INFLUENCE OF ENVIRNOMENTAL CONDITIONS ON LAKE STURGEON (*ACIPENSER FULVESCENS*) ARRIVAL AT THE SPAWNING SITE IN THE WINOOSKI RIVER, VT

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INTRODUCTION

Lake sturgeon (*Acipenser fulvescens*) are widely distributed in freshwater systems throughout North America, occupying both lake and riverine habitats. Like other sturgeons, lake sturgeon are characterized by late age-at-maturity, a long life span, high individual fecundity, and intermittent spawning (Peterson et al. 2007, Pollock et al. 2015). While these traits can buffer against the impacts of conditions that lead to low recruitment and maximize reproductive success in favorable years, they have also made the species extremely susceptible to declines due to overexploitation and habitat degradation. Lake sturgeon are not federally listed in the United States, however populations in 12 states are listed as extirpated, endangered, threatened, or of special concern (Peterson et al. 2007). Despite the fishing closures and the implementation of recovery programs, the life history of this species makes recovery slow and at times difficult to monitor. In Vermont, lake sturgeon are only found in Lake Champlain, and were listed as endangered in 1972 (MacKenzie 2016).

Historical records indicate that spawning occurred in four rivers in Vermont: the Missisquoi River, the Lamoille River, the Winooski River, and Otter Creek (Moreau and Parrish 1994). No monitoring of these populations took place until 1998, when The Vermont Fish and

Wildlife Department (VFWD) began investigating these rivers for evidence of successful spawning. While spawning adults have been captured in the Winooski River during this monitoring program, capture of sturgeon at the spawning site is rare, making it challenging to assess the status of the population using traditional mark-recapture methods.

Successful spawning for sturgeon depends on the optimal combination of flow and temperature conditions. However, these conditions can vary across populations (Peterson et al. 2007), and presence of fish at the spawning site and timing of spawning have not been well documented in the Winooski River in the past. Information on the environmental factors that influence spawning run timing could help inform future sampling efforts and maximize the chances of collecting adequate spawning fish for a population estimate. The objective of this project will be to examine the influence of temperature, flow, time of day, and time in the season on movements of lake sturgeon to the spawning site in the Winooski River.

METHODS

DIDSON Monitoring

From 10 May to 21 June 2017, a fixed-station dual-frequency identification sonar (DIDSON, Sound Metrics Corporation) was deployed in the lower Winooski River to monitor adult lake sturgeon during the spawning period. The unit was operated 24 hr/day in low frequency mode (1.1 MHz, 48 beams, 20 meter window), and was able to view 1/3 of the width of the channel at the deployment site. The DIDSON was located less than 0.5 km downstream of the lake sturgeon spawning site, so upstream movement of sturgeon targets on the DIDSON footage is assumed to represent lake sturgeon arrival to the spawning site.

A total of 1000 hours of DIDSON footage was collected in 2017. DIDSON data was manually processed to detect the hourly presence of sturgeon targets. Fish that were measured to be greater than one meter within the Sound Metrics DIDSON V5.24.43 software were classified as sturgeon. For each sturgeon observation, time of day and direction of movement were recorded. Only sturgeon targets that were migrating upstream were included in the following analysis. The last observation of a sturgeon moving upstream was recorded on 12 June 2017. As limited sturgeon observations occurred in the month of June, 12 June was determined to be the end of the spawning run and therefore the end of the data set used for the following analysis.

Regression Analysis

Sturgeon arrival (documented as presence on the DIDSON footage) at the spawning site was modeled as a Bayesian logistic regression using combinations of water temperature, discharge, time of day, and time in season as predictors. All continuous variables were z-standardized for use in regression analysis to make estimated β values comparable. A set of 12 candidate models was developed to explain sturgeon arrival at the spawning site (Table 1). Descriptions of the included predictors are outlined below.

Discharge (cubic feet per second, cfs) and water temperature (˚F) data, recorded in 15 minute intervals, were obtained from the U.S. Geological Survey (USGS) ESSV1 gage in Essex Junction, VT. Temperature values were converted from ˚F to ˚C. Hourly averages were obtained for each environmental data set. Both discharge and temperature were included in models as a quadratic predictor as there is expected to be an optimal relationship between spawning and environmental conditions.

Table 1*: Candidate models tested to predict sturgeon arrival at the spawning site during the 2017 season. Predictors include temperature (quadratic), discharge (quadratic), days since the beginning of spring-run off, and time of day (day vs night).*

Candidate Models (Response = Sturgeon Presence on DIDSON footage)	
(1)	$\beta_0 + \beta_{RO} \times DaysSinceRunOff$
(2)	$\beta_0 + \beta_{DN} \times DayNight$
(3)	$\beta_0 + \beta_T \times Temp + \beta_{T2} \times Temp^2$
(4)	$\beta_0 + \beta_D \times Discharge + \beta_{D2} \times Discharge^2$
(5)	$\beta_0 + \beta_T \times Temp + \beta_{T2} \times Temp^2 + \beta_{RO} \times DaysSinceRunOff$
(6)	$\beta_0 + \beta_D \times Discharge + \beta_{D2} \times Discharge^2 + \beta_{RO} \times DaysSinceRunOff$
(7)	$\beta_0 + \beta_T \times Temp + \beta_{T2} \times Temp^2 + \beta_{DN} \times DayNight$
(8)	$\beta_0 + \beta_D \times Discharge + \beta_{D2} \times Discharge^2 + \beta_{DN} \times DayNight$
(9)	$\beta_0 + \beta_T \times Temp + \beta_{T2} \times Temp^2 + \beta_D \times Discharge + \beta_{D2} \times Discharge^2$
(10)	$\beta_0 + \beta_T \times Temp + \beta_{T2} \times Temp^2 + \beta_D \times Discharge + \beta_{D2} \times Discharge^2 + \beta_{RO} \times DaysSinceRunOff$
(11)	$\beta_0 + \beta_T \times Temp + \beta_{T2} \times Temp^2 + \beta_D \times Discharge + \beta_{D2} \times Discharge^2 + \beta_{DN} \times DayNight$
(12)	*Full model*

In order to investigate diel movement patterns of sturgeon during the spawning season, time of day was included as a categorical predictor. The hours of 2000 to 0400 were classified as "night" observations, while the hours of 0500 to 1900 were classified as "day" observations. Additionally, the number of days since the beginning of spring run-off was included as a measure of time in the spawning season. Based on discharge data from the USGS ESSV1 gage, the beginning of spring run-off was determined to be 24 March 2017, indicated by steadily increasing discharge levels at the gage site.

All Bayesian analysis was completed in Program R v3.3.2 (R Core Team 2016). Models were constructed using JAGS (Just Another Gibbs Sampler) version 4.3.0 (Plummer 2003), and run using the R package rjags (Plummer 2016). Diffuse normal priors, $\mathcal{N}(0, 100)$, were used for all β values. Each model was run with a burn-in of 1,000 steps, and then 10,000 iterations were saved for each of the four chains. To assess convergence, the R package coda (Plummer et al. 2006) was used to visualize trace plots and calculate the potential scale reduction factor ($\hat{R}$) for each model. Model summary plots were constructed using the R package mcmcplots (Curtis 2015). Deviance information criterion (DIC) scores were calculated to identify the model with the most support. Significance of β values was determined by posterior density estimates where the 95% high density interval did not include zero.

RESULTS

A total of 781 hours were used in Bayesian logistic regression analysis, with sturgeon documented moving upstream in 20.7% of the DIDSON footage used. Water temperature ranged from 8.39 to 19.21 ˚C (median = 13.67) during the observed period, while discharge ranged from 1,460 to 7,930 cfs (median = 2,510 cfs).

After 10,000 iterations, chains for all tested models had converged ($\hat{R}$ = 1). The top three models identified by DIC analysis are reported in Table 2. Based on DIC scores, the full model was determined to be the best model in the candidate set (Figure 1). This model included temperature (quadratic), discharge (quadratic), days since the beginning of spring run-off, and time of day as predictors. The temperature terms were not significant. The β values for the discharge terms indicated a significant optimal relationship. Days since the beginning of spring run-off had a negative effect on sturgeon presence. The time of day parameter was positive, indicating that sturgeon were more likely to arrive at the spawning site at night. Based on the full model, days since the beginning of spring run-off had the largest effect on sturgeon presence (β_{RO} = -1.194), followed by discharge (β_{RO} = 1.065).

***Table 2**: Summary of the top three models identified by DIC analysis, including mean and 95% high density interval values for the posterior distribution of each predictor. Full model structure is indicated in Table 1. The fourth best model (model 1) had a ΔDIC of 37.2.*

Model	Predictor	Mean	95% HDI	DIC	ΔDIC
12	$\boldsymbol{\beta_0}$	**-2.335**	**-2.986 <** $\boldsymbol{\beta_0}$ **< -1.692**	656.4	0
	β_T	0.192	-0.0569 < β_T < 0.439		
	β_{T2}	-0.142	-0.310 < β_{T2} < 0.0181		
	$\boldsymbol{\beta_D}$	**1.065**	**0.666 <** $\boldsymbol{\beta_D}$ **< 1.473**		
	$\boldsymbol{\beta_{D2}}$	**-0.492**	**-0.800 <** $\boldsymbol{\beta_{D2}}$ **< -0.231**		
	$\boldsymbol{\beta_{RO}}$	**-1.194**	**-1.515 <** $\boldsymbol{\beta_{RO}}$ **< -0.892**		
	$\boldsymbol{\beta_{DN}}$	**0.761**	**0.364 <** $\boldsymbol{\beta_{DN}}$ **< 1.155**		
10	$\boldsymbol{\beta_0}$	**-1.257**	**-1.555 <** $\boldsymbol{\beta_0}$ **< -0.967**	668.6	12.2
	β_T	0.209	-0.037 < β_T < 0.453		
	β_{T2}	-0.142	-0.309 < β_{T2} < 0.018		
	$\boldsymbol{\beta_D}$	**1.059**	**0.672 <** $\boldsymbol{\beta_D}$ **< 1.459**		
	$\boldsymbol{\beta_{D2}}$	**-0.466**	**-0.766 <** $\boldsymbol{\beta_{D2}}$ **< -0.217**		
	$\boldsymbol{\beta_{RO}}$	**-1.182**	**-1.494 <** $\boldsymbol{\beta_{RO}}$ **< -0.881**		
6	$\boldsymbol{\beta_0}$	**-1.355**	**-1.621 <** $\boldsymbol{\beta_0}$ **< -1.095**	671.0	14.6
	$\boldsymbol{\beta_D}$	**0.852**	**0.516 <** $\boldsymbol{\beta_D}$ **< 1.202**		
	$\boldsymbol{\beta_{D2}}$	**-0.419**	**-0.702 <** $\boldsymbol{\beta_{D2}}$ **< -0.185**		
	$\boldsymbol{\beta_{RO}}$	**-0.915**	**-1.138 <** $\boldsymbol{\beta_{RO}}$ **< -0.700**		

The second best model was similar in structure to the first, but time of day was not included. Once again temperature was not significant, while discharge and days since the beginning of spring run-off were significant. Temperature was dropped for the third best model, and discharge and days since the beginning of spring run-off were significant. In both models, days since the beginning of spring run-off had the largest effect.

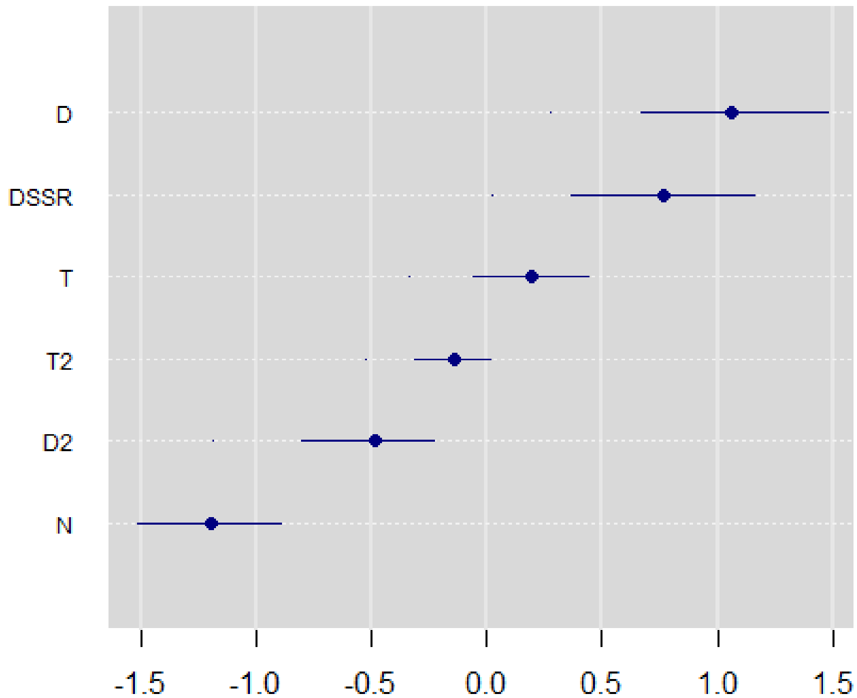

Figure 1*: Mean estimates (± 95% high density intervals) for the posterior distributions for each β values from the top model (Table 2). High density intervals that contain zero represent β values that are not significant. D = Discharge, DSSR = Days since beginning of spring run-off, T = Temperature, T2 = Temperature^2, D2 = Discharge^2, N = Time of day (night).*

DISCUSSION

The Bayesian logistic regression analysis indicated that sturgeon arrival at the spawning site was best captured by a model that included both environmental variables (temperature and discharge) and timing variables (time of day and time in season). These results reveal the complexity of describing the presence of spawning fish, which can be influenced by a variety of factors.

While temperature was included in the best supported model, the 95% high density intervals indicated that these terms were not significant. Lake sturgeon spawning can occur at temperatures between 6 and 16˚C (Bruch and Binkowski 2002). Temperatures in the Winooski

River during the sampling period ranged from 8.39 to 19.21 ˚C, with most readings being within the range of acceptable lake sturgeon spawning temperatures. Extending the sampling season to include late April to late June in 2018 may reveal the effect of temperature of sturgeon arrival to the spawning site. As expected, discharge was significant when modeled as a quadratic relationship. The spawning success of lake sturgeon can be sensitive to discharge levels throughout the spring, with higher recruitment noted in years of higher discharge (Caroffino et al. 2010). On the other hand, very high discharge levels are not ideal for lake sturgeon spawning as the eggs can be washed away before successful incubation.

In all top models, the number of days since the beginning of spring run-off had the largest effect on the probability of sturgeon arriving at the spawning site. This effect was negative, which is to be expected as the DIDSON was monitoring sturgeon movements through the end of the spawning run. The magnitude of this effect compared to the other predictors tested may have been influenced by the timing of data collection in 2017. The DIDSON was installed on 10 May, which was believed to be close to the start of the spawning run in the Winooski River in a typical year (C. MacKenzie, VFWD, personal communication). However, the stationary acoustic telemetry array that was in place in the Winooski River as part of another study documented tagged adult male sturgeon moving upstream as early as 25 April. It is possible that the DIDSON only documented the arrival of sturgeon in the mid- to late- part of the spawning run, which would point to a declining probability of sturgeon presence over time.

Lastly, this analysis revealed a significant, positive effect of nighttime on sturgeon movement to the spawning site. The tendency of adult lake sturgeon to be more active at night has recently been noted in a study that examined lake sturgeon movements throughout the year in the Niagara River, NY (Kough et al. 2017). While spawning activity occurs during both day at night in other systems (Bruch and Binkowski 2002, Chiotti et al. 2008), these results indicate that movement of sturgeon towards the spawning site is more likely to occur at night. In this case, it may be advantageous for future monitoring efforts in the Winooski River to set sampling gear overnight below the spawning site to increase captures of spawning adult lake sturgeon.

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