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ARTICLE

Simulation Modeling to Explore the Effects of Length-Based Harvest Regulations for *Ictalurus* Fisheries

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Abstract

Management of Blue Catfish *Ictalurus furcatus* and Channel Catfish *I. punctatus* for trophy production has recently become more common. Typically, trophy management is attempted with length-based regulations that allow for the moderate harvest of small fish but restrict the harvest of larger fish. However, the specific regulations used vary considerably across populations, and no modeling efforts have evaluated their effectiveness. We used simulation modeling to compare total yield, trophy biomass (B_{trophy}), and sustainability (spawning potential ratio [SPR] > 0.30) of Blue Catfish and Channel Catfish populations under three scenarios: (1) current regulation (typically a length-based trophy regulation), (2) the best-performing minimum length regulation (MLR_{best}), and (3) the best-performing length-based trophy catfish regulation (LTR_{best}; "best performing" was defined as the regulation that maximized yield, B_{trophy}, and sustainability). The B_{trophy} produced did not differ among the three scenarios. For each fishery, the MLR_{best} and LTR_{best} produced greater yield (>22% more) than the current regulation and maintained sustainability at higher finite exploitation rates (>0.30) than the current regulation. The MLR_{best} and LTR_{best} produced similar yields and SPRs for Channel Catfish and similar yields for Blue Catfish; however, the MLR_{best} for Blue Catfish produced more resilient fisheries (higher SPR) than the LTR_{best}. Overall, the variation in yield, B_{trophy}, and SPR among populations was greater than the variation among regulations applied to any given population, suggesting that population-specific regulations may be preferable to regulations applied to geographic regions. We conclude that LTRs are useful for improving catfish yield and maintaining sustainability without overly restricting harvest but are not effective at increasing the B_{trophy} of catfish.

Catfishes (Family Ictaluridae) constitute one of the most important groups of freshwater fishes in North America (Irwin et al. 1999; Michaletz and Travnichek 2011). State agency opinion surveys often reveal that catfish are the third most sought-after sport fish group (Michaletz and Dillard 1999; Stewart et al. 2012); the Blue Catfish *Ictalurus furcatus* and Channel Catfish *I. punctatus* are particularly valuable commercially, recreationally, and economically (Irwin et al. 1999; Michaletz and Dillard 1999; Stewart et al. 2012). Recently, management efforts in many ictalurid fisheries have focused on producing trophy-recreational fisheries, especially for Blue Catfish (Kuklinski and Patterson 2011; Stewart et al. 2012).

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However, both species also support commercial fisheries in at least 14 states (Graham 1999), and the increased recreational and commercial demands on these fisheries have led many agencies to re-evaluate their management of catfish populations, primarily by considering ways to limit the harvest of trophy-sized catfish.

Management of catfish fishing has traditionally involved gear restrictions and supplemental stocking (Marshall 1991). Many state agencies have begun to develop regulations that restrict the harvest of large catfish over a specified target size while allowing more liberal harvest of smaller fish (i.e., length-based trophy regulations [LTRs], which place greater restrictions on the number of large fish harvested than on the number of smaller fish harvested). The LTRs are designed to maximize the abundance of large fish so as to satisfy trophy-oriented angler interests (i.e., increase trophy potential; Kuklinski and Patterson 2011; Stewart et al. 2012) while still allowing the liberal harvest of smaller fish to satisfy harvest-oriented anglers and commercial fishers (B. Wilson, Tennessee Wildlife Resources Agency, personal communication). Versions of these LTRs for catfish exist in several U.S. states and Canadian provinces. However, the specific regulations used vary considerably (CMTC 2015), with no standard for comparability of effectiveness. Thus, effective management of ictalurid fisheries is not possible without evaluating the potential effectiveness of LTRs for increasing trophy biomass. Without such measures, ictalurid populations that are managed using these LTRs may experience risks associated with overfishing.

Simulation modeling has become an important tool in fisheries science and is well suited for evaluating the potential effectiveness of the new LTRs for catfish. The development of deterministic and stochastic simulations has allowed fisheries scientists to explore multiple questions related to fish populations, especially in the context of management strategy evaluations (Wilberg et al. 2008; Kerr et al. 2010). For example, simulations can be used to (1) test how fish stocks will respond to exploitation, (2) evaluate alternative harvest policies, and (3) determine the consequences of spatial structure or predator–prey balance within a fish stock (Hilborn and Walters 1987; Wilberg et al. 2008; Evans et al. 2014; Stewart et al. 2015). Some efforts have been made in evaluating the use of minimum length limits to limit fishing mortality in ictalurid fisheries (Slipke et al. 2002; Holley et al. 2009), but to our knowledge, no study to date has modeled the response of catfish stocks to LTRs.

Herein, we evaluate the effectiveness of regulations that are used to manage catfish stocks. Some state agencies manage Blue Catfish and Channel Catfish separately, whereas other state agencies use a single regulation that applies to both species. The present modeling exercise could aid agencies in evaluating the effectiveness of those regulations (i.e., determining whether population-specific regulations would be beneficial given the differences in growth potential among populations and between species) while identifying biological reference points that define management targets for finite exploitation rates. Our objectives were to (1) use an age-structured simulation model to determine the potential fish population responses of maximized yield, trophy biomass (based on the biomass of preferred-sized and larger fish; Kuklinski and Patterson 2011), and fishery sustainability to exploitation in relation to the finite exploitation rate; and (2) compare model output among the current regulations, alternative minimum length regulations (MLRs), and LTRs.

METHODS

Data collection.—We surveyed the scientific literature, symposia, and dissertations and solicited state agencies for demographic data on Blue Catfish and Channel Catfish fisheries from a wide spectrum of habitats throughout the United States. Analysis of data from the survey produced population-specific growth functions (e.g., von Bertalanffy growth parameters), maximum ages, length–weight relationships (Tables 1, 2), and natural mortality rates for 30 populations. These vital statistics were used to parameterize separate age-structured simulation models for each fishery and each species under three different harvest regulation scenarios (current regulation, MLR, and LTR). Growth estimates (length at age) were typically derived from lapillus otoliths, although pectoral spines were used to estimate growth in four Channel Catfish populations from Minnesota. Colombo et al. (2010) found no difference between growth and mortality estimates derived from lapillus otoliths and pectoral spines; thus, no measurable bias should be introduced by the inclusion of these four Minnesota populations in our study. For the comparison of regulations, we compared model predictions of yield, trophy potential based on the biomass of preferred-sized and larger fish (≥762 mm for Blue Catfish; ≥625 mm for Channel Catfish; Gabelhouse 1984; Kuklinski and Patterson 2011), and sustainability (i.e., spawning potential ratio [SPR]) under the current regulation, the best-performing MLR (MLR_{best}), and the best-performing LTR (LTR_{best}). We assumed that anglers do not harvest fish smaller than 305 mm even when it is legal to do so (i.e., if the current regulation does not limit the minimum size of harvest; Michaletz and Stanovick 2005).

Simulation model.—We developed an age-structured simulation model similar to that of Stewart et al. (2015). The model assumed equal numbers of males and females at all ages and used a series of Botsford's incidence functions to incorporate per-recruit dynamics. Equilibrium recruitment and age-class abundance were modeled by using a stock–recruitment function, which was formulated via Botsford's modification of the Beverton–Holt function (Botsford 1981a, 1981b; Walters and Martell 2004). We incorporated functions to account for age at maturation (m_a = 2 ± 0.50 years; Hubert 1999), stock-specific weight-at-age relationships (w_a; Tables 1, 2), and harvest vulnerability at age (V_a; Table 3).

Age-specific survivorship schedules were calculated as the number of survivors in the absence (l_a) and presence (l_{fa}) of

TABLE 1. Life history characteristics and population parameters (L_∞ = theoretical maximum length; k = Brody growth coefficient [instantaneous growth rate]; t_0 = theoretical age at zero length; b = slope of the weight–length relationship; a = y-intercept of the weight–length relationship; L_a = length at age; w_a = weight at age) that were used in model simulations of 15 Blue Catfish fisheries in five states (data sources are indicated by superscript numerals: 1 = Holley et al. 2009; 2 = Dorsey et al. 2011; 3 = Boxrucker and Kuklinski 2006; 4 = Mauck and Boxrucker 2004; 5 = Stewart et al. 2009; 6 = Greenlee and Lim 2011).

	Growth parameters[a,b]					Weight–length parameters[c,d]		
System	L_∞	k	t_0	β	α	b	a	Current regulation
Lake Wilson, Alabama[a,c,1]	1,303.00	0.08	–0.24	–	–	3.45	–6.25	Unlimited < 864 mm; 1 fish > 864 mm
Badin Lake, North Carolina[a,d,2]	1,028.00	0.14	–0.24	–	–	3.40	–6.07	Unlimited < 813 mm; 1 fish > 813 mm
Lake Norman, North Carolina[a,d,2]	939.00	0.09	–0.88	–	–	3.40	–6.07	Unlimited < 813 mm; 1 fish > 813 mm
Kaw Lake, Oklahoma[a,d,3]	853.00	0.14	–0.15	–	–	3.40	–6.07	15 total; 1 fish > 762 mm
Keystone Lake, Oklahoma[a,d,3]	940.00	0.13	–1.22	–	–	3.40	–6.07	15 total; 1 fish > 762 mm
Lake Ellsworth, Oklahoma[a,d,3]	898.00	0.06	–0.67	–	–	3.40	–6.07	15 total; 1 fish > 762 mm
Lake Eufaula, Oklahoma[a,d,3]	622.00	0.09	–2.53	–	–	3.40	–6.07	15 total; 1 fish > 762 mm
Lake Hugo, Oklahoma[a,d,3]	512.00	0.21	–0.68	–	–	3.40	–6.07	15 total; 1 fish > 762 mm
Lake Waurika, Oklahoma[a,d,3]	1,050.00	0.10	–0.11	–	–	3.40	–6.07	15 total; 1 fish > 762 mm
Lake Texoma, Oklahoma[a,d,4]	964.00	0.08	–1.84	–	–	3.40	–6.07	15 total; 1 fish > 762 mm
Fort Loudoun, Tennessee[a,c,5]	1,105.00	0.04	–1.23	–	–	3.41	–6.16	Unlimited < 864 mm; 1 fish > 864 mm
Kentucky Lake, Tennessee[a,c,5]	940.00	0.13	–1.22	–	–	3.46	–6.21	Unlimited < 864 mm; 1 fish > 864 mm
Lake Barkley, Tennessee[a,c,5]	1,115.00	0.11	–0.69	–	–	2.87	–4.60	Unlimited < 864 mm; 1 fish > 864 mm
Mississippi River, Tennessee[a,c,5]	830.00	0.15	–1.02	–	–	3.10	–5.33	Unlimited < 864 mm; 1 fish > 864 mm
James River, Virginia[b,c,6]	–	–	–	58.10	110.1	3.10	–5.33	20 total; 1 fish > 813 mm

[a] Von Bertalanffy growth function: $L_a = L_\infty\left[1 - \exp^{-k(t-t_0)}\right]$.

[b] Linear growth function: $\log_{10}(L_a) = \log_{10}(\text{age}_i)\beta + \alpha$, where $\beta = L_\infty$ and $\alpha = k$.

[c] Linear weight–length function: $\log_{10}(w_a) = \log_{10}(L_a)\beta + \alpha$.

[d] Standard weight–length equation (Muoneke and Pope 1999).

fishing. Age-specific survivorship in the absence of fishing was calculated as

$$l_a = e^{-M(\text{age}_i - 1)},$$

where M is the instantaneous natural mortality rate. We represented survivorship in the presence of fishing, l_{fa}, as

$$l_{fa} = l_{fa-1}e^{-M}(1 - UV_{a-1}),$$

where U is the annual finite exploitation rate ({0.1, 0.2, …, 1.0}) used to simulate fish that are harvested (both recreational harvest and commercial harvest, which are assumed to be additive); V_a are age-specific vulnerabilities to harvest under the MLR and LTR; and UV_{a-1} models death due to harvest for fish older than age 1 (Allen et al. 2009). Few studies have estimated recreational and commercial fishing mortality rates for Blue Catfish or Channel Catfish, so we evaluated every possible harvest scenario resulting from recreational anglers and commercial fishers by modeling the combined mortality effect as an additive response.

The proportion of fish that were vulnerable to harvest under MLRs ($V_{a,min}$) was modeled using a logistic function, specified as

$$V_{a,min} = \frac{1}{1 + e^{\left[-\frac{(\text{TL}_a - \text{TL}_{min})}{\text{SD}_{min}}\right]}},$$

where TL_a is the mean total length at age a; TL_{min} is the minimum TL limit required for harvest; and SD_{min} is the standard deviation of the logistic distribution and is set at 5% of TL_{min} (Dotson et al. 2013).

We used a double logistic function to model the vulnerability of fish under the LTRs by following a generalization to the approach of Dotson et al. (2013). This approach is the most conservative of the LTR options for catfish, as it sets the number of harvestable fish over the protected size to zero (effectively producing an inverse slot limit), whereas some state agencies still allow the harvest of one or two fish over the protected size (CMTC 2015). Modeling a "one-over" or "two-over" target size regulation was not possible because there were insufficient data for evaluating the harvest rate of large fish in the modeled fisheries. Therefore, our model may

TABLE 2. Life history characteristics and population parameters (defined in Table 1) that were used in model simulations of 15 Channel Catfish fisheries in five states (data sources are indicated by superscript numerals: 1 = Holley et al. 2009; 2 = Stiras and Miller 2013; 3 = Stewig 2012; 4 = Henry 2005; 5 = Bouska et al. 2011; 6 = Stewart and Long 2016).

	Growth parameters^{a,b}					Weight–length parameters^{c,d}		
System	L_∞	k	t_0	β	α	b	a	Current regulation
Lake Wilson, Alabama^{a,c,1}	646.00	0.15	–2.00	–	–	3.28	–5.78	Unlimited < 864 mm; 1 fish > 864 mm
Mississippi River, Minnesota^{b,d,2}	–	–	–	52.17	80.57	3.29	–5.80	5 total; 1 fish > 610 mm
St. Croix River, Minnesota^{b,d,2}	–	–	–	49.37	144.24	3.29	–5.80	10 total; no size limit
North Fork River, Minnesota^{a,d,3}	722.00	0.19	–0.60	–	–	3.29	–5.80	10 total; no size limit
Red River, Minnesota^{b,d,4}	–	–	–	38.79	117.72	3.29	–5.80	5 total; 1 fish > 610 mm
Garrison Reservoir, North Dakota^{a,d,5}	807.00	0.09	–0.63	–	–	3.29	–5.80	Unlimited; no size limit
Lake Greenleaf, Oklahoma^{a,c,6}	682.00	0.17	0.03	–	–	3.18	–5.51	15 total; no size limit
Lake Lone Chimney, Oklahoma^{a,c,6}	757.00	0.12	–0.67	–	–	3.23	–5.67	15 total; no size limit
Lake McMurtry, Oklahoma^{a,c,6}	846.00	0.08	–0.63	–	–	3.27	–5.78	15 total; no size limit
Lake Okemah, Oklahoma^{a,c,6}	779.00	0.06	–2.61	–	–	2.77	–4.52	15 total; no size limit
Lake Okmulgee, Oklahoma^{a,c,6}	731.00	0.13	–0.73	–	–	3.16	–5.52	15 total; no size limit
Lake Ponca, Oklahoma^{a,c,6}	543.00	0.26	0.00	–	–	3.33	–5.91	15 total; no size limit
Big Bend Reservoir, South Dakota^{b,d,5}	–	–	–	2.12	0.53	3.29	–5.80	10 total; no size limit
Fort Randall Reservoir, South Dakota^{b,d,5}	–	–	–	2.25	0.42	3.29	–5.80	10 total; no size limit
Oahe Reservoir, South Dakota^{a,d,5}	534.00	0.15	–1.40	–	–	3.29	–5.80	10 total; no size limit

[a] Von Bertalanffy growth function: $L_a = L_\infty\left[1 - \exp^{-k(t-t_0)}\right]$.

[b] Linear growth function: $\log_{10}(L_a) = \log_{10}(\text{age}_i)\beta + \alpha$, where $\beta = L_\infty$ and $\alpha = k$.

[c] Linear weight–length function: $\log_{10}(w_a) = \log_{10}(L_a)\beta + \alpha$.

[d] Standard weight–length equation (Brown et al. 1995).

accentuate the effectiveness of LTRs relative to regulations that allow a modest amount of harvest on large fish. If the model cannot demonstrate an advantage of LTRs in this conservative scenario, then it is clear that less-restrictive versions of the LTR would also be ineffective. The double logistic function calculates the percentage of fish in each age-class that are longer than the minimum length requirement and still small enough to be below the maximum harvest size:

$$V_{a,max} = \frac{1}{1 + e^{\left[-\frac{(\mathrm{TL}_a - \mathrm{TL}_{Low})}{\mathrm{SD}_{Low}}\right]}} - \frac{1}{1 + e^{\left[-\frac{\left(\mathrm{TL}_a - \mathrm{TL}_{High}\right)}{\mathrm{SD}_{High}}\right]}},$$

where TL_{Low} is the minimum TL requirement; TL_{High} is the length limit where the more restrictive bag limit begins (i.e., maximum harvest size in our model); and SD_{Low} and SD_{High} are the respective standard deviations, set at 5% of the low and high lengths of the harvest slot limit (Dotson et al. 2013).

Fecundity was weighted by the age-specific survivorship schedules, l_a and l_{fa}, and was summed across age-classes within each simulated year to account for the cumulative effects of fishing (Allen et al. 2012). We estimated age-specific fecundity (f_a) by calculating equilibrium lifetime egg production for the unfished (ϕ_E) and fished (ϕ_e) conditions, where f_a was set to zero if age was less than the age at maturation. Several methods exist to estimate M when catch-curve data are not available, and no single approach is universally accepted (Brodziak et al. 2011). Therefore, we addressed the uncertainty in M by using the average of the output of four estimation methods, as suggested by Brodziak et al. (2011). The four estimation methods are those described by Pauly (1980), Hoenig (1983), Jensen (1996), and Hewitt and Hoenig (2005).

Equilibrium abundance was calculated by including age-specific harvest and death rates as part of the dynamic simulations over a 100-year period and included 19 age-groups (1–20 age-classes; Walters and Martell 2004). Recruitment (i.e., abundance at age 1) was calculated by linking the abundance of reproductively mature age-classes to the number of recruits produced by using Botsford's modification of the Beverton–Holt stock–recruitment function (Botsford 1981a, 1981b; Walters and Martell 2004; Table 3). Parameters in the stock–recruit function were derived by using the Goodyear compensation ratio (Ω), which describes changes in juvenile survivorship from unfished stock size to low adult abundances (Walters and Martell 2004). We hypothesized an Ω value of 15 to describe the relationship between juvenile survival and

TABLE 3. Model procedures and dynamic state procedures that were used to describe equilibrium and time dynamics of Blue Catfish (BCF) and Channel Catfish (CCF; L_∞ = theoretical maximum length; k = Brody growth coefficient [instantaneous growth rate]; t_0 = theoretical age at zero length; b = slope parameter of the length–weight relationship; α = intercept parameter of the length–weight relationship; age$_{mat}$ = age at 50% maturity; SD$_{mat}$ = variation in age at maturity; M = instantaneous natural mortality rate; U = annualized finite exploitation rate; V_a = age-specific vulnerability to harvest; Ω = Goodyear compensation ratio; R_λ = equilibrium recruitment; E_0 = number of eggs in the unfished condition; subscript t indicates time step; subscript a indicates age-class; ε = normally distributed random deviate, ranging up to 10% of the maximum number of recruits).

Description	Equation
Model procedures	
Length at age	$L_a = L_\infty\left\{1 - \exp^{[-k(\text{age}_i - t_0)]}\right\}$
Weight at age	$w_a = 10^{\{b[\log_{10}(L_a)]+\alpha\}}$
Maturity at age	$m_a = \frac{1}{1+\exp\left[-\frac{(\text{age}_i - \text{age}_{mat})}{\text{SD}_{mat}}\right]}$
Beverton–Holt productivity parameter	$a = \Omega\left(\frac{R_\lambda}{E_0}\right)$
Beverton–Holt scaling parameter	$\beta = \frac{\Omega - 1}{E_0}$
Equilibrium eggs per recruit in the unfished state	$\phi_E = \sum_{\text{age}}^{\infty} l_a w_a m_a$
Equilibrium eggs per recruit in the fished state	$\phi_e = \sum_{\text{age}}^{\infty} l_{fa} w_a m_a$
Dynamic state procedures	
Number of fish at age 1	$N_{t+1,a=1} = \frac{aE_t}{1+\beta E_t} + \varepsilon$
Number of eggs	$E_t = \sum_{\text{age}}^{\infty} N_{t,a} w_a m_a$
Numbers of fish at age 2 and older	$N_{t+1,a+1} = N_{t-1,a-1}\exp^{-M}(1 - UV_{a-1})$
Equilibrium yield	$Y_{t\pm} = U\sum_{\text{age}}^{\infty} N_{t,a} w_a V_a$
Equilibrium trophy biomass	$TB_\pm = \sum_{\text{age}}^{\infty} N_{t,a} w_a \begin{array}{l} L_a \geq 762\,\text{mm, BCF} \\ L_a \geq 625\,\text{mm, CCF} \end{array}$

stock size under fished conditions (Goodyear 1980); this value is similar to the wide range of estimates that have been used to describe relatively long-lived species with life histories resembling those of Blue Catfish and Channel Catfish (Myers et al. 1999; Goodwin et al. 2006). The number of eggs in the unfished condition ($E_0 = R_\lambda \sum_{\text{age}}^{\infty} l_a m_a$) was expressed as a function of unfished survivorship (l_a), maturation at age (m_a), and the maximum expected recruitment (R_λ = 1,000,000), where R_λ is simply a scaling parameter that does not affect model output (Walters and Martell 2004; Allen et al. 2009). The model can include a stochastic component ε~LN(μ, σ^2) to incorporate recruitment variability, which is modeled as a lognormally distributed random deviate of 1 around the equilibrium stock–recruitment prediction (Allen et al. 2009).

Recruitment overfishing was evaluated by using the SPR (Goodyear 1993), with values greater than 0.30 indicating sustainability (Goodyear 1993; Clark 2002). The SPR was calculated as

$$\text{SPR} = \frac{\phi_e}{\phi_E},$$

which is the ratio of reproduction for the population in the fished (ϕ_e) and unfished (ϕ_E) conditions (Walters and Martell 2004).

We compared fishery performance of each scenario by calculating equilibrium yield (Y_t), trophy biomass ($B_{trophy,t}$), and SPR for Blue Catfish and Channel Catfish. We ran the modeling simulation for 100 years (to allow models to approach equilibrium, only the final 80 years were used in analyses). We used B_{trophy} to assess the potential of each scenario to produce trophy catfish. We compared the "best" regulations for each fishery as the size limits that maximized both yield and B_{trophy} while maintaining SPR at a level greater than 0.30. To evaluate LTR$_{best}$, we calculated the maximum yield in weight from a range of upper and size limit combinations and U values. This exercise resulted in a candidate set of MTRs and LTRs at which we then determined the "best" regulation for both as the size limit that maximized both yield and B_{trophy} while maintaining SPR at a value greater than 0.30. All simulations were completed using R software (R Development Core Team 2015).

RESULTS

Overall, 30 catfish populations (Blue Catfish: N = 15; Channel Catfish: N = 15) were included in the analysis (Tables 1, 2). The majority of Blue Catfish fisheries were currently managed by using an LTR, primarily structured with a 305-mm lower length limit and a reduced bag limit at lengths of 762–864 mm (with all lengths measured as TL). Bag limits restricted recreational anglers and commercial fishers to the harvest of one fish per day over the upper size limit and up to 20 fish total, although most of the states included in this study allowed for unlimited harvest below the upper size limit. Channel Catfish were commonly managed with bag limits (i.e., there were no size restrictions). The number of Channel Catfish that anglers could harvest ranged from five to unlimited. Only two states (Alabama and Minnesota) used LTRs to manage Channel Catfish; both states permitted the harvest of only one fish over 610 mm each day.

Estimates of Blue Catfish and Channel Catfish yield were significantly higher under the MLR$_{best}$ and LTR$_{best}$ scenarios than under the current length regulations used to manage ictalurid fisheries (Figures 1, 2). For 29 of the 30 fisheries examined, lake-specific MLR_{best} and LTR_{best} generally improved yield estimates relative to those obtained with current statewide regulations. On average, the MLR_{best} improved yield by 36% for Blue Catfish and by 22% for Channel Catfish relative to the current regulations, whereas the LTR_{best} generally improved yield by 27% for Blue Catfish and by 22% for Channel Catfish. Yield was similar between the MLR_{best} and the LTR_{best}, with the MLR_{best} improving yield by ≤8% compared with the LTR_{best} for Blue Catfish and by ≤1% compared with the LTR_{best} for Channel Catfish. Maximum yield typically occurred around a U value of 0.30 and was level or only slightly decreased at higher fishing mortality rates, suggesting that near-maximum yield per recruit may be obtained across a range of fishing mortality rates.

Predicted B_{trophy} estimates did not differ significantly among the current regulations, MLR_{best}, or LTR_{best} for Blue Catfish (Figure 3) or for Channel Catfish (Figure 4). Although these patterns varied between species and among fisheries, Blue Catfish and Channel Catfish B_{trophy} estimates became substantially lower as the fishing mortality rate increased. The highest estimates of B_{trophy} were achieved at U values less than 0.30.

Fishery sustainability (SPR) was strongly related to the regulation being modeled (Figures 5, 6). Based on our simulated estimates, the current size regulations used by state agencies were not sustainable (SPR < 0.30) at U values over 0.25 for Blue Catfish or over 0.35 for Channel Catfish. The MLR_{best} and LTR_{best} delayed the harvest of catfish until a larger size was reached (usually ≥450 mm for Blue Catfish; ≥375 mm for Channel Catfish), unlike the current regulations used by state agencies (typically set at 305 mm). The greater size at harvest based on the best-performing models led to increased resilience to fishing pressure by maintaining higher SPR values for each species. The MLR_{best} resulted in higher SPRs for Blue Catfish than the LTR_{best}, whereas SPR values for Channel Catfish were similar between the MLR_{best} and LTR_{best}. Both the MLR_{best} and the LTR_{best} resulted in higher SPR levels than the regulations that are currently used to manage Blue Catfish and Channel Catfish. Although it was possible to prevent recruitment overfishing at U values exceeding 0.35, the cost was a more restrictive lower limit for the MLR_{best} and LTR_{best}.

DISCUSSION

Our results contribute to the growing body of literature on length-based regulations as an effective policy choice for managing fisheries (Myers and Allen 2005; Colombo 2007; Dotson et al. 2013). Previous studies have found that high MLRs could significantly increase catfish yield but are unlikely to be welcomed by anglers (Holley et al. 2009). We found that for both Blue Catfish and Channel Catfish, the predicted responses of yield, B_{trophy}, and sustainability were similar between MLR_{best} and LTR_{best}. This was true even though our LTR was overly conservative (i.e., did not allow for any harvest over the protected size instead of the more typical one- or two-fish daily limit allowed by some state agencies that employ LTRs); thus, our model simulated the potential maximum effectiveness of LTRs. Therefore, any harvest of “protected” trophy fish will act to decrease the SPR and B_{trophy} even more so than indicated by our reported estimates. Such findings suggest that high MLRs can produce results similar to those of LTRs, but the LTRs might be more appealing to anglers because they lack the imposition of restrictive MLRs (Stewart et al. 2012). However, slow growth (15–20 years are required for fish to reach the size where protection is provided by the upper size limit) further hinders the effectiveness of any regulation for protecting and increasing the B_{trophy} of catfish.

Length-based regulations (including our LTRs) were not effective at increasing the B_{trophy} of catfish, at least not with the range of regulation lengths tested here. Typical exploitation rates range between 4% and 31% for most ictalurid fisheries (Graham and Deisanti 1999; Hubert 1999; Timmons 1999; Shrader et al. 2003; Holley et al. 2009), and our results indicate that these rates would yield the highest B_{trophy} of catfish regardless of species or length-based regulation. If the annual U exceeds 0.30, then our simulation models indicate that length-based regulations would not be effective at maintaining trophy fish regardless of the regulation used. This can be especially problematic in areas that allow commercial harvest, as commercial fisheries can account for the majority of catfish harvest (Pitlo 1997; Slipke et al. 2002; Stewart 2009). Given that catfish are typically slow growing and given the extended time (15–20 years) it takes for an individual to reach the protection of the restricted harvest portion of length-based regulations (Graham 1999; Hubert 1999), the current length-based regulations that many agencies have adopted are no different than a minimum size limit because few (if any) fish ever grow large enough to benefit from the regulations’ protection for larger fish. The ability of length-based regulations to increase B_{trophy} seems limited unless the upper size limit of the restricted bag portion can be substantially reduced.

Regulations for managing fisheries across a broad region (e.g., statewide regulations) are easy to enforce, but they are often ineffective at sustaining the fishery and improving yield due to the varying growth potential among fisheries (Myers and Allen 2005). For example, managing Largemouth Bass *Micropterus salmoides* was less likely to be effective in lakes with standard statewide MLRs than in lakes with specific regulations (Myers and Allen 2005). For a single regulation to be the most effective for an entire region, the lakes within that region must have similar population dynamics. If variation exists among populations, then the use of a single regulation for the region could greatly increase the risk of recruitment overfishing in fisheries with slower growth or higher M values. Our results revealed that no single regulation performed similarly within a state; this was particularly well

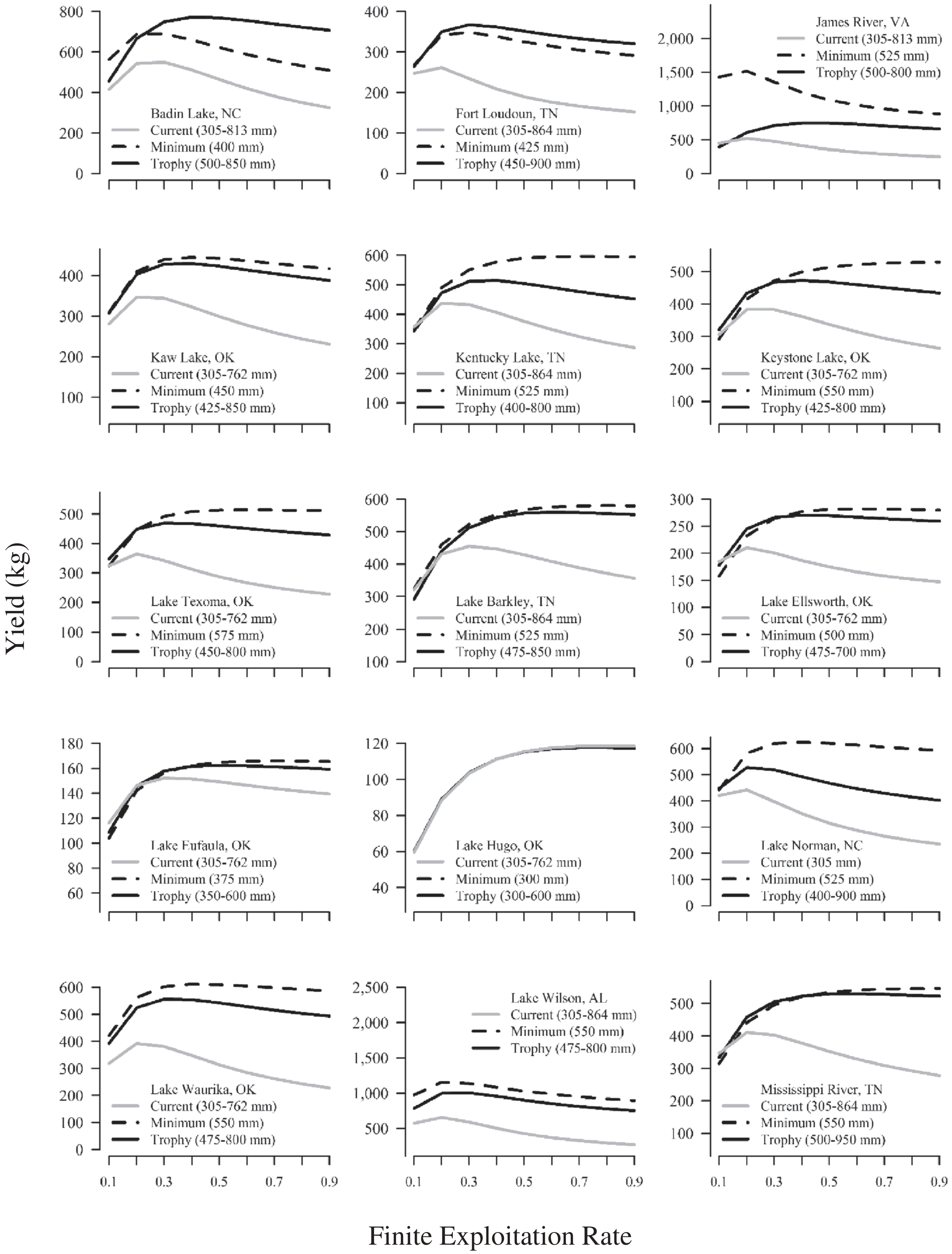

FIGURE 1. Yield modeling results in relation to varying finite exploitation rates and length regulations (current regulation, minimum length regulation, and length-based trophy catfish regulation) for 15 Blue Catfish fisheries in five states.

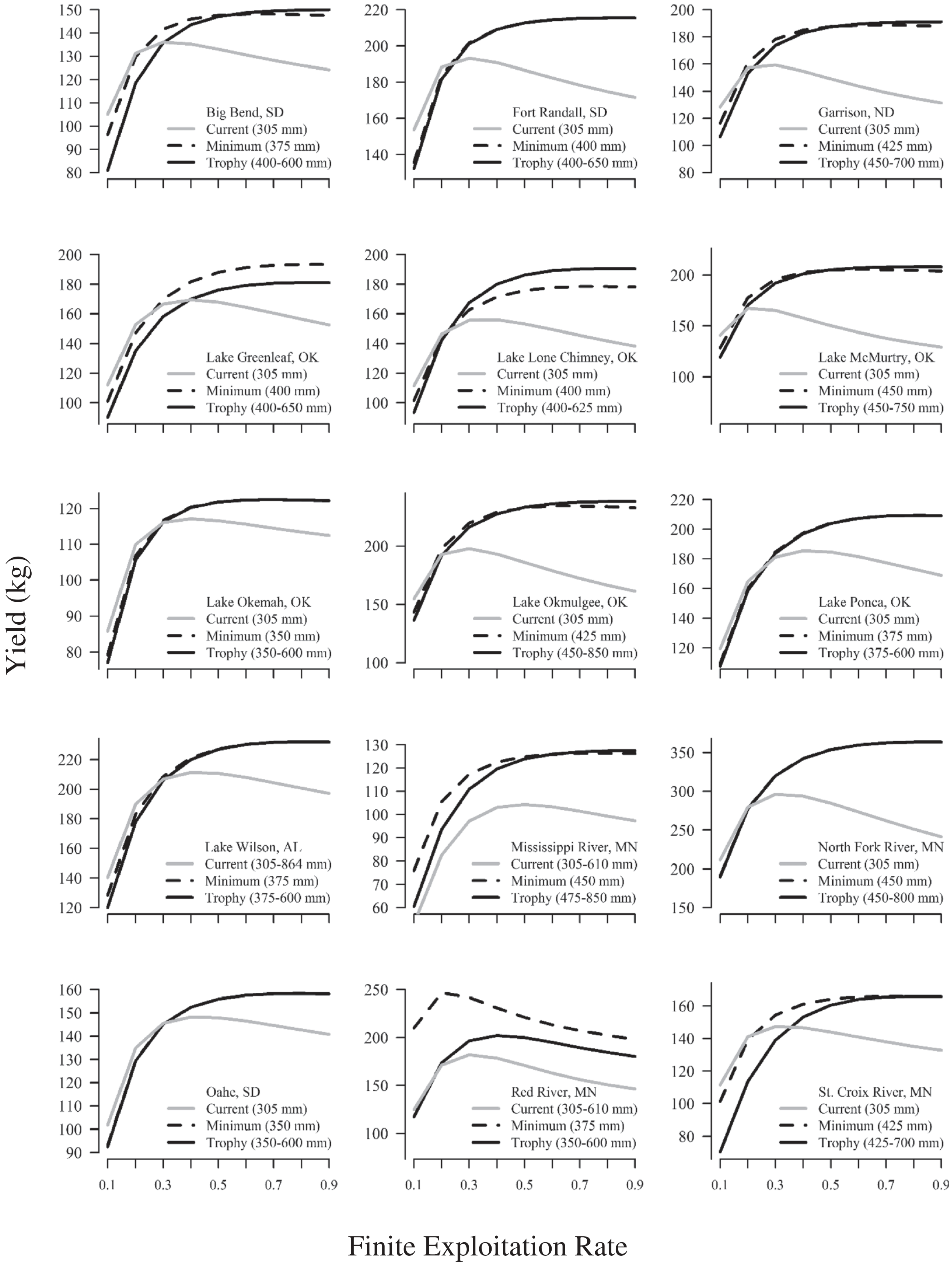

FIGURE 2. Yield modeling results in relation to varying finite exploitation rates and length regulations (current regulation, minimum length regulation, and length-based trophy catfish regulation) for 15 Channel Catfish fisheries in five states.

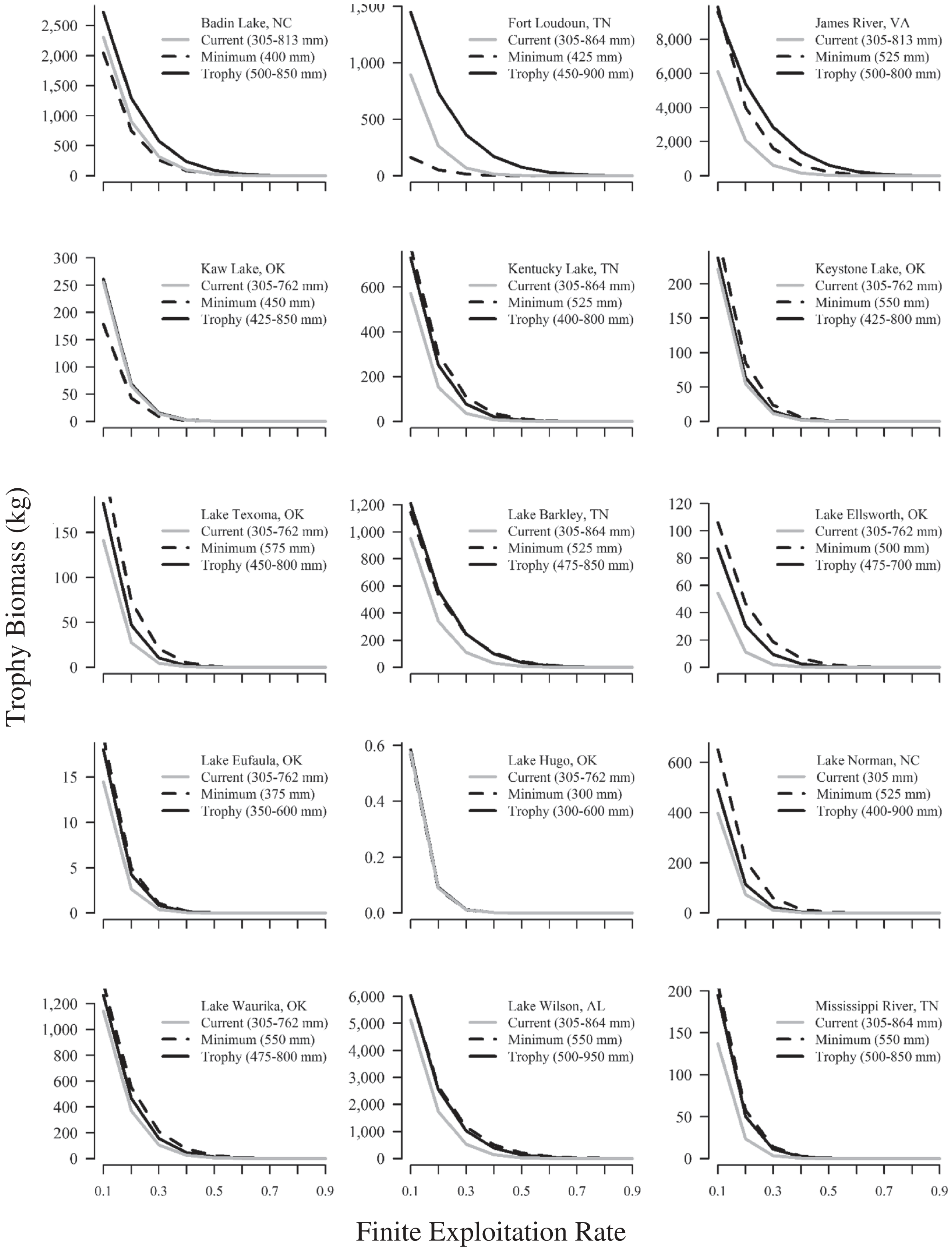

FIGURE 3. Trophy biomass modeling results in relation to varying finite exploitation rates and length regulations (current regulation, minimum length regulation, and length-based trophy catfish regulation) for 15 Blue Catfish fisheries in five states.

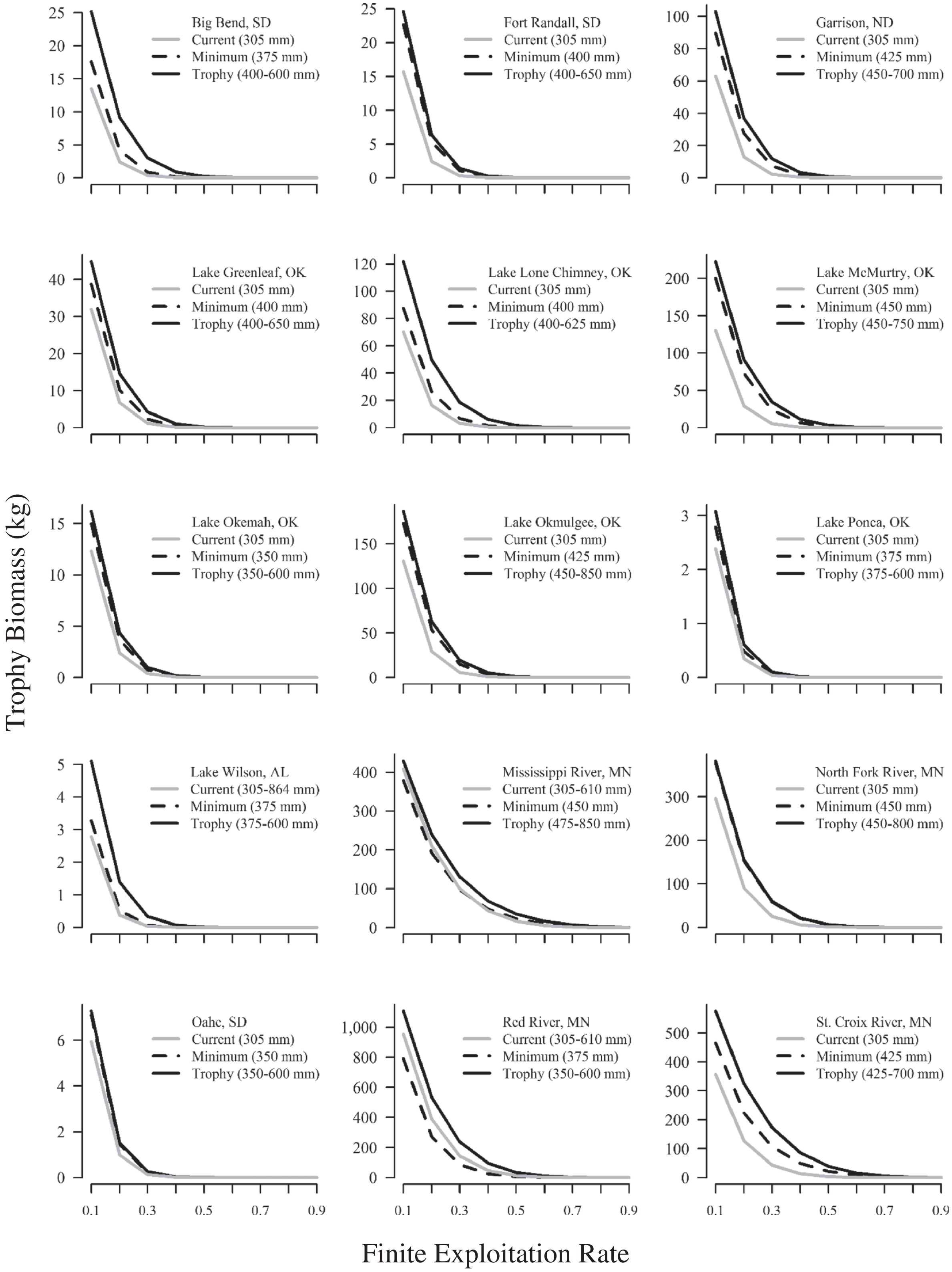

FIGURE 4. Trophy biomass modeling results in relation to varying finite exploitation rates and length regulations (current regulation, minimum length regulation, and length-based trophy catfish regulation) for 15 Channel Catfish fisheries in five states.

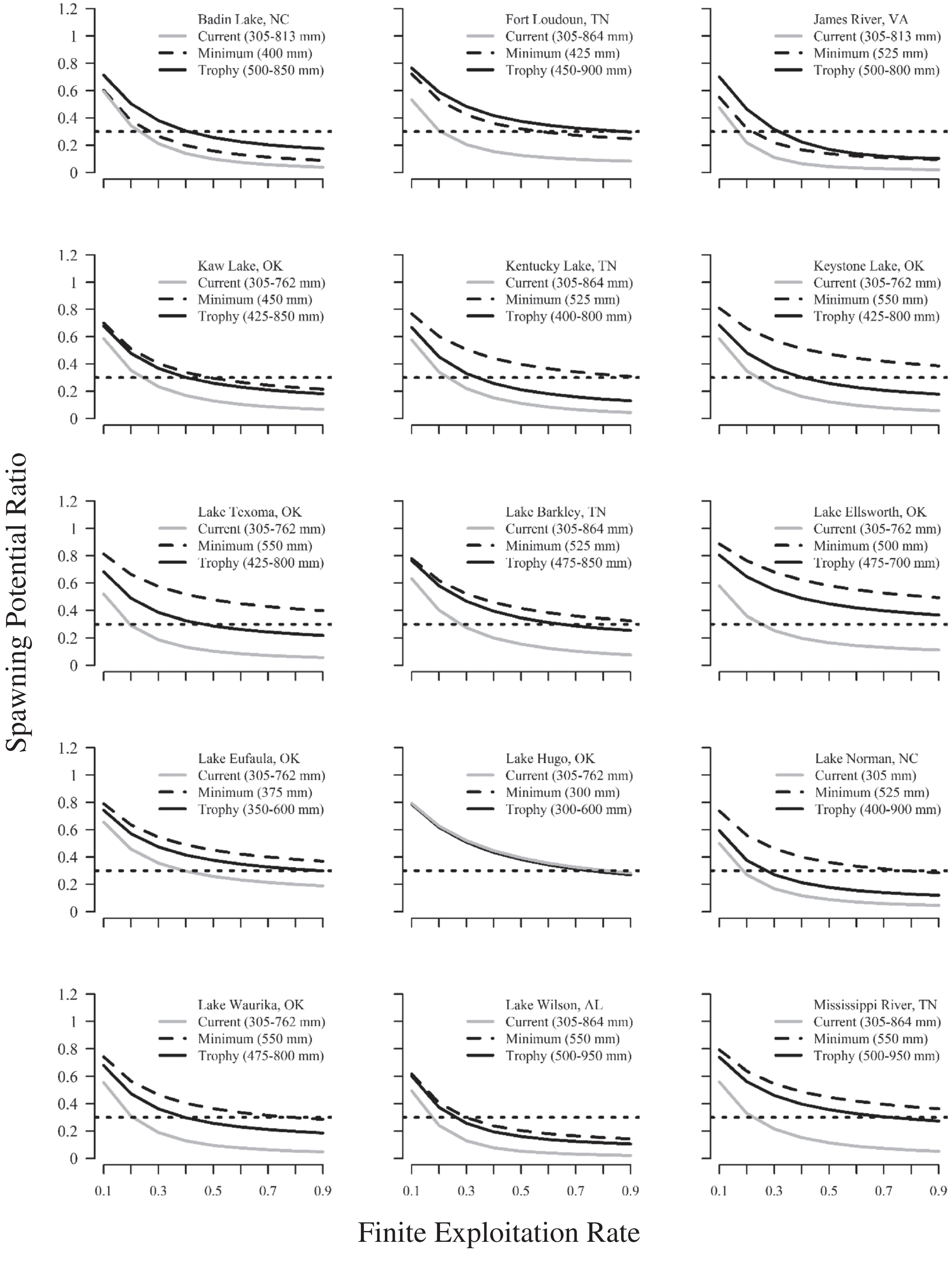

FIGURE 5. Spawning potential ratio (SPR) modeling results in relation to varying finite exploitation rates and length regulations (current regulation, minimum length regulation, and length-based trophy catfish regulation) for 15 Blue Catfish fisheries in five states. The SPR of 0.30 is indicated by the dashed horizontal line.

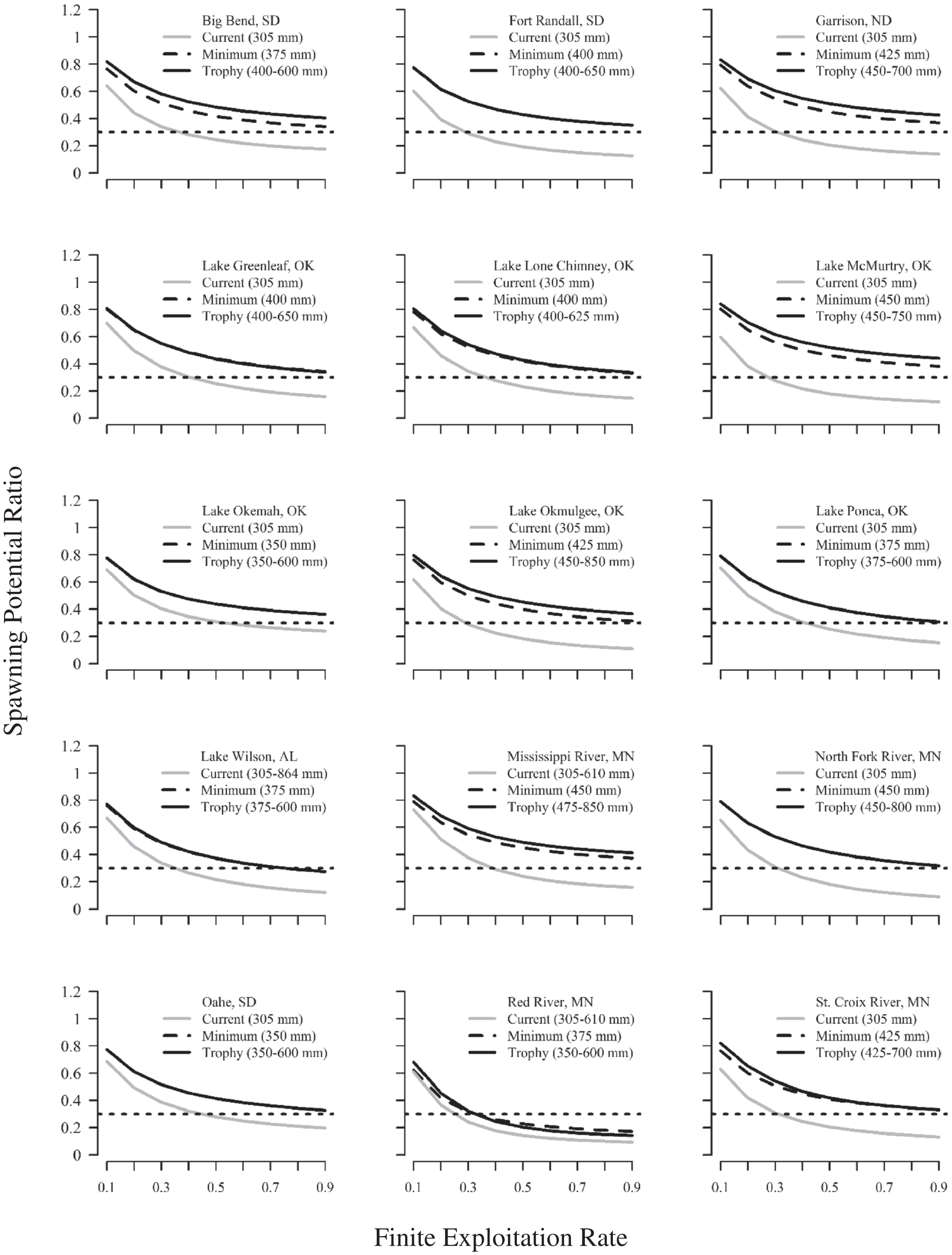

FIGURE 6. Spawning potential ratio (SPR) modeling results in relation to varying finite exploitation rates and length regulations (current regulation, minimum length regulation, and length-based trophy catfish regulation) for 15 Channel Catfish fisheries in five states. The SPR of 0.30 is indicated by the dashed horizontal line.

illustrated for states like Tennessee and Oklahoma, where data from multiple fisheries were available for use in model simulations. Although we reported results from multiple fisheries for only a few states, in those cases our results clearly showed that variation in yield among systems was greater than the variation in yield among regulations within a given system. Furthermore, our results suggest that length-based regulations would be more effective if implemented on systems that favor rapid fish growth. Clearly, other considerations may factor into the decision to use regional regulations (e.g., a lack of lake-specific information; or a desire to keep regulations simple for anglers to understand), but our results indicate that the regional approach is unlikely to be the most efficient for maximizing the yield or B_{trophy} of catfish fisheries. Further research is needed to determine the population characteristics that are most conducive to manipulation by harvest regulations, as such information would further guide the development of catfish regulations.

Our results were based on simulations that did not incorporate postrelease mortality. Although postrelease mortality may undermine the effectiveness of harvest regulations for some species (Coggins et al. 2007), results from previous studies indicate that catfish postrelease mortality is low and only affects smaller size-classes (post-release mortality was 2.5% for preferred-sized fish and <1% for trophy-sized fish even after a prolonged hooked time related to capture by jug fishing; Schmitt and Shoup 2013). The percentage of the entire population that is captured but released is expected to be well short of 100%; hence, postrelease mortality would be unlikely to have a measurable population-level effect (e.g., if 25% of the population is captured and released, then 2% postrelease mortality would produce an annual mortality rate of 0.5% [2 × 0.25] at the population level). Postrelease mortality estimates are so low that methods to determine total mortality rates (e.g., catch-curve analysis) are not precise enough to detect the small increases in mortality that might result from catch-and-release angling. Based on this information, the incorporation of postrelease mortality would have had little effect on our estimates.

Length-based regulations could benefit targeted species by protecting them from overfishing. Other studies have indicated that low MLRs could not prevent growth overfishing (Holley et al. 2009). Our simulation models indicate that both MLRs and LTRs could be used to prevent growth overfishing and recruitment overfishing of Blue Catfish and Channel Catfish. At the 305-mm MLR currently used by many agencies to manage Channel Catfish, growth overfishing was observed at annualized fishing mortality rates greater than 0.30. Our results are similar to those of Colombo (2007), who completed simulations for Channel Catfish fisheries in Indiana and Illinois; growth overfishing was found to occur without the use of a current restrictive regulation, whereas overfishing was prevented and yield was improved by the use of restrictive regulations (MLR > 330 mm), even at increased harvest rates. Under the current statewide LTRs that are used to manage many Blue Catfish fisheries, a much-higher fishing intensity could result in recruitment overfishing (i.e., unsustainable SPR) instead of just growth overfishing (i.e., reduced yield due to poor size structure).

Management of catfish typically includes maximizing yield and/or increasing B_{trophy} while maintaining population sustainability, which requires the development of biological reference points to identify fishing mortality targets for management (Brodziak et al. 2011). Our model results can be used to produce mortality reference points for Blue Catfish and Channel Catfish. For example, our analysis suggests that yield increases with an increasing U value, at least up to a point, and that maximum yield is first realized at exploitation rates of around 0.30–0.50 in most fisheries. Our simulations also indicate that yield would not be maximized at U values that are sustainable (sustainability required fishing mortality < 0.30 in many populations). Because most ictalurid fisheries are typically data poor, with no available time series of biomass estimates, we assessed sustainability via SPR (the ratio of ϕ_e and ϕ_E), and we set the threshold for sustainability at 30% (Goodyear 1993). Although some species can withstand harvest that reduces SPR to less than 30%, catfish are slow growing and long lived, and they have low M but mature quickly (e.g., at age 2; Graham and Deisanti 1999; Hubert 1999), suggesting that these species may only be moderately resilient to fishing mortality, so we chose 30% as a conservative estimate. Therefore, it would be reasonable to consider reference points at U values less than 0.30 to ensure reproductive sustainability and safeguard spawning potential rather than maximize yield.

Simulation modeling provided further insight into the effectiveness of length-based regulations for the management of Blue Catfish and Channel Catfish. Other studies have used a before-and-after approach to evaluate the effects of regulations (Pitlo 1997; Cornelius and Margenau 1999). Pitlo (1997) reported that Channel Catfish recruitment and the number harvested significantly increased after a length-based regulation was implemented. However, these types of study require a significant amount of time and effort, extensive data collection before and after the change in regulation, and an appropriate experimental design with which to infer cause and effect between length-based regulations and changes in fishery characteristics. Simulation modeling provides a more feasible option in providing the quantitative assessment needed to evaluate a fishery's response to restrictive regulations (Hilborn and Walters 1987); thus, many conclusions can be drawn from our simulation models. First, the life history characteristics of catfish (i.e., large life span and slow annual growth rates; Graham 1999; Hubert 1999) may reduce the effectiveness of restrictive regulations that have been designed to improve the B_{trophy} of catfish. Many individuals may remain in the fishery for more than 10 years before growing long enough to be protected by the upper size limit of LTRs.

Second, high MLRs and LTRs performed similarly at maintaining yield and sustainability with increasing fishing intensities; however, imposing a high MLR (350–550 mm) may not be welcomed by anglers, whereas the LTRs may be a more popular policy choice given that they allow some harvest of smaller fish. Third, length-based regulations could be used to decrease fishing mortality and prevent growth overfishing or recruitment overfishing. Pitlo (1997) demonstrated that MLRs substantially improved the number of Channel Catfish spawners in the Mississippi River. Only a few Channel Catfish fisheries are managed with regulations, and our results suggest that regulations can prevent growth overfishing and recruitment overfishing.

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