EVALUATING GENOMIC ESTIMATES AND RECONSTRUCTED PEDIGREES AS ASSESSMENT TECHNIQUES FOR SEA LAMPREY POPULATIONS

By

Ellen M. Weise

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Sea lamprey (*Petromyzon marinus*) are an extremely harmful invasive species in the Great Lakes. The species decimated native fish populations, causing harm to the ecosystem. To aggressively respond to the invasion, a bi-national program has been dedicated to reducing sea lamprey numbers. Control of lamprey populations includes physical barriers to prevent spawning adults from entering streams, and applications of lampricide (3-trifluormethlyl-4-nitrophenol or TFM) to kill larvae living in stream substrates. Annual assessments of adult sea lamprey are conducted, but are limited to a small number of streams. This study generated genetic data for sea lamprey larvae to reconstruct parental genotypes and estimate effective size of spawning populations. In Chapter 1, we use this information to evaluate the magnitude of barrier failures in three streams. In Chapter 2, we genotyped larvae from 18 streams with different physical characteristics across the Great Lakes and examined the effects of different factors that could affect spawning populations. Additionally, we generated simulated sea lamprey populations to evaluate the effects of sample size, number of genotypes, and true effective population size on the accuracy and precision of genetic estimates. Our simulations showed that a sample size of at least 100 individuals, along with maximization of SNP set size, allows for accurate estimates for all effective population sizes tested. Our work demonstrates that pedigree-based inferences can be effectively used as a management tool to characterize sea lamprey spawning abundance, poorly understood aspects of the species mating system, and relationships between adult reproductive success and associated stream characteristics.

ABSTRACT

EVALUATING GENOMIC ESTIMATES AND RECONSTRUCTED PEDIGREES AS ASSESSMENT TECHNIQUES FOR SEA LAMPREY POPULATIONS By

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Sea lamprey (*Petromyzon marinus*) are an invasive species in the Great Lakes. Their invasion resulted in the decimation of native fish populations, and a large control program has been dedicated to reducing lamprey populations. Control measures are mainly based on the construction of barriers to limit access to spawning habitat and the use of lampricides, such as 3trifluormethlyl-4-nitrophenol, to kill developing larvae in stream sediments. Current assessment techniques in Great Lakes tributaries include mark-recapture estimation of census size of sea lamprey adult populations. We expanded traditional assessment techniques by generating reconstructed pedigrees and estimates of effective breeding size (N_b) and minimum spawning size (N_s) of sea lamprey populations using single nucleotide polymorphism (SNP) genotypes of larval sea lamprey. In Chapter 1, we evaluated efficacy of barriers to adult upstream passage in three streams using population genomic data. In Chapter 2, we elucidated the effects of several sampling and environmental factors on N_b and N_s estimates from 18 streams across the Great Lakes. Additional analyses were conducted to examine the effects of sample size, number of SNP loci, and true N_b on estimated N_b and N_s using simulated sea lamprey populations. As true N_b increased, different methods of estimating N_b and N_s showed different types and levels of bias, highlighting the need for multiple methods of estimating these parameters, as well as sufficient sample sizes and numbers of SNP loci. Overall, the analyses conducted provided unique insight into sea lamprey spawning populations and have potential as annual assessment techniques for evaluating both current and future sea lamprey control efforts.

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THESIS INTRODUCTION

Sea Lamprey in the Great Lakes

Sea lamprey (*Petromyzon marinus*) arrived in the Great Lakes following the expansion of the Welland Canal in 1919, and became a destructive invasive species across the ecosystem (Lawrie, 1970). Native fish parasitized by lamprey experienced a subsequent crash in population size, with annual catch rates significantly reduced compared to periods prior to the arrival of sea lamprey (Heinrich et al., 2003; Koonce, Eshenroder, & Christie, 1993; Lawrie, 1970). By the 1950s, a large annual control and assessment program was established to control sea lamprey population size in the Great Lakes.

Sea lamprey have a multi-stage life cycle that takes place over several years (Applegate, 1950; Manion & Smith, 1978; Morkert, Swink, & Seelye, 1998). The larval phase takes place in the stream beds where the sea lamprey spawned (Dawson, Quintella, Almeida, Treble, & Jolley, 2015). Larvae embed in soft sections of substrate and filter feed for 3-7 years (Manion & Smith, 1978; Morkert et al., 1998). Over these years, these larvae can occasionally drift downstream, particularly if their current substrate environment becomes poor filter feeding ground (Hardisty & Potter, 1971; Potter, 1980). Due to the variable length of the larval development period, larvae present in the sediment represent multiple age classes. Length distributions are used to estimate larval age in the stream. Age-0 and age-1 individuals can be separated from larger/older age groups using these data, but age 2+ individuals have overlapping size ranges that can be difficult to separate (Dawson, Jones, Scribner, & Gilmore, 2009). Additionally, there is evidence that the quality of the river environment influences larval size and growth rates, particularly for older lamprey (Dawson, Higgins-weier, Steeves, & Johnson, 2020). Once larvae reach a certain size, approximately 130-145mm, they metamorphosize and migrate into the Great Lakes to begin the

parasitic phase of their life cycle (Griffiths, Beamish, Morrison, & Barker, 2001; Henson, Bergstedt, & Adams, 2003).

As parasitic juveniles, sea lamprey feed on several types of medium to large fish species, including lake trout (*Salvelinus namaycush*; Harvey, Ebener, & White, 2008; Pycha & King, 1975), Chinook salmon (*Oncorhynchus tshawytscha*; Adams & Jones, 2020), and lake whitefish (*Coregonus clupeaformis*; Ebener, Brenden, & Jones, 2010; McLeod, Cottrill, & Morbey, 2011). Sea lamprey attach to a fish and bore a hole into the scales to feed on the blood of their host, where each lamprey can cause between 5 and 20 kg of fish mortality during their feeding phase (Swink, 2003). Sea lamprey can travel large distances over their year as a parasitic juvenile as their host fish migrate around the lakes, leading to dispersal of lamprey across the Great Lakes system (Waldman, Grunwald, & Wirgin, 2008).

The spawning season for sea lamprey occurs in the spring, when adults reenter streams to spawn. Adult sea lamprey do not home to natal streams to spawn (Bergstedt & Seelye, 1995a), instead sea lamprey respond to pheromone cues produced by developing larvae, implying the existence of large larval populations and implicitly, good spawning habitat (M. B. Twohey et al., 2003). Once the adults enter the stream system, male sea lamprey make nests in rocky substrate and female sea lamprey visit several nests to spawn, leading to a polygamous mating structure (Applegate, 1950; Dhamelincourt, Buoro, Rives, Sebihi, & Tentelier, 2020; Johnson, Buchinger, & Li, 2015).

Sea Lamprey Control and Assessment

The life cycle of sea lamprey is used by management agencies to target sea lamprey in streams for control and assessment efforts. Annual control efforts are undertaken primarily

through the use of barriers and 3-trifluormethlyl-4-nitrophenol (TFM), a selective lampricide (Applegate, 1950; McDonald & Kolar, 2007; Smith & Tibbles, 1980). Physical barriers prevent spawning adults from entering stream systems and limit available spawning habitat (Lavis, Hallett, Koon, & McAuley, 2003; McLaughlin, Marsden, & Hayes, 2003). The first lampreyspecific barriers expanded on dams already present in large rivers in the Great Lakes. Recently, year-round barriers are slowly being removed due to their effects on the stream ecosystem, but electric barriers and seasonal barriers are increasingly common (Jensen & Jones, 2018a; McLaughlin, Hallett, Pratt, O'Connor, & McDonald, 2007).

TFM is a lampricide applied on a three to four year cycle in streams with prevalent larval populations to eliminate most larvae before they metamorphosize into parasitic juveniles. TFM was designed to be lamprey specific, but it has been shown to be detrimental to native lamprey larvae as well as some native fish species, particularly juvenile sturgeon (Boogaard, Bills, & Johnson, 2003; Pratt et al., 2020; Weisser et al., 2003). TFM targets the nervous system by creating a mismatch between ATP generation and consumption, leading to a drop in glycogen and eventual death (Birceanu, McClelland, Wang, & Wilkie, 2009). Lamprey appear to be particularly sensitive to TFM as a lethal agent, when compared to other fish species like bluegill (*Lepomis macrochirus*) or catfish (*Ictalurus punctatus*), which are largely unaffected by TFM (Lawrence et al., 2021; Lech & Statham, 1975).

Annual assessments across the Great Lakes region are used to estimate sea lamprey prevalence as larvae, juveniles, and spawning adults. Larval surveys are used to prioritize streams for TFM treatments each year based on the number of large larvae in the stream that are expected to metamorphosize into the parasitic life stage (Hansen et al., 2003). Lake trout caught in gill nets are used to estimate the number of actively parasitizing juveniles in each lake and

assess damage to commercial fisheries (Jones, 2007). Finally, mark-recapture efforts are used to estimate the abundance of spawning adults using trapping in an index group of streams in each Great Lake (Harper et al., 2018a).

Adult mark-recapture is used in a small number of streams to evaluate the prevalence of spawning adults in annual lamprey-producing streams. In 2018, the Peterson method of mark-recapture (Peterson & Cederholm, 1984) became the primary model used for adult assessment (Barber & Steeves, 2019). The estimated abundance of spawning adults in the stream is considers the total number of adults, the number of marked individuals, and the number of marked individuals recaptured. The abundance index is estimated using a model that incorporates trapping efficiency for each stream, as well as previous data on lamprey abundance across streams (Barber & Steeves, 2019). Prior to 2015, models using mark-recapture estimates of abundance as well as drainage area, time since TFM treatment, and other environmental variables were used to predict lake-wide adult sea lamprey abundance (Mullett et al., 2003). Since 2015, the sum of annual mark-recapture estimates across streams within lakes is used to generate an index of adult abundance based on the group of streams where trapping occurs (Adams, Barber, Bravener, & Lewandoski, 2021; Sullivan, Adair, & Woldt, 2016).

Sea lamprey populations are currently much smaller than at their historical peak in the 1950s (K. F. Robinson, Miehls, & Siefkes, 2021), indicating that control efforts have been successful at reducing sea lamprey abundance, but there is a need for additional control and assessment techniques. Some of the largest streams across the Great Lakes are not currently index streams measured for adult assessment, meaning that potentially large spawning populations of sea lamprey are not currently assessed. Additionally, the trapping techniques required for generating mark-recapture estimates are not possible due to environmental

conditions in some streams, limiting the group of streams that can be used for adult assessment. For situations like barrier failure, spawning populations often cannot be assessed since the failure was not discovered until larval assessments in subsequent years, and trapping cannot be performed retroactively. For all of these situations, alternative assessment techniques for spawning populations are required.

In addition to alternate assessment techniques, there are several limitations to control techniques, indicating a need for supplemental control. There has long been concern about sea lamprey developing resistance to TFM, although to date there is no evidence of that resistance in Great Lakes populations (Dunlop et al., 2018). However, genetic models indicate that resistance could start to develop in the near future, and alternative controls would become increasingly necessary (M. R. Christie, Sepúlveda, & Dunlop, 2019). Additionally, the removal of barriers from many streams could increase the amount of sea lamprey spawning habitat in the system, and supplemental control techniques will be needed to prevent an increase in sea lamprey population numbers. As sea lamprey control becomes more complex, additional assessment techniques will be necessary to evaluate the effectiveness of control methods. Particularly, there is a lack of assessment on the number of successfully spawning adults, and assessment of adults in a larger number of stream systems will become necessary to evaluate new control efforts in those streams.

Genetic Population Assessment

Genetic assessment is an increasingly common tool in management as genotyping costs decrease and sequencing efficiency increases, making genomic sequencing as a tool for widespread annual assessment possible (e.g. Ovenden et al. 2016; Hunter et al. 2020).

Additionally, sea lamprey are an emerging model species for genomic analysis due to the recent completion of genomic resources. A somatic genome was sequenced in 2013 (Smith et al., 2013), followed by a germline genome in 2018 (Smith et al., 2018) and a chromosome-level genome assembly in 2020 through the vertebrate genome project (Rhie et al., 2020). Additionally, genomic resources that facilitate efficient reduced-representation genomic sequencing have been developed and recently published by Sard et al. (2020).

Recent development of genomic resources facilitates the use of population genomic methods for assessment. Valuable information on families can be obtained through populationlevel genotyping and pedigree reconstruction. This can be done with a combination of parent and offspring genotypes (parentage analysis), or with exclusively offspring genotypes (pedigree reconstruction) (Wang, 2004). If only offspring genotypes are available, parental genotypes can be reconstructed from offspring genotypes (Blouin, 2003; Wang, 2004). Reconstructed pedigrees provide information on family relationships that can be utilized to assess populations for either conservation or control purposes. Reconstructed pedigrees have previously been used to evaluate reproductive success of spawning individuals, examine rates of inbreeding, evaluate the potential for inbreeding depression, quantify genetic diversity, and estimate effective population size (De Barba et al., 2010; Keogh, Webb, & Shine, 2007).

Genetic data and reconstructed pedigrees can be used to generate estimates and metrics that serve as tools for population assessment. Effective population size (N_e) estimates the size of an idealized population consistent with levels of genetic diversity, inbreeding, and genetic drift in the sampled population (Wright, 1931). Differences in fecundity, variance in reproductive success, fluctuation in population size over time, and skewed sex ratios among spawning

individuals all reduce effective population size compared to the census size of the population (Waples, Luikart, Faulkner, & Tallmon, 2013).

 N_e is used as a benchmark estimate in conservation genetics for detecting inbreeding depression and the potential for an extinction spiral in a population (Frankham, Bradshaw, & Brook, 2014). The values generally used to evaluate a population are that a population with an N_e of under 50 is at short-term risk of extinction (Soule, 1980), and a population with an N_e of under 500 will lose genetic diversity and is at long-term risk of extinction (Franklin, 1980; Franklin & Frankham, 1998). These metrics have been used to evaluate species for extinction risk in a management context (Mace et al., 2008). However, there is debate about whether the 50/500 numbers are too low, and if higher values like 100/1000 should be used instead (Frankham et al., 2014). Regardless of the debate on the specific benchmarks that should be used, the incorporation of N_e in addition to census size (N_c) as an assessment metric is important to evaluate populations for their extinction risk beyond low population numbers (Garner et al., 2016; Hoban et al., 2021). The N_e of a population influences many indicators of extinction, such as high levels of inbreeding (Armbruster & Reed, 2005) and loss of genetic diversity (Blomqvist, Pauliny, Larsson, & Flodin, 2010). Additionally, N_e can be used to evaluate the success of management actions like reintroduction (Anderson et al., 2014; Cochran-Biederman, Wyman, French, & Loppnow, 2015; Evans et al., 2015; N. M. Sard et al., 2020) and genetic rescue (Fitzpatrick et al., 2016; Frankham, 2015; Heber, Briskie, & Apiolaza, 2012) that are used for declining populations. Outside of conservation, N_e estimates are used to examine the effects of stocking on fished populations (Gossieaux, Bernatchez, Sirois, & Garant, 2019; Petereit et al., 2018a).

Effective population size (N_e) is calculated on a generation scale rather than a spawning event scale. Effective breeding size (N_b) is a similar metric that estimates the effective population size for a single cohort of offspring rather than a generation (Waples, Antao, & Luikart, 2014). In species with a semelparous life history, $N_e = g * N_b$, where g is the generation time for the species (Waples, 1990). Depending on the life history of the organism, N_b can be a more appropriate assessment metric than per-generation effective population size. Effective population size is complicated by overlapping generations (Waples et al., 2013), and may require multiple sampling periods or the sampling of multiple cohorts (Waples et al., 2014). Sea lamprey are a semelparous organism, so spawning adults will only be represented in one cohort of offspring. However, due to the varied length of time that larvae spend in substrate sea lamprey have overlapping generations. Due to these two factors, N_b is a more appropriate metric for estimating sea lamprey spawning abundance in streams.

 N_b and N_e can be calculated using similar methods. N_b can be estimated using a single larval sampling event with a variety of approaches, including linkage disequilibrium (Hill, 1981a), sibship frequency (Wang, 2009), and parentage without parents (Waples & Waples, 2011) methods. In the sibship frequency method, the rate of full and half-siblings present in sampled offspring is used to estimate N_b (Wang & Santure, 2009; Wang, 2009). Similarly, N_b estimates from the parentage without parents method are based on the variance in family size rather than the frequency of sibship (Waples & Waples, 2011). The linkage disequilibrium method (Hill, 1981a) quantifies the level of non-random association of alleles in genotypes at multiple loci, which is generally due to physical proximity in the genome, sample size, or the linkage that occurs from finite population size. By eliminating physical linkage as a source, and accounting for influences of sample size with correction factors, the linkage from finite populations size can be used to estimate effective population size (Waples & Do, 2010).

In addition to N_b , reconstructed pedigrees can be used to estimate the minimum number of spawning adults (N_s) in a reproductive event. N_s is calculated by estimating the number of parental genotypes required to produce the sampled offspring genotypes. N_s is obtained directly from the number of unique parental genotypes required to produce sampled offspring genotypes, thus it is limited to twice the sample size of offspring. This can be a large source of bias in the metric, particularly if the sample size is small. However, if there is some presence of sibship within the sampled offspring, the number of parental genotypes can be extrapolated to estimate the minimum number of parents for the population represented by the sampled offspring. The total number of spawning adults can be estimated using a technique similar to a species accumulation curve in community ecology, where unique species accumulate as the number of sampled sites increases (Sard et al., in press). As the total number of species is approached, the number of new species per site decreases, leading to an asymptote at the true number of species. A pedigree rarefaction curve works in a similar way, where the number of unique parental genotypes is accumulated as the number of sampled offspring increases (Israel & May, 2010; Rawding, Sharpe, & Blankenship, 2014; Sard et al., in press). Eventually the number of unique parental genotypes will approach the total number of parents in the population, and that asymptote can be estimated (\widehat{N}_s) . This extrapolation decreases the bias in N_s from limited sample sizes.

Objectives

 N_b and N_s have significant potential as assessment metrics for the estimation of sea lamprey spawning population size, but they need to be further validated prior to incorporation into management and control efforts. Genetic estimates of spawning abundance were utilized to assess barrier efficacy in three streams in Chapter 1, and across a larger number of streams to quantify associations between N_b , N_s , N_c and the stream's management history (e.g., lampricide treatment interval) and environmental characteristics in Chapter 2. Environmental, biotic, and sampling variables were examined for associations with N_b and N_s estimates in these systems. Additionally, a subset of sequenced streams are also index streams for mark-recapture census size estimates for adult populations, and the potential correlations between N_b , N_s , and N_c were examined. To evaluate the sampling and genotyping effort required to effectively estimate N_b and N_s across stream systems, simulations were conducted for a variety of population sizes to compare the accuracy and precision of N_b and N_s estimates as sample size and the number of SNP loci increased.

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CHAPTER 1: PEDIGREE ANALYSIS AND ESTIMATES OF EFFECTIVE BREEDING SIZE CHARACTERIZE SEA LAMPREY REPRODUCTIVE BIOLOGY

ABSTRACT

The sea lamprey (Petromyzon marinus) is an invasive species in the Great Lakes and the focus of a large control and assessment program. Current assessment methods provide information on the census size of spawning adult sea lamprey in a small number of streams, but information characterizing reproductive success of spawning adults is rarely available. We used RAD-capture sequencing to genotype single nucleotide polymorphism (SNP) loci for ~1600 sea lamprey larvae collected from three streams in northern Michigan (Black Mallard, Pigeon, and Ocqueoc Rivers). Larval genotypes were used to reconstruct family pedigrees, which were combined with Gaussian mixture analyses to identify larval age classes for estimation of spawning population size. Three complementary estimates of effective breeding size (N_b) , as well as the extrapolated minimum number of spawners (N_s) , were also generated for each cohort. Reconstructed pedigrees highlighted inaccuracies of cohort assignments from traditionally used mixture analyses. However, combining genotype-based pedigree information with length-at-age assignment of cohort membership greatly improved cohort identification accuracy. Population estimates across all three streams sampled in this study indicate a small number of successfully spawning adults when barriers were in operation, implying that barriers limited adult spawning numbers but were not completely effective at blocking access to spawning habitats. Thus, the large numbers of larvae present in sampled systems were a poor indicator of spawning adult abundance. Overall, pedigree-based N_b and N_s estimates provide a promising and rapid assessment tool for sea lamprey and other species.

INTRODUCTION

Invasive species are a substantial threat to biodiversity and management intervention is often required to mitigate their effects on the ecosystem. Annual control programs to reduce the population size of widespread invasive species (Prior, Adams, Klepzig, & Hulcr, 2018) often include strategies to reduce recruitment and spread, like barriers that limit access to spawning habitat (Sharov & Liebhold, 1998). More recently, genetic control techniques like the release of sterile individuals or gene drive have been developed as additional options for control (Bajer et al., 2019).

Genetic technology, used in combination with field techniques, allow managers opportunities to efficiently and cost-effectively sample large areas to quantify the presence of species, community composition, and species biomass and abundance. Environmental DNA was used as an early detection tool for specific invasive species like American Bullfrogs (Lithobates catesbeianus) and invasive shellfish species, allowing for rapid response after the invasion (Dejean et al., 2012; Leblanc et al., 2020). To evaluate widespread invasions, demographic modeling has been used to track the spread of invasive species across a system to determine the introduction point and generate hypotheses for the mechanism of introduction (Blakeslee et al., 2017; Sherpa et al., 2019). Additionally, determining the founding effective size of an invasive population can provide insight into the mechanism of invasion and the severity of the bottleneck present in an introduced species (Sard, Robinson, Kanefsky, Herbst, & Scribner, 2019). Genetic parentage assessment and effective size estimates can be used to evaluate the size and diversity of spawning populations as an annual assessment tool for managed populations (Taylor, Bangs, & Long, 2021). This can be used to evaluate the success of control efforts for an invasive species.

Sea lamprey (*Petromyzon marinus*) are a widespread invasive species in the Laurentian Great Lakes (McGeoch et al., 2010). The expansion of the Welland Canal in 1919 allowed sea lamprey to spread from Lake Ontario to the rest of the Great Lakes by 1938 (Lawrie, 1970). Sea lamprey contributed to major declines in commercially valuable fish species like lake trout (*Salvelinus namaycush*) and lake whitefish (*Coregonus clupeaformis*) throughout the Great Lakes basin (Heinrich et al., 2003; Koonce et al., 1993; Lawrie, 1970). As a result of the ecological and economic impacts of the invasion, an annual control and assessment program was implemented in the 1950s to reduce sea lamprey abundance and assist recovery of native fish populations (Smith & Tibbles, 1980).

The primary methods of sea lamprey control since the 1950s have been physical barriers that block adults from reaching spawning habitat and application of the selective lampricide 3-trifluormethlyl-4-nitrophenol (TFM) to kill larvae (Applegate, 1950; McDonald and Kolar, 2007; Smith and Tibbles, 1980). Several barrier designs have been implemented since the beginning of the control program to reduce migration of sea lamprey into streams (Lavis et al., 2003; McLaughlin et al., 2007). However, these barriers also impede the movement of numerous ecologically and culturally important native fish species (Jensen & Jones, 2018b). Adjustments and alternative barrier designs have been used to reduce effects on native fish (Katopodis et al., 2009), such as seasonal electric barriers or the addition of a fish ladder (Lavis et al., 2003; Zielinski et al., 2019). Many barriers have been removed altogether, resulting in an increase in spawning habitat for sea lamprey throughout the Great Lakes. Additionally, sea lamprey larvae are occasionally found upstream in systems with barriers. In these cases, managers want to know when and how many adult sea lamprey escaped upstream of the barrier, but given uncertainty in stock-recruitment relationships and a limited ability to age larvae, these questions are largely

unanswered (Dawson, Jones, Scribner, & Gilmore, 2009; Jones, 2007). Population genetic data can address these questions by estimating the number of successfully spawning adults that contributed to a year class of larvae and tracking the movements of individuals from each year class over several years (Ovenden et al., 2016; Sard et al., 2020).

Sea lamprey have a multistage anadromous life history that can span up to 9 years (Applegate, 1950). Adults migrate upstream, spawn in spring and summer, and die afterward (Johnson et al., 2015). Larvae reside in streams and lentic areas near streams and feed on algae and detritus while burrowed into soft sediment (Dawson et al., 2015). After two (Morkert et al., 1998) to seven years (Manion & Smith, 1978) in the larval stage, larvae undergo metamorphosis, migrate to the Great Lakes, and feed on fishes for 12-18 months. Adult sea lamprey do not return to natal streams to spawn (Bergstedt & Seelye, 1995b), but instead stream selection is guided by chemosensory cues released by larval sea lamprey (Fissette et al., 2021). Therefore, population structure of sea lamprey is weak relative to other homing fishes (Bryan et al., 2005). Key uncertainties regarding sea lamprey demographics include stock-recruitment relationships (Dawson & Jones, 2009), larval survival (Jones et al., 2009), and age at metamorphosis (Griffiths et al., 2001; Treble, Jones, & Steeves, 2008) in part, because of difficulty aging larvae (Dawson, Higgins-Weier, Steeves, & Johnson, 2020).

Recent developments in sequencing technologies, the declining costs of high-throughput sequencing, and expanding genomic resources for sea lamprey (Smith et al., 2013, 2018; Sard et al., 2020) present an opportunity to incorporate population genomic methods and data analysis into invasive species assessment efforts. Reduced representation sequencing technologies such as Restriction-site Associated DNA (RAD) sequencing (Baird et al., 2008) and locus-targeted RAD-Capture (Ali et al., 2016) allow for the collection of genome-scale data from large

population-level sample sizes. The use of genomic data to study invasive species populations offers numerous applications to assist managers in assessing sea lamprey reproductive ecology in natural stream settings. These data also provide a means to evaluate the effectiveness of experimental barriers and gain additional insight into sea lamprey reproductive ecology in Great Lakes tributaries.

Several parameters are routinely estimated based on genetic data to quantify spawning adult abundance and reproductive success (e.g., Sard et al. 2020 for sea lamprey). Effective population size (N_e) is the size of an idealized population that experiences the same amount of genetic drift, inbreeding, or loss of diversity as the population in question (Wright, 1931). N_e has been used in assessments of populations and as an indicator of potential for future declines in abundance (Antao, Pérez-Figueroa, & Luikart, 2011). Low Ne can also be an indicator of low levels of genetic diversity in a population (Frankham, 2010). In many species, multiple generations produce offspring simultaneously, resulting in overlapping generations (Waples, Antao, & Luikart, 2014). In this situation, the effective number of breeding individuals contributing to a spawning event (N_b) can also be estimated using samples from a single year class (Robinson & Moyer, 2013; Waples et al., 2014; Waples & Do, 2010). Ne can be reduced relative to census size by several factors, including skewed sex ratios and variation in reproductive success (Waples, 2010). The ratio of N_b to N_e has been shown to be strongly associated with life history traits such as time to sexual maturity and adult lifespan (Waples, Luikart, Faulkner, & Tallmon, 2013). In addition to N_b, the minimum number of spawning adults (N_s) can also be calculated from reconstructed pedigrees as the minimum number of parental genotypes required to produce the sampled offspring genotypes. Using approaches to estimate total species richness from the field of community ecology (Chao 1987; Heltshe and Forrester
2009), information on the contribution of inferred parental genotypes to sampled larvae can provide estimates of the total number of parents contributing to a cohort (Hunter et al., 2020), including asymptotic estimates of total spawning adult numbers (Sard et al., in press).

 N_b can be estimated from population genetic or genomic data using several methods. Here we apply three approaches to estimate sea lamprey effective breeding size: linkage disequilibrium (LD; Waples and Do 2010), sibship frequency (SF; Wang 2009), and parentagewithout-parents (PwoP; Waples and Waples 2011). The LD method uses non-random associations of alleles across loci that result from finite population size or physical linkage (Hill 1981a,b). If chromosomal locations of loci can be established and effects of physical linkage can be removed, LD resulting from finite breeding population size can be estimated to characterize effective breeding size (Waples, Larson, & Waples, 2016). In contrast, SF and PwoP both use reconstructed pedigrees, where sampled offspring are used to reconstruct unsampled parental genotypes (Bravington, Skaug, & Anderson, 2016; De Barba et al., 2010; Keogh et al., 2007). SF uses the frequency of sibling relationships identified in the pedigree to infer N_b (Wang, 2009), while the PwoP method uses the mean and variance in reproductive success of parents reconstructed from the sampled individuals in the pedigree (Waples & Waples, 2011). Notably, both the SF and PwoP methods rely on reconstructed pedigrees for the sampled offspring and they are known to provide equivalent, but not identical, estimates of N_b (Ackerman et al., 2017).

In this study, our objective was to estimate effective breeding size and minimum number of spawners for larval sea lamprey cohorts collected from streams above barriers to upstream migration in three locations in the northern Lower Peninsula of Michigan: the Black Mallard, Pigeon, and Ocqueoc Rivers. In all three locations, the presence of larvae upstream of barrier locations raised concerns about barrier failure to impede spawning migrations. We used the

estimates above to evaluate barrier efficacy in all three systems. Furthermore, we used reconstructed pedigrees of each collection along with Gaussian mixture analysis to estimate the number of larval age classes present in each system. We discuss possible explanations for barrier failure in these systems, highlight the utility of population genomic data for rapid assessment of spawning populations and how genetic data can be integrated into monitoring and control efforts for invasive species.

METHODS

Study System and Sample Collection

Sampling of larval sea lamprey was conducted in the Black Mallard, Ocqueoc, and Pigeon Rivers, which are located in the northern Lower Peninsula of Michigan, USA (Figure 1). In all three systems, larval sea lamprey were collected above barriers designed to preclude access to spawning habitat. The spatial extent of sampling was extensive in all rivers to define the distribution of the larval sea lamprey infestations and to obtain a comprehensive spatial representation of larvae produced from all family groups.

The Black Mallard River had an electric barrier installed in 2016 following a lampricide treatment that occurred in June 2015. In September 2017, larvae in the section of the Black Mallard River downstream from Black Mallard Lake were collected using backpack electrofishing (n = 387). Sea lamprey were sampled from habitat spanning 500 m upstream and downstream of Ocqueoc Lake Road and U.S. Highway 23. These two sampling points represented the furthest upstream and downstream extent of the lower river with stream substrate suitable for larval sea lamprey, and covered about 50% of the available larval habitat in the lower river. Lampricide treatment of the Black Mallard River downstream of Black Mallard Lake occurred in July 2018, and dead sea lamprey larvae were collected post treatment by two staff that walked the entire stream length from Ocqueoc Lake Road to U.S. 23 (n=667). These collections will be referred to hereafter as the 'Lower Black Mallard River.' Variation in larval length in the samples raised concerns that larvae might include individuals from multiple age classes that would indicate that the barrier had failed repeatedly. Larvae were also collected upstream of Black Mallard Lake in May 2019 when lampricide was applied. Two staff walked 2 km downstream and 2 km upstream from Elah Road, and covered the entire known distribution

of larval sea lamprey in the upper river. Surveys were also conducted upstream and downstream of Elah Road post lampricide treatment but no sea lampreys were found. This collection will be referred to hereafter as the 'Upper Black Mallard River.'

The Ocqueoc River has had an electric barrier in place since 1951 (Smith & Tibbles, 1980), with a permanent barrier installed since 1999. The area upstream of the barrier is the site of annual experiments that involve the release of thousands of adult female sea lamprey (Buchinger et al., 2020; Johnson, Thompson, Holbrook, & Tix, 2014; Wagner, Hanson, Meckley, Johnson, & Bals, 2018). Adult males are not included in experimental releases, so no successful spawning was expected in the system. However, a population of larvae was found above the barrier in 2018 and surveys conducted throughout the river identified a roughly 5 km infested reach downstream of Ocqueoc Falls. Lampricide was subsequently applied in the stream in September 2018 and larvae were collected during treatment using dip nets and drift nets by four staff that walked the entire infested area (n = 396). Surveys for dead sea lamprey were also conducted at Pomranke Road (5 km downstream of infested area) and in Silver Creek (tributary to Ocqueoc River), but no sea lampreys were found.

The Cheboygan River system has a dam at the mouth of the river, but has small sea lamprey populations which complete the juvenile parasitic phase of their life cycle in several upstream lake and stream systems; the Pigeon River is one such tributary (Johnson et al., 2020). To depress or eradicate these populations, releases of sterile males have been used as a supplemental control technique to limit successful female reproduction (Johnson et al., 2020; Kaye et al., 2003; M. Twohey, 2016). During these efforts, a small number of larvae (n = 29) were found at Webb Road in the Pigeon River in September 2018. Ten other locations spanning

a 55 km section of the Pigeon river were also sampled in 2018 (some upstream and some downstream), but no sea lamprey were collected at those other sites.

Sea lamprey collected from all systems were euthanized, preserved in 95% ethanol and returned to the lab. Length and weight were measured for each individual sampled, to estimate age class. A tissue sample was taken for genetic analysis.



Figure 1.1. Map of the study area where larval sea lamprey were collected. The Black Mallard River is separated into upper and lower sections by Black Mallard Lake. The top-right inset shows the location of the sampled river systems in the Great Lakes region. River lines in black denote sampling locations of the river systems, blue lines denote all other rivers in the region.

RAD-capture Sequencing

DNA was extracted from each larva using DNeasy blood and tissue kits (QIAGEN, Carlsbad, CA). DNA concentrations were initially quantified using a Nanodrop ND-1000 Spectrophotometer (ThermoFisher Scientific, Waltham, Massachusetts) and Quant-iTTM PicoGreenTM dsDNA Assay Kits (ThermoFisher Scientific, Waltham, Massachusetts) on a QuantStudio 6 Flex Real-Time PCR system (Thermo Fisher Scientific Inc., Waltham, Massachusetts). Samples were standardized to a concentration of 10 ng/ 1 for RAD sequencing.

RAD library preparation was performed on 100 ng of DNA per individual using a modified version of the BestRAD protocol (Ali et al., 2016). DNA was digested using an *Sbf1* restriction enzyme, and a biotinylated BestRAD adaptor was ligated to the DNA, which functioned as an individual barcode. DNA from groups of 96 barcoded individuals was pooled, concentrated, and sheared using a Covaris m220 focused-ultrasonicator (Covaris, Woburn, Massachusetts) using manufacturer recommended settings for a fragment size of 325 bp. Next, a streptavidin bead binding assay was used to select DNA fragments with RAD tags attached and a size selection was used to select only the target size fragments for sequencing. Size selection was done using Ampure beads with a 22:50 ratio to select long fragments and a 13:72 ratio to separate target size fragments from shorter fragments. Finally, NEBNext Kits (New England BioLabs Inc, Ipswich, Massachusetts) were used to ligate plate-specific Illumina adaptors and a universal adaptor for sequencing.

Library concentrations were quantified using a Picogreen assay, and the quality of the library was assessed via Tapestation (Agilent, Santa Clara, California) analysis. Libraries were pooled in groups of four to be enriched for a set of 3446 RAD loci that are known to be variable in sea lamprey populations (Sard et al., 2020). Loci were targeted using the RAD-capture

approach (Ali et al., 2016) with a custom MyBaits hybridization capture kit (Arbor Biosciences, Ann Arbor, MI) following the manufacturer recommended protocol. Eleven cycles were used in the final amplification step in the capture kit. Libraries were sequenced on four Illumina HighSeq X lanes at Novogene (Chula Vista, CA) using paired-end 150 base pair sequencing. Sequencing data for the project are available on the NCBI sequence read archive (Accession #: will be provided prior to publication).

Genotyping Analysis

Raw sequence data were processed using a bioinformatic pipeline described in Sard et al. (2020). Prior to the pipeline, a quality control report was constructed for each library using FastQC (Andrews, 2010) and evaluated. First, sequences from the HighSeq X run were oriented using the custom perl function bRAD flip trim.pl (originally developed by Paul Hohenlohe, University of Idaho, and modified by Brian Hand and Seth Smith, University of Montana) and demultiplexed using the Stacks 2.0 (Catchen, Hohenlohe, Bassham, Amores, & Cresko, 2013) module 'process radtags'. PCR duplicates were removed using 'clone filter'. Next, sequences were quality trimmed using Trimmomatic with a minimum length of 50, a sliding window of 4 bases, and a minimum quality score of 15 (Bolger, Lohse, & Usadel, 2014). Sequences were then mapped to the sea lamprey reference genome (Smith et al., 2018), and indexed using bwa and bwa-mem (Li, 2013; Li & Durbin, 2010). Samtools (version 1.9) was used to sort reads with default settings (Li et al., 2009). Genotypes were called using the Stacks 2.4 (Catchen et al., 2013) module 'gstacks', and the module 'populations' was used generate a .vcf file containing genotypes for all individuals. To avoid the inclusion of paralagous loci in the data set, the software HDplot (McKinney, Waples, Seeb, & Seeb, 2017) was used to identify and exclude

potential paralogs. Loci were removed if observed heterozygosity was > 0.6 or the read ratio deviation statistic (D; McKinney et al., 2017) in heterozygotes was greater than 7 in absolute magnitude. Individuals with more than 80% missing SNPs in the set were removed from analysis to minimize missing data. Each SNP set was checked for significant deviance from Hardy-Weinberg equilibrium across populations using the output from the Stacks 2.0 'populations' function prior to use in downstream analyses. Final genotype calls were filtered to exclude samples with < 8X coverage. To determine which SNPs were located on the sections of the genome targeted by the RAD-capture baits, the position of each SNP were compared to the genome position ranges for each RAD-capture tag (Sard et al., 2020).

To ensure that all individuals were sea lamprey samples rather than misidentified native Northern or American brook lamprey (*Ichthyomyzon fossor; Lampetra appendix*), comparative analyses were conducted. RAD-capture sequences of known American and Northern brook lamprey were aligned to the sea lamprey genome along with sampled individuals. A principal component analysis (PCA) was conducted for both native lamprey species and sampled individuals to identify clusters of individuals based on genotypes. All sampled individuals were compared to look for individuals that were identified as lamprey but clustered with native species, and none were found (Figure S.1). Additionally, neighbor-joining phylogenetic trees were constructed using SNP differences as an additional check for misidentified individuals, and all trees separated along species lines with no sampled individuals sorted with either native lamprey species.



Figure S.1. Visualization of principal component analysis (PCA) used to compare sea lamprey larval individuals from two native lamprey species (*Lethenteron appendix, Ichthyomyzon fossor*). Purple dots labeled *P.marinus* represent sequenced individuals, green dots labeled *I. fossor* represent known Northern brook lamprey, and blue dots labeled *L. appendix* represent known American brook lamprey.

Gaussian Mixture Analyses

Offspring from sea lamprey and other fish species often exist in mixtures of individuals of different ages (cohorts), and these age classes need to be separated for estimation of N_b and N_s . We developed a novel extension of Gaussian mixture methods by combining mixture models with reconstructed pedigrees (Figure 1.2). Given the semelparous life history of sea lamprey, full and half-sibling relationships should not span different cohorts; therefore, all individuals connected in the pedigree were assumed to be from the same age class. Aging methods like statolith aging have been found to be unreliable (Dawson et al., 2015), and length-based aging methods have been primarily used by management agencies for sea lamprey (Hardisty & Potter, 1971; Sethi, Gerken, & Ashline, 2017; Slade et al., 2003). Lengths of sea lamprey larvae were used in Gaussian mixture analyses to classify individuals into putative age-classes prior to estimation of effective breeding size (N_b) and the minimum number of spawners (N_s). Mixture analyses were conducted separately for each stream and each collection year due to variation in larval length between streams and collection years.

Mixture models were constructed using the R packages BayesMix (Grün & Leisch, 2010) and bmixture (Mohammadi et al., 2013) to infer the number of age classes (K) and generate individual assignments to those cohorts. We used two different approaches to assess the number of cohorts represented by a sample of sea lamprey larvae. Birth-death MCMC treats K as a model parameter that is allowed to increase or decrease in successive steps of the MCMC chain to provide posterior probabilities for each potential K value (Mohammadi et al., 2013; Stephens, 2009). Rousseau and Mengersen (2011) proposed a cluster determining method that involves fitting a mixture model with a large K value and eliminating clusters with membership proportions below a certain cutoff (between 0.01 and 0.05; Nasserinejad, Rosmalen, De Kort, &

Lesaffre, 2017). For this project, a cutoff of 0.035 and a K of 10 was used. The consensus from birth-death MCMC and the Rousseau and Mengerson (2011) approaches was used as the K value in a BayesMix model to determine individual assignments to clusters. If consensus was not reached, the output with a higher likelihood was used as the K value. All analyses were conducted in R (version 3.6.2). All scripts, data, and documentation for these analyses are available at https://github.com/weiseell/NbdLamprey.



Figure 1.2. A flow chart describing how inferred cohort assignments from the Gaussian mixture models are combined with information in the reconstructed pedigrees.

Reconstructed Pedigrees

SNP genotype data were used to reconstruct pedigrees for larvae sampled from all locations. SNP loci were selected from the filtered group of SNPs for each population using the following criteria: minimum separation of adjacent SNP loci of 1MB to reduce the influences of physical linkage, variant position with the highest minor allele frequency (MAF > 0.05), and highest percent of individuals genotyped with a minimum criteria of 80%. If two or more SNPs met all three criteria equally, a random SNP was selected from that group. For each stream system, pedigree analysis was conducted in Colony version 2.0.6.6 (Jones & Wang, 2010) using the full-likelihood approach. Due to differences in sample size among systems, a medium length run was used for the Lower Black Mallard and Ocqueoc Rivers, and a long run was used for the Pigeon and Upper Black Mallard Rivers. Other input parameters included unknown allele frequencies, polygamous mating, and no sibship scaling or prior sibship reported. All other parameters were kept at default settings.

Colony clusters from the reconstructed pedigree were compared to cohorts determined by the Gaussian mixture analysis to check for discrepancies between clusters of related individuals in the pedigree and cohorts assigned by the mixture analysis. A family cluster from Colony is defined as a group of offspring that are connected in the pedigree through parentage, but are not necessarily full- or half-siblings. For example, if offspring 1 and offspring 2 are half-siblings, and offspring 2 and offspring 3 are half-siblings, then offspring 1 and offspring 3 are considered to be in the same Colony cluster due to their connection in the pedigree through offspring 2. For each collection with multiple inferred cohorts from the Gaussian mixture analysis, individuals were evaluated for the level of family overlap between inferred cohorts. If there was no overlap of Colony cluster groups between inferred cohorts, they were left separate for subsequent

analysis. If individuals in the inferred cohorts were related (as full- or half-siblings), these individuals were combined into a single cohort for subsequent analyses. If there were multiple sample collections from the same location, the comparison was repeated to determine which cohorts should be combined across collections, and to approximate growth between collections to help separate year classes. Length histograms from previous studies (Dawson et al., 2020), as well as information on barrier installation and TFM treatment years, were used to estimate the cohort year classes. A flow chart of the decision-making process is shown in Figure 2. Additionally, the same decision-making tree was used with full-sibling groups and produced the same cohort groups as the Colony cluster groups.

N_b , N_s , and \hat{N}_s estimates

Colony was used to estimate N_b using the SF method (Wang and Santure, 2009), and the family information from Colony was used to estimate N_b using the PwoP method (Waples and Waples, 2011). Additionally, mean (\bar{k}) and variance (V_k) of adult reproductive success (number of offspring assigned based on the pedigree produced from the full-likelihood implementation in Colony) were calculated for the contributing individuals in the reconstructed parental populations. To generate confidence intervals for the PwoP method, a method based on Wang (2009) confidence intervals used for the SF method, which combines uncertainty in the pedigree reconstruction with uncertainty from sampling. The variance in $1/2 N_b$ was calculated for archived configurations from Colony to evaluate uncertainty in the pedigree, and the variance in $1/2 N_b$ for 1000 simulation populations with equal sex ratio with the same N_b as the empirical data set. These two variances were summed and the square root of the summed variance was used to calculate 95% confidence intervals. N_s was generated using the number of inferred

parents represented in each cohort. N_s was extrapolated using a 'parentage accumulation curve,' which is akin to a species accumulation curve (Colwell, Chang, & Chang, 2004; Israel & May, 2010; Rawding et al., 2014), to count the number of unique parental genotypes as the number of offspring genotyped in the sample increases (Hunter, 2018; Sard et al. in press) Briefly, the specaccum function from the R package vegan (Oksanen et al., 2019) was used to generate pedigree accumulation curves and the total number of parental genotypes contributing to each cohort (\hat{N}_s) was estimated using the Chao (Chao, 1987a) and jackknife (Heltshe & Forrester, 2009) methods in the vegan function specpool (Oksanen et al., 2019).

The SNP panel used for estimates of N_b from the LD method (LD) was selected with a separate set of criteria due to inherent differences in the estimation methods. SNPs were selected to only include loci in regions of the genome targeted by the Sard et al. (2020) Rapture panel. Within those RAD tags, SNPs with the highest percentage of individuals genotyped were selected and ties were broken with a random variable. NeEstimator (Do et al., 2013) was used for each cohort and stream sample with only the LD method selected, no comparisons within chromosomes were allowed (to avoid LD due to physical linkage of SNP markers; Waples et al. 2016). SNPs with a MAF < 0.05 were removed to avoid potential upward bias from low-frequency alleles (Robin S. Waples & Do, 2010). Estimates were generated using an allele frequency inclusion criterion of p_{crit} = 0.05, and jackknife confidence intervals produced by NeEstimator were used (A. T. Jones, Ovenden, & Wang, 2016). All analyses for N_b , N_s , and \hat{N}_s estimates, with the exception of the Colony and NeEstimator programs, were conducted in R (version 3.6.2; R Core Team, 2019), all scripts and documentation for these analyses are available at <u>https://github.com/weiseell/NbdLamprey</u>.

RESULTS

Genotyping Analysis

Sequencing generated more than 3 billion total reads with an average of approximately 2 million reads for each individual (range: ~2000-12 million reads). After removal of PCR duplicates and quality filtering, reads were mapped to the sea lamprey reference genome (Smith et al., 2018). Of the filtered mapped reads, 88% were from sections of the genome targeted by the Rapture panel developed by Sard et al. (2020). Average sequencing depth in targeted regions was 34X. The SNPs targeted by the Rapture panel also had a higher proportion of loci with MAF > 0.05 (0.25) when compared to non-targeted SNPs (0.177), and a higher mean proportion of individuals genotyped per SNP (on-target = 0.56, off-target = 0.20).

Mixture Analyses and Reconstructed Pedigrees

In the Lower Black Mallard River, two age-classes were identified based on clusterdetermining methods for both collection years, shown in the histograms in Figure 1.3. The number of cohorts was determined by consensus for the 2018 collection, and for the 2017 collection the Rousseau and Mengersen (2011) criteria had a higher likelihood (Table 1.1). Length distributions among the inferred age-classes overlapped, with the exception of a small group in the Lower Black Mallard River 2017 collection, as shown by the boxplots in Figure 1.4. The reconstructed pedigree had 104 full-sibling families and 14 Colony clusters. Figure 1.5 visualizes the family structure across both collections compared to the inferred cohorts from the mixture analysis. The largest Colony cluster contained 755 (75%) of the sampled offspring. The individuals in this cluster were present in both length-inferred age classes for the 2018 collection and the larger age class in the 2017 collection. The small age class in the 2017 collection likely comprises offspring from spawning in 2016 (Figure 1.3), whereas the rest of the sampled individuals represent the 2015 cohort. No sibling relationships were inferred between the Lower and Upper Black Mallard River collections, indicating that larvae in these two areas were produced by different sets of spawning adults. Due to the small sample size from the Upper Black Mallard River population, the cluster determining models did not converge, and the mixture analysis was not conducted.

The mixture models for the Ocqueoc River indicated that one age-class of individuals had been collected (Table 1.1, Figure 1.3). The pedigree reconstruction contained 17 clusters and 18 full-sibling families. The pedigree reconstruction contained two half-sibling families that contributed 89% of sampled offspring (Figure 1.5). All of the individuals from those families were collapsed into the same Colony cluster (Figure 1.4).

Cluster likelihood (the likelihood that a Colony cluster cannot be split) was inconsistent for pedigrees derived from the Ocqueoc and the Lower Black Mallard Rivers. The cluster likelihood for the largest cluster in both systems was < 0.5. Small clusters in each location had higher probability (Figure 1.4) suggesting some assignment uncertainty for a small group of individuals in each sample.

The reconstructed pedigree in the Pigeon River had six small full-sibling families that were mostly unrelated to each other. The sample size from the Pigeon River was too small to quantitatively compare inferred cohorts and the family structure from the reconstructed pedigree or run mixture models.

Table 1.1. Summary of results for identifying the optimal number of clusters (K) in the mixture analysis for sea lamprey. Analyses were performed for each larval collection with a range of K=1-4 clusters. R&M criteria and BD-MCMC shows the estimated probability of each K value from the Rousseau and Mengersen (2011) criteria and Birth Death Markov Chain Monte Carlo (BD-MCMC; Mohammadi, Salehi-Rad, & Wit, 2013), respectively. The optimal number of clusters from each method is bolded.

Lower Black Mallard River – 2017 Collection (n = 386)									
K	R&M Criteria	BD-MCMC							
1	0.074	0.008							
2	0.912	0.067							
3	0.013	0.385							
4	0.000	0.540							
Lower Black Mallard River – 2018 Collection (n = 614)									
K	R&M Criteria	BD-MCMC							
1	0.008	0.112							
2	0.827	0.478							
3	0.164	0.319							
4	0.000	0.091							
Ocqueoc River – 2018 Collection (n = 396)									
K	R&M Criteria	BD-MCMC							
1	0.998	0.143							
2	0.002	0.538							
3	0.000	0.277							
4	0.000	0.042							



Figure 1.3. Length frequency distributions for larval sea lamprey from all rivers and collection years, fill colors represent individual cluster assignment from the Gaussian mixture analysis. If mixture models were not completed due to small sample size, length histograms are included and shaded as a single cohort.



A) Lower Black Mallard River

Figure 1.4. Boxplots of length distributions for each sea lamprey Colony cluster from the Lower Black Mallard River (A) and the Ocqueoc River (B). Colony clusters are defined as groups of offspring in the pedigree that are connected by parentage, but are not necessarily full- or half-siblings. Plots are separated by collection. The probability that the Colony cluster cannot be split is represented by a continuous shading scale for both subplots (red clusters have a lower likelihood, white clusters have a higher likelihood).



Figure 1.5. Visualization of reconstructed sea lamprey pedigrees. The center represents genotyped individuals, and dots represent inferred parents. Lines connect each reconstructed parent to sequenced offspring in the pedigree. Black boxes represent cohorts inferred by the mixture method. Note: Since parents were not sequenced, and due to the lack of known sex-determining genes for sea lamprey, the sex of reconstructed parents cannot be determined. Parent 1 and Parent 2 are used instead.

N_b and N_s calculations

 N_b and N_s estimates for all cohorts are summarized in Table 1.2, and \hat{N}_s accumulation curves are shown in Figure 1.6. For the Lower Black Mallard River, the N_b estimates for the 2015 cohort ranged from 24 to 32 (Table 1.2), and accumulated N_s ranged from 108 to 110 (Table 1.2). The 2016 cohort had N_b estimates that ranged from 5 to 29 (Table 1.2) and N_s estimates that ranged from 19 to 24 (Table 1.2, Figure 1.6). For the Upper Black Mallard River collection, N_b estimates ranged from 3 to 8 (Table 1.2) and N_s estimates ranged from 15 to 16 (Table 1.2, Figure 1.6). In the Ocqueoc River, N_b estimates ranged from 9 to 50 (Table 1.2) and N_s estimates ranged from 90 to 98 (Table 1.2, Figure 1.6). Confidence intervals were small, partially due to the large numbers of loci used in the estimates. N_b estimates for the Pigeon River collections ranged from 6 to 8 (Table 1.2), while Chao and jackknife estimates of N_s ranged from 14 to 18 (Table 1.2, Figure 1.6). Table 1.2. Estimates of the effective number of breeding adults (N_b) and the number of unique inferred parental genotypes in the inferred pedigree (N_s) for each stream and sea lamprey cohort. Locations are shown in Figure 1. N is the number of larval sea lamprey sampled for a stream and year. V_k and \bar{k} represent the inferred variance in reproductive success and mean number of offspring per adult in the population, respectively. LD refers to N_b estimates derived from the linkage disequilibrium method. SF refers to N_b estimates from the sibship frequency method. PwoP refers to N_b estimates from the parentage-without-parents method. $\widehat{N_s}$ – Chao and $\widehat{N_s}$ – Jackknife represent accumulated N_s estimates using the Chao and the Jackknife methods, respectively.

Location ¹	Full- sibs	Clusters	Cohort	n	\overline{k}	V_k	LD	SF	PwoP	Ns	\widehat{N}_s - Chao	\widehat{N}_s - Jackknife
Lower Black	104	14	2015	1024	21.78	945.70	24.5	32	31.88	94	110.06	108.99
Mallard River (A)							(22.7-26.5)	(20-50)	(31.68-32.14)		± 11.02	±3.87
Lower Black			2016	16	1.78	0.51	4.7	13	29.18	18	$19.53 \pm$	$23.625 \pm$
Mallard River (A)							(2.2-13.4)	(7-30)	(16.99-103.25)		1.82	2.30
Upper Black	9	4		35	5.23	24.02	3.1	7	7.59	13	$15.18 \pm$	$15.91 \pm$
Mallard River (A)							(2.4-5.9)	(4-21)	(6.95-8.35)		3.30	1.68
Ocqueoc River	87	87 17	396	206	10.24	700 50	50.2	9	8.90	76	90.66±	$98.94 \pm$
(B)				10.24	799.30	(45.6-55.2)	(5-24)	(8.81-8.94)	70	8.00	5.55	
Pigeon River (C)	6	3		16	4.22	13.51	7.6	10	5.76	9	$13.26 \pm$	$11.84 \pm$
							(2.8-21.7)	(5-28)	(5.04-6.71)		6.83	2.14



Figure 1.6. The estimated number of unique parental genotypes in the pedigree (\hat{N}_s) characterized using pedigree accumulation curves for all three stream systems. For all locations, boxplot distributions for each step size overlay a line plot with a grey background for +/- one standard error, and labeled horizontal lines represent \hat{N}_s estimates from the jackknife and chao methods. Due to the large number of individuals, the Ocqueoc River boxplots are plotted in step sizes of 5 sampled individuals and the Lower Black Mallard River boxplots are shown for sample sizes increasing by 10 individuals. The boxplots for all other locations are plotted for a step size of 1 sampled individuals.

DISCUSSION

N_b and N_s estimates

Genetic estimates of N_b and \hat{N}_s allow inferences pertaining to the number of successful spawning adults in a Great Lakes tributary. N_b and \hat{N}_s estimates both provide information about spawning populations that can be used to make inferences in management and conservation contexts. In the sampled systems, N_b estimates and reconstructed pedigrees indicated skewed sex ratios in the Ocqueoc River. The \hat{N}_s estimates provided insight into the number of successfully spawning adults upstream of control barriers. Despite the small to moderate effective breeding sizes estimated for each sampled cohort, larvae were abundant in all systems (estimates range from approximately 3500 larvae in the Upper Black Mallard River in 2017 to 124,000 larvae in the Pigeon River in 2019; unpublished data, A. Jubar, USFWS). In all systems, the vast majority of individuals had half- and full-siblings within the areas sampled. In the Ocqueoc, 89% of individuals were in two half-sibling families. In the Black Mallard River, 75% of individuals were in a single Colony cluster, and 97.3% of the individuals were determined to be in a single cohort from 2015, prior to the barrier construction.

Increasing sample size and the number of loci analyzed improves N_b estimates based on all three methods (England, Cornuet, Berthier, Tallmon, & Luikart, 2006; Wang, 2016; Waples, 2016). Based on simulations conducted by Sard et al. (2020), a high degree of accuracy in the pedigree assignments from Colony is expected given the expected spawning adult population size for these systems and the number of SNP loci used for the analysis. The large number of SNP loci used for pedigree reconstruction and N_b estimation resulted in high confidence in inferred relationships and confidence intervals that were substantially smaller than those for typical microsatellite datasets (Flanagan & Jones, 2019; J. D. Robinson & Moyer, 2013). For the

LD estimates, confidence intervals can be artificially narrowed by large numbers of loci, although the corrected jackknife confidence interval approach reduces this effect (Waples, Grewe, Bravington, Hillary, & Feutry, 2018). Additionally, the high cluster probabilities for large Colony clusters in the Black Mallard and Ocqueoc Rivers bolster confidence in the family relationships identified by Colony. However, individual misassignment could stem from several potential sources. Pedigree reconstructions for the Black Mallard and Ocqueoc Rivers also contain a small group of individuals that were unrelated to any large family groups. These outlier groups are most likely unrelated individuals, but they could be the result of Colony assignment error (Butler et al., 2004). Outlier groups were confirmed to be sea lamprey from a PCA, rather than misidentified native lamprey (*Lethenteron appendix, Ichthyomyzon fossor*).

Our results provide an empirical application of \hat{N}_s , a comparatively new method of quantifying spawning adults. Previous work has used accumulation curves to evaluate spawner abundance in green sturgeon (Israel & May, 2010) and chinook salmon (Rawding et al., 2014). \hat{N}_s has been used for lake sturgeon (*Acipenser fulvescens*) previously to estimate the number of adults recruited to a spawning site (Hunter, 2018; Sard et al., in press). Given sufficient sample sizes, this method can be used to estimate the number of adults contributing to a cohort (Figure 6). N_s estimates without an accumulation method have direct dependence on sample size since they are calculated as the number of unique reconstructed parental genotypes for a set of offspring and are thus limited by sample size. By applying methods designed to estimate total species richness to reconstructed pedigrees, that dependence is reduced.

Cohort identification

Mixture analysis in sea lamprey has several sources of uncertainty. Techniques rely on the presence of several large cohorts in a stream sample to provide accurate cohort assignments and are expected to be most effective for age-0 and age-1 individuals where length distributions are more distinct from older cohorts (Dawson et al., 2009). Additionally, environmental conditions affect the growth rate of larvae. Variables such as growing degree days, stream temperature and larval sea lamprey density are all significant predictors of larval growth in streams (Dawson et al., 2020).

 N_b and N_s are both estimates generated for a single spawning year, meaning that the ability to separate offspring into cohorts is vital for accurate estimates. Combining Gaussian mixture models with reconstructed pedigree data allows for the identification of potentially misidentified cohorts from the length data alone, minimizing error in cohort identification. Including individuals from multiple cohorts in N_b and N_s calculations generated from the reconstructed pedigree would upwardly bias estimates due to the inclusion of parents from multiple spawning events (Wang, Santiago, & Caballero, 2016). For the linkage disequilibrium estimates, linkage that arise from two separate spawning groups are included, leading to an downward bias (Waples & England, 2011).

Uncertainty in the cohort assignments from the mixture analysis was evident in the Black Mallard River samples. Larvae were separated into multiple cohorts with overlap between length distributions for individuals assigned to older cohorts. Additionally, variability in growth within age classes was greater than previously assumed (Figure 1.4), potentially contributing to the over-splitting of larval cohorts observed in both streams. Incorporating family pedigree information further supported the conclusion that number of cohorts was overestimated by the

mixture analysis, as several sibling groups spanned multiple inferred cohorts. In the Black Mallard River, length-based mixture analysis divided members of the largest family cluster into three cohorts, again indicating over-splitting. In semelparous species like the sea lamprey, family structure present in reconstructed pedigrees can be combined with length data as complementary information to verify cohort assignments.

Importance of Sample Size in N_b and N_s estimates

Estimates of N_b and N_s can be sensitive to small sample size. For estimates generated using reconstructed pedigrees, small sample size can lead to missing family groups. If estimated levels of LD among a set of polymorphic loci can be explained by sample size alone, no signal remains to estimate effective size of the sampled population (Waples & Do, 2010). Increasing sample size and the number of markers thus increases the power for estimation of effective population size (Waples, 2016). Non-representative sampling of a population can lead to downward bias in N_b and N_s estimates due to missing diversity in sampled individuals (Whiteley et al., 2012). Minimizing costs for a project while still obtaining accurate point estimates is partially balanced by selecting appropriate sample sizes for a given study system. If the N_b of the stream is expected to be small (like the Black Mallard River), then sample size could be proportionally smaller to minimize field and sequencing costs necessary for the project. However, if N_b is unknown or expected to be large, a larger sample size is necessary to ensure accurate estimates (Wang, 2016; Waples, Grewe, Bravington, Hillary, & Feutry, 2018).

Application of Results

Population estimates across all three streams sampled in this study imply that barriers

limited adult spawning numbers but were not completely effective at blocking access to spawning habitats. Thus, the large numbers of larvae present in sampled systems were a poor indicator of spawning adult abundance, which is an important finding for managers. Another important finding was that members of full- and half-sibling families were identified in multiple year cohorts, which is impossible due to the species' semelparous life history. Cohort assignments identified by mixture models (i.e., in the absence of confirmatory genetic data) showed that length-based analysis alone does not provide accurate cohort assignments. Our analyses illustrate the potential to improve cohort assignments by incorporating population genomic data and pedigree analysis for sampled sea lamprey larvae. Collectively, effective size, minimum spawning size estimates, and reconstructed pedigrees based on larval sequencing were successfully used to make inferences about spawning adult populations in three streams. Recent developments, including the availability of a reference genome (Smith et al., 2013, 2018) and the RAD-Capture marker panel (Sard et al., 2020) employed in this study, position Great Lakes sea lamprey as an emerging model system for the study of species invasions.

Population genomic data were used to infer aspects of sea lamprey biology that contribute valuable information for sea lamprey assessment. Results from the Lower Black Mallard River indicated that the majority of individuals originated from a single cohort due to the existence of full-sibling relationships between inferred cohorts from the mixture analysis. These data are consistent with the expectation that a moderate number of adult sea lamprey spawned in the Black Mallard River in 2015 after lampricide treatment, but prior to the electric barrier installation in 2016. Collectively, our data suggest that the electric barrier in the Black Mallard River was effective at reducing sea lamprey migration upstream, as N_b of the 2016 cohort was much smaller than N_b of the 2015 cohort, and a 2017 cohort was not confidently

identified by our mixture analyses for the Lower Black Mallard River collections. There are alternative explanations for small N_b , such as high variance in reproductive success and strongly skewed sex ratios, as seen in the Ocqueoc River estimates. Additionally, the lack of family relationships between the Upper and Lower Black Mallard River implies two separate subsets of spawning adults. In the Ocqueoc River, 89% of larvae were from two half-sibling families, indicating that a small group of fertile males were present above the barrier along with the females released for research experiments. Estimates from samples collected in the Pigeon River indicated that both N_b and N_s were small, which is consistent with the expectation that releases of sterile males decreased the number of successful spawning adults in the system.

Although sea lamprey are invasive in the Great lakes, they are endangered in parts of Europe, and conservation efforts are underway to protect declining populations (Hansen et al., 2016). Many of the same questions related to management of invasive Great Lakes populations also apply to threatened marine sea lamprey populations spawning in North American and European tributaries of the Atlantic Ocean. Estimates of N_b and the per-generation effective population size (N_e) can provide important information on patterns of relatedness, the rate of diversity loss due to genetic drift and inbreeding, and the species' potential for adaptation.

Population genomic data, including estimates of effective size, have been used as a monitoring tool in many conservation and management situations for other species, such as translocations and reintroductions (Hess et al., 2015; Roques, Berrebi, Rochard, & Acolas, 2018; Whitlock, Schultz, Schreck, & Hess, 2017), quantifying genetic diversity to prevent extinctions (Faulks, Kerezsy, Unmack, Johnson, & Hughes, 2017), and identifying ecologically significant units (Blower, Pandolfi, Bruce, Gomez-Cabrera, & Ovenden, 2012). Parentage has been used to evaluate the size of invading populations in species like the Asian Swamp Eel (*Monopterus* *albus*) (Taylor et al., 2021). Genetic data were used in all of the above situations to evaluate the population or assess the success of a management action, and this type of assessment is increasingly needed among managed populations (Hoban et al., 2021). Thus, population genomic data and estimation of effective population sizes could be used to assess the efficacy and level of success of management actions related to invasive species, endangered populations, species of conservation concern, and managed species (Nunziata & Weisrock, 2018).

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CHAPTER 2: THE EFFECTS OF SAMPLING, BIOTIC, AND ENVIRONMENTAL VARIABLES ON ESTIMATES OF SEA LAMPREY EFFECTIVE BREEDING SIZE AND MINIMUM NUMBER OF SPAWNERS IN GREAT LAKES TRIBUTARES

ABSTRACT

Sea lamprey (*Petromyzon marinus*) are a harmful invasive species in the Great Lakes, and a large annual control and assessment program is dedicated to reducing their population size. Sea lamprey assessment is performed using larval electrofishing surveys as well as adult markrecapture estimates for estimating the number of adult sea lamprey entering streams to spawn. This assessment data are used to estimate the abundance of adult and larval sea lamprey stream populations over time to evaluate the effectiveness of control efforts. The number of successfully spawning adults is not currently assessed. Mark-recapture estimates are performed in a small number of index streams compared to the number of streams where larval assessment is conducted. Effective breeding size and minimum number of spawners were estimated for 18 larval stream populations using SNPs generated from RAD-capture sequencing. To evaluate the effects of environmental, biotic, and sampling factors on effective breeding size (N_b) and the minimum number of spawning adults (N_s) , generalized linear models were constructed. Associations between mark-recapture estimates and N_b and N_s estimates were evaluated. Simulations were conducted to evaluate the potential biases of N_b and N_s estimates as sample size, number of SNPs, and true N_b in the population increased. We found that sample size collected and genotyped, a sampling factor, was a significant predictor of empirical N_b estimates; however, no correlation between mark-recapture estimates and N_b or N_s estimates was found. Simulations indicated that sample size and a sufficient number of SNPs become increasingly important as true N_b increases. Additionally, the different methods of estimating N_b have

different biases. The Chao method of calculating N_s has less bias than the jackknife method when true N_b is large. Overall, our results highlight the utility of N_b and N_s by providing insight into sea lamprey spawning populations, further demonstrate the complicated relationship between N_b and census size, and highlight the importance of representative sampling in empirical data sets.

INTRODUCTION

Sea lamprey (*Petromyzon marinus*) are a destructive invasive species in the Great Lakes region. Sea lamprey arrived in the system after the expansion of the Welland Canal in 1919, and their subsequent expansion was partially responsible for the population crash of several native fish species, including lake trout (*Salvelinus namaycush*) (Lawrie, 1970). Sea lamprey have a multi-stage life cycle that spans several years (Applegate, 1950). Larval lamprey spend three (Morkert et al., 1998) to seven years (Manion & Smith, 1978) filter feeding on algae and detritus in the soft sediment sections of stream beds (Dawson et al., 2015), before metamorphosing into parasitic juveniles and migrating out of the streams. Once the individuals are in the lakes, they parasitize fish species for 12-18 months. In the following spawning year, they travel back into streams to spawn. Lamprey have a semelparous life history, only spawning once in their life cycle (Renaud, 2011). Lamprey do not return to natal streams to spawn, instead they enter streams based on temperature (Binder & McDonald, 2008) and pheromone cues from larvae in the stream (Wagner, Twohey, & Fine, 2009).

To control lamprey population numbers, a large control and assessment program was implemented in the region (Smith & Tibbles, 1980). The primary methods of control since the start of the program are the selective lampricide 3-triflouromethyl-4-nitrophenol (TFM) and the use of several types of barriers to reduce upstream passage. TFM is applied in streams to kill larval lamprey in the substrate (Applegate, 1950; McDonald & Kolar, 2007; Smith & Tibbles, 1980), and barriers reduce the migration of adult lamprey into streams to spawn (Lavis et al., 2003; McLaughlin et al., 2007). Emerging technologies like sterile male release control and trapping techniques are utilized in a small number of streams, but are not widely applied across the region (Hume et al., 2015; Kaye et al., 2003).

The success of sea lamprey control methods is evaluated by assessment techniques such as mark-recapture estimates generated for adult spawning populations. Mark-recapture is conducted through trapping annually in a small group of index streams to estimate the number of spawning adults entering the stream system (Steeves & Barber, 2020). Prior to 2015, these markrecapture estimates were combined with environmental data such as drainage area and years since TFM treatment to produce models of lake-wide abundance (Mullett et al., 2003).

Recently, mark-recapture estimates have been summed to provide an index of abundance for each lake that can be tracked across years, rather than an estimate of total abundance (Sullivan et al., 2016). Mark-recapture is an effective technique for estimating the number of potentially spawning adults in the stream, but mark-recapture cannot be conducted in many streams due to the environmental conditions in those systems, and the cost associated with evaluating a larger number of streams. Additionally, violation of assumptions of mark-recapture models like repeated capture of individuals, trap avoidance, and small recapture rates can complicate estimates in systems where mark-recapture is conducted annually (Bravener & McLaughlin, 2013).

Larval surveys are an assessment technique to evaluate larval presence, the number of cohorts, cohort abundance, and distribution to prioritize streams for TFM treatments (Christie et al., 2003). Surveys use backpack electrofishing to check for the presence of larval populations in streams. Length is used to determine the number of potential transformers in the system (Christie & Goddard, 2003; Hardisty & Potter, 1971). Length can also be used to determine the number of cohorts in the stream, but separating age classes with length alone is difficult, particularly for larger larvae (Dawson et al., 2009). The addition of information about the stream environment can improve cohort determination using length (Dawson et al., 2020). Larval surveys are

conducted in a larger number of systems than mark-recapture surveys, but annual assessment of larval population numbers is uncommon, and parent populations cannot be evaluated with current larval assessment techniques. By generating genomic data sets for larval populations, spawning populations can be assessed.

Using genomic data, several types of parameters can be estimated and inferences based on pedigrees can be made that are useful for managing populations. Effective population size (N_e) is a parameter describing the size of an idealized population that experiences drift or inbreeding at the same rate as the sampled population. N_e is affected by skewed sex ratios, and the level of drift present in the population. N_e estimation can be further complicated by large census size and highly dispersed species (Waples, Grewe, Bravington, Hillary, & Feutry, 2018). Nonetheless, N_e is a common and informative metric used in management contexts to evaluate species of conservation and invasive concern, and there are several common methods of estimation. The linkage disequilibrium (LD; Waples & Do, 2010) method uses nonrandom associations between alleles in a set of loci to estimate N_e . Linkage between two loci can be caused by physical linkage through proximity on the genome or from finite population size. Thus, correlations in allele frequencies between loci that are not physically linked can provide an estimate of N_e . Sibship frequency (SF; Wang, 2009) and parentage without parents (PwoP; Waples & Waples, 2011) methods both use reconstructed pedigrees to estimate N_{e} . SF utilizes the rates of full- and half-siblings present in the sequenced offspring (Wang, 2009), while PwoP uses the variation in family size to provide estimates of N_e (Waples & Waples, 2011). N_e is generally calculated on a generational basis (Waples, 2016; Waples, Antao, & Luikart, 2014), but a related measure, the effective breeding size (N_b) , can be calculated for individual cohorts with appropriate sampling (Wang, 2009; Waples, 2005; Waples & Antao, 2014).

Another per-cohort parameter to describe adult spawning population size using genotyped offspring is the minimum number of spawning adults (N_s). Parental genotypes reconstructed from sequenced offspring can be used to estimate the minimum number of adults required to produce the genotypes present in the offspring. However, each offspring only has at most two unique parent genotypes to contribute to the total number of spawning adults so N_s is inherently limited by sample size, and can be reduced if the sample is not representative of the total stream population. However, these estimates can be extrapolated to the full stream population, minimizing the sample size limitation, by estimating the asymptote of an accumulation curve of unique parental genotypes (Israel & May, 2010; Rawding et al., 2014). Like a species accumulation curve, unique parent genotypes are accumulated like unique species occurrences as the number of offspring increases. The asymptote can be calculated using a Chao or a Jackknife method, and is an estimate of the total number of successfully spawning adults in a stream system (Sard et al., in press).

In addition to genetic factors, N_b and N_s can also be influenced by a variety of environmental and sampling factors. Mark-recapture estimates of sea lamprey are influenced by drainage area and years since TFM treatment, and these factors could also impact N_b and N_s . Previous work on salmonids indicated that environmental variables like stream flow and other environmental factors influence N_b estimates, the ratio between N_b and N_c , and the variance of parental success (V_k) (Whiteley et al., 2015). Additionally, adequate sample size and representative sampling is vital for obtaining accurate N_b and N_s estimates that represent the full system (Whiteley et al., 2012). If there is a relationship between N_b and N_s and sampling factors that could imply that sample size was too small or that sampling was not representative of the full stream population.

Due to recent advances in genotyping technology and resources, population assessment with large sample size and SNP sets has become more feasible. Developing genomic technologies like restriction site associated DNA (RAD; Baird et al. 2008) and RAD-capture (Ali et al., 2016) sequencing allow for efficient parallel sequencing, increasing the number of sequenced individuals. A chromosome-level and a germline genome have been assembled for sea lamprey (Smith et al., 2013, 2018). Additionally, a RAD-capture panel was recently published for sea lamprey (Sard et al., 2020), allowing for the sequencing of a large number of individuals at a specific known group of variable sequences present in the sea lamprey genome.

Due to annual collections during larval assessment, there is an opportunity to use population genetics methods to assess adult spawning populations using larval collections. Additionally, assessments of N_c in a group of index streams allows for comparison between census size and genetic estimates. N_b and N_s need to be assessed for utility in sea lamprey both through empirical data sets with sequenced offspring and compared through simulated populations to examine the relative performance of all estimate types as sample size, SNP set, and true N_b of the system changes. Additional testing to evaluate the effects of environmental, biotic, and sampling factors on N_b and N_s and the correlation between N_b , N_s , and mark-recapture census size estimates is needed. In this study we estimated N_b and N_s in a series of Great Lakes tributaries to assess the utility of these estimates for sea lamprey assessment and evaluate the influences of environmental, biotic, and sampling variables on effective breeding size and the minimum number of spawners.

METHODS

Sample Collection

Sea lamprey larvae (n = 1,877) were collected via backpack electrofishing during larval assessment surveys in 18 streams across the Great Lakes system by collaborators at US Fish and Wildlife Service, United States Geological Survey, and Fisheries and Oceans Canada (Figure 2.1). Collections occurred in the summer and fall of 2019, with the exception of the Middle River, where collections occurred in the summer of 2017. Stream systems ranged from large rivers like the Muskegon River (Drainage = 7,327 ha) to small streams like Swan Creek (Drainage = 5ha). All systems are annual sea lamprey producing streams, where TFM treatments were conducted within 10 years of sample collection. At each collection site, larvae were identified to species, anesthetized with MS-222, and euthanized with 95% ethanol.



Figure 2.1. Map showing all sampled streams with their location in the Great Lakes system. Each dot represents a stream system.

Sequencing Library Preparation

A tissue sample from each larva was preserved in 95% ethanol for subsequent DNA extraction and sequencing. DNA extractions were performed using Qiagen DNeasy blood and tissue kits (QIAGEN, Carlsbad, CA) and all DNA concentrations were quantified with a Nanodrop ND-1000 Spectrophotometer (ThermoFisher Scientific, Waltham, Massachusetts) and Quant-iTTM PicoGreenTM dsDNA Assay Kits (Thermo Fisher Scientific Inc., Waltham, Massachusetts) with a QuantStudio 6 Flex Real-Time PCR system (Thermo Fisher Scientific Inc., Waltham, Massachusetts). DNA was standardized to concentrations below 100 ng/µl for RAD library constructions. Stream populations were randomly distributed across libraries to minimize library effects.

Reduced representation libraries were constructed using a modified version of the BestRAD protocol from Ali et al. (2016). DNA was digested with an *Sbfl* restriction enzyme and biotinylated BestRAD adapters were ligated to samples to serve as individual barcodes. The barcoded DNA was pooled, concentrated with Ampure beads (Beckman Coulter, Indianapolis, Indiana), and sheared to 325 bp using a Covaris m220 focused-ultrasonicator (Covaris, Woburn, Massachusetts). DNA fragments with attached bestRAD tags were selected using a streptavidin bead binding assay, and size selection was used to select target size fragments. A 22:50 ratio of Ampure beads was used to select long fragments and a 13:72 ratio was used to separate target size fragments from short fragments. NEBNext kits (New England BioLabs Inc, Ipswich, Massachusetts) were used to ligate plate-specific Illumina adaptors and an Illumina universal adapter was used to prepare the library for sequencing. ~3400 SNPs across individuals were targeted for sequencing using a custom MyBaits hybridization capture kit (Arbor Biosciences, Ann Arbor, MI), designed by Sard et al. (2020), with the manufacturer protocol and eleven PCR

cycles in the final amplification step. All libraries were sequenced on an Illumina HighSeq X at Novogene (Chula Vista, CA) with paired-end 150 base pair sequencing.

Bioinformatic Analysis

A bioinformatic pipeline based on Sard et al. (2020) was used to process read data. First, reads were oriented with a custom perl script bRAD flip (originally developed by Paul Hohenlohe, University of Idaho, and modified by Brian Hand and Seth Smith, University of Montana) and demultiplexed from library to individual data with the Stacks 2.0 function process radtags (Catchen et al., 2013). Cloned reads were removed from each individual with Stacks 2.0 function cloneFilter (Catchen et al., 2013), and trimmed and quality filtered with Trimmomatic (Bolger et al., 2014) with a minimum length of 50, a sliding window of 4 bases, and a minimum quality score of 15. BWA-mem (Li, 2013; Li & Durbin, 2010) was then used to map all reads to the sea lamprey chromosome-level reference genome (https://genomes.stowers.org/sealamprey). SAMtools (version 1.9; Li et al., 2009) was used to sort mapped reads. The sorted reads were genotyped using the stacks function gStacks (Catchen et al., 2013), and a sorted VCF file was generated along with population-level statistics using the Stacks function populations. SNP data were initially filtered for 8X depth for final genotype calls. For each population, HDplot was run to filter potentially paralogous loci from the data set. If observed heterozygosity was greater than 0.6 or the absolute value of the read ratio deviation statistic (D) was greater than 7, the locus was removed from the data set (McKinney et al., 2017). Additionally, SNPs were checked for deviance from Hardy-Weinburg equilibrium across populations using the output from populations (Catchen et al., 2013). No SNPs were found to be deviant from Hardy-Weinburg equilibrium across populations.

Estimation methods for generating N_b estimates and reconstructed pedigrees have different data requirements to run optimally. Thus, two SNP sets were generated for each population with different filtering parameters: one for linkage disequilibrium N_b estimates, and the other to generate a reconstructed pedigree. For both datasets, SNPs were filtered to exclude loci that were not targeted by the RAD-capture bait panel, and loci where fewer than 80% of individuals were genotyped. The linkage disequilibrium dataset was limited to one SNP per RAD-capture tag, where the selected SNP had the highest percentage of individuals genotyped among the SNPs on the tag. SNP loci in the dataset used for pedigree reconstruction in Colony (Jones and Wang 2010) were selected using a sliding window of 1MB to minimize linkage among SNPs, with selection biased towards high minor allele frequency (minimum value of 0.05) and high percent genotyped to maximize information content of the dataset. Colony version 2.0.6.6 (Jones & Wang, 2010) was run for each stream population to reconstruct the pedigrees of each system for the cohort-determining models described below. The full-likelihood approach with a medium-length run was used for all streams. Other input parameters changed from default settings were unknown allele frequencies, polygamous mating, and no sibship scaling or prior sibship reported.

The accidental inclusion of native lamprey in genomic estimates of sea lamprey could cause bias and N_b and N_s estimates, thus potential native lamprey samples need to be identified and excluded from subsequent analysis. To identify sampled lamprey to species, 10 individuals from two native lamprey samples (*L. appendix* and *I. fossor*) were sequenced using the same library preparation and SNPs were identified using the techniques as the sampled individuals. A PCA was conducted with known native lamprey and sampled individuals for each stream population to identify outliers that sort with native lamprey samples instead of the other stream

samples. No outliers were identified, indicating that all samples that were sequenced were sea lamprey samples.

Cohort-determining models

Length measurements and blotted weight were taken for all collected individuals for mixture models first introduced in Chapter 1. A combination of Gaussian mixture models and reconstructed pedigree data were used to determine the cohort assignments of larval offspring (Figure 1.2). First, inferred cohort groupings were generated from length data using the R packages bmixture (Mohammadi et al., 2013) and BayesMix (Grün & Leisch, 2010). The number of inferred cohorts (K) was determined by using the birth-death MCMC algorithm implemented in bmixture (Mohammadi et al., 2013) with a maximum K of 4 and 500,000 iterations. The posterior probability of K values was estimated using the proportion of MCMC iterations with a given K value. BayesMix was also used to select K with criteria proposed by Rousseau and Mengerson (2011), which involves fitting a model with a large K value (n = 10) and identifying the number of non-empty clusters (less than 0.035 sorted into the given K value) after 500,000 iterations (Nasserinejad et al., 2017; Rousseau & Mengersen, 2011). Locations with a sample size of less than 80 were excluded from mixture models based on recommendations from Rousseau and Mengerson (2011), which indicated that mixture models with small sample size produced variable results. The posterior probability of K values was based on the proportion of steps with K non-empty clusters. BayesMix was rerun with the optimal K value for each stream to generate individual cohort assignments based on length.

For locations with multiple length cohorts, the level of colony clusters across inferred cohorts was assessed and used to check the cohort assignments with the decision-making chart

defined in Chapter 1 (Weise et al in review). Colony clusters refer to groups of offspring that connected in the pedigree but are not necessarily full- or half-siblings. For example, if offspring 1 and offspring 2 are maternal half-sibling, and offspring 2 and offspring 3 are paternal halfsiblings, offspring 1 and 3 are unrelated but still connected in the pedigree through offspring 2. All three of those individuals would be in a single colony cluster. All analyses were conducted in R (R Core Team, 2019).

N_b and N_s estimates

For all cohorts, three estimates of N_b and two estimates of N_s were generated. Estimates from the linkage disequilibrium method (LD; Waples and Chi 2008) were calculated using NeEstimator (Do et al., 2013). A MAF cutoff of 0.05 was specified and locus pairs within chromosomes were excluded from the calculation of correlation in allele frequency to reduce the effects of linkage from proximity in the genome (Waples, Larson, & Waples, 2016). Confidence intervals were estimated using a jackknife method with a correction to minimize effects of large SNP sets on confidence intervals (Jones, Ovenden, & Wang, 2016). Colony was run with the same parameters as full stream populations to calculate N_b with the sibship frequency method (SF; Wang and Santure 2009). Estimates of N_b from the parentage without parents method were calculated using a custom R script based on equations in Waples and Waples (2011), and the uncertainty of those estimates was generated based on equations from Wang 2009. Specifically, variance for $1/2N_b$ was calculated for archived configurations of the reconstructed pedigree generated by Colony and for simulated populations with equal sex ratio and the same N_b as the empirical estimates. These sources of variance were summed and converted into confidence intervals that incorporate sampling uncertainty and uncertainty associated with the construction

of the reconstructed pedigree. Additionally, the mean (\overline{k}) and variance (V_k) of adult reproductive success for contributing adults were calculated for each reconstructed pedigree. N_s was estimated by counting the number of unique parent genotypes in the reconstructed pedigree, then extrapolated to the minimum number of parents in the stream system $(\widehat{N_s})$ using both the Chao (Chao, 1987) and jackknife (Heltshe & Forrester, 2009) methods with the function specpool from the R package vegan (Oksanen et al., 2019).

Statistical Analyses

Sampling, biotic, and environmental factors may influence estimates of N_b and $\widehat{N_s}$ in the sampled systems. For instance, if sampling sizes are too small or if sampling is not representative, there could be a linear relationship between N_b and $\widehat{N_s}$ estimates and sampling size or the number of sampling sites. Linear models were used to assess the influence of several factors on N_b , $\widehat{N_s}$, and V_k for the sampled systems. We evaluated a global model that included several stream characteristics that can affect the N_b to N_c ratio or N_b and $\widehat{N_s}$ estimates: representations of sampling structure (sample size, the linear distance of sampling sites for each stream), population size of spawning adults (census size for index streams, drainage area of the stream), and factors that could lead to bias in mark-recapture estimates (trapping distance from the mouth of the river for index streams). Publicly available reports on current sea lamprey control and assessment methods were used to collect information on TFM treatment years and census size estimates for the adult population that was assumed to have produced the sequenced larvae (Barber & Steeves, 2019; Mullett & Sullivan, 2017). Personal communications with USFWS collaborators and unpublished data from co-authors were used to obtain data on drainage area for each stream (J. Adams, pers. comm.) and the distance of trap sites from the

mouth of the river for mark-recapture streams (G. Bravener, pers. comm.). The number of larval collection sites and approximate distance of larval collection were also included in a separate model that did not include N_c estimates or trapping distance to minimize missing data from both models.

Generalized linear models with the above environmental variables as factors were generated for the estimate of N_b based on both LD and SF methods, Chao estimates of $\widehat{N_s}$, as well as V_k . Model selection was conducted using Akaike Information Criteria (AIC; Akaike, 1974) values with a sample size correction (AICc; Hurvich and Tsai 1989). Akaike weights were used to sort models from most to least probable, and the confidence set of models was defined as the best-supported models with a cumulative Akaike weight of 0.9 (Akaike, 1978). Relationships between mark-recapture estimates of census size (Barber & Steeves, 2019; Mullett & Sullivan, 2017) and estimates of N_b and N_s across streams were evaluated via Pearson product-moment correlation tests.

Effects of Sample Size, SNP set size, and stream N_b on genetic estimates

Factors like sample size, the number of SNP loci, and N_b of the sampled population can affect the accuracy and precision of N_b and $\widehat{N_s}$ estimates. To specifically examine the effects of these factors, we estimated N_b and $\widehat{N_s}$ (using each the methods described above) in simulated genetic datasets. The individual-based simulation model implemented in the R package rmetasim (Strand, 2002) was used to generate 50 replicate populations of six different sizes ($N_b = 50$, 100, 500, 1000, 5000, and 10000) by initializing a landscape with a carrying capacity of the desired N_b , polygamous mating for both males and females, and no survivorship after mating to represent semelparous life history. Allele frequencies in simulated populations were initialized using empirical allele frequencies from the individuals sequenced in Chapter 1 for 1,200 diploid SNP loci from the data set. After 50 generations of burn-in, 200 generations were run where both genotypes and heterozygosity were tracked. Fixed SNPs were removed and all individual genotypes were output for each simulation. True N_b was calculated using V_k and \overline{k} estimates generated from each simulated population, and the number of parents in the full population was used as true N_s . These replicates were subsampled for five sample size values (25, 50, 100, 150, and 200 individuals) and three SNP set sizes (100, 500, and 1000 loci). N_b and $\widehat{N_s}$ for all simulated datasets were estimated using the programs NeEstimator (Do et al., 2013) and Colony (Jones & Wang, 2010) with similar input parameters as used for empirical datasets. In NeEstimator, no reference genome was used since the simulated SNPs were modeled as unlinked, independent loci. For the Colony pedigree reconstruction analyses, the FPLS (combined full-likelihood and pairwise-likelihood score) method was used instead of full likelihood for computational efficiency.

 N_b and $\widehat{N_s}$ were estimated using the same methods described for the empirical data. Harmonic mean and median point estimates from each scenario were compared to the true N_b and N_s value from full simulated populations to examine the accuracy of estimated N_b and $\widehat{N_s}$ for each parameter set. Root-mean-square error (RMSE) were calculated for each parameter set. All scripts and summary files are available on Github (<u>https://github.com/weiseell/OliviaSims</u>).

RESULTS

Read Processing

Larval sea lamprey were sequenced in 20 libraries across 5 sequencing lanes, with an average read count of 234,404,375 reads per library. The average number of demultiplexed reads was 2,085,919 per individual. The average depth per individual was 26X across all SNPs. After applying a depth filter of 8X, 200,190 identified SNPs remained in the data set. 64.48% of those identified SNPs matched to the Rapture panel, and an average of 16.1% of individuals were genotyped per SNP. The SNP sets for the linkage disequilibrium estimates contained between 2,659 and 3,018 SNPs with an average 97.7% percent of individuals genotyped and 0.12 average MAF (Table 2.1). The SNP sets for pedigree reconstruction contained between 627 and 683 SNPs with 92.5% percent of individuals genotyped and 0.24 average MAF (Table 2.1). Between populations, there was an average of 69.5% overlap between SNPs selected for the Colony sets, and 21.0% overlap among the NeEstimator SNPs. However, there was 98% overlap among targeted loci selected for the NeEstimator SNP sets.

Table 2.1. Table showing the SNP set size, as well as the average MAF and percent of individuals genotyped, for each SNP set. SNPs refers to the size of the SNP set, pGT refers to the proportion of individuals genotyped across SNPs in the SNP set, and MAF refers to the average minor allele frequency across SNPs in the SNP set.

			Ne	eEstimat	tor	Colony			
Lake	Stream	Рор	SNPs	pGT	MAF	SNPs	pGT	MAF	
Superior	Bad River	BAD	2810	0.953	0.19	658	0.929	0.23	
Michigan	Betsie River	BEI	3012	0.991	0.06	683	0.924	0.23	
Superior	Betsy River	BET	3008	0.985	0.11	682	0.924	0.24	
Superior	Brule River	BRL	2937	0.986	0.17	675	0.925	0.24	
Erie	Cattaraugus River	CAT	3010	0.98	0.09	679	0.925	0.24	
Huron	East Au Gres River	EAG	2990	0.977	0.12	678	0.92	0.23	
Michigan	Ford River	FOR	3015	0.995	0.05	680	0.925	0.23	
Michigan	Manistee River	MAN	3016	0.996	0.03	683	0.924	0.24	
Michigan	Manistique River	MAI	2883	0.949	0.18	682	0.925	0.23	
Superior	Middle River	MIR	3018	0.98	0.07	679	0.926	0.24	
Superior	Misery River	MIS	2914	0.977	0.17	670	0.924	0.23	
Michigan	Muskegon River	MUS	2985	0.989	0.13	677	0.925	0.24	
Huron	Ocqueoc River	OCQ	2999	0.987	0.1	680	0.926	0.23	
Huron	Pigeon River	CHE	2872	0.98	0.16	627	0.926	0.28	
Ontario	Sterling River	STE	2985	0.978	0.13	679	0.921	0.22	
Michigan	Swan Creek	SWN	2659	0.92	0.21	661	0.929	0.23	
Superior	Tahquamenon River	TAQ	2982	0.972	0.12	678	0.924	0.24	
Superior	Two-Hearted River	TWO	2946	0.984	0.16	676	0.925	0.24	

Mixture Models

Across 18 locations, ten had a sample size sufficient for cohort-assignment models (n > 80 individuals). Of those locations, four had multiple inferred cohorts based on the mixture analysis results (Table 2.2, Figure 2.2). When the two methods did not agree, the method that yielded a higher posterior probability was used to determine the K used for the Gaussian mixture models. Additionally, the Middle River and the Manistee River were the only locations with sequenced individuals sorted into multiple cohorts based on both the mixture analysis results (Table 2.2, Figure 2.2) as well as the cohort assignments as visualized in the boxplots (Figure 2.3). For other locations with multiple inferred cohorts, only inferred age-1 individuals were sequenced.

All cohorts of sequenced offspring had full- or half-sibling families present in the sample (Figure 2.4). Cohorts identified in most streams have a mixture of full- and half-sibling families. However, Swan Creek and Bad River have a small number of full-sibling families, and comparatively few half-sibling families (Figure 2.4). Locations like the Ocqueoc River and the Muskegon River are represented by mostly unrelated individuals (Figure 2.4). Table 2.2. Summary of results for identifying the optimal number of clusters (K) in the mixture analysis for sea lamprey. Analyses were performed for each larval collection with a range of K=1-4 clusters. R&M criteria and BD-MCMC shows the estimated probability of each K value from the Rousseau and Mengersen (2011) criteria and BD-MCMC, respectively. The optimal number of clusters from each method is bolded. If the two methods disagree, the method with the higher probability is used.

				K - BD-	MCMC						
Lake	Stream	Рор	1	2	3	4	1	2	3	4	SelectK
Michigan	Betsie	BEI	0.048	0.223	0.469	0.26	0.673	0.278	0.044	0.004	1
Superior	Betsy	BET	0.018	0.116	0.407	0.459	0.954	0.046	0.001	0	1
Erie	Cattaraugus	CAT	0.013	0.094	0.398	0.495	0.461	0.539	0	0	2
Michigan	Ford	FOR	0.188	0.693	0.113	0.006	0.918	0.079	0.003	0	1
Michigan	Manistee	MAN	0.027	0.144	0.406	0.423	0	0.996	0.004	0	2
Superior	Middle	MIR	0.001	0.027	0.346	0.626	0	0.899	0.101	0	2
Huron	Ocqueoc	OCQ	0.012	0.088	0.416	0.484	0.915	0.082	0.003	0	1
Ontario	Sterling	STE	0.162	0.608	0.208	0.022	0.918	0.08	0.003	0	1
Superior	Tahquamenon TA		0.054	0.253	0.45	0.243	0.876	0.112	0.006	0	1



Figure 2.2. Length frequency distributions for larval sea lamprey from all rivers and collection years, fill colors represent individual cluster assignment from the Gaussian mixture analysis. If mixture models were not completed due to small sample size ($n \le 80$), length histograms are included and shaded as purple.



Figure 2.3. Boxplots showing the length distributions of each Colony cluster of sequenced offspring. Boxes are shaded by the cluster likelihood, where lower likelihoods are shaded towards red and higher likelihoods are shaded towards white. Boxplots are limited to clusters with 3 or more individuals. The East Au Gres and the Muskegon River are not shown because they do not have any clusters larger than 3 individuals.



Figure 2.4. Diagrams of reconstructed pedigrees for all stream systems. The offspring are in the center of the diagram and are connected to their reconstructed parents by grey lines. The offspring are sorted first by parent 1 sibling groups, then parent 2 sibling groups.

N_b, N_s , and $\widehat{N_s}$ estimates

In most systems, N_b estimates were of similar magnitude across the three methods. Estimates from the PwoP method and SF method matched more closely with each other than with estimates from the linkage disequilibrium method (Table 2.3), which was expected based on previous work comparing the two estimators (Ackerman et al., 2017). In systems where the LD method did not agree with the PwoP and SF methods, LD was generally lower than the N_b estimates from the reconstructed pedigrees (Table 2.3). The largest estimates occurred in the Middle River (N_b =230-350 and the Muskegon River (N_b =255-309, and the smallest estimates occurred in Swan creek (N_b =6-7), the Bad River (N_b =3-6), and the East Au Gres River (N_b = 0.2-0.3). Five locations had N_b estimates under 10 across all three methods. Variance in individual reproductive success (V_k) was less than 50 across most systems, the highest variance occurred in the Sterling River (V_k =347.92).

The Chao and Jackknife extrapolated estimates of $\widehat{N_s}$ were similar in most sampled systems, and were generally higher than the N_b estimates for each cohort. Some systems had a small sample size (less than 50 individuals), but finite estimates were still calculable due to the fact that all samples contains some related individuals (Figure 2.5). Confidence intervals were potentially artificially narrow due to the large number of SNPs used in the analyses (Waples, Waples, & Ward, 2020), although the corrected jackknife estimates used should reduce that bias. All seven locations with small sample size had LD N_b estimates of less than 100. Of these locations, three had mark-recapture estimates of over 10,000 and N_s estimates of less than 100 (Table 2.3).

Table 2.3. N_b and N_s estimates and population-based information. N indicates the number of sequenced offspring for the cohort, N_c is the census-size estimate based on mark-recapture during the spawning year. linkage disequilibrium (LD), parentage without parents (PwoP) and sibship frequency (SF) columns are N_b point estimates with corresponding uncertainty. LD: N_c and SF: N_c refer to the ratios between the LD and SF method of estimating N_b and the mark-recapture N_c estimates. \overline{k} and V_k are the mean and variance in reproductive success inferred from the reconstructed pedigree. N_s is the number of reconstructed parent genotypes for each cohort, and Chao and Jackknife are the $\widehat{N_s}$ estimates and their corresponding 95% confidence intervals.

Lake	Stream	Рор	N	Nc	LD	PwoP	SF	LD: N _c	SF: Nc	\overline{k}	V_k	Ns	Chao	Jackknife
Superior	Bad River	BAD	37	11301	2.7 (2.3- 3.3)	6.22 (5.78- 6.74)	6 (2- 20)	0.0002	0.0005	8.22	37.06	9	9.97± 2.2	10.95 ± 1.96
Michigan	Betsie River	BEI	160	1654	62.1 (48.7- 82.1)	80.51 (68.58- 95.5)	80 (58- 113)	0.0375	0.0484	2.03	1.92	78	97.41 ± 8.32	112.58± 7.41
Superior	Betsy River	BET	246	1097	58.6 (46.2- 75.8)	78.78 (71.06- 88.13)	78 (57- 107)	0.0534	0.0711	2.34	4.15	105	188.34 ± 31.22	159.55± 9.58
Superior	Brule River	BRL	33	36558	73.2 (40.5- 230.5)	112.89 (77.29- 209.29)	111 (72- 203)	0.0020	0.0030	1.29	0.36	51	161.82 ± 55.62	89.79± 8.52
Erie	Cattaraugus River	CAT	241	1637	33.3 (29.3- 37.7)	39.81 (38.38- 41.35)	40 (28- 62)	0.0203	0.0244	6.89	42.67	70	$76.02 \pm \\ 4.78$	80.95 ± 4.11
Huron	Pigeon River	CHE	51	NA	8.0 (6.3- 9.7)	3.90 (3.74- 4.07)	4 (2- 12)	NA	NA	9.27	163.65	11	$\begin{array}{c} 11.98 \pm \\ 1.84 \end{array}$	12.96 ± 1.39
Huron	East Au Gres River	EAG	21	2124	0.3 (0.2- 0.3)	172.2 (90.93- 1619.39)	168 (84- 1201)	0.0001	0.0791	1.14	0.12	37	134.52 ± 56.47	67.48 ± 7.59
Michigan	Ford River	FOR	122	NA	44.2 (33.1- 60.4)	40.33 (37.68- 43.4)	40 (27- 62)	NA	NA	2.18	10.56	112	188.76± 25.13	178.45 ± 10.08
Michigan	Manistique River	MAI	30	10420	6.7 (3.7- 10)	12.04 (10.44- 14.22)	11 (6- 26)	0.0006	0.0011	4.00	7.6	15	22.73 ± 11.28	18.87 ± 1.93
Michigan	Manistee River	MAN	185	7219	126.0 (100.8- 162.4)	178.32 (160.94- 199.91)	178 (141- 227)	0.0175	0.0247	1.90	1.92	180	312.60 ± 35.68	281.40 ± 13.21

Table 2.3 (cont'd).

Superior	Middle River	MIR	447	4705	230.9 (204.6- 262.4)	350.01 (330.07- 372.50)	350 (293- 413)	0.0744	0.0491	2.17	2.86	401	567.75 ± 31.77	590.56± 16.58
Superior	Misery River	MIS	37	NA	9.8 (7.9- 12.0)	9.58 (8.70- 10.65)	9 (5- 24)	NA	NA	5.29	17.63	14	$\begin{array}{c} 14.24 \pm \\ 0.71 \end{array}$	14.97 ± 0.97
Michigan	Muskegon River	MUS	53	NA	255.0 (172.8- 467.0)	309.17 (209.62- 588.8)	306 (202- 594)	NA	NA	1.19	0.18	89	263.28 ± 62.16	160.62 ± 11.01
Huron	Ocqueoc River	OCQ	121	4813	134.3 (105.0- 179.9)	184.56 (158.87- 220.17)	184 (142- 237)	0.0279	0.0382	1.09	1.09	147	$\begin{array}{r} 248.05 \pm \\ 28.88 \end{array}$	234.27 ± 11.01
Ontario	Sterling River	STE	105	2868	6.6 (5.2- 7.9)	5.74 (5.60- 5.90)	6 (3- 21)	0.0023	0.0382	17.50	347.92	12	12 ± 0.47	12.99 ± 0.99
Michigan	Swan Creek	SWN	39	NA	1.9 (1.7- 2.0)	4.41 (4.09- 4.78)	4 (2- 12)	NA	NA	11.14	81.55	7	9.92± 4.33	9.92 ± 2.19
Superior	Tahquamenon River	TAQ	94	3974	52.0 (39.0- 72.3)	68.93 (61.49- 78.43)	69 (49- 98)	0.0131	0.0174	2.29	3.26	82	125.86 ± 14.67	118.61 ± 7.35
Superior	Two-Hearted River	TWO	43	NA	25.6 (17.2- 40.7)	30.21 (25.95- 36.14)	30 (19- 51)	NA	NA	2.05	3.62	42	77.16 ± 19.89	65.44 ± 6.51



Figure 2.5. Minimum number of spawning adults $(\widehat{N_s})$ accumulation curves showing the increase in unique parent genotypes as the number of sequenced offspring increased for each cohort. The dark red lines in each plot represent the chao asymptote estimates (Chao, 1987a), and the dark blue lines represent the jackknife asymptote estimates (Heltshe & Forrester, 2009).
Correlations and Linear Modeling

Correlations between N_c , N_b , and $\widehat{N_s}$ were not significant with either a Pearson productmoment correlation or a non-parametric Spearman rank order test (Figure 2.6). N_b and $\widehat{N_s}$ estimates were highly correlated (SF and $\widehat{N_s}$: corr= 0.954 (p < 0.001), LD and $\widehat{N_s}$: corr = 0.951 (p < 0.001)), indicating consistency across the two types of genetic estimates. Additionally, a version of the model run with an N_c estimate corrected for the number of lamprey removed from the stream during mark-recapture was run. This version was run to correct for the fact that removed lamprey are less likely to be among the contributing parents in the stream, and thus may not be represented in N_b and $\widehat{N_s}$ estimates. However, the corrected version of the model that corrected also had no correlation with N_b and N_c . Additionally, when a version of the model that corrected for small sample size was evaluated there was still no relationship with N_b and N_c .

The linear models with subsets of environmental, biotic and sampling variables (Table 2.4) consistently found that sampling variables were significant predictors for both N_b and $\widehat{N_s}$ estimates. In order to minimize missing data, three subsets of models were run. A version was run using variables with no missing data across streams: years since TFM treatment, drainage area, the number of sampling sites, and sample size (n=18). An additional set added the distance between the river mouth and traps, which only applied to some streams (n=12). Finally, a third set of models was run for $\widehat{N_s}$ and V_k with N_c estimates (n=13).

For the LD models, sample size was in the confidence set for both subsets of response variables (Table 2.5A and 2.5B). For the version of the model with only response variables collected for all stream locations, the global model, the number of sampling sites and drainage area were also included in the confidence set (Table 2.5B). Sample size (coefficient = 0.40 and 0.46) and drainage area (coefficient = 0.023) were the only significant predictors across the

models (Figure 2.7). Both were positively associated with LD-based estimates of N_b . The SF models found that sample size and the number of sampling sites were in the confidence set for both subsets of response variables (Table 2.5A and 2.5B), with sample size (coefficients = 0.54and (0.59) and the number of sampling sites (coefficient = 37.2 and 37.92) as significant predictors (Figure 2.7), both were positively associated with SF estimates of N_b . Sample size and the number of sampling sites were both included in the confidence set of all three model subsets tested for the Chao models (Table 2.5A, 2.5B, and 2.5C). Sample size was a significant predictor in all three model subsets (coefficients = 1.05, 1.07, and 1.05), and the number of sampling sites was a significant predictor (coefficient = 62.73) in the model subset with the N_c estimates (Figure 2.7). The V_k models had more variance in confidence sets across model subsets. In the version of the model with only response variables collected for all stream locations, drainage area, the number of sampling sites, and the years since TFM treatment were all included in the confidence set (Table 2.5A). When the distance between mark-recapture traps and the mouth of the river is included in the model, it is included in the confidence set along with drainage area and years since TFM treatment (Table 2.5B). When N_c is included as a variable, it is included in the confidence set along with the years since TFM treatment, drainage area, and the number of sampling sites (Table 2.5C). However, none of the models in the confidence set contain significant coefficients.



Figure 2.6. Scatterplots of effective breeding size (N_b) , minimum number of spawning adults $(\widehat{N_s})$, and census size from mark-recapture (N_c) estimates. N_c is shown on the x-axis, the N_b or N_s estimate is shown on the y-axis. No lines of best fit were included due to the lack of significant correlation between variables in the plots.

Table 2.4. Environmental, biotic, and sampling variables used in linear models. Treatment year refers to the most recent TFM treatment that occurred in the stream, N_c is the census-size estimate based on mark-recapture for the years 2016, 2017, and 2018, and 'Trap efficiency 2018' refers to estimated trap efficiency in 2018 (used to generate N_c). Drainage refers to the drainage area of the stream (in hectares), larval potential is a categorical variable that refers to the history of larval production and TFM treatments in the stream, trap to mouth distance refers to the distance in km between the mouth of the river and the traps used for N_c estimates. Sampling sites refers to the number of collection locations for the larval collections, years since treatments is the number of years between the last TFM treatment and the collection year. Sampling distance refers to the approximate distance sampled in each stream. If only one site was sample 0.2 km was used based on the standard transect distance for backpack electrofishing.

Lake	Stream	Рор	Treatment Year	Treatment Month	Nc 2016	Nc 2017	Nc 2018	Trap Efficiency 2018	Drainage	Larval potential	Trap To Mouth Distance	Sampling Sites	Year Since Treat	Sampling Distance
Superior	Bad	BAD	2017	September	1605	5878	11301	6	2270	1	23	1	2	0.2
Michigan	Betsie	BEI	2017	June	1259	984	1654	61	590	1	14	1	2	0.2
Superior	Betsy	BET	2017	July	396	3778	1097	25	230	1	9	2	2	0.2
Superior	Brule	BRL	2018	June	3194	21024	36558	9	408	1	6	1	1	0.2
Erie	Cattaraugus	CAT	2016	May	NA	5901	1637	10	1129	1	33	4	2	11.0
Huron	Pigeon	CHE	NA	NA	NA	NA	NA	NA	1550	1	2	3	NA	6.0
Huron	East Au Gres	EAG	2018	June	1846	1542	2124	27	653	1	17	2	1	3.0
Michigan	Ford	FOR	2017	May	NA	NA	NA	NA	1216	1	NA	1	2	0.2
Michigan	Manistique	MAI	2016	September	8191	6549	10420	54	3631	1	1	1	2	0.2
Michigan	Manistee	MAN	2016	August	2486	2972	7219	6	546	1	32	1	2	0.2
Superior	Middle	MIR	2013	June	4705	4519	3113	0	142	1	5	7	3	6.0
Superior	Misery	MIS	2018	August	18	18	NA	NA	102	1	2	1	1	0.2
Michigan	Muskegon	MUS	2017	September	NA	NA	NA	NA	7327	1	NA	1	2	0.2
Huron	Ocqueoc	OCQ	2016	July	6016	2539	4813	70	363	1	4	2	3	3.0
Ontario	Sterling	STE	2018	May	NA	1891	2868	21	80	1	NA	1	1	0.2
Michigan	Swan	SWN	2013	July	NA	NA	NA	NA	5	2	NA	1	6	0.2
Superior	Tahquamenon	TAQ	2015	October	9465	10549	3974	24	2176	1	16	1	4	0.2
Superior	Two-Hearted	TWO	2016	August	NA	NA	NA	NA	521	1	NA	1	3	0.2

Table 2.5A. Table for environmental, biotic, and sampling linear models. Significant variables are bolded along with the corresponding coefficient and p-value. In Table 2.5A, the global model consists of the following variables: years since TFM treatment, drainage area, number of sampling sites and sample size.

Response	Explanatory Variables	Coefficient	p-value	AICc	Akaike Weight
	Sample Size	0.4034	0.0264	196.4321	0.3712363
quilibrium	Years Since TFM Treatment Drainage Sample Sites Sample Size	0.672 0.023 -7.741 0.605	0.9543 0.0122 0.7179 0.0826	197.6451	0.20241474
ise	Sample Sites	22.4	0.0689	198.3243	0.14413415
e D	Drainage	0.017	0.105	199.1191	0.09686757
inkag	Sample Size Sample Sites			199.3055	0.08824683
	Intercept			199.6083	0.07584604
N_{b}	Years Since TFM Treatment			202.1526	0.02125438
	Sample Sites	37.2	0.0216	206.4399	0.42189059
cy	Sample Size	0.5414	0.0287	207.011	0.31709707
uanba	Sample Sites Sample Size	26.502 0.1805	0.45 0.732	209.2815	0.1018986
Fre	Intercept			210.023	0.07032968
[di	Drainage			211.169	0.0396551
N _b - Sibsh	Years Since TFM Treatment Drainage Sample Sites Sample Size			211.7466	0.02970713
	YearSinceTreat			212.5966	0.01942183

Table 2.5A (cont'd).

Response	Explanatory Variables	Coefficient	p-value	AICc	Aikike Weight
	Sample Size	1.047	0.0005	209.0347	0.724473908
	Sample Size Sample Sites	1.072 -1.783	0.076 0.962	212.0209	0.162772636
	Sample Sites			212.9807	0.100731972
- Chao	Years Since TFM Treatment Drainage Sample Sites Sample				
$\widehat{N_s}$	Size			217.9207	0.00852031
	Intercept			220.5784	0.002256035
	Years Since TFM Treatment			223.1463	0.000624782
	Drainage			223.1605	0.000620357
	Intercept	33.3	0.122	202.0964	0.421149264
	Drainage	-0.009	0.433	203.9984	0.162716566
	Sample Sites	-6.272	0.653	204.4507	0.129781287
	Years Since TFM Treatment	-7.511	0.666	204.4682	0.12865016
V_k	Sample Size			204.6794	0.11575345
	Sample Size Sample Sites			206.7859	0.040375772
	Years Since TFM Treatment Drainage Sample Sites Sample			212 2759	0.001573502
	Treatment Drainage Sample Sites Sample Size			213.2758	0.001573:

Table 2.5B. Table for environmental, biotic, and sampling glm models. Significant variables are bolded along with the corresponding coefficient and p-value. In Table 2.5B, the global model consists of the following variables: years since TFM treatment, drainage area, number of sampling sites, sample size, and distance from the mouth of the river to the mark-recapture trap site.

Response	Explanatory Variables	Coefficient	p-value	AICc	Akaike Weight
	Sample Size	0.4597	0.001	129.3633	0.704144855
	Sample Size Sample				
	Sites			131.5453	0.236509564
III	Sample Sites			135.2397	0.037293206
rii	Drainage			138.8017	0.006282662
llib	Years Since TFM				
mb	Treatment			138.8339	0.006182494
ise	intercept			138.9071	0.005960196
D	Trap To Mouth				
age	Distance			141.6403	0.001519708
nk:	environmental			142.2926	0.001096781
Li	Years Since TFM				
- q ₁	Treatment Drainage				
<	Sample Sites				
	Sample Size Trap to				
	River Mouth				
	Distance			142.4564	0.001010534
	Sample Size	0.5866	0.0106	142.6609	0.4623211
	Sample Sites	37.92	0.0138	143.256	0.3433462
	Sample Size Sample	0.3903	0.434		
	Sites	14.28	0.662	146.0585	0.08456122
cy	Drainage			147.1802	0.04826085
ien	Intercept			147.9442	0.03293873
nba	Years Since TFM				
Fre	Treatment			149.9014	0.01237913
[di	environmental			150.7518	0.008091478
lls	Trap To Mouth				
Sib	Distance			150.7556	0.008076147
- 9	Years Since TFM				
N	Treatment Drainage				
	Sample Sites				
	Sample Size Trap to				
	River Mouth				
	Distance			162.295	2.52032E-05

Table 2.5B (cont'd).

Response	Explanatory Variables	Coefficient	p-value	AICc	Aikike Weight
	Sample Size	1.0693	0.001	209.0347	0.724473908
	Sample Size Sample Sites	1.2398 12.4086	0.0764 0.7697	212.0209	0.162772636
	Sample Sites			153.1286	0.08926541
	Drainage			158.44	0.006270724
	Intercept			158.895	0.004994732
Chao	Years Since TFM Treatment			160.0882	0.002750579
$\widehat{N_s}$ -	Trap To Mouth Distance			161.7535	0.001196181
	environmental			162.0578	0.00102735
	Years Since TFM Treatment Drainage Sample Sites Sample Size Trap to River			167 5906	(102275 05
	Mouth Distance			167.5806	6.49327E-05
	Distance	1 3573	0.11	101 7188	0 3189623
	Intercent	10.053	0.11	102.0076	0.2760846
	Drainage	0.0037	0.379	102.0070	0.1037338
	Dramage	0.0034	0.381	105.7055	0.1057550
	environmental	0.6279	0.124	104.3042	0.08756584
	Years Since TFM Treatment	-1.984	0.708	104.7636	0.06959273
V_k	Sample Sites			104.8159	0.06779892
	Sample Size			104.9146	0.06453247
	Sample Size Sample Sites			108.3277	0.01171205
	Years Since TFM Treatment Drainage Sample Sites Sample Size Trap to River Mouth Distance			121.3673	1.72637E-05

Table 2.5C. Table for environmental, biotic, and sampling glm models. Significant variables are bolded along with the corresponding coefficient and p-value. In Table 2.5C, the global model consists of the following variables: years since TFM treatment, drainage area, number of sampling sites, sample size, and Nc estimates. In Table 2.5C, only N_s – Chao and V_k were considered as response variables.

Response	Explanatory Variables	Coefficient	p-value	AICc	Akaike Weight
	Sample Size	1.0516	0.002	150.5441	0.6762677
	Sample Sites	62.73	0.008	153.1635	0.1825183
	Sample Size Sample				
	Sites			154.1869	0.1094195
	Drainage			158.5344	0.01244596
•	Intercept			158.9242	0.010242
ha	Years Since TFM				
	Treatment			160.1061	0.00567209
$\langle N_{s} \rangle$	N_c Estimate			161.8385	0.002385413
	environmental			163.6739	0.0009528
	Years Since TFM				
	Treatment Drainage				
	Sample Sites				
	Sample Size Nc				
	estimates			168.2597	9.62108E-05
	Intercept	37.58	0.214	147.6474	0.3422417
	Years Since TFM				
	Treatment	-42.11	0.218	148.6694	0.2053103
	Drainage	0.019	0.498	150.0009	0.1055069
	N _c Estimate	-0.002	0.622	150.2749	0.09200045
	Sample Sites	-8.344	0.635	150.2974	0.09097165
	Sample Size			150.5627	0.07967152
V_k	environmental			151.0046	0.06387491
	Sample Size Sample				
	Sites			153.2862	0.02041256
	Years Since TFM				
	Treatment Drainage				
	Sample Sites				
	Sample Size Nc				
	estimates			168.5276	1.0006E-05



Figure 2.7. Plots of significant predictors of N_b and $\widehat{N_s}$ estimates based on the results of the environmental models.

Effects of Sample Size, SNP set size, and stream N_b on genetic estimates

Rmetasim simulated populations with true N_b values within 7% of the input N_b value after 50 generations of burn-in. True N_s , or the total number of parents in the population, were within 6% of other replicates.

Point estimates of N_b across methods were accurate for populations with small true N_b (N_b < 1000), but accuracy varied when N_b was large. Particularly when sample size or SNP size were small, the PwoP and SF N_b estimates had a downward bias compared to true N_b , where the estimated Nb values do not increase as true Nb increases (Figure 2.8A,2.8C). Conversely, the LD estimate had an upward bias at some scenarios, although the bias is smaller than the other two estimates (Figure 2.8B). The LD method had more variation in point estimates across replicates than the other two N_b estimation methods (Figure 2.9A-C). RMSE values were generally higher when sample size was small across methods (Figure 2.10A-C), indicating that small sample size decreased precision in estimates across N_b methods.

When N_b is small, the Chao and Jackknife method estimates performed similarly when compared to true N_s (Figure 2.9D-E). However, as N_b increased, the Jackknife method had a larger downward bias compared to the Chao method across sample size and SNP groups (Figure 2.9D-E). The Chao method shows a downward bias as well when SNP set size or sample size are small for large true N_b populations (Figure 2.9D). For both the Chao and the Jackknife method, RMSE increased with true N_b of populations, indicating that variation in estimated $\widehat{N_s}$ increases as the true N_b of the population increases (Figure 2.10D-E). When N_b is greater than 1000, RMSE values are similarly high across SNP size and sample size for the Jackknife method, but in the Chao method increasing the number of SNPs decreases RMSE (Figure 2.10D-E).



Figure 2.8A. A figure that visualizes the ratio between estimated N_b and the true N_b estimate from each simulation. The sample size parameter is on the x-axis, the SNP set size is separated by color, and the plots are subset by the effective breeding size parameter. Figure 2.8A is the sibship frequency method.



Figure 2.8B. A figure that visualizes the ratio between estimated N_b and the true N_b estimate from each simulation. The sample size parameter is on the x-axis, the SNP set size is separated by color, and the plots are subset by the effective breeding size parameter. Figure 8B is the linkage disequilibrium method.



Figure 2.8C. A figure that visualizes the ratio between estimated N_b and the true N_b estimate from each simulation. The sample size parameter is on the x-axis, the SNP set size is separated by color, and the plots are subset by the effective breeding size parameter. Figure 2.8C is the parents without parents methods.



Figure 2.9A. Plots (plot 2.9A-2.9E) to show accuracy of point estimates for simulated populations. The x-axes are log_{10} of the parameter effective breeding size (N_b), and the y-axes are log_{10} of the estimated N_b or the minimum number of spawning adults (N_s). The plots are subset by SNP set size and sample size, and figures are separated by each method. Figure 2.9A shows results from the sibship frequency estimates.



Figure 2.9B. Plots (plot 2.9A-2.9E) to show accuracy of point estimates for simulated populations. The x-axes are log_{10} of the parameter effective breeding size (N_b), and the y-axes are log_{10} of the estimated N_b or the minimum number of spawning adults (N_s). The plots are subset by SNP set size and sample size, and figures are separated by each method. Figure 2.9B shows results from the linkage disequilibrium estimates.



Figure 2.9C. Plots (plot 2.9A-2.9E) to show accuracy of point estimates for simulated populations. The x-axes are log_{10} of the parameter effective breeding size (N_b), and the y-axes are log_{10} of the estimated N_b or the minimum number of spawning adults (N_s). The plots are subset by SNP set size and sample size, and figures are separated by each method. Figure 2.9C shows results from the parentage without parents estimates.



Figure 2.9D. Plots (plot 2.9A-2.9E) to show accuracy of point estimates for simulated populations. The x-axes are log_{10} of the parameter effective breeding size (N_b), and the y-axes are log_{10} of the estimated N_b or the minimum number of spawning adults (N_s). The plots are subset by SNP set size and sample size, and figures are separated by each method. Figure 2.9D shows results from the chao estimates.



Figure 2.9E. Plots (plot 2.9A-2.9E) to show accuracy of point estimates for simulated populations. The x-axes are log_{10} of the parameter effective breeding size (N_b), and the y-axes are log_{10} of the estimated N_b or the minimum number of spawning adults (N_s). The plots are subset by SNP set size and sample size, and figures are separated by each method. Figure 2.9E shows results from the jackknife estimates.



Figure 2.10A. Root mean squared error (RMSE) plots (plots 2.10A-2.10E) for each type of estimate to show the variance in point estimates for simulated populations. RMSE (y-axis) is plotted versus the sample size (x-axis). The line colors are the SNP set size, where yellow corresponds to SNPs=100, dark blue corresponds to SNPs=500, and green-grey corresponds to SNPs=1000. The plots are subset by parameter effective breeding size (N_b), and the figures are separated by N_b and the minimum number of spawning adults (N_s) estimate method. Figure 2.10A shows results from the sibship frequency estimates.



Figure 2.10B. Root mean squared error (RMSE) plots (plots 2.10A-2.10E) for each type of estimate to show the variance in point estimates for simulated populations. RMSE (y-axis) is plotted versus the sample size (x-axis). The line colors are the SNP set size, where yellow corresponds to SNPs=100, dark blue corresponds to SNPs=500, and green-grey corresponds to SNPs=1000. The plots are subset by parameter effective breeding size (N_b), and the figures are separated by N_b and the minimum number of spawning adults (N_s) estimate method. Figure 2.10B shows results from the linkage disequilibrium estimates.



Figure 2.10C. Root mean squared error (RMSE) plots (plots 2.10A-2.10E) for each type of estimate to show the variance in point estimates for simulated populations. RMSE (y-axis) is plotted versus the sample size (x-axis). The line colors are the SNP set size, where yellow corresponds to SNPs=100, dark blue corresponds to SNPs=500, and green-grey corresponds to SNPs=1000. The plots are subset by parameter effective breeding size (N_b), and the figures are separated by N_b and the minimum number of spawning adults (N_s) estimate method. Figure 2.10C shows results from the parentage without parents estimates.



Figure 2.10D. Root mean squared error (RMSE) plots (plots 2.10A-2.10E) for each type of estimate to show the variance in point estimates for simulated populations. RMSE (y-axis) is plotted versus the sample size (x-axis). The line colors are the SNP set size, where yellow corresponds to SNPs=100, dark blue corresponds to SNPs=500, and green-grey corresponds to SNPs=1000. The plots are subset by parameter effective breeding size (N_b), and the figures are separated by N_b and the minimum number of spawning adults (N_s) estimate method. Figure 2.10D shows results from the chao estimates.



Figure 2.10E. Root mean squared error (RMSE) plots (plots 2.10A-2.10E) for each type of estimate to show the variance in point estimates for simulated populations. RMSE (y-axis) is plotted versus the sample size (x-axis). The line colors are the SNP set size, where yellow corresponds to SNPs=100, dark blue corresponds to SNPs=500, and green-grey corresponds to SNPs=1000. The plots are subset by parameter effective breeding size (N_b), and the figures are separated by N_b and the minimum number of spawning adults (N_s) estimate method. Figure 2.10E shows results from the jackknife estimates.

DISCUSSION

Genetic assessment using N_b and N_s estimates provides unique insights into sea lamprey systems that cannot be obtained from other types of adult assessment. N_b and N_s provide information on the number of successfully spawning adults in streams, and reconstructed pedigrees show the variation in reproductive success and family size for spawning populations. N_b and N_s are informative particularly for streams with potential barrier failure or streams where trapping is difficult. Understanding the influences of environmental, biotic, and sampling factors on N_b and N_s is important but the specific factors influencing these estimates in a given stream system can be difficult to predict. Simulated sea lamprey populations showed that N_b and N_s estimates can be obtained for ecologically realistic sea lamprey stream populations if SNP sets are sufficiently large (greater than 500 SNPs), which can be obtained using a RAD-capture panel. Additionally, obtaining a sample size of 100 individuals or greater will help to minimize bias in estimates.

The use of N_b as a genetic assessment technique has been well-documented in the literature. N_b has previously been used to evaluate rates of inbreeding and genetic diversity for threatened and endangered species (Duong, Scribner, Forsythe, Crossman, & Baker, 2013; Waller & Keller, 2002). It has also been used to assess conservation management actions like stocking (Kazyak, Rash, Lubinski, & King, 2018; Petereit et al., 2018b) and genetic rescue (Hedrick, Peterson, Vucetich, Adams, & Vucetich, 2014). Genetic estimates are used both as a primary assessment technique as well as a supplementary tool paired with assessment techniques like mark-recapture estimates of adult abundance. In this study, the utility of N_b and N_s as an assessment tool is illustrated through their estimation in eighteen great lakes tributaries.

However, obtaining representative and sufficient samples in a stream, as well as accurately separating those samples into their respective cohorts, is crucial for obtaining accurate estimates.

Simulation Recommendations

Simulated populations showed that genomic data sets provide the power necessary to estimate N_b and N_s even when true N_b is large. However, estimates based on the reconstructed pedigrees underestimate N_b and N_s when true $N_b > 500$, particularly if the SNP set used is too small (n = 100) regardless of sample size (Figure 2.9A,C). In contrast the average LD estimate is closer to true N_b when SNP size is low compared to methods generated with a reconstructed pedigree, but the variation in estimates is much greater (Figure 2.9B). The results of our simulation study are consistent with previous simulations studying the biases of LD that showed a small upward bias with large true N_e (Waples, 2016), that SF can have a downward bias especially when true N_e is large (Wang, 2016), and other N_b method comparison simulation studies highlighting better precision for estimates with small true N_e (Robinson & Moyer, 2013). The bias in N_s estimates is consistent with known limitations from sample size, since N_s is directly based on the number of parent genotypes. Additionally, a small SNP set may lead to more falsely inferred sibling relationships, leading to a downward bias of extrapolated estimates compared to the true N_s value. However, when true N_b is large, the Chao estimator outperforms the Jackknife, suggesting that the Chao estimator is the better tool to use particularly for large populations. Our simulations are informative for future attempts to sample for N_b and N_s estimates. If expected N_b is large, obtaining a greater number of sampled offspring and generating sufficient numbers of SNPs should be prioritized to ensure minimal bias in estimates.

Reconstructed Pedigrees and Genetic Estimates

Reconstructed pedigrees were generated for a variety of streams in the Great Lakes region, and they provide a unique look into the diversity of family structure across sea lamprey larval populations in the region. Locations range from a small number of full-sibling families, to groups of mostly unrelated individuals, to large interconnected populations of half-sibling families (Figure 2.4). This variety shows that sea lamprey spawning dynamics are highly variable among lamprey-producing streams across the region, highlighting the importance of evaluating lamprey spawning populations on a per-stream basis.

Accurate separation of cohorts is vitally important for estimation of N_b and N_s . Reconstructed pedigree data, namely Colony clusters, can be used to evaluate individual cohort assignments generated from mixture models and larval length data in semelparous species like sea lamprey. When two individuals were assigned to different cohorts on the basis of length, but connected in the pedigree, we reclassified individuals into cohorts associated with their full- or half-siblings. However, corrections in the opposite direction, where the mixture models indicate a singular cluster when multiple clusters are suspected from patterns in length and/or genomic data, are not possible given this approach (Figure 1.2). This could be the case for the Ocqueoc River, where two clear modes are present in the length-frequency histogram (Figure 2.2) and boxplots of Colony cluster lengths (Figure 2.3) that there are two groups of unrelated individuals with a length cutoff of approximately 37mm. However, the mixture analysis results indicated one cohort, so the groups were not separated for subsequent analyses. If individuals from multiple cohorts are combined, bias can be introduced into estimates of N_b and N_s . For example, the full population of the Ocqueoc produced an SF N_b estimate of 184 and an LD N_b estimate of 134.3 but given patterns in the length-frequency histograms and the distributions of lengths of

individuals connected in the reconstructed pedigree for this population, it seems possible that these estimates combine individuals from two cohorts (i.e., 2018 and 2019 year classes). If the two cohorts are separated, the 2019 N_b estimates (length < 37mm) are 51 (SF) and 33.7 (LD), while the 2018 N_b estimates are 134 (SF) and 104.2 (LD). Future research will evaluate other methods for aging lamprey using genomic techniques, or improvements to the mixture analysis that would reduce uncertainty in situations like that seen in the Ocqueoc River.

N_b and N_c relationship and Sampling Effects

The relationship between N_b and N_c estimates is dependent on a large number of sampling and environmental factors, and obtaining a model for that relationship remains difficult. Our models primarily showed the influence of sample size and the number of sampling sites as influences on N_b and N_s estimates. N_b is influenced by many factors that vary across reproductive events, including variation in reproductive success, skewed sex ratios, and the fecundity of spawning individuals. Previous work estimating N_c considered variables similar to the environmental data used in the generalized linear models in the study (Mullett et al., 2003), and thus the lack of significance of those environmental variables conflicted with some of our expectations. For example, streams recently treated with TFM should have lower adult recruitment the following year due to weaker larval cue, leading to lower N_b and N_s estimates, but there was not a significant relationship between our estimates and years since TFM treatment. However, variables like drainage area did have the expected positive relationship with N_b using the LD method.

When N_c is large and the representative sequenced larvae have significant family structure coupled with small sampled size, there is some concern that estimates may be

representative of a small group of families rather than the full spawning population in a stream (Whiteley et al., 2012). In three of our stream locations, N_c was greater than 10,000, the sampled offspring group was less than 30, and the sample was collected from a single site in the stream. In these systems, non-random sampling may be leading to downward bias in these estimates. The correlations between N_b , N_s and N_c were conducted with and without these locations and the relationships remained nonsignificant. There is not a universal solution to remove the bias that could exist from family effect, especially since representative family structure is necessary to calculate both N_b and N_s (Waples & Anderson, 2017). To combat this potential bias, sampling multiple locations in a stream that are spread across larval habitat in the stream can minimize potential family effect bias and ensure that sampling is representative of the true spawning event. In addition to family effect, there are sources of uncertainty present in the N_c estimates that could have further complicated models involving those estimates. Low trap efficiency and variation in trap efficiency across years and index streams, as well as variation in catchability for individual lamprey all contribute to uncertainty in N_c (Harper et al., 2018b).

Across systems, N_b and N_c have not necessarily had a correlative relationship (Bernos & Fraser, 2016; Whiteley et al., 2015), especially when the population size is large (Waples, 2016). However, some studies have found a relationship when environmental factors and population dynamics could be adjusted for to account for variation in the $N_e:N_c$ ratio (Ruzzante et al., 2016). In particular, the relationship between sufficient and representative sampling was highlighted (Whiteley et al., 2012), which is consistent with the modeling results found in our study. When the sample size and sampling distance is small, there is the possibility of non-random sampling leading to N_b and N_s estimates that represent the small number of families in the sample rather than the full stream population, known as the family effect. Additional environmental variables like the amount of spawning habitat, density of spawning adults and stream flow during spawning could also affect N_b and N_s estimates and were not included in models for this study (Whiteley et al., 2015). A further potential complication is genetic compensation, which is when variation in reproductive success decreases in small populations, inflating N_b estimates compared to N_c (Ardren & Kapuscinski, 2003; Whiteley et al., 2015). The lack of significance in N_b and N_c estimates in this study, as well as the significant relationship between sampling factors and N_b estimates in our models, underscores the need for large and representative sampling when estimating N_b from population genomic data.

Applications in Management

 N_b and N_s can be used to provide additional information about sea lamprey spawning systems as an augmentative annual assessment technique. If an index group of streams are assessed over a larger number of years, families and cohorts can be evaluated as an annual larval and adult assessment technique, which can be utilized to assess larval growth rates and larval dispersal in streams. N_b and N_s can also be used to evaluate the efficacy and effectiveness of supplemental control techniques like sterile male release and repellant/attractants in push-pull configurations to increase trapping efficiency, and the use of alarm cue as a barrier technique. Additionally, N_b provides information on inbreeding, drift, and loss of diversity that is present in the population, all of which can be used to further evaluate control techniques. N_s estimates also can provide an annual metric of the minimum number of successfully spawning adults, which could be used as an annual assessment metric for the amount of successful spawning that occurs in streams across the region. While sea lamprey are one of the most destructive species in the Great Lakes region, the species is under threat in parts of its native range, namely in the Eastern Atlantic. Genetic assessment techniques like N_b and N_s can be utilized for both control and conservation efforts for sea lamprey and other species. Although connections between N_b and N_c are complicated by a variety of factors, genetic estimates provide a unique look into the genetic structure of a population that can aid in monitoring efforts to conserve or control a species.

APPENDIX

APPENDIX

Table of Acronyms

- RAD: Restriction-site Associated DNA
- MAF: Minor Allele Frequency
- V_k : The variance in family size for adults represented in sampling
- *N_e*: Effective population size
- *N_b*: Effective breeding size
- *N_c*: Census size estimate based on mark-recapture trapping methods
- Ns: The minimum number of spawning adults

 $\widehat{N_s}$: The minimum number of spawning adults extrapolated using a 'pedigree reconstruction curve'

RMSE: Root mean squared error

LD: N_b estimate using the linkage disequilibrium method

- SF: N_b estimate using the sibship frequency method
- PwoP: N_b estimate using the parentage without parents method
- SNP: Single nucleotide polymorphism
- TFM: 3-triflouromethyl-4-nitrophenol, a selective lampricide
- AIC: Akaike information criterion
- AICc: Akaike information criterion, corrected for small sample size

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CONCLUSIONS

Overall, the experiments and results detailed above demonstrate the utility of reconstructed pedigrees and N_b and N_s estimates for evaluating sea lamprey spawning populations in streams. With regards to determining the number of cohorts, a necessary step in calculating N_b and N_s , mixture analysis models using length data alone were insufficient to separate individuals into cohorts, particularly for age 2+ individuals. Reconstructed pedigrees and the presence of family structure can be combined with length data using a decision-making matrix to identify cohorts that are oversplit by the mixture analysis models to more accurately generate cohort assignments for genotyped populations.

 N_b and N_s estimates, along with the analysis of reconstructed pedigrees, are useful in assessing various management actions in the context of invasive species. By using larval genotypes, parental genotypes can be reconstructed to obtain information on adults years after spawning occurs. This allows for assessment of barrier efficacy if larvae are found in subsequent years. In Chapter 1, we determined that despite the presence of larvae above barriers in northern Michigan, spawning of most larvae occurred prior to barrier construction (in the case of the Black Mallard), or were from a group of mostly half-siblings implying a small number of males (in the case of the Ocqueoc) In both cases, results indicated that barriers in two systems did not have a large-scale failure. In Chapter 2, by sequencing a larger number of streams we saw a large variety in the types of family structure as well as N_b and N_s estimates, showing that spawning populations differ widely from stream to stream. This indicates that the control efforts and methods required to minimize sea lamprey spawning may be different depending on spawning structure.

We also evaluated N_b and N_s along three parameters relevant to sea lamprey populations: true N_b , sample size, and SNP set size. We found that genomic estimates generated with large SNP set were robust and accurate even when the true N_b of the simulated population was very large. However, sample size and SNP set size becomes an important factor for estimates generated from a reconstructed pedigree at a large true N_b , particularly for N_s estimates. Additionally, our linear models showed that sample size was a significant predictor for N_b and N_s estimates in our empirical data set, highlighting the importance of sufficient sampling for accurate N_b and N_s estimation. Additionally, representative sample across potential spawning habitat is vital for obtaining N_b and N_s estimates that reflect the full stream population. N_b and N_s estimates are an emerging technique for the assessment of invasive species, and have been established an effective technique for evaluating species of conservation concern. Due to the expanding genomic resources and extensive research efforts, sea lamprey are an emerging model system for long-term management. Providing N_b and N_s estimates and simulating sea lamprey populations has shown that genomic assessment is a valuable addition to sea lamprey assessment and evaluating control efforts, including new supplemental control techniques.