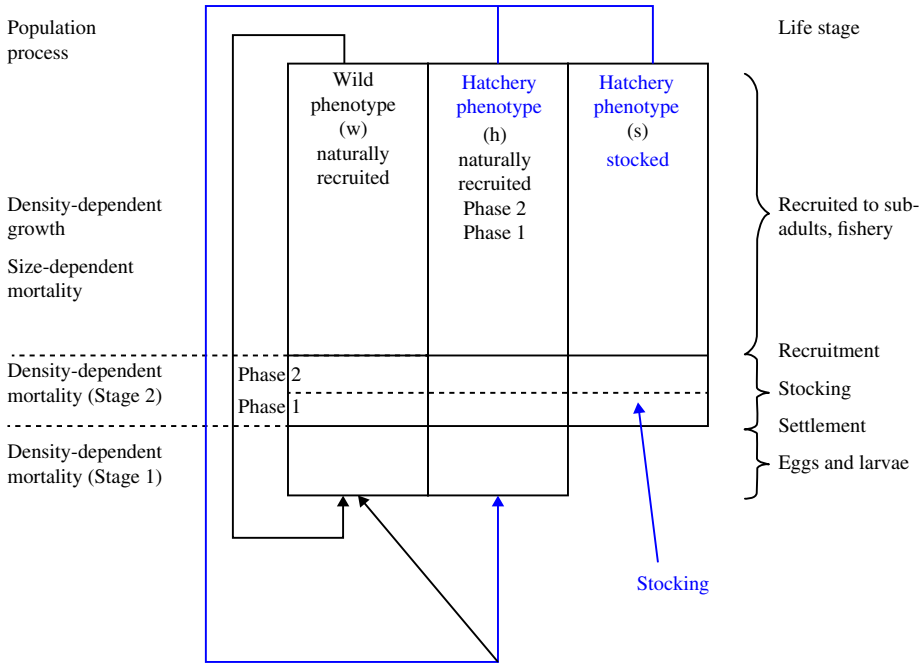


Fig. 1. The structure of the model accounts specifically for phenotypes, life stages and related population processes.

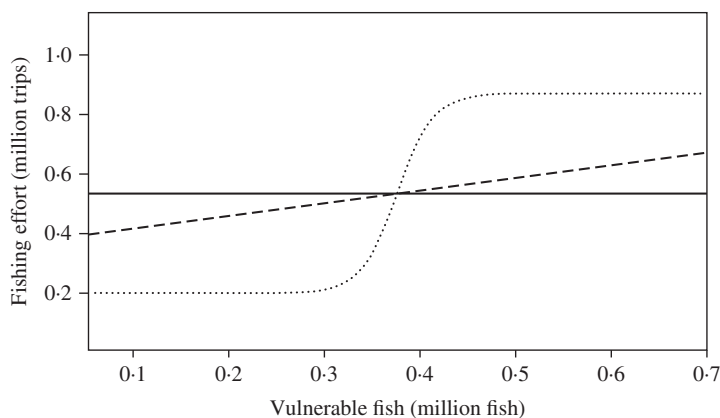


FIG. 2. Alternative assumptions of the response of aggregate fishing effort to the abundance of all fish vulnerable (based on size) to capture for recreational fishing. —, unresponsive of flat effort; ---, moderately responsive effort; ·····, sharply responsive effort.

to sub-adults, and mortality in this stage is assumed to be density dependent. For the purpose of modelling the stocking of juvenile fishes, this juvenile stage is further sub-divided into two consecutive phases of density-dependent mortality, below and above the size at stocking. Phase 1 of recruitment stage 2 accounts for density-dependent survival of wild fish (w) and hatchery offspring (h) from size at settlement (L_0 ; Table I) until size at which stocking occurs (L_s), and phase 2 accounts for density-dependent survival of wild (w), hatchery (h) and stocked (s) fish from size at which stocking occurs (L_s ; Table I) until size at recruitment to sub-adult stages (L_r ; Table I), *i.e.* the cessation of density-dependent mortality. Overall base survival rates for both phases are size and growth dependent (equations 9 and 10 in Table II), but are then modified by relative fitness of stocked and hatchery fishes (equations 12 and 13 in Table II) and by the densities of fish in each phase (equation 14 in Table II). Survival is dependent on the combined density of wild, stocked and hatchery fishes and density dependence is assumed to act symmetrically on all stock components. Thus, total recruits from each wild, hatchery and stocked sub-population to sub-adult life stages are represented by two Beverton–Holt stock–recruit functions (Walters & Korman, 1999), the first accounts for recruitment stage 1 (density-independent mortality) and phase 1 of recruitment stage 2 (density-dependent mortality) (Fig. 1 and equations 16–18 in Table II), while the second accounts for phase 2 of recruitment stage 2, during which mortality is density dependent (Fig. 1 and equations 19–21 in Table II). In this case, it is assumed that *S. ocellatus* recruit to sub-adults at 0.75 years, so for convenience of accounting for ages at whole year increments, the numbers of fish entering the first year of life are further reduced by a back-scaled, size-dependent, density-independent mortality rate ($S_{0.5}$, Table I and equations 22–24 in Table II).

ANGLER EFFORT DYNAMICS

Aggregate fishing effort each year (F_t) is modelled to respond to harvestable fish abundance through a logistic function (equation 29; Table II) (Walters & Martell, 2004; Allen *et al.*, 2012). Varying the s.d. (σ ; Table I) of this function allows consideration of different strengths of effort–abundance relationships, including a strong (sharp) response, a proportional (moderate) response and no response (flat) as shown in Fig. 2. While a moderate effort and abundance relationship is commonly thought to exist in recreational fisheries (Johnston *et al.*, 2010; Allen *et al.*, 2012), very few empirical estimates exist, particularly for this fishery, for it to be assumed with certainty (Camp *et al.*, 2013). Uncertainty of this key relationship is accounted for by evaluating enhancement outcomes under alternative scenarios of strength of effort response.

SOCIOECONOMIC ELEMENTS

Aggregate fishing effort (total number of fishing trips) was considered a proxy for the economic (*i.e.* market) activity, as has been commonly assumed for recreational fisheries (Cox *et al.*, 2003). This simplifying assumption is reasonable because the regional revenue generated from a recreational fishery depends on the cost paid by fishers to fish, including variable costs (*e.g.* cost of fuel, ice, fishing bait, terminal tackle and boat maintenance) and probably fixed costs (*e.g.* boat and equipment) (Propst & Gavrilis, 1987). Over the long run, it is reasonable to consider these total costs to be a function of number of trips (Cox *et al.*, 2003). It is important to acknowledge that not all trips produce the same economic activity, *e.g.* trips of longer duration or travel distance will probably incur greater cost and thus produce greater market activity, *ceteris paribus*. For this work, the simple assumption is made that the average expected value of cost per trip did not change substantially with the advent of stocking, thus justifying the use of aggregate effort as a proxy.

Total social utility (H_t) was represented by calculating total satisfaction per trip (A_t ; Table II), which was calculated as the sum of two components, weighted catch rate-related satisfaction (δA_{t_c} ; Table II) and non-catch rate-related satisfaction (A_{t_n} ; Table II). Non-catch rate-related satisfaction represents the utility experienced by an angler simply going fishing, and so is considered a constant per trip, with a magnitude similar to catch rate-related satisfaction attributed to moderate catch rates. Catch rate-related satisfaction (δA_{t_c} and equation 39 in Table II) is, of course, largely a function of catch rate (Cox *et al.*, 2002), representing angler utility as these two components recognize that (1) utility depends on more than simply catch rate and (2) catch rate-related satisfaction is a large component of satisfaction that is most likely to vary between trips (Finn & Loomis, 2001; Arlinghaus, 2006). Altogether, the catch rate-related and non-catch rate-related components yielded an overall satisfaction (equation 39; Table II).

Total socioeconomic value was calculated as the product of H_t (per trip) and the total number of trips, aggregate effort (equation 40; Table II), following Cox *et al.* (2002). This produces a socioeconomic metric represented in units of utility. The assumptions that effort is driven by abundance of fish, that market activity is proportional to effort and that satisfaction is driven by catch rate are simplistic but useful, as they are optimistic relative to the management strategy evaluated (stock enhancement). Accordingly, results from this work should be interpreted as what is possible with stock enhancement. Uncertainty in outcomes owing to these assumptions was explored with various model runs.

MODEL TUNING

The model described above was tuned to represent the *S. ocellatus* recreational fishery of Tampa Bay, Florida, in terms of both parameters and output. Key life-history parameter values, *e.g.* natural mortality (M ; Table I) and maximum age (A_m ; Table I) for this model were obtained from the most recent *S. ocellatus* stock assessment (Murphy & Muyandorero, 2009) and from other studies describing Florida *S. ocellatus* populations (Peters & McMichael, 1987; Murphy & Taylor, 1990). Other biological parameters not known at this small spatial scale (specifically R_0 recruitment at unfisher conditions, q catchability and $1 - k$ voluntary release rate; Table I) were estimated by minimizing a negative log likelihood, summing log deviances between observed and predicted effort, catch, harvest, harvested fish per unit effort and escapement for the counties surrounding Tampa Bay (NMFS, 2013) and the model predictions. The likelihood weighted evenly the deviances from each metric, and deviances for each were calculated using a single value (the average of the last 3 years from the Marine Recreational Information Program data, MRIP; <http://m.myfwc.com/research/saltwater/fishstats/recreational-fisheries/landings/>). This tuning falls short of fitting the model to the full time series, which was not necessary in this case as (1) the research objectives were not to perform a stock assessment and (2) much information from the stock assessment was already incorporated into the model and (3) the data available are not considered by managers to be sufficient for conducting a stock assessment at this spatial scale. This tuning, however, did ensure that important but unknown parameter values (*e.g.* strength of dynamic effort response) used in the model would produce a reasonable representation of the Tampa Bay fishery. More importantly, by fitting the simulation model to observed current (and thus pre-stocking) conditions, a *ceteris paribus* baseline can be established with which simulated effects of stocking can be compared.

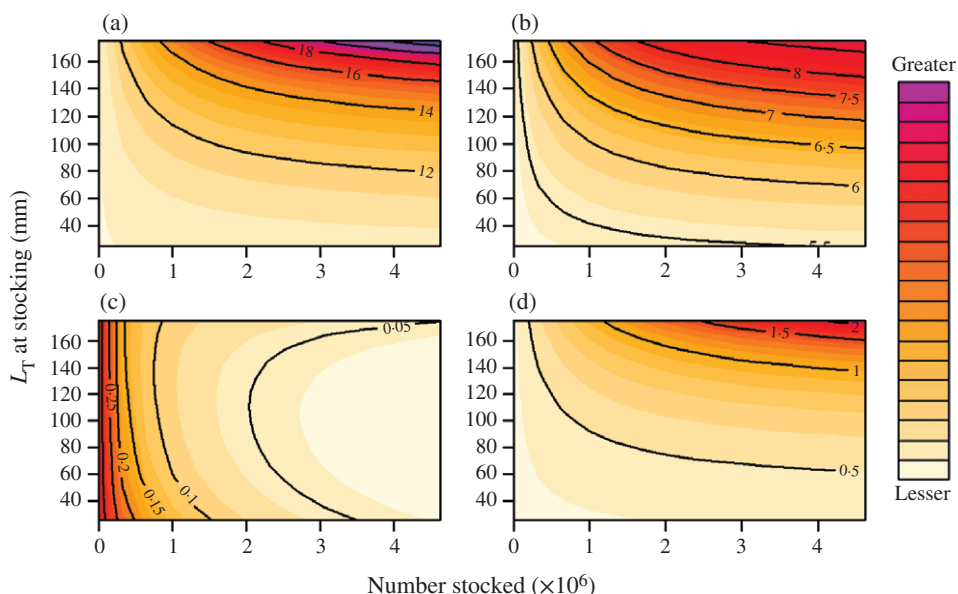


FIG. 3. The equilibrium results of (a) satisfaction per angler trip, (b) effort (in 100×10^3 trips), (c) proportion of wild spawning biomass relative to unfished conditions (% unfished) and (d) total catchable fish ($\times 10^6$) depend upon the total length (L_T) of fish at stocking (y-axis) and the number of fish stocked per year (x-axis, in millions). Darker colours show greater values of each response metric corresponding to the L_T and number of fish stocked, and contour lines show actual values.

Assessing the sensitivity of the described model to key parameters is critical to ensure that reported results are not merely artefacts of the parameter values selected. One of the parameters used here that is most uncertain is the baseline annual instantaneous mortality of a 10 mm fish, referred to as M_1 (Table I). Here, a value of 15 year^{-1} was assumed (Table I), although this has not explicitly been evaluated for *S. ocellatus*. To assess how this uncertainty might have affected the results of the model, the sensitivity of the model outcomes to M_1 was evaluated by assessing the per cent change in response metrics realized *via* a 10% increase in the value of M_1 (to 16.5).

MODEL ANALYSES

Three types of results are described: an evaluation of overall outcomes in terms of multiple objectives, an evaluation of the sensitivity of key outcomes to uncertain parameters and a practical assessment of resource commitments necessary to achieve the stated stock enhancement objective. Importantly, the first two analyses describe theoretically possible outcomes that are not probably attainable given the resource limitations (*e.g.* it is not currently realistic to stock millions of large juvenile fishes), whereas the third analysis is aimed to provide practically useful information. Each analysis considered at least one of the five response metrics: the ratio of wild spawning biomass relative to that at unfished conditions, aggregate angler effort (F_t), angler satisfaction (A_t), total (stocked, hatchery and wild) vulnerable fish and overall socioeconomic value (V_t). For the first analysis, to evaluate expected outcomes, the response metrics considered were satisfaction per trip, fishing effort, wild spawning biomass and total vulnerable fish over a range of number of fish stocked (T_t) and sizes of stocked fish (L_s) and assuming a moderate angler effort response and full satisfaction from catch rate (Fig. 3). The second analysis evaluated how the response metrics satisfaction, effort and wild spawning biomass were sensitive to assumptions of effort response (Fig. 4), and then assessed the overall value assuming different combinations of effort response and satisfaction from catching fishes (Fig. 5). For the last, only

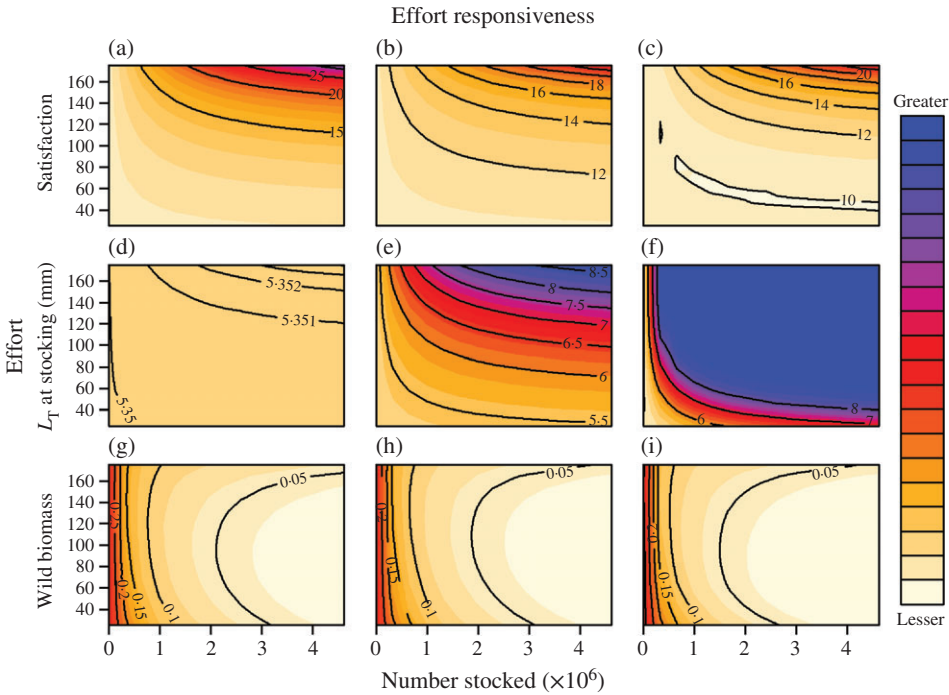


FIG. 4. The equilibrium results of (a–c) satisfaction per trip, (d–f) effort (in 100×10^3 trips) and (g–i) proportion of wild spawning biomass relative to unfished conditions for different total lengths (L_T) of fish stocked (y-axis of each panel) and number stocked (x-axis of each panel, $\times 10^6$) are shown for different assumptions of effort responsiveness: (a, d, g) flat, (b, e, h) moderate or (c, f, i) sharp. Darker colours show greater values of each response metric corresponding to the L_T and number of fish stocked, and contour lines show actual values.

value is reported, because these differing assumptions of catch-related satisfaction have no effect on wild spawning biomass. Response metric values reported for the first two analyses are final values from 100 year model runs, which are considered equilibrium values. These values are given to illustrate the expected behaviour of recreational enhanced systems. The third analysis considered what resources would be necessary to realize a given increase in total vulnerable fish in or around the Tampa Bay estuary (Table III) in 10 years of stocking. This response depends in part on the effort response assumed, and so multiple responses are considered. Here, these resources are represented in terms of both numbers of fish that would need to be stocked and the approximate cost of stocking in dollars (C. Young, pers. comm.).

RESULTS

MODEL TUNING

Tuning this model to recent point estimates of the Tampa Bay, Florida, *S. ocellatus* fishery output produced equilibrium conditions that represent the current state of the fishery, with deviances for all metrics $<6\%$ (Table IV). The estimate of voluntary release discard (73%) was surprisingly high, although not unreasonable given the one fish bag limit in Tampa Bay, and so for the purposes of this study (and in the absence

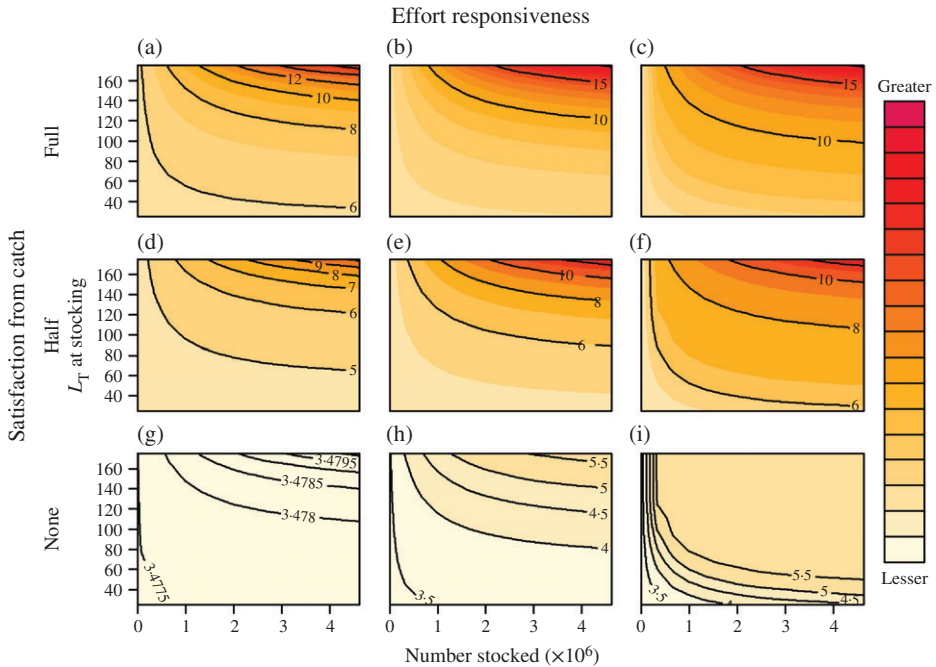


FIG. 5. The equilibrium results of overall socioeconomic value in units of satisfaction ($\times 10^6$) at different total lengths (L_T) (y-axis) and numbers of fish stocked (x-axis, $\times 10^6$) for different types of satisfaction: (a–c) full satisfaction from catch, (d–f) half satisfaction from catch and (g–i) no additional satisfaction from catch, and for different assumptions of effort responsiveness: (a, d, g) flat, (b, e, h) moderate or (c, f, i). Darker colours show greater values of each response metric corresponding to the size and number of fish stocked, and contour lines show actual values.

of direct empirical estimates) is considered adequate. The catchability estimate was an order of magnitude greater than the current stock assessment estimate (5.1×10^{-6} v. 9.0×10^{-7}). This may reflect different catchability in Tampa Bay relative to the rest of Florida's Gulf coast or, more likely, the fact that nuisance parameters such as catchability routinely absorb error in fisheries model, such as incorrect assumptions regarding effort dynamics. The latter case is not particularly troublesome, because the effect of uncertainty in this assumption was explicitly considered.

The sensitivity analysis results revealed that the model was largely insensitive to the parameter for annual instantaneous mortality of a 10 mm fish, M_I (Table V). In the absence of stocking, response metrics are not at all affected by the M_I value, as the parameter controls the mortality experienced prior to the density-dependent mortality stage, such that the abundance of fish leaving the density-dependent stage will not change with changing numbers of fish entering it. Under moderate stocking levels ($10 \times$ recruitment at unfished conditions), the model results remained insensitive to the changes in M_I (Table V). Biologically, this is reasonable because the overall survival is density dependent, such that changes in the baseline survival rates during the density-dependent survival stages will result in less proportional changes in overall recruits or metrics dependent upon recruits (e.g. vulnerable fish, effort and satisfaction). This is achieved mathematically as the M_I parameter is applied through

TABLE III. Evaluation of how many *Sciaenops ocellatus* would need to be stocked, and what it would cost to realize a 25% increase in *S. ocellatus* abundance 10 years after commencing stocking, under different recruitment and effort responses. These estimates include some instant mortality from stocking and slightly lower survival of stocked fish relative to wild. Cost basis of U.S.\$ 0.15 per 25 mm, U.S.\$ 0.46 per 100 mm and U.S.\$ 1.58 per post-recruit in 2012 (C. Young, unpubl. data)

L_T at stocking (mm)	Effort response		
	Sharp	Moderate	Flat
25	$4.6e^{17}$ (U.S.\$ $6.9 \times 10_{16}$)	$4.5e^{17}$ (U.S.\$ 6.7×10^{16})	$4.6e^{17}$ (U.S.\$ 6.9×10^{16})
100	712 624 (U.S.\$ 327 807)	727 565 (U.S.\$ 334 679)	721 870 (U.S.\$ 332 060)
175	189 784 (U.S.\$ 299 860)	190 242 (U.S.\$ 300 582)	188 537 (U.S.\$ 297 888)

L_T , total length.

the exponent after being divided by generally a large number (v), such that M_1 is <1 , and is applied to a survival rate that is by definition <1 . A 10% change in M_1 therefore leads to a less than proportional (*i.e.* $<10\%$) change in the survival rates applied to fishes. The change in M_1 is even less noticeable in response metrics effort and satisfaction, as the relationship between these metrics and vulnerable fish is already less than proportional.

MODEL ANALYSES

Model results suggest that certain scenarios of *S. ocellatus* stock enhancement may increase the socioeconomic objectives associated with this recreational fishery, although at a cost. This is illustrated by the increases in aggregate fishing effort (related to market activity) and satisfaction (driven largely by catch rates) under certain stocking scenarios related to increases in total vulnerable fish [Fig. 3(a), (b),

TABLE IV. Comparisons between region-specific observations from the Marine Recreational Information Program (MRIP) and tuned model (with no stocking) predictions. Model was fitted assuming a flat (non-responsive) effort response

Output	MRIP for Tampa Bay region	Model	Deviance (MRIP Model): MRIP
Effort (trips)	535 618	534 965	<0.01
Catch (numbers of fish)	827 059	828 997	<-0.01
Harvest (numbers of fish)	93 011	91 316	-0.06
CPUE	1.54	1.55	<-0.01
KPUE	0.17	0.17	-0.01
Unfished recruitment (R_o)*	NA	464 685	NA
Catchability (q)*	NA	5.10×10^{-6}	NA
Kept proportion*	NA	0.27	NA
Escapement	NA	0.35	NA

NA, not applicable; CPUE, catch per unit of effort; KPUE, harvest per unit of effort.

*Leading estimated parameters from tuning procedure.

TABLE V. Evaluation of the model sensitivity to the M_1 parameter, which represents the annual instantaneous mortality of a 10 mm total length (L_T) fish. Evaluations were run assuming a moderate effort response and a full amount of satisfaction from catching fish, and stocking intensity at $0.1 \times R_0$ (recruitment at unfished conditions). The results show the per cent change in the given response metric (columns) to a 10% increase in M_1 , from 15 to 16.5, for different L_T of fish stocked

L_T stocked (mm)	Wild spawning biomass (%)	Vulnerable fish (%)	Aggregate effort (%)	Satisfaction per trip (%)
No stocking	0.00	0.00	0.00	0.00
25	0.55	-0.03	$-8.07 \times 10_{-3}$	$-8.28 \times 10_{-3}$
100	0.24	-0.05	-0.02	-0.02
175	0.02	-0.02	$-6.47 \times 10_{-3}$	$-6.23 \times 10_{-3}$

(d)]. Increases in the vulnerable fish and the related effort and satisfaction, however, are only possible when fishes are stocked at larger sizes. Even very high number of fishes stocked at small sizes failed to produce increases in vulnerable fish or associated socioeconomic metrics [Fig. 3(a), (b), (d)]. One of the most important results is that any amount of stocking will cause decreases in abundance of wild fishes, and these decreases are exacerbated by increasing numbers of fish stocked, regardless of the size of fish stocked [Fig. 3(c)]. This suggests that stocking small fishes will cause declines in wild fish abundance without returning socioeconomic benefits. In concert, evaluations of these metrics suggest an apparent trade-off between the conservation objectives of not negatively influencing wild fish populations and the socioeconomic objectives of continued consumer benefit and total number of trips related to market activity.

Evaluations of alternative angler effort responses revealed a secondary trade-off between satisfaction and effort. A flat effort response can cause the greatest increases in satisfaction (*via* increased catch rate), as total vulnerable fish increase but effort does not change [Fig. 4(a)]. Conversely, sharp effort responses can actually lead to bubbles of decreases in satisfaction, if effort has increased proportionally more than vulnerable fish [Fig. 4(c)]. Aggregate effort (and related market activity) has the greatest potential to increase with sharply responsive effort [Fig. 4(f)], and unresponsive effort will obviously lead to no increases regardless of how many fishes are stocked of any size [Fig. 4(d)]. The broader conservation–socioeconomic trade-off was not generally sensitive to alternative assumptions of effort responses. Wild fishes are still likely to decline under any effort response [Fig. 4(g)–(i)], indicating that the biological effects of stock enhancement on wild fishes (*e.g.* competition in recruitment) are substantial enough to cause declines even in the absence of attracted fishing effort. The substantial declines in wild fish populations, however, occur at lower stocked numbers under sharp angler-effort response [Fig. 4(g)] relative to flat [Fig. 4(i)] or moderate response [Fig. 4(h)], suggesting that the attracted effort still affects wild fishes.

These results suggest that increases in overall socioeconomic values will be greatest when effort is responsive and substantial satisfaction is derived from increased catch rates (Fig. 5). Some increases are possible as long as effort is somewhat responsive to fish abundance or satisfaction is somewhat related to catch rate [Fig. 5(b)–(i)]. It should be noted that the alternative assumptions of satisfaction alter the magnitude

of the value, but do not affect the wild spawning biomass. Therefore, the losses of wild fish would be the same as seen in Fig. 4, changing with the assumptions of effort response. As a whole, these results suggest that alternative assumptions particularly regarding uncertain elements of recreational fisheries do little to alleviate the trade-off between increased socioeconomic objectives and sustained wild fish populations caused by stock enhancement.

The resource commitments necessary to produce the stated objective (25% increase in harvestable *S. ocellatus* 10 years after commencement of stocking) are substantial, but driven by size at which fishes are stocked (Table III). This work suggests that stocking quite small *S. ocellatus* (25 mm total length, L_T) is incomprehensively costly ($\times 10_{12}$ fish stocked and dollars spent per year), whereas stocking larger-sized fishes is at least potentially possible (700 000–1 000 000 fishes stocked at a cost of <U.S.\$ 400 000 year⁻¹ in 2012). Resources needed were generally greater if effort responded sharply to fish abundance, because the gains in harvestable fishes from stocking are quickly lost to growing effort, requiring more stocking to attain the stated goal.

DISCUSSION

The greatest utility of this work arises from its integration of individual components, population dynamics of stocking enhancement, angler effort dynamics and socioeconomic value, to produce a quantitative model broad enough to represent important conservation and socioeconomic objectives, but straightforward enough to be readily described and tuned to commonly available data. This tuning is an important step forward, as it lends greater empirical credibility to predictions, which can be produced at scales appropriate for addressing specific management questions. One formidable challenge to constructing integrated models is describing appropriate linkages between components, such as linkages between population dynamics and socioeconomic value (Lorenzen, 2008). Two primary options exist for creating these linkages, either individual site-choice models (common in economic literature) or broader-scale models where the aggregated population effects of choices are represented (Walters & Martell, 2004; Fenichel *et al.*, 2013). The latter was chosen due to its transparency, and accounts for inherent uncertainty inherent by (1) investigating a range of strengths of linkages between both fish populations and fishing effort as well as between catch rates and satisfaction and (2) describing probable implications of additional assumptions. This approach has yielded several specific findings that improve the socioecological understanding of stock enhancement of recreational fisheries.

The most important finding of this work is the trade-off realized under stock enhancement between conservation and socioeconomic objectives, where greater socioeconomic value may be achieved with stocking, but at a cost to wild fish populations. Surprisingly, this loss of wild fishes was largely insensitive to the strength in angler effort response. This is probably due to the short time during which *S. ocellatus* are highly vulnerable to harvest or capture (1 and 3 years, respectively) relative to their lifespan (30–40 years). While not commonly recognized in the literature (van Poorten *et al.*, 2011), socioeconomic–conservation trade-offs should be expected with stock enhancement (Camp *et al.*, 2013). Stocking smaller or larger fishes can lead to replacement of wild fishes directly or *via* stocked fish offspring, and stocking larger fishes that more feasibly increases overall abundance (and can lead to greater socioeconomic

value) may lead to increased overall effort and fishing mortality on wild and stocked fishes (Baer *et al.*, 2007). This work also made explicit a secondary trade-off that was realized under stock enhancement, between social utility and aggregate effort, related to market activity. The trade-off here should also be anticipated, as higher effort will drive catch rates (affecting utility) down (Cox *et al.*, 2002).

A key implication from the recognition of both socioeconomic–conservation and effort–catch rate trade-offs is the importance of explicitly describing to stakeholders the probable outcomes of stock enhancement in terms of expected costs (wild fishes, aggregate fishing trips and market activity or catch rate-related satisfaction). Failure to do so may forward the unrealistic expectation of stock enhancement as a panacea that can simultaneously buoy wild-fish population, catch rates and effort (van Poorten *et al.*, 2011), whereas explicit recognition of the specific type of socioeconomic gains and potential wild fish losses supports the view of stock enhancement as a potentially useful management tool, provided the costs are acceptable. More reasonable and explicit objectives regarding enhancement should promote greater success at their achievement (Washington & Koziol, 1993; Naish *et al.*, 2007) and help avoid the primary pitfall of poorly defined management objectives (Walters, 1986; Possingham *et al.*, 2001; Martin *et al.*, 2009).

This work specifies the influence of the size of fishes at stocking on enhancement outcomes, relative to the size at recruitment. Fishes stocked at a size prior to most density-dependent survival in the wild (*e.g.* *S. ocellatus* stocked at 25 mm L_T) were unlikely to increase the total population or lead to socioeconomic benefits. At best (worst), the result will simply be a replacement of wild fishes with stocked fishes. This finding is based on tautological theory of recruitment dynamics; so long as recruitment overfishing is minimal it is unlikely stocking reasonable numbers of fish prior to cessation of strong density-dependent mortality could augment total numbers of fish (Leber *et al.*, 2005; Rogers *et al.*, 2010; Camp *et al.*, 2013). While this appears evident, it is not always recognized, and many hatchery programmes still stock very small fishes (McEacheron *et al.*, 1998; Serafy *et al.*, 1999; Scharf, 2000; Tringali *et al.*, 2008) that may replace wild fishes if they survive through the density dependence stage following release. This understanding of the recruitment dynamics depends upon the foundational theory of sustainable fishing and has a clear implication for how enhancements are monitored and evaluated. Traditionally, per cent contribution (proportion of stocked fishes divided by proportion total fishes recaptured) has been used as a proxy for survival of stocked fishes and thus relative success of enhancement at augmenting the fishery. It is clear that such a ratio depends as much upon the numbers of wild fishes available for capture as it does on the survival of stocked fishes. If such a metric is used, any replacement of wild fishes by stocked fishes would probably be misunderstood as greater success of enhancement, rather than loss of a wild population and little change in the overall abundance. Preferably, monitoring would measure actual changes in fish populations following enhancement (represented by total vulnerable fish in this work), or directly measure the changes in socioeconomic objectives (*e.g.* effort and satisfaction).

Achieving the desired 25% increase in the overall abundance of harvestable *S. ocellatus* is possible at an estuarine scale and would be expected to lead to greater market activity from increased trips or satisfaction related to greater catch rates, provided larger fishes are stocked and the costs (in terms of wild fishes and dollars) are amenable. It is critical to recognize that this 25% increase in catchable fishes would probably cause

only slight increases in these socioeconomic metrics relative to the many-fold increases described in the theoretical results (which corresponded to many-fold increases in catchable abundance), and such an increase is only possible after 10 consecutive years of successful stocking. Given inherent variability in natural recruitment, angler catch rates or numbers of trips and hatchery rearing, this should temper expectations of enhancement dramatically altering the fishery.

Here, the outcomes of both the theoretical and practical analyses are subject to several uncertainties unaccounted for in the analysis. The positive socioeconomic outcomes associated with stocking larger *S. ocellatus* may be optimistic because fishes were assumed to experience minimal and immediate post-stocking mortality (e.g. due to transit shock) and were assumed to survive after recruitment as well as wild fishes, and they may not (Lorenzen, 2000; Sherwood *et al.*, 2004; Melnychuk *et al.*, 2013). Further, because this fishery is managed *via* a bag limit, if abundance and catch rate increase disproportionately greater than effort, then on average a greater proportion of captured fishes will be released and subjected to discard mortality, potentially dampening gains in socioeconomic value. This work also did not account for the potential of hatchery programmes to increase risk of disease in wild fish, a common concern (Washington & Koziol, 1993; Naish *et al.*, 2007; Lorenzen *et al.*, 2012). Additionally, while density-dependent growth effects of enhancement are possible (Baer & Brinker, 2008), none were assumed in this model and such effects are not intuitive because slower growth could prolong the time period during which *S. ocellatus* are harvestable as well as delay their reaching harvestable size. Effects of angler crowding, which can negatively affect angler satisfaction (Schuhmann & Schwabe, 2004; Hunt, 2005), were also not assessed in this model. Positive effects of stocking could also exist beyond those described here. Enhancement may be useful as a tool to explore strength of effort–abundance relationships or dynamics of stakeholder attitudes (Camp *et al.*, 2013), but learning opportunities are not well documented and so are not represented in this model. Finally, this work is useful for understanding both ecological and socioeconomic outcomes of enhancement in a single area *in absentia* of other regions, but this represents an unrealistic abstraction. In reality, the presence of alternative fisheries or fishing sites suggests that some increase in effort and overall socioeconomic value from stocking are simply redistributions of effort from other areas (Sutton & Ditton, 2005; Askey *et al.*, 2013). Given what has not been represented in this work, the results are best interpreted as an optimistic assessment of what may be possible with enhancement and an explicit accounting of some minimum costs of achieving this.

Despite limitations, this work has clear implications for the biological and socioeconomic conditions under which enhancement may be most successfully employed in Florida's *S. ocellatus* fishery. Recreational fisheries systems where effort is responsive and satisfaction is driven by catch rates may experience the greatest gains in overall socioeconomic value, as stocking (at high enough rates) can potentially cause absolute increases in both effort and catch rate-related satisfaction (although the trade-off will limit the amount of possible satisfaction increase). Positive socioeconomic outcomes may be most noticeable if the areas stocked already have low abundances of wild fishes but sufficient juvenile habitat, such as areas where wild *S. ocellatus* have been essentially recruitment overfished. Alternatively, if high fishing effort causes rapid depletion of vulnerable fish, through harvest or release mortality (Cox & Walters, 2002), enhancement of larger juvenile *S. ocellatus* could temporarily increase catch rate experienced by anglers. Due to dynamic effort, this increased catch rate would be

expected to dissipate quickly as anglers are attracted from alternative areas or fisheries, ultimately resulting in little increase in catch rate but in greater aggregate effort (unless enough fish are stocked to satiate effort) (Baer *et al.*, 2007). If effort satiation is not possible (which is likely), high catch rate enhanced fisheries can be achieved only through effort limitation (Cox *et al.*, 2003). Such limitation is expected to be quite undesirable in marine fisheries, but may be entertained experimentally in smaller, semi-discrete regions.

This work suggests that stock enhancement of non-overfished recreational fisheries is likely to negatively affect wild fish populations. Associated with wild fish losses, socioeconomic gains are possible but require stocking fish large enough to avoid the majority of density-dependent mortality. The effects and limitations of stock enhancement described here are an indictment of all recreational enhancements. Rather, the utility of enhancing specific fisheries is best assessed in the context of other viable alternative strategies (*e.g.* bag limits and habitat restoration). Explicit comparisons of outcomes expected from such alternative strategies would promote objective decision analysis, and represents an area for future research.

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