POPULATION STATUS AND TRENDS OF COLORADO PIKEMINNOW IN THE GREEN RIVER SUB-BASIN, UTAH AND COLORADO, 2000–2013

by

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EXECUTIVE SUMMARY

Multiple-pass, capture-recapture sampling was conducted in 2011–2013 in about 88% (819 river km) of warm-water reaches of the Green River sub-basin, Utah and Colorado, to estimate abundance and demographic rates for juvenile (< 400 mm total length [TL]), recruit (400–449 mm TL), and adult (≥ 450 mm TL) Colorado pikeminnow *Ptychocheilus lucius*. Three to six sampling passes were completed in each year for the Yampa River, middle Green River, White River, Desolation-Gray Canyon, and lower Green River reaches. Parameter estimates derived from a Huggins robust-design, multi-state model suggested a decline in abundance of adult Colorado pikeminnow since the previous abundance estimation period in 2006–2008. Abundance declines were substantial in all reaches, and especially in the Yampa River, the middle Green River, and the White River and weighted regression indicated abundance of adult Colorado pikeminnow declined substantially; the latter two reaches supported the most adult Colorado pikeminnow in the Green River basin in 2000-2003 and 2006-2008. Over the 2000–2013 period, weighted regression indicated abundance of adult Colorado pikeminnow in the Desolation-Gray Canyon and lower Green River reaches was stable. Green River subbasin abundance estimates from 2011–2013 are substantially lower than the recovery goal target of 2600 adult fish.

Previously low probabilities of capture declined further in each of the three main sampling periods, 2000–2003, 2006–2008, and 2011–2013, and produced estimates with relatively wide and mostly overlapping confidence intervals within reaches. Multiple lines of evidence support the notion of decreased abundance of adult Colorado pikeminnow in the Green River sub-basin. In 2011–2013, for example, abundance estimates for recruit-sized fish (those

that reach maturity one year after capture) were relatively high only in 2011. Recruit abundance declined after that to levels that would not replace mortalities of adult fish, thus contributing to declining adult abundance. Substantial numbers of recruits and juveniles evident in 2011 from abundance estimates, as well as length-frequency histograms of fish captured in downstream nursery habitat reaches, the lower Green and Desolation-Gray Canyon reaches, were not evident in 2012 and 2013 and those fish may have died.

Walleye *Sander vitreus* invaded the lower Green River reaches in especially high numbers in 2010 or 2011, had large body size, and based on numbers captured, were more than twice as abundant as adult Colorado pikeminnow. Walleye captures relative to Colorado pikeminnow captures and their estimated abundance indicated several hundred walleye were present in the lower Green River alone in the 2011–2013 period. Predation by abundant large walleye would have reduced the substantial numbers of juvenile Colorado pikeminnow in those reaches, even if individual walleye predation rates were low. Decline in abundance of larger recruit-sized Colorado pikeminnow in 2012 and 2013 is more difficult to explain but may be partially attributed to negative effects of walleye predation on the smallest individuals and to competition.

Average survival rates estimated for all sizes of Colorado pikeminnow captured in all reaches during 2000–2013 was moderate (0.73) compared to slightly higher estimates in the 2006–2008 period (0.80) but higher that for 2000–2003 (0.65); model analysis results not presented indicate survival rates for the entire period are similar to that for just the 2011-2013 period. Slightly reduced survival of Colorado pikeminnow in 2011-2013 may be related to very high flows in 2011 (wet year) and low flows in 2012 and 2013 (dry or moderately dry years) as well as predation and competition.

Increased recruitment and survival of Colorado pikeminnow is needed to reverse population declines and increase prospects to stabilize or increase populations. This was evident from relationships that showed adult abundance was positively related to abundance of age-0 fish produced in year classes 7-10 years prior. Decreased survival and abundance of Colorado pikeminnow emphasizes the need to maintain or increase ongoing nonnative fish removal programs, especially when new predators such as walleye invade critically important Colorado pikeminnow nursery habitat in the Green River. Equally or more important is implementing summer flow recommendations in the Green River to produce strong year classes of age-0 Colorado pikeminnow, especially since pikeminnow require seven or more years to mature. The long time horizon for recruitment to the adult life stage indicated that means to increase survival and recruitment of younger life stages of Colorado pikeminnow is a critical, immediate need and should be an annual management.

We recommend the Program:

1. Continue with the current sampling protocol for Colorado pikeminnow in the Green River sub-basin.
2. Investigate means to obtain higher probabilities of capture of Colorado pikeminnow, especially in reaches where abundance estimates were relatively imprecise. This may include addition of other gears such as fyke nets, increasing crew training to increase sampling efficiency, longer duration of sampling passes, more sampling passes, and incorporation of PIT tag antenna data. Minimally, sampling effort similar to that during 2000–2003 is needed.
3. Investigate reasons why capture probabilities for Colorado pikeminnow are declining over time.

4. Conduct an empirical analysis of growth of Colorado pikeminnow, based on tag recaptures in the Green River sub-basin or by using length-frequency or scale aging information. This would verify veracity of patterns borrowed from the Colorado River that are important to assess recruitment schedules for age-0 fish. This is especially important since growth rates of larger and older Colorado pikeminnow from the Colorado River are slower than for the Green River subbasin.
5. Effort to reduce abundance of walleye in the middle and lower Green River should be continued or increased, as predation may remove entire large year-classes of juvenile Colorado pikeminnow.
6. Implement recommendations of investigations that linked abundance dynamics of early life stages of Colorado pikeminnow with flow patterns in the middle Green River (Bestgen and Hill 2016).
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INTRODUCTION

Demographic parameters that describe birth, movement, mortality rates, and estimates of abundance are useful to understand dynamics and status of animal populations. Responses of those population parameters to biotic or abiotic drivers are of interest to ecologists attempting to understand the fundamental basis for population change. They are also useful to managers attempting to maintain or enhance abundance of free-ranging animal populations, particularly when the species of interest is rare and in need of conservation. Demographic parameters that describe the life history of endangered Colorado pikeminnow *Ptychocheilus lucius*, endemic to the Colorado River basin, guide managers attempting to improve the conservation status of this rare fish species.

Colorado pikeminnow is a large, migratory, and predaceous cyprinid of the Colorado River basin. Once widespread and abundant throughout warm-water reaches of the basin, wild Colorado pikeminnow are presently restricted to the upper Colorado River basin in the Colorado, Green, and San Juan River sub-basins. Reasons for decline of Colorado pikeminnow and other native fishes center mainly on negative effects of habitat alteration from river regulation and nonnative fishes (Minckley 1973; Carlson and Muth 1989; Tyus 1991; Olden et al. 2006; Zelasko et al. 2018; Bestgen et al. In press). Over 140 main stem and tributary dams and reservoirs, and several trans-basin water diversions provide agricultural and municipal water supplies to a rapidly expanding human population and have transformed water in the Colorado River basin into one of the most tightly controlled supplies in the world (Iorns et al. 1965; Carlson and Muth 1989). Effects of main stem dams on biota have been damaging because they restrict movements of highly migratory fishes such as Colorado pikeminnow, reduce the

naturally variable discharge and water temperature regimes and sediment supply, and increase daily hydrograph variation (Vanicek and Kramer 1969; Holden 1979; Ward and Stanford 1979; Stanford et al. 1996; Poff et al. 1997). No fewer than 65 nonnative fishes are established in the Colorado River basin, many of which prey upon or compete with various life stages of native species (Carlson and Muth 1989; Ruppert et al. 1993; Bestgen et al. 2006a). The outcome of these environmental and biotic changes for the highly endemic fish fauna of the Colorado River basin has been dramatic: three of the 35 native species in the basin are extinct, an additional 23 species or subspecies are federally listed as threatened or endangered, and most others are listed by one or more basin states or Mexico as declining and needing conservation (Stanford and Ward 1986; Carlson and Muth 1989; Bezzerides and Bestgen 2002; Mueller and Marsh 2002; Bestgen et al. in press). Colorado pikeminnow is federally listed as endangered under the Endangered Species Act of 1973, as amended (U. S. Fish and Wildlife Service 1974).

Colorado pikeminnow and endangered bonytail *Gila elegans*, humpback chub *G. cypha*, and razorback sucker *Xyrauchen texanus* are the focal species of the Upper Colorado River Endangered Fish Recovery Program (Recovery Program) in the Upper Colorado River basin (Wydoski and Hamill 1991). Recovery goals for Colorado pikeminnow provide criteria that must be achieved before downlisting or delisting can be considered (U.S. Fish and Wildlife Service 2002). Recovery criteria include demographic attributes that describe the required number of sub-basin populations and individuals (adults and juveniles) within each population, and recovery factor criteria, which are directly linked to management actions and tasks needed to minimize or remove threats.

Maintenance of a metapopulation is central to Colorado pikeminnow recovery, and demographic criteria require “a genetically and demographically viable, self-sustaining

population in the Green River sub-basin; and self-sustaining populations that meet or exceed estimated carrying capacity either in only the upper Colorado River sub-basin, or in both the upper Colorado River sub-basin and San Juan River sub-basin" (U.S. Fish and Wildlife Service 2002).

For consideration of downlisting or delisting, specific demographic criteria for the Green River sub-basin portion of the Colorado pikeminnow metapopulation require that, over the specified monitoring period, (1) trends in abundance estimates for adults (≥ 450–mm total length, TL) in Green River sub-basin do not decline significantly, (2) estimated mean recruitment of fish 400 to 449–mm TL (recruit-sized fish) equals or exceeds estimated mean annual adult mortality for the sub-basin, and (3) each abundance estimate for the sub-basin exceeds 2,600 adults (U.S. Fish and Wildlife Service 2002).

Sampling from 2011 to 2013 was undertaken as described in the Recovery Goals and consisted of three consecutive years of sampling for Colorado pikeminnow abundance estimation followed by two years with no specific Colorado pikeminnow sampling (U. S. Fish and Wildlife Service 2002). Our goal was to obtain abundance estimates and demographic parameters for Colorado pikeminnow in the Green River sub-basin. Study objectives listed for the Green River Colorado pikeminnow abundance estimates to achieve that goal were summarized as follows:

1. Complete three or more sampling passes through the study area to capture recruit-sized and adult Colorado pikeminnow;
2. Obtain highest possible rates of capture of Colorado pikeminnow within concentration habitats and maximize number of individuals marked on each sampling occasion; and

3. Calculate estimates of probability of capture and abundance for Colorado pikeminnow in each reach and for the entire study area.

This report describes the third major effort to quantify abundance, survival rates, recruitment, and population trends for Colorado pikeminnow in the Green River sub-basin based on sampling conducted from 2011–2013. The first two periods were 2000–2003 (year 2000 estimates were only from the middle Green River, and the White and Yampa River reaches) and 2006–2008.

Status and natural history of Colorado pikeminnow.— Historically, Colorado pikeminnow achieved 1.8 m in length and 40 kg in weight (Jordan and Evermann 1896; Minckley 1973; Tyus 1991; Quartarone 1995), although the largest individual known since intensive sampling began in the late 1970's was 1,240-mm TL (Bestgen et al. 2007). Large individuals may be 35 to 50 years old, and are very slow-growing, based on average growth rates of 10 mm/yr or less for relatively large recaptured individuals (Osmundson et al. 1997). Sexual maturity is not reached until seven or more years of age at a length of 450 to 550-mm TL (Vanicek and Kramer 1969; Osmundson et al. 1997; Osmundson and Burnham 1998; Osmundson 2006).

Abundance of Colorado pikeminnow varies in the three occupied sub-basins of the upper Colorado River basin. The wild population in the San Juan River sub-basin, which is largely isolated from the remainder of the upper Colorado River basin by Lake Powell, is relatively small or extirpated, although stocking is underway to bolster populations (Platania et al. 1991; Holden 2000). In the Colorado River sub-basin, abundance estimates for Colorado pikeminnow were conducted from 1991–1994 and 1998–2000, 2003–2005, 2008–2010, and 2013–2015 using multiple-pass capture-recapture sampling. Abundance estimates for the 278-river km (RK) reach

from 1991–2005 increased by about 2x from 440 fish in 1992 to nearly 900 in 2005 (Osmundson and White 2009; 2014). However, abundance of Colorado pikeminnow declined after that to about 1992 levels, likely a product of weak year classes of young fish that led to reduced recruitment.

Green River sampling from 2000–2003 showed that populations of Colorado pikeminnow exceeded the minimum recovery goal abundance criterion, with an estimated population of nearly 4,100 adults in 2000 (Bestgen et al. 2005; Bestgen et al. 2007). However, by 2003, population abundance declined because of low recruitment of young fish produced after 1993, and reduced survival of adults (Bestgen et al. 2007). Reductions were most severe in the middle Green River and the White River, sub-basin segments which supported the largest number of Colorado pikeminnow in 2000. Populations of Colorado pikeminnow apparently rebounded in the 2006–2008 period, based on strong recruitment of the 2000 year-class. Estimates in that period were characterized as imprecise, however, especially in 2008, which was the largest abundance estimate of the period (Bestgen et al. 2010). Imprecision was primarily due to low numbers of recaptures in most reaches. This trend in abundance estimates and shifts in those numbers due to more comprehensive estimation procedures will be discussed in detail later because of abundance levels that were subsequently altered, and gave a different picture than recovery of the population.

In the Green River sub-basin, adults migrate to two main spawning areas in late spring when snow-melt runoff subsides and water temperatures warm (Tyus 1990; Irving and Modde 2000). Migrations up to 745-RK round-trip to and from spawning areas have been documented by radio-tracking adults in spring and summer, and those fish often return to established home ranges (Tyus 1990; Irving and Modde 2000). Colorado pikeminnow in the Colorado River are

much less mobile during the reproductive season and make only local movements to spawning areas (McAda and Kaeding 1991). Colorado pikeminnow typically began spawning around the summer solstice, when flows decline to near base level and water temperatures range from 16 to 22°C (Haynes et al. 1984; Tyus 1991; Bestgen et al. 1998). Eggs are deposited over geomorphically complex riffle habitat and embryos hatch within four to seven days at water temperatures of 18 to 26°C (Hamman 1981; Marsh 1985; Tyus 1990; Harvey et al.1993; Bestgen and Williams 1994). About five to nine days later, emerging larvae are transported downstream 40 to 200-RK or more to alluvial river reaches, where they rear in low-velocity shoreline areas such as backwaters throughout the summer (Haines and Tyus 1990; Tyus and Haines 1991; Bestgen 1996; Bestgen et al. 1998).

Variation in abundance of adult Colorado pikeminnow in the Colorado River was attributed to changes in abundance of young-of-year that reared mostly in the lower portion of the river (Osmundson et al. 1997; Osmundson and Burnham 1998). Recruits moved upriver as subadults and eventually established home ranges (Osmundson et al. 1998), apparently in response to a productivity gradient that increased upstream (Osmundson et al. 1998; Osmundson et al. 2002). In the Green River sub-basin, size-structure stratification of Colorado pikeminnow was similar to that in the Colorado River, as most juveniles and recruits (400-449 mm TL) captured were found in downstream reaches (Osmundson et al. 1997; McAda 2002; Bestgen et al. 2007). Growth analysis of Colorado pikeminnow, based on capture-recapture data, has not previously been conducted in the Green River sub-basin, but movement and recruitment have been studied via transition rate estimation of marked animals (Bestgen et al. 2007; Bestgen et al. 2010). Those investigations revealed a pattern similar to that in the Colorado River because downstream areas such as the lower Green River served as nursery habitat for young Colorado

pikeminnow. Those fish later moved upstream as large juveniles or recruits to the Desolation-Gray Canyon and middle Green reaches of the Green River, as well as the White and Yampa rivers.

Most Colorado pikeminnow inhabit rivers regulated by main stem dams. Thus, flow and water temperature management in the Green, Colorado, and San Juan rivers have focused on restoring regimes that more closely resemble historical conditions (Poff et al. 1997; Muth et al. 2000; Bestgen and Hill 2016). Release of propagated Colorado pikeminnow in the Colorado and Green River sub-basins has been limited because natural populations were thought sufficient to achieve recovery (Tyus 1991). Only in the San Juan River sub-basin has use of propagated fish been extensive. Another emphasis of the Recovery Program during this study was to reduce effects of nonnative fishes, particularly large-bodied piscivores. Smallmouth bass *Micropterus dolomieu*, walleye *Sander vitreus* and northern pike *Esox lucius*, are formidable threats to all life-stages of Colorado pikeminnow including large adults, particularly in the Yampa River of the upper Green River sub-basin (Martinez et al. 2014). Those threats have diminished slightly due to reduced abundance of northern pike, particularly large individuals (Hawkins et al. 2009; Zelasko et al. 2015; 2016), but expanding walleye populations, as well as smallmouth bass, are a threat throughout the upper Colorado River basin and will be discussed in more detail later.

STUDY AREA

The Green River sub-basin drains high-elevation areas in southwestern Wyoming, northeastern Utah, and western Colorado (Figure 1). The study area consisted mainly of warm-water river reaches designated as critical for recovery of Colorado pikeminnow (U. S. Fish and Wildlife Service 2002), including the downstream most 193 RK of the Yampa River except for

the lowermost 74 RK in Yampa Canyon, the 555.6-RK reach of the Green River (including the lower 0.5 km of the Duchesne River) downstream of the confluence of the Yampa River to the Colorado River, and the lower 167.4 RK of the White River. River geomorphology in the study area consisted of relatively low gradient, depositional reaches in valleys interspersed with higher gradient, erosive, canyon-bound reaches. Alluvial river reaches were more braided, had mostly sand or gravel substrate, meandered to some extent within the floodplain, and were dominated by run and pool habitat. Canyon-bound river reaches were typically constrained, single-thread channels, with a mix of riffles, runs, and pools, and substrate that ranged from sand to boulder-sized particles. River flows are snow-melt driven, and highest in spring and early summer and declining to base level by mid-summer (Figure 2). Flows were relatively higher in the 2006 to 2008 period, particularly in 2008, compared to the drought period from 2000 to 2003. Flows in the period 2011–2013 were very high the first year and low in the latter two.

The Green River sub-basin was divided into five main reaches: the Yampa and White rivers, and three reaches of the Green River. The Yampa River reach was 118-RK long and extended from RK 192 just downstream of Craig, CO, to RK 74 just upstream of Yampa Canyon; few Colorado pikeminnow have been documented upstream of that area (Holden and Stalnaker 1975, Finney 2006). The canyon-bound lower reach of the Yampa River (74 RK) was excluded mostly because few fish were thought to occur there outside of the spawning season, and also because logistical constraints prevented extensive sampling there (Holden and Stalnaker 1975). The sampled reach of the Yampa River flowed mostly through alluvial valleys but included Little Yampa Canyon in the upper portion of the study reach. The 5 RK-long Cross Mountain Canyon and the 3 RK-long Juniper Canyon were not sampled because they were

inaccessible. The Yampa River reach was sampled by personnel from the Larval Fish Laboratory, Colorado State University, and Colorado Parks and Wildlife.

The middle Green River study reach was 143-RK long and extended from RK 539.4 (16.2 RK downstream of the Yampa River confluence) downstream to White River confluence (RK 396). The reach was in an alluvial valley, with the exception of Split Mountain Canyon (RK 528.2 to 513.8), which was not sampled. The 16.2 RK-long Whirlpool Canyon reach from the confluence of the Yampa River downstream to upper Island Park was also excluded from sampling. Most of the relatively short reaches within the study area that received only cursory or no sampling in this study historically held few Colorado pikeminnow (Holden and Stalnaker 1975). The middle Green River reach was sampled by the Utah Division of Wildlife Resources, Vernal, Utah.

The White River study reach was 167.4-RK long and extended from Taylor Draw Dam downstream to the confluence with the Green River. Although Colorado pikeminnow historically occurred above Taylor Draw Dam, few or none are thought to occupy that reach since Kenney Reservoir began filling in 1984 (Martinez 1986; Martinez et al. 1994). The White River winds through alluvial valleys interspersed with steeper canyon reaches where higher gradients prevail. The U. S. Fish and Wildlife Service, Vernal, Utah, was responsible for sampling the White River and the Desolation-Gray Canyon reach of the Green River (below).

The Desolation-Gray Canyon Green River reach was 189.8-RK long and extended from the confluence of the White River at RK 395.9 downstream to the lower end of Gray Canyon at RK 206.1. That reach was mostly canyon-bound and geomorphically constrained. The reach between RK 206.1 (at Tusher Wash Diversion) and 193.2 was not sampled because of access issues.

The lower Green River reach was 193.2-RK long and extended from the town of Green River downstream to the confluence with the Colorado River (RK 0), and passed through the low-gradient Labyrinth and Stillwater canyons. The Utah Division of Wildlife Resources, Moab, Utah, was responsible for sampling there.

During low flow periods in all reaches, low-velocity habitat was near shore, in small eddies and pools, behind or adjacent to mid-channel sand or gravel bars, or in tributary mouths. When flows were elevated by snow-melt runoff in spring, main channel velocities were swifter, and low-velocity areas were more limited, often consisting of near shore runs, flooded tributary mouths and canyon washes, and a few large backwaters.

Additional areas not sampled that may harbor Colorado pikeminnow included smaller tributaries such as the Price, San Rafael, upper Duchesne, and Little Snake rivers (McAda et al. 1980; Wick et al. 1991; Cavalli 1999; Muth et al. 2000; Bestgen et al. 2010). Adult Colorado pikeminnow use those areas seasonally (e.g., Bottcher et al. 2013) but Colorado pikeminnow are thought relatively rare compared to larger main stem reaches because habitat size was small, or because use occurred in seasons outside of our sampling period. The Green River in Browns Park and Lodore Canyon upstream of the Yampa River was also known to support adult Colorado pikeminnow (Bestgen and Crist 2000; Kitcheyan and Montagne 2005, Bestgen et al. 2006b; Bestgen et al. 2010; annual Recovery Program reports for Project FR115) and implications of that sampling will be discussed.

METHODS

Sampling and fish handling.—Sampling for abundance estimation was conducted in spring in each year in the 2011–2013 in each of the five study reaches. However, we modeled all

data collected during the 2000–2003, 2006–2008, and 2011–2013 sampling periods in one overarching analysis. We used Pollock's robust design to allocate sampling effort (Pollock 1982; Pollock et al. 1990). This was accomplished by conducting at least three short-term sampling occasions (usually 7 to 11 days each) through each reach at approximately the same time (mid-April to late May) in spring of each year, and repeating that design over the remainder of the study years. Short-term sampling occasions were conducted in spring between the times when ice off occurred and prior to or during spring runoff before Colorado pikeminnow spawning migrations began. Using hard-bottomed boat or inflatable raft-based electrofishing as the standard technique, sampling during each occasion began at the top of each reach and proceeded downstream. Boats were used in the Yampa, middle Green and lower Green reaches, and rafts were used in the White River and Desolation-Gray reaches. Smith-Root or ETS Electrofishing Systems electrofishing units were used to apply electrical current to one or two anode booms (rafts or boats, respectively) equipped with spherical electrodes. Electrofishing output consisted of pulsed-DC waveforms standardized according to ambient water temperature and conductivity as described in Martinez and Kolz (2016). Two boats were typically used on each sampling occasion, one on each shoreline, and one or two netters in rafts or boats, respectively, captured stunned Colorado pikeminnow. All near shore habitat was electrofished, including both sides of side channel and island habitat when boats were used.

Approximately 7 to 10 d elapsed between short-term sampling occasions in each reach to allow for sufficient mixing of marked and unmarked fish. A block-and-shock technique was sometimes used, in which a large, nearshore, quiet-water area (e.g., backwater, flooded wash) was isolated from the main channel with a trammel net and electrofishing commenced inside the block net. Colorado pikeminnow were captured by netters when stunned by electricity or in

trammel nets as they attempted to leave the backwater for the main channel. Use of these techniques was limited in most years and reaches.

In most reaches, sampling focused only on Colorado pikeminnow, although other endangered fishes, and some nonnative species such as northern pike, walleye, or smallmouth bass, were also captured. Colorado pikeminnow were measured (TL, nearest mm), weighed (nearest g), scanned for the presence of a passive integrated transponder (PIT) tag, and unmarked fish (>150 mm) received a PIT tag inserted into the body cavity just posterior to the pelvic girdle. The initial capture and release location (nearest 0.15 RK) was determined from river maps and Global Positioning System units and all Colorado pikeminnow were released within 0.15 km of their capture location. Crews were instructed to scan recaptured fish for two tag types, the older 400 kHz frequency tag, as well as the newer 134.2 kHz tags. Double scanning was needed because scanner settings to detect newer tags did not always detect old frequency tags. A result of not doing this would be interruption of the capture series for an individual fish, such that an undetected 400 kHz tag would essentially result in treating the fish as newly captured and previously undetected. A high incidence of this would result in reduced survival rates because encounter history lengths would be reduced. All fish with older tags were usually tagged with the newer 134.2 kHz tag.

Additional data used in this study was the Interagency Standardized Monitoring Program (ISMP, McAda 2002). The ISMP sampled adult and sub-adult Colorado pikeminnow from ten reaches (8 to 25 RK-long) of the Green River sub-basin, five from the Green River (RK 539.4 to 526.5, 513.6 to 483, 418.6 to 394.5, 185.2 to 154.6, 90 to 64), three from the Yampa River (RK 167.4 to 153, 128.8 to 112.7, 86.9 to 78.9), and two from the White River (RK 169.1 to 153, 33.8 to 0). The reaches totaled about 23% of Colorado pikeminnow critical habitat in the Green River

sub-basin and were chosen because they were accessible by a flat-bottom boat and represented reaches known to support Colorado pikeminnow. Sampling was conducted during spring each year from 1986 to 2000 when water levels were rising due to snow-melt runoff but were usually below peak runoff levels. A single electrofishing sampling pass was conducted along each shoreline, stunned Colorado pikeminnow were captured with dipnets, and electrofishing effort (seconds) was recorded. Captured fish were tagged, measured, and released with a protocol similar to that described above for abundance estimation sampling. Sampling effort was stratified among four to eight sub-reaches of each river reach and catch per unit effort statistics were calculated for each sub-reach sample. Variances and standard errors for catch/effort indices were calculated based on those samples. Prior to 1991, Colorado pikeminnow were tagged with Carlin dangler tags, which were presumed subject to relatively high tag loss which would confound analyses of tag-recapture data (population rates of change) and comparisons with catch-effort data. Therefore, data from 1986 to 1990 was not included in analyses. After 1990, tag loss was considered negligible because all Colorado pikeminnow were PIT-tagged.

To facilitate comparisons between Colorado pikeminnow abundance estimation sampling and historical ISMP sampling we calculated catch/effort statistics from estimation sampling conducted during 2001–2003, 2006–2008, and 2011–2013 within ISMP reaches. It was then possible to examine trends in Colorado pikeminnow catch rates from 1991 to 2013, exclusive of 2004–2005 and 2009–2010. Because ISMP sampling was not conducted in the Desolation-Gray Canyon reach of the Green River, no comparisons were available for that reach.

Robust design multi-state models for capture-recapture studies.—Robust-design sampling and analysis capitalizes on the strengths of closed and open population models used to estimate demographic parameters (Pollock 1982; Pollock et al. 1990). Sampling occasions

completed at closely-spaced intervals (e.g., weeks) were used to estimate population size using closed population models. That level of sampling completed in two or more consecutive years allowed for estimation of population size of adults, recruits, and juveniles and survival rates between years. In some reaches and years, data from two sample passes made closely in time were combined to achieve a maximum of three passes of sampling data and maintain symmetry of the capture histories and enhance model fitting. Data was combined after analyses showed that <1% of fish moved between sampling reaches between passes within a year. Thus, potential confounding due to within year fish movement to spawning areas was minimized.

Statistical modeling.—The combined robust-design (Kendall 1999; Kendall et al. 1995; Kendall et al. 1997) multi-state (Brownie et al. 1993; Hestbeck et al. 1991) model in Program MARK (White and Burnham 1999) was used to estimate survival in year t (S_t), probability of transition between reach i and j (ψ_{ij}), capture-recapture probabilities within reach i (reach is the state) for each year t and sampling pass k (p_{itk}), and Colorado pikeminnow adult, recruit, and juvenile abundance in each reach i for each year t (N_{it}). This model utilized all data collected during the 2000–2003, 2006–2008, and 2011–2013 sampling periods. Abundance of adult, recruit, and juvenile Colorado pikeminnow in each reach was estimated with the Huggins estimator (Sananathan 1972; Huggins 1989; Alho 1990; Huggins 1991). Abundance estimates from the Huggins model were derived for each reach and year by the equation:

$$\hat{N} = \sum_{k=1}^{M_{t+1}} (1/\, p_k^*)$$

where k was indexed for all individuals and M_{t+1} was the number of unique animals captured over all L short-term sampling passes (usually 3 in this study) in a year, and

$$p_k^* = 1 - \prod_{l=1}^{L} (1 - p_l)$$

where $p_{l,}$ was the probability of initial capture within the L passes during the sampling season for each reach. Individual covariates (here TL or polynomials for such) were incorporated to estimate p, ψ, and S, where appropriate. Information for the p^* estimates (defined just above) are from both the closed-capture portion of the likelihood used for abundance estimation and the Cormack-Jolly-Seber (CJS) component of the model used to estimate annual survival rates. With the information provided about p^* from the CJS portion of the likelihood, the individual p's per pass within the annual sampling period are identifiable based on the numbers of fish initially captured during each sampling pass within a year. Thus, we were able to calculate abundance estimates for river reaches and years where no fish were recaptured between passes within a single year (e.g., Yampa River 2007, Bestgen et al. 2007; Bestgen et al. 2010), which assume equivalent capture probabilities across reaches. In addition to the CJS contribution to p^*, recaptures of fish in reaches between passes within a single year provided more efficient estimates of abundance. River-wide abundance estimates were obtained by summing the separate reach estimates in each year. Standard errors for river-wide estimates were obtained from the variance-covariance matrix of the likelihood produced from program MARK. We used confidence intervals and their overlap among pairs of estimates to assess significance; high precision estimates had coefficients of variation (CV's) < 10%, moderate precision estimates had CV's of 10-25%, and low precision estimates had CV's > 25%.

Unlike our previous analysis where TL at first capture was held constant (Bestgen et al. 2007), we used a von Bertalanffy function to estimate fish growth between years after first capture. The function was based on Green River length data collected from 2000 to 2013. To

use length as a covariate, lengths for each captured fish were needed for each year of the study. However, because individual fish were not captured in each sampling year, their lengths in years when not captured had to be estimated by interpolation or extrapolation. For fish that were captured more than once within a year, the mean of the measured lengths was used for that year. The von Bertalanffy model was used to estimate missing lengths following Osmundson and White (2017). To fit the von Bertalanffy model, a difference equation was assumed, following procedures of White and Brisbin (1980). For the von Bertalanffy model:

$$L_{i+1} = (t_{i+1} - t_i)k(L_\infty - L_i) + L_i \,,$$

where L_i is the length at year i, t_i is the actual year of the observation, k is the von Bertalanffy growth coefficient, and L_∞ is the asymptotic length. To estimate the two parameters, the equation was implemented recursively, with $t_{i+1} - t_i = 1$. The von Bertalanffy growth equation parameter estimates used are k = 0.188 (0.176–0.199, 95% confidence interval [CI]) and L_∞ = 655.4 mm TL (646.4–664.4 mm TL, 95% CI), which was estimated with 1,305 pairs of Colorado pikeminnow capture and recapture lengths. To predict a length for a fish not captured in 2013 from a length from the same fish in 2011, for example, the equation was first applied with the observed length from 2011 to predict a 2012 length. The predicted length in 2012 was then used to predict a length in 2013. The model was thus used to produce individual covariate values of length for each year. Fish captured that were larger than the asymptote TL of 655.4 mm were assigned that length throughout the capture history, unless they were captured again. Then, changes in length were interpolated between the two occasions. Using these lengths, an input file for Program MARK was created. Use of the more complicated von Bertalanffy growth

estimation approach, rather than assuming no change in TL, was justified because it was more realistic to assume fish growth and allowed probabilities of capture to change as fish length increased over this extended study duration. It is important to test for the effect of the covariate TL in abundance or survival estimation modeling because of potential effects of fish size on probabilities of capture. Abundance estimators such as those in program CAPTURE (White et al. 1982) do not have the capability to use individual covariates because the likelihood includes probabilities for animals that are never captured, so the covariates are unknown.

Previous analyses demonstrated that capture probabilities were equal to recapture probabilities among the short-term and annual sampling occasions (i.e., $p_k = c_k$), so heterogeneity due to capture effects was assumed minimal (Bestgen et al. 2007; Bestgen et al. 2010). We initially tested for differences in rates of capture and recapture in various models to evaluate if behavior effects (e.g., fish avoidance) were influencing recapture rates. We also fit mixture models of Pledger (2000) in a preliminary analysis (not reported), which were designed to incorporate heterogeneity caused by differing probabilities of capture for different population segments. Similar to our previous study, we did not consider these models further because higher numbers of recapture occasions (e.g., minimum of 5) were needed to detect differences in capture probabilities among groups of animals in the same population. We also attempted to explain individual heterogeneity by including the covariate TL in other analyses, so heterogeneity effects were presumed minimized.

Because we noticed that capture probabilities declined over time in the 2000–2013 period, we investigated possible reasons for that. One approach was to examine the proportions of fish captured only once during a year, compared to fish captured multiple times, to determine if those proportions changed over time. Declining proportions of fish captured 2 or more times

in a year over time or increasing proportions of fish captured just once may indicate fish avoidance behavior of boats or electrofishing gear. We also fit a model in program MARK that added a covariate to indicate if a fish was captured in a prior occasion. For one model we fit a prior recapture covariate if a fish was captured the previous year of sampling, and in another model, added a covariate if a fish was ever captured in the history of sampling. In both cases, that covariate was added to the current top model with n = 182 parameters. The hypothesis was that if a fish was captured in a prior year, those may be less susceptible to recapture, which would reduce their recapture probability, essentially fitting a $p \neq c$ model where time is a year or more interval between the first and later recaptures. We investigated effects of flow magnitude on capture probability, because it was noted that in some very high flows (e.g., 2011) fish may have spread out and become more difficult to encounter. In contrast, during low flow years (2002, 2012), the sampling season may be shortened, fish may not be concentrated in higher velocity channel margins, or concentration habitat may not be available to sampling craft like it is at intermediate flows. We used mean daily flow in May at the U.S. Geological Survey Jensen, Utah gauge for capture data collected in all reaches. Flows from that gauge should be a reasonable indication of flow level for Green River reaches as well as tributaries, because a high flow year in one area typically corresponds to a high flow year in a different area. There was slight evidence that low and high flow years had lower capture probabilities and intermediate years were slightly higher (e.g., slight dome-shaped curve). However, a linear model that fit probabilities of capture as a function of flow and flow^2 was not significant ($P = 0.40$) and model fit was low ($R^2 = 0.23$). Thus, flow did not appear to have an important effect on probabilities of capture.

To assist reader understanding, a simple means of illustrating how capture probabilities are used to generate abundance estimates is to simply divide the number of animals in the capture sample by the probability of capture, and assume all animals at risk of capture in the population have identical capture probabilities (i.e., the same TL in this case). For example, this canonical estimator indicated if 100 animals were captured in a sample and the animals had a known and constant probability of capture of 0.10, there must have been 1,000 animals in the population (100/0.10 = 1,000). In this example, each fish in the capture sample contributes equally to the abundance estimate. Because capture probabilities of individuals often varied spatially (river reach) or over time (sampling pass) or with fish size (small fish typically more difficult to capture than large), model selection supported inclusion of reach-, sampling pass-, and year-specific capture probabilities, as well as length effects on capture. Thus, capture probabilities account for most factors that cause heterogeneity, which are then adjusted for in abundance estimates.

The robust-design multi-state models in program MARK (White and Burnham 1999) were used to estimate reach-specific apparent survival for Colorado pikeminnow captured in the Green River sub-basin. Apparent survival rates (S) were the joint probability of a fish surviving from one year to the next and remaining in the population available for capture. In other words, estimates from these models do not distinguish a fish that died in the study area from one that survived and moved from the study reach to outside the study area. Because of that, survival rates obtained from only ISMP data were likely conservative (low) because capture data were gathered from reaches that represent only about 23% of the basin. Thus, Colorado pikeminnow that moved out of reaches sampled by ISMP and were never recaptured would be treated as mortalities. These models also could not distinguish if fish that were previously captured

avoided subsequent recapture by some behavioral change mechanism. Such a behavioral change would result in reduced capture probability and lower apparent survival rates. Assuming that no behavioral change occurred, survival rate estimates obtained from 2000–2003, 2006–2008, and 2011–2013 during abundance estimation sampling likely approached true survival, because nearly all the Green River sub-basin habitat where Colorado pikeminnow likely occurred was sampled. The goal of survival analyses was to determine if a composite, and perhaps conservative, survival rate from 1991–1999 was different than survival in the 2000–2003 period, and the 2006–2008 and 2011–2013 periods. Detecting differences in survival rates over time are useful to interpret trends in population abundance. Model selection was performed with information-theoretic procedures (Akaike's Information Criterion adjusted for small sample size [AIC_c], Burnham and Anderson 1998). We were careful to guard against overfitting models (e.g., ones with complex interaction terms) with the sometimes sparse data available for some reaches or rivers and focused on those that gave reasonable estimates of parameters that were critical to understanding the status of Colorado pikeminnow in the Green River sub-basin.

To call attention to reach-specific abundance trends of different life stages of Colorado pikeminnow, we fit regression relationships of abundance as a function of time, and included intercept-only models, as well as those with linear (T) and quadratic (T^2) terms to describe changes in abundance over time. We used all estimates available from reaches in 2000–2003, 2006–2008, and 2011–2013 study periods to analyze trends. Support for the intercept-only model would indicate no substantial change (minimal slope, stable population) in abundance over time, a linear model would describe a population relationship as increasing or decreasing in a substantial but straight line manner, and a quadratic model would describe changes in abundance (positive, negative, or both) that vary among time periods. For example, a negative

linear term in a quadratic model might describe a declining population in the 2000 to 2003 period, and a positive quadratic term may indicate a substantial population increase in the 2006 to 2008 period. However, because these estimates have sampling covariances among them induced by common parameters across reaches and size classes, we performed non-linear weighted regressions (Proc IML, SAS Institute, Cary, NC) to obtain best inferences regarding trends in population abundance over time. We accomplished this by using estimates from the variance-covariance matrices produced by program MARK as weights for abundance estimates in the 2000 to 2003 data, as well as those from 2006 to 2008 and 2011 to 2013 data, such that estimates with high variance were weighted less (lower reliability), and estimates with low variance were weighted more (higher reliability). We then regressed abundance as a function of the intercept, time, and time squared (quadratic) variables. This analysis is more conservative (fewer significant relationships) than simply regressing the abundance values over time as if no uncertainty existed. We also fit weighted regression models for recruits and juveniles and reported weights in the text where appropriate, noting that when no estimate was possible because of lack of captures of a particular life stage in some years, no variance-covariance was produced, and thus, no calculations of weights or relationships over time were possible (e.g., no relationships for Yampa and White River recruits and juveniles). Relationships were plotted for abundance as a function of time and could show a positive or negative trend, even if model weights indicated an intercept-only (stable population) model was most appropriate. This was done to show the general trajectory in estimates even though they were often imprecise and the slopes were not statistically significantly different than 0.

We used AIC_c model selection and model weights to assess the level of support for intercept only, linear, or quadratic models used to describe Colorado pikeminnow abundance

trends over time. Model weights were proportions between 0 and 1, with weights of the competing intercept-only, linear, or quadratic models summing to 1, and represented the likelihood (probability) of a certain model among the three types. This is a departure from the typical approach where model selection is based on decisions regarding inclusion or exclusion of model explanatory variables using subjective alpha-levels to specify Type I error rates (e.g., alpha ≤ 0.05). It is also a departure from typical approaches because more than one model is considered as a candidate to explain the data. Fitting of several models better reflected the uncertainty in abundance estimates and their trend over time compared to a single model, and allowed objective comparison of the robustness of conclusions regarding trends.

RESULTS

River-reach abundance estimates.—In 2011–2013, we captured or recaptured 1,336 Colorado pikeminnow (n = 1,223 individuals) in 45 sampling occasions (3 passes per year, 5 reaches, 3 years; Table 1, shows total individuals with various capture histories so numbers are lower than total capture occasions). Appendices I-X report data associated with passes and effort for each sampling year. In comparison, 3,411 Colorado pikeminnow were captured or recaptured in the period 2000–2003 (n = 2,204 individuals), and 2,043 were captured or recaptured in 2006–2008 (n = 1,787 individuals). Of the 1,223 individual fish captured from 2011–2013, most fish (n = 1,114) were captured only once in a year (Table 1), whereas a total of 109 were captured two or more times and four were captured in all three passes in a year. The proportion of fish captured only once in a year was highest in 2011–2013 at 91%, compared to 87% and 86% in the 2000–2003, and 2006–2008, respectively. Also notable was the increasing proportion of pikeminnow captured on the first pass during sampling over the three main

periods, increasing from 34% in 2000–2003, to 43% in 2006–2008, and finally to 50% in 2011–2013.

We estimated abundance of Colorado pikeminnow adults, recruits, and juveniles in each of the five river reaches of the Green River sub-basin for each sampling year in the entire 2000–2013 period to determine spatial abundance patterns and temporal dynamics. A set of 14 models was fit to the data to estimate survival (*S*), reach transition probabilities (ψ, probability of a fish moving from one reach to another), and capture probabilities (*p*'s, Table 2). The top model in the set of 14 contained 100% of the AIC_c weight and had 182 estimable parameters, the most complex among all the models considered.

The top model included a TL (and a TL^2) effect with survival, transition rate, and probabilities of capture including session and TL. That top model had survival rates for each reach plus length effects, 20 estimates of ψ (one each for fish in a given reach moving to any of the other four reaches for each of five reaches, no year effect but a TL effect), and the remainder were estimates of *p* (one for each year, reach, and pass combination). Also included were separate TL and TL^2 effects (session effect) for each period 2000–2003, 2006–2008, and 2011–2013 to reflect differing (declining) probabilities of capture over time.

Based on trends in point estimates over the period 2000–2013, abundance of adult Colorado pikeminnow showed an apparent decline in three of five river reaches, the middle Green River, and the White and Yampa rivers (Tables 3–7, Figures 3–7). Only the Desolation-Gray Canyon and lower Green River reach Colorado pikeminnow showed a stable trend (Table 8), although estimates varied widely over time. It should be noted that abundance estimates based on all available capture-recapture data collected during 2000–2013 have changed from values reported earlier (Bestgen et. al 2007; Bestgen et al. 2010) which drew on the more limited

subsets of data available during each period. Notable differences include slightly higher abundance estimates during 2000–2003, but lower abundance during 2008, and an overall declining trend in abundance over time rather than an increase in abundance in 2008.

Abundance of adult Colorado pikeminnow in the Yampa River reach was the lowest observed among the five study reaches (Tables 3-7, Figures 3-7). Abundance estimates were similar across years in the recent 2011–2013 period (48 to 123) and averaged only 85 fish/yr. In 2012 and 2013, only six and seven individuals were captured, respectively, with no recaptures, so estimates are suspect and likely biased high in those years. Recall that estimates were possible in reaches and years without recaptures because probabilities of capture that incorporate TL can be estimated for such reaches, and result in an estimate of abundance. Estimates in 2012 and 2013 had high CV's and relatively low precision, owing to the low number of fish captured and no recaptures. The estimate in 2011 had better precision and a relatively low CV. No meaningful estimate of Colorado pikeminnow recruit or juvenile abundance was available in any year for the Yampa River, because few or no fish < 450 mm TL were captured in those years. Overall, capture probabilities were low, especially in the most recent time period (Table 9).

Population trend analysis via weighted regression of abundance estimates as a function of time showed a continued decline in the Yampa River population of adult Colorado pikeminnow (Table 8). Model weights suggested a quadratic model with a negative slope coefficient and a small but positive quadratic term had the most support (0.85); the only other model with substantial support was the linear model with a declining slope (0.145). The quadratic model fit could be described as bowl-shaped but tipped on its right side to reflect that 2011–2013 estimates flattened out the line slightly, but only the linear trend was displayed.

Abundance of adult Colorado pikeminnow in the White River was higher than that observed in the Yampa River from 2011–2013, but estimates declined since the 2000–2003 period by nearly half (Table 4, Figure 4). Confidence intervals for abundance estimates in 2011 and 2012 did not overlap and indicated a significant and substantial decline. Numbers of unique animals captured was low for the White River, a minimum of 59 in 2013 and a maximum of 77 in 2011 (106–265 in 2000–2003). Adult Colorado pikeminnow abundance estimates in the White River had moderate precision, with CV's ranging from 16–25%.

Population trend analysis via weighted regression of White River adult pikeminnow abundance estimates over the three sampling periods (2000–2003, 2006–2008, 2011–2013) showed most support for the linear model with a negative coefficient for slope (weight = 0.56, Table 8) followed by the quadratic model (0.40), which also had a large and negative linear slope coefficient. The quadratic model fit again was bowl-shaped but tipped on its right side to reflect that 2011–2013 estimates flattened out the line slightly. There was little support for the intercept only model (0.04) which would indicate a stable population.

Number of Colorado pikeminnow recruits in the White River was variable during the recent study period (2011–2013) and ranged from 12 to 84 (Figure 4, Table 4). Confidence intervals for abundance estimates of recruits present in the White River overlapped and CV's were relatively large, especially in 2012. Estimates over the entire sampling period (2000–2013) showed low abundance of Colorado pikeminnow recruits in the White River (Figure 4). We did not perform weighted regression analysis of recruit abundance as a function of time because absence of recruits in 2003 (no variance or weight estimates were available for that year) caused model non-convergence.

Number of juvenile Colorado pikeminnow in the White River was variable from 2011–2013 (17–134), but increased over the period 2000–2013 (Figure 4, Table 4). Confidence intervals for abundance estimates of juveniles present in the White River were relatively wide and CV's were relatively large in 2011–2013 at 54–71%.

Abundance of adult Colorado pikeminnow in the middle Green River was variable in 2011–2013, and increased by 100% in 2013 compared to 2011 or 2012 (Table 5, Figure 5). However, the 2011 and 2012 estimates were lowest ever recorded for the reach, the location where the largest population typically resides. Variable abundance was likely due to sampling condition differences among years, where flow affected sampling. For example, the third 2011 sampling pass was never completed because high water prevented boat passage under bridges. In contrast, flows in 2012 were so low that only the third pass had sufficient water to efficiently access habitats, which is when captures increased. Confidence intervals for abundance estimates overlapped in all years. Number of unique animals captured declined from 80 in 2011 to 44 in 2013. Abundance estimates for the middle Green River reach had moderate to low precision, with CV's ranging from 21 (2011) to 38% (2013). The high 2013 estimate had particularly low precision and was based on capture of only 44 adult Colorado pikeminnow. The relatively high CV's for all years were due to the relatively low numbers of captured and recaptured fish.

Weighted regression of abundance estimates for adult Colorado pikeminnow in the Middle Green River over the 2000–2013 period showed most support for the linear model (weight = 0.61) where the slope coefficient was negative and indicated a substantial decline in abundance (large and negative linear coefficient relative to the standard error; Table 8). The quadratic model (0.39) also had substantial support and showed a large and negative linear slope coefficient.

Colorado pikeminnow recruit abundance in the middle Green River reach was variable in the 2011–2013 period and overall, was stable to slightly declining during 2000–2013. Estimates of Colorado pikeminnow recruit abundance in the middle Green River had low precision, with CV's that ranged from 38 to 100; only one recruit-sized fish was captured in 2012. Weighted regression analysis of recruit abundance as a function of time for the middle Green River (not shown) showed most support for the intercept only model (0.66) or a linear model (0.32) with a negative slope coefficient.

Abundance of juvenile Colorado pikeminnow declined in the middle Green River over the recent study period, as well as over the 2000–2013, although confidence intervals overlapped in the latter period (Table 5). Estimates of Colorado pikeminnow juvenile abundance in the middle Green River had low precision in 2011–2013, with CV's that ranged from 47 to 105%. The simple linear regression trend depicted for juvenile Colorado pikeminnow abundance as a function of time over the 2000–2013 period was also negative (Figure 5), but model weight (0.84) suggested an intercept-only model was appropriate.

Abundance estimates for adult Colorado pikeminnow in the Desolation-Gray Canyon reach of the Green River were relatively consistent from 2011–2013, and the highest recorded in the study area on average (Figure 6, Table 6). Overlapping confidence intervals among pairs of point estimates indicated that none of the estimate differences among years were statistically significant. Numbers of unique animals captured varied from 52–118, with commensurate shifts in precision of estimates, where precision was higher when larger numbers of adults were captured. Estimates of adult abundance in the Desolation-Gray Canyon reach of the Green River in the 2011–2013 period had moderate precision (CV range = 17–24%). Weighted regression of Desolation-Gray Canyon abundance estimates for adult Colorado pikeminnow over the 2001–

2013 period showed most support for the intercept only model (0.81), and less support for the linear model with a negative coefficient for slope (0.18, Table 8).

Similar to the 2001–2003 and 2006–2008 periods, the Desolation-Gray Canyon reach of the Green River supported a relatively large, albeit variable, population of Colorado pikeminnow recruits. Recruit abundance was lowest in 2012 among years in the recent period of sampling and was nearly an order of magnitude lower than the prior year, 2011. Estimates of Colorado pikeminnow recruit abundance in the Desolation-Gray Canyon reach of the Green River were less precise than abundance estimates for adults during 2011–2013, with CV's that ranged from 25 to 43%. Recruit abundance trends analyzed with weighted regression showed a stable trend and high support for the intercept only model (0.90); support was lower for a linear model (0.10) with a negative slope coefficient (Figure 6). This is one of the examples where weighted regression results differ substantially from unweighted regression. The linear regression line depicting unweighted estimates showed a positive slope. In contrast, the weighted regression, which reduces the importance of the highest estimates in 2007 and 2011 because of their high variances, shows that abundance of recruits in the Desolation-Gray Canyon reach was stable.

Estimates of juvenile Colorado pikeminnow abundance were also relatively high during the study period in the Desolation-Gray Canyon reach of the Green River although abundance declined from 2011 to 2013. Estimates of Colorado pikeminnow juvenile abundance in the Desolation-Gray Canyon reach of the Green River had low but consistent precision, with CV's that ranged from 33 to 37%.

The high abundance of juvenile fish present in Desolation-Gray Canyon in 2011 was not evident in 2012 or 2013, as larger juveniles, nor as recruits in 2013, a year when some of those Colorado pikeminnow would be expected to be that size based on anticipated growth rates. The

trend was for a negative relationship of juvenile Colorado pikeminnow abundance as a function of time over the 2000 to 2013 period (Figure 6) which was supported by weighted regression (0.56), but the intercept only model was also supported (0.43).

Estimates of adult Colorado pikeminnow abundance in the lower Green River reach were variable over time and abundance was stable from 2001 to 2013. Numbers of unique animals captured was 91 in 2011, but declined to only 15 in 2013 when electrofishing equipment was not operating correctly, which made estimates from that year unreliable. Lower Green River reach abundance estimates had moderate to low precision (CV's = 18 to 41%), and was lowest in 2013 when few adult fish were captured or recaptured.

Over the longer study period (2000–2013), Colorado pikeminnow adult abundance in the lower Green River showed a relatively stable trend (Table 7, Figure 7). Weighted regression of lower Green River abundance estimates for adult Colorado pikeminnow over the three main sampling periods showed most support for the intercept only model (0.89, Table 9) with little support (0.08) for the linear model with a slightly increasing slope (Figure 7).

Estimates of Colorado pikeminnow recruit abundance in the lower Green River reach were relatively high and variable over 2011–2013 as well as for the entire study period. Estimates of Colorado pikeminnow recruit abundance in the lower Green River were imprecise and especially so in 2013. Lower Green River sampling in 2013 was hindered by electrofishing equipment issues so abundance estimates for Colorado pikeminnow of any size in that reach and year are suspect and should be treated cautiously, as should estimates from other reaches that are discussed later. Weighted regression analysis of abundance estimates of Colorado pikeminnow recruits over the 2000–2013 period showed most support for the intercept only model (0.87),

with the remaining modest support (0.08) for an increasing abundance trend in the lower Green River (Figure 7).

In contrast to trends for adults and recruits, juvenile Colorado pikeminnow in the lower Green River showed apparent decreased abundance over time in both the period from 2011–2013 and the 2000–2013 period. Juvenile abundance was the highest ever recorded in 2011 but declined dramatically by 2012 and 2013. The high abundance of juvenile Colorado pikeminnow in 2011 was not evident in 2012 or 2013, nor as recruits in 2013, a year when some of those 2011 fish would be expected in that size group based on anticipated growth rates. The simple unweighted linear trend was for a negative relationship of juvenile Colorado pikeminnow abundance as a function of time (Figure 7) but model weights for weighted regression supported an intercept-only model (0.91).

Basin-wide abundance estimates.—River-wide annual abundance estimates for Colorado pikeminnow adults, recruits, and juveniles were reported for the period 2011 to 2013 (Table 10, Figure 8 [2000–2013]). Abundance of adult Colorado pikeminnow was relatively stable in 2011–2013 at about 2000 fish, and indicated declines from previous periods had perhaps been arrested. Estimates of Colorado pikeminnow adult abundance in the 2011–2013 period had moderate precision, with CV's that ranged from 11 to 19%. Confidence intervals for all pairs of estimates overlapped. The trend for abundance estimates over the period 2000–2013 (year 2000 abundance is from a mix of estimates, that includes Yampa, White and middle Green River reaches from 2000, and 2001 estimates from the lower Green and Desolation-Gray Canyon reaches, since no estimates were available for the latter two reaches in 2000) showed a decline in the Green River sub-basin population of adult Colorado pikeminnow (Table 8, Figure 8). Weighted regression of 2001–2013 estimates (year 2000 excluded due to lack of variance

estimates) showed a substantial decline in adult abundance with the linear model having 91% of the weight. Weighted regression that included the partial-basin estimate for year 2000 also showed a similar decline and had 94% of the weight; had estimates been available for the two downstream most reaches of the Green River, the declining trend would have been even more substantial. It is important to note that nearly 50% of the 2013 abundance estimate for adult Colorado pikeminnow in the Green River sub-basin is from the unreliable middle Green River reach estimate; recall that estimate was based on capture of only 44 individual Colorado pikeminnow. The middle Green River reach estimate, which when coupled with the unreliable lower Green River estimate in 2013, makes the entire sub-basin estimate questionable.

River-wide estimates of Colorado pikeminnow recruit abundance were high in 2011 but low in 2012 and moderate in 2013. Estimates were variable over the 2000–2013 period and indicated a stable to slightly increasing trend and were strongly influenced by the abundant 2008 and 2011 groups, the latter of which largely disappeared in subsequent years. Weighted regression indicated a stable population trend (intercept-only model) with high support (model weight = 0.90) from 2001–2013. Estimates of Colorado pikeminnow recruit abundance were less precise than for adults, with CV's that ranged from 15 to 29%. Abundance of juvenile Colorado pikeminnow in the Green River sub-basin was relatively high in 2011 but lower in 2012 and 2013. Weighted regression indicated stable juvenile abundance over time, as the intercept-only model had a high weight (0.90).

Survival estimates.—Survival estimates were fit with splines (a curve smoothing function) in the top model because simpler linear or quadratic effects on TL produced uninterpretable, but relatively highly ranked model estimates. The top model survival rate curve for the 2000–2013 data was oddly shaped (Appendix XII), with peaks at about 400 and 700 mm

TL and a dip at 600, and thus not intuitive; model fit was vastly improved and can be seen in the weight differences between the top model and others without splines. Thus, we present reach-specific survival estimates for 2000–2013 from the top-ranked model without any TL effects on survival (Table 11). Those estimates ranged from 0.70–0.78, and were slightly lower than those in 2006–2008, but higher than in 2000–2003.

Probabilities of capture.—Model selection supported estimation of capture probabilities for Colorado pikeminnow that were specific to each sampling pass, reach, and year. In addition, effects for TL (and TL^2) specific to each of the three major study periods was important. As was apparent from estimation and model selection, probabilities of capture were relatively low, imprecise, and varied widely among sampling occasions, reaches, and years (Table 9). Capture probabilities per sampling pass ranged from 0.005 to 0.216. Average probabilities of capture were highest in the middle Green River, followed by the Yampa and White rivers, the Desolation-Gray Canyon reach, and the lower Green River. Capture probabilities were very low in the Yampa River in 2012 and 2013 when few fish were captured with no recaptures. Remember that because of the TL covariate, a probability of capture can be estimated even when there are no recaptures in a reach on a given pass or year because information is being "borrowed" from other reaches and years. Year 2011 was characterized by very high and cool flows, and 2012 and 2013 had much lower and warmer flows, but those variable flows had no consistent effect on capture probabilities across reaches; in a few cases capture probabilities were reduced in low flow years. Trajectories of probabilities of capture by reach and year were mixed, with some increasing with later season passes (e.g., White River), while others remained stable (e.g., Desolation-Gray Canyon), or declined as the season progressed (lower Green River).

Mean capture probabilities plotted by reach and sampling period (2000–2003, 2006–2008, and 2011–2013) indicated declining rates over time for all reaches, and for every sampling period, with one exception (Figure 9). In the middle Green River, capture probabilities were highest in the first period, lowest in the second, and intermediate in 2011–2013. Mean capture probability for all reaches was 0.090 in 2000–2003 but declined 44% to 0.050 in 2011–2013.

Consistent with declining probabilities of captures in each of the main sampling periods, declining numbers of fish captured were also noted by year within each main period (Figure 10). For example, in the 2000–2003 period, the most fish were captured in 2001 and 2000 (no sampling conducted in the two most downstream Green River reaches), compared to lower numbers 2002 and 2003. Number of fish captured increased in 2006, albeit not to levels present in 2000 or 2001, and subsequently declined in 2007 and 2008, and a similar pattern of slight recovery followed by decline was noted in 2011–2013.

Probabilities of transition.—Transition probabilities (ψ_{ij}) estimated the likelihood that a tagged fish would move between any two of the five different Green River sub-basin reaches between years, which is the time after which sampling stops one year and before it begins the next. Estimates of reach transition probabilities also gave insights into rates and direction of movement of Colorado pikeminnow to and from various reaches. Transition probabilities were highest for smaller fish and declined as fish became larger and indicated reduced movement (Figure 11). Precision of the ψ_{ij} estimates was relatively low.

In general, most ψ's for Colorado pikeminnow were low to moderate, especially those for non-adjacent reaches (e.g., lower Green River to the White or Yampa River, Table 12, 13). Average transition probabilities for Colorado pikeminnow moving to the Yampa River (0.05) and the lower Green River (0.05) were low and more fish left those reaches than entered, as

evidenced by the negative net transition rates (Table 13). Transition rates to the White River (0.13) and particularly the middle Green River and Desolation-Gray Canyon reaches were higher (0.25 and 0.29, respectively). High transition rates from the Yampa River and lower Green River relative to transition to those reaches resulted in net transition rates that were negative. All other reaches were positive, with the middle Green River having the highest net transition rate (0.11) and Desolation-Gray Canyon Colorado pikeminnow having the second highest (0.08), reflecting that fish moved to those reaches and stayed.

The relatively high and negative net ψ's for the relatively small fish in the lower Green River (see length frequency histograms below) reflected upstream transition rates (fewer fish stayed or moved back into the reach). High (about 0.25) transition rates were estimated for fish moving downstream from the White and Yampa rivers to adjacent sections, and the middle Green River to Desolation-Gray Canyon (Table 12). We did not estimate transition rates for every year because the additional number of parameters would make models unwieldy and uninterpretable.

ISMP catch/effort trends, 1991 to 2013.—Catch/effort indices at standard ISMP sites for Colorado pikeminnow in the four reaches of the Green River sub-basin for which data were available were variable over years but generally increased to year 2000, declined through 2003, increased in 2006–2007 (but not 2008) and declined further in 2011–2013 (Figure 12). The 2013 catch rates were among the lowest on record for all reaches.

Length-frequency distributions.—Length-frequency distributions for the upstream Yampa River, White River, and middle Green River reaches (Figures 13–15) suggested presence of a larger proportion of relatively large Colorado pikeminnow, and relatively fewer fish less than 450 mm TL. This was the case in the recent 2011–2013 sampling period as well as for prior

periods. Desolation-Gray Canyon and lower Green River reaches supported most of the fish captured in most years that were < 450 mm TL (Figures 6–7, 16–17), in both the recent and past abundance estimation sampling periods.

Population structure of recruit and adult Colorado pikeminnow in ISMP-reach samples changed dramatically between the four periods, 1991–1999, 2000–2003, 2006–2008, and 2011–2013 (Figure 18). Number of Colorado pikeminnow recruits (*n* = 186 total) during 1991–1999 averaged 24.7% (7.9 to 58.5% per sample) of the number of adults in samples (*n* = 826). During 1991–1999, there were four years (three from 1992–1994) when proportion of recruits was high (>20%), three years when proportion of recruits was moderate (>10 to 20%), and two years when it was low (0 to 10%). In 2000–2003, number of Colorado pikeminnow recruits per year (*n* = 14 over all years) was low, at only 3.4% (0 to 6.6%, mean of annual percentages) of the number of adults captured (*n* = 418), and was zero in three of those (2001–2003). In the period 2006–2008, and consistent with abundance estimates, the percentage of Colorado pikeminnow recruits in ISMP samples increased to an average of 22.1% (9.2 to 33.3%) of the number of adults captured (*n* = 166), with % recruits increasing each year through the period. However, in the recent period, and using a slightly different but comparable method to estimate % recruits, the proportion of Green River recruits in samples was high in 2011 (28%) but only 4% in 2012 and 12% in 2013.

DISCUSSION

Abundance estimates derived from capture-recapture sampling indicated adult Colorado pikeminnow in the Green River sub-basin declined since 2000. This was after an apparent increase in 2006–2008 (Bestgen et al. 2010), especially in 2008, an increase which is now less

prominent after reanalysis with the entire capture-recapture data set (2000–2013: Figure 19, Appendix XI). The declining abundance trend for Colorado pikeminnow in the Green River sub-basin was also supported by other data and analyses, which showed reduced overall numbers of fish captured compared to earlier periods. Adult Colorado pikeminnow abundance in the Green River subbasin has also dropped below the recovery goal abundance threshold of 2,600 fish in each year in 2011–2013 (U.S. Fish and Wildlife Service 2002). Reduced adult abundance in the recent period was not expected given relatively high abundance noted in 2008, although that estimate had considerable uncertainty associated with it. Reduced adult abundance throughout the 2011–2013 period was also not expected, especially in the Desolation-Gray and lower Green River reaches, where the high (800+) estimated abundance of recruit-sized fish (400–449 mm TL) present in 2011 was expected to result in higher adult abundance as fish subsequently grew to adult size in 2012 and 2013 (Osmundson et al. 1997). Instead, adult abundance estimates in those reaches were little changed or were even lower in 2012 and 2013 than in 2011. Likewise, abundant juvenile Colorado pikeminnow (< 400 mm TL) present in 2011 in those two most downstream Green River reaches (nearly 2,400 fish, mainly 150–250 mm TL) were seemingly not observed again in the numbers expected in any Green River reaches or tributaries, based on expected survival rates of fish that size. Reductions in juvenile abundance was likely due to predation by large-bodied and abundant walleye, which with normal survival rates, would have added several hundred adults to the population. Juvenile cohort succession in 2011–2013 was in contrast to the cohort succession observed during the 2006–2008 sampling period, where the high abundance of lower Green River Colorado pikeminnow juveniles in 2006 led to high abundance of recruits in 2007, which in turn resulted in high abundance of adults in 2008 (Bestgen et al. 2010), high uncertainty of that estimate notwithstanding. Below we discuss the

multiple and consistent lines of evidence that support the thesis of decreased Colorado pikeminnow abundance in the Green River sub-basin in 2011–2013, but acknowledge that some estimates were imprecise due to low recapture rates (e.g., lower and middle Green rivers 2013). We also discuss the abundance estimation model, model assumptions, implications of parameter estimates, and potential reasons for the apparent decline in abundance of Colorado pikeminnow in the Green River sub-basin during the study period.

Model selection and assumptions.—We used an estimating model for the complete 2000–2013 dataset to take advantage of information that can be shared across sampling periods. We explored a series of increasingly complex models that led us to choose the Huggins robust-design multi-state model as the most realistic. The sampling design (three primary sampling periods with three or more years, with three or more closely-spaced secondary sampling occasions in each year) led logically to a robust-design estimator which allowed estimation of Colorado pikeminnow abundance for every sampling year and potentially, estimation of survival between years of sampling. The Huggins model allowed use of the individual covariate TL, which was important because fish size was known to affect capture probabilities and survival rates of fishes, including Colorado pikeminnow (Bestgen et al. 2007; Bestgen et al. 2010). Incorporation of size effects into survival and capture probabilities allowed for more efficient and realistic population modeling and TL effects were highly supported in analysis of the larger dataset.

The multi-state (states are reaches, called “strata” in Bestgen et al. 2007) aspect of the estimating model was important because of the five-reach sampling design, and because differences in size-structure of Colorado pikeminnow among reaches affected capture probabilities and ultimately, abundance estimates. Differences in capture probabilities across reaches might also be expected because of differences in geomorphic conditions (canyon vs.

valley), sampling crews, and the type of sampling craft (raft vs. boat) used in each reach. Another factor may have been that crews were transitioning to new and unfamiliar ETS electrofishing units, which operate differently than the Smith-Root units used previously, with attendant potential differences in capture efficiency. Finally, this model offered the further flexibility of estimating effects of fish moving from one reach to another (ψ) between years. Thus, the manner in which the data were collected, and the biology of the subject animal, logically led to use of this estimating model.

Fulfilling the assumptions of the underlying model was a critical first step in obtaining reliable abundance estimates. Aspects of the experimental design employed in this study ensured that most assumptions of closed-model abundance estimators were met. The assumption of demographic closure was met, in part, because within-year sampling was limited to a relatively short time period in spring prior to Colorado pikeminnow migration to spawning areas. This reduced the possibility of movement to the geographically small areas that were not sampled. Static population size was also ensured in the period encompassed by within-year sampling occasions, because of the large size of the study area. The only location of emigration/immigration for fish was from the distant and downstream confluence of the Green and Colorado rivers. The likelihood of substantial movement from there was much reduced at that time of year because fish tend to occupy relatively small and stable home ranges for most of the year except during periods of reproduction (Tyus 1990; Irving and Modde 2000). This notion was further supported by the low number of Colorado pikeminnow moving between river reaches within a sampling season (Bestgen et al. 2007; Bestgen et al. 2010), as well as low movement of fish from the Green to the Colorado River (Osmundson and White 2014; 2017).

The short period encompassed by the sampling occasions also ensured that mortality and recruitment were minimized.

The assumption of homogeneity of capture probabilities was unlikely to be fulfilled except in all but the most restricted conditions. We attempted to minimize heterogeneity effects by incorporating the covariate TL into analyses. That covariate was included with effects for year, reach, and sampling pass to account for differences in capture probabilities among primary sampling periods 2000–2003, 2006–2008, and 2011–2013. This was done because we noted declining capture probabilities for each reach over time (e.g., Figure 9, 10).

In a prior analysis (Bestgen et al. 2007), we investigated the likelihood of a population composed of groups of individuals with inherently different capture probabilities. We found no support for such based on preliminary analyses using mixture models (Pledger 2000) for data collected in the period 2000 to 2003, so we did not attempt further analyses. Further, with only three secondary occasions per primary occasion, the data were likely inadequate to detect two mixtures with the Pledger model. Prior analyses also demonstrated that initial capture probabilities were equal to recapture probabilities among the short-term sampling occasions (i.e., $p_k = c_k$) by including an additive parameter to the top model (additive model is #4 in the set, in Bestgen et al. 2007) but those results were inconclusive. Thus, to the extent possible, we have tested for and found no effects of heterogeneity.

We did find reduced capture rates of Colorado pikeminnow over time in the Green River basin, based on both mean capture probabilities for main sampling periods (e.g., 2000–2003, 2006–2008, 2011–2013), as well as among years within those periods. The cause of reduced capture probabilities was not clear. One explanation is a behavioral response, where fish can detect boats and electricity and move away to avoid capture. Under such a scenario, one would

expect data to show that sampling captures fewer fish over time, which we observed. A similar pattern would likewise be exhibited if there were fewer fish to sample. Gear avoidance could also be invoked if fewer fish were captured in first passes within a year compared to later ones, which we also observed. Under this scenario, unsuspecting fish would be easier to capture on the first sampling pass, than in subsequent passes where fish learn to avoid gear. We saw a rebound in numbers of fish captured between main sampling periods, such as between 2000–2003 and 2006–2008, and 2006–2008. Such a pattern could be explained by a reduction in gear avoidance behavior between sampling periods by fish present in the earlier period, and also by new, naïve fish being recruited to the population, that are less aware of sampling gear.

To test for a prior capture effect, we ran additional Program MARK models with two prior year covariates in them, one for if a fish was captured the prior year, and one for if a fish was ever captured in any prior sampling year. The covariates had a small effect, supporting the idea that previously recaptured fish were only slightly more difficult to capture, but the models with the extra prior capture effect in them were not substantially better than the original model we chose to interpret. Thus, we discounted a prior capture effect.

Other effects that could alter capture probabilities over time are gear or personnel effects. For example, the situation in the lower Green River in 2013, where electrofishing gear was ineffective because of reverse polarization (cathode was the anode and vice versa) was a reason for reduced fish captures and imprecise and perhaps biased abundance estimates. Similar effects would be evident if personnel could not effectively sample the available habitat. This occurred in the middle Green River in 2011, when one sampling pass could not be completed because high water levels prevented boats from going under bridges. A similar but opposite situation occurred in the low water year 2012, when less habitat was available to sample because shoreline

habitat was inaccessible to boats. Lack of permission to sample the lower reach (24 river miles) of the White River in the first two passes in 2011 also caused reduced numbers of fish captured and recaptured, and likely reduced abundance estimates.

Another reason for reduced capture probabilities may be changes in electrofisher types, which began around 2011, but was not completed until 2012. Electrofishing gear was swapped so field sampling could be conducted to minimize damage to fish caused by potentially harmful waveforms of electricity (Martinez and Kolz 2016). Differences in wave forms and electrofishing power among different gear and manufacturers may cause differences in catchability of fish. Biologists have noted that Colorado pikeminnow are less stunned when boated after being captured using the new gear, and often are more difficult to net, which will reduce number of fish captured and recaptured.

The issue of long-term reductions in capture probabilities is important because of its potential effects on abundance estimate accuracy and precision and should be further investigated. One means to do this is to incorporate different gear types to determine if fish are being missed in reaches at higher rates than normal. This could be examined via comparisons with stationary or mobile PIT tag detection antennas. Examination of PIT tag records gathered with antennas would also be useful to understand if electrofishing gear is ineffective to capture large fish after first capture. In other words, are large fish really never seen again, or are large fish not in recapture samples because of electrofishing gear avoidance but are detected with antennas, which fish cannot actively avoid. We are beginning some of those investigations at this time.

Another relevant assumption in this study was that animals mixed freely among concentration habitats (backwaters, shorelines, eddies) and the rest of the channel between

sampling occasions such that all animals in the population were available for capture. A corollary assumption was that sampling effort was distributed over most occupied habitat. Evidence from the Colorado River indicated Colorado pikeminnow mixed between concentration areas and other habitat types among sampling occasions; Osmundson and Burnham (1998) found high probabilities of capture within concentration backwater habitat in a single sampling occasion, but relatively low probabilities of recapture in those same locations between occasions. The logical explanation for this capture pattern is that many fish moved into and out of concentration habitat between sampling occasions. In the Green River sub-basin during this and past studies (Bestgen et al. 2007; Bestgen et al. 2010), we demonstrated similar mixing because initial capture probabilities were equal to recapture probabilities among the short-term sampling occasions (i.e., $p_k = c_k$). If fish were not mixing, we would expect that recapture probabilities would be much higher than initial capture probabilities, because the same shoreline habitat was sampled during each pass. We probably had low sampling efficiency in very deep pools (> 2-m deep) at most times, but the amount of that habitat type relative to shallower, easier-to-sample areas where Colorado pikeminnow typically resided was small (Tyus and McAda 1984). Thus, short-term fish movement patterns, analysis of capture and recapture rates, and our relatively complete sampling coverage of occupied habitat likely minimized bias due to incomplete mixing of marked and unmarked animals.

We also assumed that recognition of marked Colorado pikeminnow was high (all were scanned) and that tag loss was low. We also recognize that differences in crew experience can affect capture rates of Colorado pikeminnow. Although differences in capture rates may exist because of differences in crew experience or effort, we presume effects of such on abundance

estimates should be minimized because capture probabilities were estimated using all sampling occasions, reaches, years, and for the three major sampling periods.

Abundance estimates.—Confidence intervals for annual abundance estimates for individual reaches generally overlapped during the 2011–2013 period. This was due in large part to imprecise estimates when relatively few captures and recaptures were made. However, consistent declines in abundance estimates over time and in most river reaches suggested a river-wide decline in abundance of adult Colorado pikeminnow in the Green River sub-basin between the 2006–2008 and 2011–2013, and likely over the entire 2000–2013 period. Decline in adult abundance during this period was especially substantial in the White and Yampa river reaches and, despite high and imprecise estimates in 2013, in the middle Green River.

Only the relatively small group of adult Colorado pikeminnow in the lower Green River reach and those in the Desolation-Gray Canyon reach showed a relatively stable adult abundance level from 2000–2013. However, those two reaches constituted only 30–40% of the adult population basinwide. Given the absence of obvious violations of assumptions for abundance estimation models, and that trends in estimates for reaches with the largest populations were declining, we consider the conclusion of reduced abundance of adult Colorado pikeminnow in the entire Green River sub-basin to be valid. Details associated with other life stages or reach-specific estimates are discussed below.

Abundance estimates for adult Colorado pikeminnow in the Yampa River declined dramatically in 2012 and 2013 and in general, supported a declining trend that began in the 2000 to 2003 period. While abundance estimates based on so few fish captured are less reliable, declines in numbers of captured fish and associated catch rates points to the continued and rapid decline of adult Colorado pikeminnow in the Yampa River. For example, 82 and 120 individual

Colorado pikeminnow were captured in 2000 and 2001, respectively, while only 6 and 7 individuals were captured in 2012 and 2013, respectively, and with substantially greater sampling effort in later years.

Despite intensive removal efforts, continued presence of predaceous northern pike in some reaches of the Yampa River may yet be suppressing abundance of Colorado pikeminnow, although abundance of the largest northern pike has been reduced (Zelasko et al. 2015; 2016; see also annual nonnative fish removal reports to the, Recovery Program). Continued and more widespread northern pike removal in upstream source reaches may enhance Colorado pikeminnow abundance in the Yampa River in the future.

Abundance of Colorado pikeminnow recruits was much higher in 2006–2008 than from 2000–2003, which was certainly responsible for the increased abundance of adults as recruits grew to ≥450 mm TL in 2008. This scenario was reasonable based on expected growth rates and changes in length-frequency histograms, especially in the Desolation-Gray Canyon and lower Green River reaches. This pattern was apparently not sustained after that time in spite of high recruit abundance in 2011 in the two most downstream Green River reaches. Recruitment was dynamic for Colorado pikeminnow as abundances of young fish fluctuated over time in the Colorado and Green River systems (Osmundson and Burnham 1998, Bestgen et al. 2007). Increased abundance of young fish occurred during 2006–2008 and in 2011, when abundant juvenile and recruit-sized year classes were detected.

Despite a stable abundance trend, low overall abundance of recruit-sized fish in the middle Green River and other downstream reaches is also a likely reason for sustained low abundance of adult Colorado pikeminnow in the Yampa River, because that system relies entirely on fish moving into the river to sustain populations. In other words, the Yampa River

does not produce its own recruits so if no Colorado pikeminnow move into the system, populations will decline over time via mortality of adults. The only known recruit-sized Colorado pikeminnow found in the Yampa River in recent years was entrained in the Maybell Ditch and likely died (Speas et al. 2014).

There was also evidence that Colorado pikeminnow were moving out of the Yampa River at a faster rate than they were moving in. That evidence was from transition rates from 2000–2013 that showed a relatively high net movement of adult Colorado pikeminnow from the reach, even when few fish resided there. Reduced fish captures and resulting reduced abundance estimates in the 2011–2013 period both showed that the largest recent declines were after 2011. Both 2012 and 2013 were relatively low water years where habitat was reduced in the Yampa River, and perhaps fish moved downriver in 2012 and 2013 and did not return. Transition rate estimate precision in 2012 and 2013 was also low due to absence of recaptures.

Reduced abundance of adult Colorado pikeminnow in the White and middle Green River reaches is a concern because those segments supported the largest numbers of Colorado pikeminnow in the 2000–2003 and 2006–2008 periods (Bestgen et al. 2007; Bestgen et al. 2010). Increased abundance of adult Colorado pikeminnow in those reaches through 2008 almost certainly derived from upstream movement of large numbers of juvenile and recruit-sized Colorado pikeminnow that originated in lower reaches of the Green River in 2006 and 2007. Bestgen et al. (2010) cautioned "While the thesis of increased Colorado pikeminnow abundance in those reaches appears sound, higher numbers of captures and recaptures are needed in the next set of abundance estimates (2011–2013) to better understand the magnitude of population change." The population increases apparently were not as pronounced as previously thought,

and certainly were not sustained. This was in spite of large numbers of recruit-sized fish in downstream reaches Desolation-Gray Canyon and the lower Green River in 2011.

The dramatic increase in adult abundance in Desolation-Gray Canyon in 2008 was noted by Bestgen et al. (2010) who cautioned, "…the 2008 abundance estimate had a very wide confidence interval and was less reliable than others" (see Figure 19). However, the large population was expected based on the high number of recruits present. Specifically, the Desolation-Gray Canyon reach supported a large number of recruits in the reach in 2007 (about 400) that would grow into the adult life stage by 2008 (Bestgen et al. 2007), and, based on expected transition rates, the reach also received a large number of recruits and perhaps small adult fish moving from the lower Green River. The thesis of high adult abundance in 2008 may have been wrong.

Temporal succession of juvenile, recruit, and adult cohorts could also explain trends in 2011–2013 because recruit-sized fish were abundant in the lower Green River and Desolation-Gray Canyon reaches in 2011. Those recruits, and most of the abundant juveniles in the same reaches, were essentially absent in abundance estimates in 2012 and 2013. This was because expected adult Colorado pikeminnow population increases were not detected in adjacent reaches, nor were sustained abundances of juveniles in 2012 and 2013 noted in any reach of the Green River or tributaries, where some of those fish would be expected to move. The few captures of Colorado pikeminnow in the lower Green River in 2013, due to gear inefficiency, reduced the reliability of estimates for any life stage in that reach. The same might be said for the middle Green River reach, and perhaps other reaches, because of flow-induced differences in capture efficiency, and effects of transitioning to new and unfamiliar electrofishing gear.

Other hypotheses for reduced abundance of Colorado pikeminnow in the Green River basin are possible. For example, runoff from areas burned in 2012 may have had some impact on water quality and fish survival. Although effects are unquantified, and few fish mortalities were observed, fish in reaches downstream of burned areas have been known to suffer mortalities. Increased mortality of young Colorado pikeminnow (juveniles and recruits) due to entrainment into Tusher Canal is also a possibility. High entrainment rates in low flow years such as 2012 and 2013, when the canal diverts a relatively large portion of the river, may have negatively affected survival of the large number of young fish noted in 2011. Because most of those fish would not be tagged, in general, they would not necessarily be detected by PIT tag antennas at the diversion entrance.

Trends in the ISMP catch/effort indices for adult Colorado pikeminnow were generally consistent with abundance estimates through 2013. Catch rates in 2011–2013 were among the lowest ever recorded for most reaches. For example, in the middle Green and White River reaches catch rates in 2013 were only 14 and 7 % of those measured in 2000, the years of highest abundance.

Survival rates.—Estimating survival rates for Colorado pikeminnow over the extended 2000–2013 period was complicated. Initial attempts at survival estimation showed high survival rates for small and large fish and low survival rates for intermediate sized fish, opposite of what was expected based on past efforts and general knowledge (Bestgen et al. 2007; Bestgen et al. 2010). The addition of the splines in the estimating function, which assist with curve smoothing, helped slightly and resulted in a bell-shaped curve somewhat like what was produced in the past. However, the dome of the curve had two irregularly-shaped humps, the right one lower than the left (Appendix XII), a pattern which was difficult to interpret. The survival rates reported were

for the top model in the absence of any length effects, which should give the reader a general idea of survival rates over time. Overall, the combined 2000–2013 survival rates were intermediate between the lower rates for 2000–2003, and the higher ones for 2006–2008, so these may be reasonable approximations for the 2011–2013 period as well.

Survival rate variation of Colorado pikeminnow across river reaches was moderate, and highest in the lower Green River and lowest in the middle Green River; those differences were significant. Intuitive reasons for that variation were not evident, as survival rates for the relatively small lower Green River fish might be expected to be lower. It is possible that Colorado pikeminnow mortality associated with higher angling pressure, aimed mainly at expanded walleye populations in the middle Green River, may be a factor (personal observation, M. Breen). The middle Green River also has higher abundance of large-bodied and piscivorous northern pike. The survival rates and TL relationships for Colorado pikeminnow were different for each of the periods 2011–2013, 2006–2008, 2000–2003, and 1991–1999, further complicating comparisons. Although unsuccessful, we ran many models attempting to obtain more reasonable and consistent estimates of survival across the sampling periods. One thing that was certain is that for all models that fit a TL effect, a downward trend in survival was evident for larger fish. Contributing to the pattern was the few large fish in samples (e.g., >800 mm TL), particularly in 2000–2003, many of which were never recaptured (Bestgen et al. 2007; Bestgen et al. 2010).

Continued removal of large and piscivorous fish, including northern pike, may continue to benefit Colorado pikeminnow in some portions of the basin such as the middle Green River, where pike abundance remained relatively low through the study period. However, in the Yampa River where the largest northern pike populations in the Green River sub-basin occurred

and removal of pike is ongoing (Zelasko et al. 2015; 2016), the small population of Colorado pikeminnow continued to decline. This may be due to insufficient removal of predators in the Yampa River or, because recruitment from downstream reaches was insufficient to sustain abundance of adults in the Yampa or White rivers. Declining abundance of White River adults, which also relies on upstream immigration of fish to replenish the population, may also be due to low recruit abundance in downstream reaches. Mechanisms affecting recruitment of age-0 Colorado pikeminnow in the Green River were discussed in Bestgen and Hill (2016).

Bestgen et al. (2007) discussed at length the potential negative effects of electrofishing on Colorado pikeminnow survival in the Green River sub-basin, and based on field observations and specific experimental results of other studies (Meismer 1999), found no support for that hypothesis. Findings during the 2006–2008 and 2011–2013 further support the thesis of minimal electrofishing sampling effects on survival of Colorado pikeminnow, because we were sampling a relatively small portion of the population each year based on relatively low capture probabilities, and because we see few or no injured fish each year. We also did not detect substantial size-dependent effects on survival in the period 2006 to 2008 (size dependence not analyzed in 2011–2013), which further substantiated the idea that electrofishing sampling did not negatively affect large Colorado pikeminnow.

It is also possible that Colorado pikeminnow are exhibiting a gear avoidance behavior. The many sampling passes for this project as well as for nonnative fish removal may condition fish to move away from boats and the electrofishing field during sampling. That behavior would result in fewer fish captured and recaptured, and if behavior of large fish are especially affected, alterations to abundance estimates and their precision, and survival rates would be expected.

Apparent survival estimates reflect that estimates of *S* were the joint probability of an individual surviving, and remaining, in the reach so that it was available for sampling. Thus, if a fish moved from a sampled reach to an unsampled one and remained there, by definition, that fish was deemed a mortality. We did not sample about 12% of critical habitat occupied by Colorado pikeminnow in the Green River sub-basin. Those areas such as Lodore Canyon of the Green River just upstream of the Yampa River have supported Colorado pikeminnow in the past (Bestgen and Crist 2000; Kitcheyan and Montagne 2005; Bestgen et al. 2006b, project FR115 annual reports). Although modest numbers of Colorado pikeminnow have been occasionally captured in such reaches, particularly Lodore Canyon and Browns Park, occupancy of those areas sometimes occurred in seasons other than spring when abundance estimation sampling was conducted. For example, based on telemetry and tag recapture data, most Colorado pikeminnow that moved to Lodore Canyon in portions of 2001, and all of 2002 and 2003, did so in summer, with most fish coming from the Green River in Island Park, other downstream portions of the middle Green River reach, or even the Yampa River (Kitcheyan and Montagne 2005; Bestgen et al. 2006b; see also Recovery Program study FR-115 annual reports). We have sampled up to a dozen adult Colorado pikeminnow in a year at the Green River-Vermillion Creek confluence during high flow events since 2010 and many more were detected with PIT tag antennas in spring 2017 (http://www.coloradoriverrecovery.org/documents-publications/work-plan-documents/project-annual-reports.html; Recovery program annual reports FR-115). However, we do not believe numbers of adult Colorado pikeminnow exist in large enough numbers that could explain large declines in abundance in reaches sampled in this study.

Recruitment rates.—The links between environmental conditions, especially flow regimes, and production of large year-classes of age-0 Colorado pikeminnow in the Green River

have been identified (Bestgen and Hill 2016). They found the strongest year-classes of age-0 Colorado pikeminnow were produced in years when adequate larvae emerged from spawning areas, when Green River flows in summer were moderate at about 1700-3000 ft^3/sec, and when flows declined to lower levels by the time pikeminnow larvae emerged from spawning gravel. The timing of flows is important because suitable backwater habitat conditions when larvae are present is important. They also found that higher flows within the preferred flow range reduced abundance of red shiner, which may contribute to higher abundance of young Colorado pikeminnow in some years via reduced shiner predation or competition (Bestgen et al. 2006a).

We have also linked abundance of age-0 Colorado pikeminnow to abundance of older life stages, and found that differences in recruitment of young plays a large role in abundance dynamics of adult Colorado pikeminnow years later in the Green River sub-basin (Bestgen et al. 2007; Bestgen et al. 2010). Based on expected growth of about 43 mm/yr for Colorado pikeminnow in the 400–449-mm TL recruit size-class (Osmundson et al. 1997; U.S. Fish and Wildlife Service 2002), the average recruit-sized Colorado pikeminnow would become part of the adult population the following year. The expectation of recovery goals was that recruitment will, over time, equal or exceed mortality of adults to produce a stable or increasing Colorado pikeminnow population. In other words, the adult population was maintained when the number of adults that die in year i is balanced by the number of recruits present in year $i - 1$ that survive to the following year i. Adult Colorado pikeminnow abundance declined in the period 2000 to 2003 when the number of recruits was only 4.9–13.3% of all fish sampled, numbers which were insufficient to offset the 35% apparent annual mortality rate ($1 - S*100$). The mortality rate in that period was for the average size fish in samples (in adult size class, 560 mm TL). However, abundance of adult Colorado pikeminnow increased in the periods 1991 to 1999 and 2006 to

2008, when the average proportion of recruits in the population (25% in 1991–1999 [Bestgen et al. 2007] and 22% in 2006–2008 [Bestgen et al. 2010]) exceeded the mortality rate of adults in each period (about 20%). Reduced abundance of adult Colorado pikeminnow in 2011–2013 was again consistent with reduced numbers of recruit-sized fish in the system, especially in 2012 and 2013. The relatively abundant group of young fish produced in the middle Green River in 2009 would likely be only juvenile life stage (five-year-old fish) and was not expected to contribute to recruit-sized fish by 2013.

The mechanism driving the frequency and strength of recruitment events was the strength of age-0 Colorado pikeminnow year-class production in backwater nursery habitats, particularly those in the lower Green River in recent years. For example, high production of recruits from 1992 to 1994 was apparently derived from strong year-classes of age-0 fish from 1986 to 1989 (Figure 20). Similarly, a strong recruit year class in 1999 was apparently produced by a large group of age-0 fish hatched in 1993. That year class would have first contributed adult Colorado pikeminnow to the Green River population in year 2000, the year when estimated abundance of adults was high at over 4,000 fish (Bestgen et al. 2007). Those events were largely responsible for expanding populations of Colorado pikeminnow adults in the Green River sub-basin from 1991 to 2000. The pattern of increasing numbers of adults, but attendant declining abundance of age-0 fish in nursery areas through 1998 was noted in Muth et al. (2000). The period of increased adult abundance through year 2000 was followed by a population decline from 2001 to 2003 (Bestgen et al. 2007). A main contributing factor to that decline was low abundance of recruit-sized Colorado pikeminnow in 2000 to 2003 which was a function of relatively low abundance of young-of-year produced in nursery areas in most years from 1994 to 1999 (Figure

20, Muth et al. 2000; McAda 2002; Utah Division of Wildlife Resources, unpublished data, Project 138 annual reports).

A more explicit recruitment link to adult abundance was also made with the age-0 life stage. This analysis was completed in conjunction with a recent Colorado pikeminnow population viability analysis (PVA), which was completed after the review drafts of this report were completed so Methods were not placed in the usual location. We reasoned, based on growth rates of young Colorado pikeminnow, that the first year class of age-0 fish that would contribute to the adult life stage would be seven years after hatching (Osmundson et al. 1997). This is true because a pikeminnow larva growing at average rates over time would be just over 450 mm TL after seven years (456 mm TL, Table 1 in Osmundson et al. 1997). We further reasoned that seven-year-old fish plus the next three year classes (eight-, nine-, and ten-year-old fish) are the year classes most recently transitioned to the adult life stage and thus, should be the most abundant fraction of the adult population. Furthermore, published growth rates (Osmundson et al. 1997) indicate that nine- and 10-year-old fish should, on average, be about 550 mm TL. That size usually constituted the most abundant length classes in most reaches of the Green River in most years (see length-frequency histograms) and further substantiated the idea that those age classes should comprise a large proportion of the adult population. Thus, average relative abundance of four successive age-0 Colorado pikeminnow cohorts should provide a reasonable index to abundance of adults seven years after the last age-0 cohort (of four) became established. For example, the adult population present in year 2000 was likely composed mostly of fish from year classes from 1990–1993, even though many older (10+) year classes contributed. Similarly, adults in 2007 most likely derived from age-0 fish produced in 1997–2000.

Correlation of the adult abundance in a given year to the mean abundance of age-0 Colorado pikeminnow captured in Green River (lower and middle Green River) ISMP seine samples 7-10 years prior showed a strong positive relationship (r = 0.95, r^2 = 0.87; Figure 21 upper panel). In other words, a metric of abundance of age-0 Colorado pikeminnow produced 7-10 years prior strongly predicted abundance of adults through time. To assess the temporal trajectory of Colorado pikeminnow abundance, we plotted abundance of adults estimated from our sampling during 2000–2013 and compared that with the corresponding mean abundance of age-0 fish captured in ISMP samples 7, 8, 9, and10 years prior to the adult estimate. The declining relationship of age-0 Colorado pikeminnow abundance that would have contributed to the adult population over the 2000–2013 period demonstrated that reduced young pikeminnow abundance was a primary reason for declining abundance of adults in that same period. Patterns of abundance of young relative to adults are not obvious in the Colorado River, where survival of young fish may be more variable and lower (Osmundson and White 2014; 2017).

In making links of age-0 pikeminnow abundance to adult fish, we relied on growth estimates of Colorado pikeminnow from the Colorado River. A key assumption was that growth relationship were similar for Green River pikeminnow and this key assumption should be validated with more empirical data and analyses, as growth rates between the two systems differ. For example, the von Bertalanffy growth equation parameter estimates used to estimate lengths of Colorado River Colorado pikeminnow between capture occasions for abundance estimation, indicated growth substantially lower than that for pikeminnow in the Green River basin. The von Bertalanffy growth equation parameter estimates used in Osmundson and White (2014, updated to include 2014 and 2015 fish) was k = 0.079 (0.064–0.0887, 95% confidence interval [CI]) and L_∞ = 830.4 mm TL (803.0–857.8 mm TL, 95% CI). Effects of different growth

relationships on recruitment and the general understanding of Colorado pikeminnow ecology may assist with recovery and requires further investigation.

A high pikeminnow recruitment episode seemed imminent in 2011, where high abundance of recruit-sized Colorado pikeminnow would grow to adult size and expand populations in the Green River sub-basin. It was not obvious which year class of age-0 fish was responsible for that large group of recruit-sized fish because abundance of the presumed contributing cohort (2005) was low. However, large numbers of juvenile fish found in 2011 that were 150-250 mm TL were likely the result of stronger year-classes produced in 2007 and 2009, especially in the lower Green River; the relatively strong 2010 year class would not contribute to that size classes of fish because young pikeminnow do not grow that fast. Regardless, both recruit-sized and juvenile-sized Colorado pikeminnow were much reduced in 2012 and 2013.

Reduced abundance of smaller juvenile or recruit Colorado pikeminnow in 2012 and 2013 could be due to a several reasons. First, 2011 was a very high flow year. It is a remotely possible that high flows and cool water temperatures imposed higher mortality on those fish, although exact mechanisms were difficult to determine.

Another more likely reason for reduced abundance of juvenile Colorado pikeminnow is increased predation associated with a recent and large population expansion by walleye in nursery habitat reaches in the lower Green River, a location where large-bodied nonnative predators were historically rare. By about 2010 or 2011 sampling showed that large numbers of walleye had invaded the Green River in the middle Green River, lower Green River and Desolation-Gray Canyon reaches as well as the lower Colorado River, presumably moving upstream from an expanded population in Lake Powell and/or escaping from Starvation Reservoir (Figure 22). Walleye were abruptly abundant in lower Green River nursery habitat

reaches, and sampling observations from the lower Colorado River (pers. comm. T. Francis, U. S. Fish and Wildlife Service, Grand Junction, CO) documented at least two instances of predation by large-bodied walleye on juvenile pikeminnow > 300 mm TL, a location where juvenile abundance is low relative to the Green River. Walleye persist at relatively high levels, although in 2015, their abundance was somewhat reduced, perhaps because of combined effects of reduced immigration and increased removal efforts which began in 2013.

An efficient predator like walleye would certainly be capable of consuming all sizes of juvenile Colorado pikeminnow present in 2011 (about 2,400 present in both the lower Green and Desolation-Gray Canyon reaches of the Green River), because captured walleye had mean TL of 460-500 mm and some individuals exceeded 600 mm TL. Although no abundance estimates available, number of walleye captured in years from 2011–2013 (79, 136, 105, respectively) outnumbered adult Colorado pikeminnow captured (91, 63, 15, respectively), by a composite margin of 2.2:1. Number of walleye captures relative to Colorado pikeminnow captures and their estimated abundance indicated several hundred walleyes were present in the lower Green River reach alone in the 2011–2013 period, if capture probabilities of the two taxa were similar. Predation by large walleye in those numbers could easily account for the large reduction of smaller Colorado pikeminnow in those reaches.

Reduced abundance of the recruit-sized fish in 2012 and 2013 that were present in 2011 (about 800 fish) in both of the lowermost reaches of the Green River was more difficult to explain. The largest walleye present may be capable of consuming the smaller recruit-sized fish just over 400 mm TL but that would not account entirely for the dramatic reduction in abundance. Natural mortality would also account for some reduction in abundance, and perhaps increased competition for food resources from walleye may also have contributed.

Characterization of entrainment of Colorado pikeminnow in the Green River canal (Green River, UT) has not been fully investigated at this time, although considerable entrainment data exists for the years 2013-present which should be evaluated in future reports. Nevertheless, the large group of 2011 recruits went essentially undetected in subsequent abundance estimates of adults in the Green River in 2012 and 2013, noting that low sampling efficiency in the lower Green River reach in 2013 may have affected estimates. Loss of that large group of recruits, which was likely partially due to walleye predation, the second-highest abundance level ever documented (highest was 2008), was a large loss to the Green River population. Even after accounting for annual mortality of 20-30%, that large group of 800+ recruit-sized fish present in 2011 would likely have contributed several hundred individuals to the adult life stage in 2012 and 2013.

Abundance pattern changes between 2000–2003 and 2011–2013.—Patterns of abundance estimates derived from data collected during 2000–2003 and 2006–2008 were somewhat different than those obtained using data from the entire period, 2000–2013 (Figure 18). The main difference was that abundance estimates declined at a slower rate from 2000–2003 and the subsequent upturn in abundance in 2008 was smaller. The types of estimating models used in these analyses borrow data from across all sampling occasions to arrive at capture probabilities and other estimates, so it is reasonable that estimates should differ somewhat. A main reason for changes was that capture probabilities continued to decline through the 2011–2013 period. Including that data resulted in declining capture probabilities over time, which increased some of the earlier estimates. We also call attention to the 2008 abundance estimate which had a very wide confidence interval, and was the single most important estimate to reverse the negative population trends that began in 2000–2003. We think

changes in abundance over time reflect model uncertainty and low precision of estimates, and reinforce the idea that short-term trends are not reliable for long-term management decisions.

Other factors that may have played a role in changed abundance estimates over time was additional data inquiries that allowed matching up different tag type data and identification of longer encounter histories than were possible during prior estimation periods. Those discoveries were made when encounter histories of older Colorado pikeminnow originally tagged with older PIT tags (400 kHz), were matched with newer PIT tags (134.2 kHz). Detection of older tags would not be possible if investigators did not scan for the older tag and retagged the fish with a newer tag, such that the fish appeared to be tagged for the first time. Subsequent recapture of such a fish by an investigator who scanned and discovered both tag types would allow uniting the encounter histories, which would change outcomes of analyses, particularly for survival rates. Other data sleuthing added or subtracted records as was appropriate and may have contributed to the different estimates.

We also attempted to run many other models (50+) with subsets of the data to obtain parameter estimates that were more consistent over time, but none of those models produced reasonable results. For example, we conducted analysis of the 2011–2013 data separately, and considered adding those abundance estimates to the existing 2000–2008 data string. Those abundances were slightly higher than the estimates reported here, but were extremely imprecise or estimates were not even possible due to the relatively sparse data that was available compared to the entire data set. For example, confidence intervals for four of the 15 estimates for each of the reach and year combinations (3 years x five reaches = 15 estimates) included zero, including those for the largest populations. Further, year-to-year variation in estimates was extreme, which is unreasonable for these populations. For example, estimated abundance of adult Colorado

pikeminnow in the White River declined from 1,513 fish in 2011 to 281 in 2012, and then rose to 599 in 2013, with the variation due to variable numbers of captured fish and imprecise and likely biased recapture rates. That level of variation was unreasonable for adult life stages of these large and long-lived fishes that tend to occupy consistent home ranges and have relatively low recruitment rates. Using the full data set smoothed out such variation to levels that were reasonable so analyses using just the 2011–2013 data were rejected. We also considered adding streamflow in the various years as a covariate in the analysis, but because we estimate probabilities of capture for every pass, reach, and year, much of that variation was already be accounted for, as explained in Methods.

Regardless of changes in abundance patterns for adult Colorado pikeminnow through 2008 using different datasets, management actions proceeded after the 2006–2008 estimation period consistent with the goal to enhance their abundance and that of other endangered fish species. Those efforts came in the form of continued smallmouth bass and northern pike removal in many reaches of the Green River sub-basin. Additional walleye removal effort in the lower and middle Green River nursery habitat reaches began in 2014 and 2015, to replace effort expended during 2011–2013 pikeminnow abundance estimation sampling when walleye removal also occurred. Further management to enhance Colorado pikeminnow was the realization that age-0 survival was best in moderate (1,700-3,000 ft^3/sec) summer flow scenarios (Bestgen and Hill 2016). Additional management (flow manipulation) may have assisted with production of relatively large year classes of age-0 Colorado pikeminnow in the Green River in 2009, 2010, and 2015. Flows were higher or lower than optimum for production of age-0 Colorado pikeminnow in most other years since 2008, such as in the high flow year 2017 when only a single age-0 Colorado pikeminnow was detected in the middle Green River.

Probabilities of capture.—Previous analyses demonstrated that small (<250 mm TL) and very large (>800 mm TL) Colorado pikeminnow had very low probabilities of capture, and intermediate sizes were more susceptible (Bestgen et al. 2007), resulting in bell-shaped curves of capture probabilities. Overall, probabilities of capture were lower during 2011–2013, compared to 2006–2008, which were lower than during 2000–2003, based on mean values exclusive of length effects. Reductions in the number of passes completed, reduced sampling effort per pass, and reduced overall electrofishing effort in several study reaches (independent of probability of capture for individual fish) were likely the main factors responsible for reductions in the number of fish captured and recaptured during 2006–2008 compared to 2000–2003. The White River, middle Green River, and Desolation-Gray Canyon reaches had fewer sampling passes, fewer sampling days, and apparently reduced electrofishing hours (total and per day), during 2006–2008. In the Yampa River, sampling effort based on all metrics was greatly increased during 2006–2008 and 2011–2013, in part because of supplemental effort conducted during nonnative fish removal, yet numbers of Colorado pikeminnow captured remained low. Efforts to increase pikeminnow captures in 2011–2013 in other reaches did not substantially increase captures.

Continued decline of capture probabilities in the most recent 2011–2013 period following 2006–2008 sampling is more difficult to explain. There was no consistent relationship with capture probability changes and flow levels for example, as flows varied dramatically from the very high year 2011, to low years in 2012 and 2013. We discussed inclusion of flow directly in the analysis but dismissed it, as described above. The lower number of fish captured and recaptured and smaller capture probabilities contributed to lower precision of estimates. Even small amounts of bias would have relatively large effects on abundance estimates, given the small magnitude of the estimates. In other words, although changes in absolute capture

probabilities from 2000–2003 to 2011–2013 seem small (e.g., 0.05 to 0.03 = 0.02), this 44% decline would have a large effect on estimates. For example, if one captured 100 fish and the unbiased capture probability was 0.05, the result would be an abundance estimate of 2000 (100/0.05). However, if sampling and estimation resulted in a biased and lower capture probability estimate of 0.03, the abundance estimate for the same 100 fish capture sample would increase to 3,333 fish. Reductions in capture probabilities over time could be due to several factors, including reduced efficiency of sampling gear, differences in crew experience, and increased fish avoidance of gear.

Transition rates.—Transition probabilities (ψ_i) reflected a general pattern of relatively small Colorado pikeminnow moving from the lower Green River and the Desolation-Gray Canyon reaches, which had the highest transition rates, to upstream reaches. The high movement rate from downstream Green River reaches was not surprising given the abundance of relatively small Colorado pikeminnow in those reaches, including recruits, compared to other reaches, patterns consistent with previous studies in the Green River and elsewhere (Osmundson et al. 1998; Bestgen et al. 2007; Osmundson and White 2009; Bestgen et al. 2010). Something of a surprise was the relatively high net emigration of adult fish, the only life stage present, from the Yampa River. That population was already small and negatively affected by nonnative fish predation or competition. A net movement of adult Colorado pikeminnow from the Yampa River, which was partially a function of low recruitment rates (low positive transition rate into the Yampa River), furthered the decline of that population.

Summary.—Colorado pikeminnow abundance declined from 2000–2003 to 2006–2008, and then from 2006–2008 to 2011–2013. Comparison of pairs of abundance estimates across years showed substantial and significant declines. For example, confidence intervals about

estimates from 2001 and 2002 do not overlap with those from 2006 and 2007 and 2011 or 2012 (Figure 19). Weighted regressions also show a preponderance evidence (high weights) for declining population abundance at the scale of reaches as well as the entire Green River subbasin, and simple numbers of individual fish captured each year showed substantial declines over time. Thus, we feel confident in our conclusions regarding reduced abundance based on the many divergent lines of support. Also, estimated survival rates for adult fish in 2011–2013 declined slightly compared to 2006–2008, which is consistent with reduced adult abundance. High estimated abundance of recruits and juveniles in 2011 was expected to boost populations of adults in 2012 and 2013 but those large groups of fish were not detected in those years. An influx of large and abundant walleye in the lower Green and Desolation-Gray Canyon river reaches was detected and likely occurred in 2010 or 2011. Walleye were abundant enough to reduce juvenile Colorado pikeminnow abundance in those nursery reaches such that the large 2011 group of fish was largely undetectable in 2012 and 2013. The fate of the large number of recruit-sized fish present in 2011 that were not detected in 2012 or 2013 is less certain. Some of those could be consumed by the largest walleye, and natural mortality and lower survival rates likely also accounted for some of the reduction, but absence of the remaining estimated 800+ recruit-sized Colorado pikeminnow in the Green River sub-basin after 2011 is a conundrum. Regardless, the decline of adult Colorado pikeminnow in most reaches of the Green River sub-basin, and relatively low numbers of recruits or juveniles in 2013, does not bode well for increased abundance in the near future. Analyses showed adult abundance estimates are closely and positively linked with abundance of age-0 fish 7–10 years earlier, indicating recruitment and increased adult abundance requires many years. Sustained efforts must begin immediately to bolster young fish survival and abundance by implementing summer base flow recommendations

in the Green River (Bestgen and Hill 2016), which when coupled with effective nonnative fish control, is the main means to increase and stabilize abundance of the adult population.

CONCLUSIONS

1. The sampling design fulfilled assumptions of the estimating model sufficiently well. The level of sampling effort and number of fish captured supported a relatively realistic model that was used to obtain reliable abundance estimates and other demographic parameters for Colorado pikeminnow in the Green River sub-basin, although reduced captures and reduced capture probabilities in 2011–2013 are worrisome. Higher capture probabilities are needed to obtain more precise abundance estimates for Colorado pikeminnow, especially for small populations. Reasons for reduced capture probabilities should be investigated.
2. Analysis of capture-recapture data gathered from 2011–2013 indicated a decline in abundance of adult Colorado pikeminnow in the Green River sub-basin, Colorado and Utah since 2000–2003. All 2011–2013 adult abundance estimates were below the Recovery Goal threshold of 2,600 fish. Based on trends in annual point estimates, declines in adult abundance were most apparent in the middle Green River, and White River reaches. Abundance of adult Colorado pikeminnow, both in terms of estimates and numbers of fish captured, was low in the Yampa River, and the population showed continued decline since about 2002. Abundance of adult Colorado pikeminnow in the lower Green River and Desolation-Gray Canyon reaches were stable in the 2000–2013 period, but relative to the entire basin, those populations were relatively small.
3. Survival rates for adult Colorado pikeminnow increased in the 2006 to 2008 period compared to the 2000 to 2003 period but were apparently slightly lower in 2011–2013, based on the

lowered composite estimates for the 2000–2013 period. Along with reduced recruitment as a main effect, reduced survival rates also contributed to the decline in Colorado pikeminnow abundance in the Green River sub-basin during the study period.

4. Similar to 2000–2003 and 2006–2008, there was no support for the hypothesis that sampling activities increased mortality of adult Colorado pikeminnow during 2011–2013. Few or no adult moralities were noted.
5. Abundance of recruit and juvenile Colorado pikeminnow during 2006–2008 was high and much increased compared to 2000–2003, and a large year class of juveniles and recruits was present in 2011. However, increased adult abundance in 2008 was not sustained, and the large number of recruits and juveniles present in 2011 was unexpectedly reduced by 2012 and 2013. The large influx of predaceous walleye into all reaches of the Green River in 2010 or 2011 was likely responsible for reduced abundance of juveniles and perhaps some recruits. Recruitment rates lower than mortality rates and reduced survival rates were likely responsible for reduced abundance of Colorado pikeminnow in the Green River sub-basin in 2011–2013 compared to earlier years. Population abundance basinwide was similar across the three years in 2011–2013 period, but the wide confidence intervals and associated lack of precision of the 2013 estimate and the low numbers of fish captured render that estimate unreliable.
6. Increased abundance of juvenile fish in 2011 likely resulted from stronger year classes in 2007 and 2009. A year class source for the abundant recruit-sized fish in 2011 was less certain. Reduced abundance of juvenile life stages of Colorado pikeminnow in the Green River during 2012 and 2013 was likely due to predation by walleye.

7. There was a strong relationship between abundance of adults and abundance of young fish produced in the period 7-10 years prior, emphasizing the importance of producing strong year classes. Summer baseflow management in Green River nursery habitat is a means to increase abundance and survival of young fish.

RECOMMENDATIONS

1. Continue with the current sampling protocol for Colorado pikeminnow in the Green River sub-basin.
2. Investigate means to obtain higher probabilities of capture of Colorado pikeminnow, especially in reaches where abundance estimates were relatively imprecise. This may include addition of other gears such as fyke nets, increasing crew training to increase sampling efficiency, longer duration of sampling passes, more sampling passes, and incorporation of PIT tag antenna data. Minimally, sampling effort similar to that during 2000–2003 is needed.
3. Investigate reasons why capture probabilities for Colorado pikeminnow are declining over time.
4. Conduct an empirical analysis of growth of Colorado pikeminnow, based on tag recaptures in the Green River sub-basin or by using length-frequency or scale aging information. This would verify patterns borrowed from the Colorado River that are important to assess recruitment schedules for age-0 fish.
5. Effort to reduce abundance of walleye in the middle and lower Green River should be continued or increased, as predation may be able to remove entire large year-classes of juvenile Colorado pikeminnow.

6. Implement recommendations of investigations that linked abundance dynamics of early life stages of Colorado pikeminnow with flow patterns in the middle and lower Green River (Bestgen and Hill 2016).
7. Managers should exercise caution when interpreting short-term (ca. 3-5 years) trends in Colorado pikeminnow abundance as population trajectories can change with the addition of new data.

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Table 1. Capture histories for Colorado pikeminnow captured during 2011–2013 in the Green River sub-basin, Colorado and Utah. The capture history digits represent whether an individual fish was captured in sampling years from 2011–2013, from left to right respectively, where a 1 denotes that an individual was captured in a sampling pass in any year and 0 indicates that an individual was not captured in that pass. For example, the most common capture history (*n* = 612) reflects a fish that was captured on the first sampling pass within a year (1) and then was not seen again (00).

Capture History	2000–2003		2006–2008		2011–2013	
	Freq.	%	Freq.	%	Freq.	%
1 0 0	745	33.8	764	42.8	612	50.0
0 1 0	806	36.6	502	28.1	322	26.3
0 0 1	370	16.8	278	15.6	180	14.7
1 1 0	143	6.5	150	8.4	62	5.1
1 0 1	36	1.6	40	2.2	28	2.3
0 1 1	92	4.2	40	2.2	15	1.2
1 1 1	12	0.5	13	0.7	4	0.3
totals	2,204		1,787		1,223	

Table 2. Robust design multi-state models to estimate abundance (derived from Huggins model parameters), survival (*S*), probability of capture (*p*), and transition rate (*psi*) among reaches for Colorado pikeminnow in the Green River sub-basin, 2000–2013. Covariates include river reach (reach of river), sampling year or pass (year or pass), and fish total length (TL = total length predicted by year from a von Bertalanffy function, the polynomial terms indicated by the caret sign and a numeral where 2 = quadratic term). The AICc was Akaike's Information Criterion, AICc Weights *W* is model weight, *L* is the likelihood of the model based on the weights, and Num. Par is the number of model parameters.

	Model	AICc	Delta AICc	AICc Weights	Num. Par	Deviance
1	{S(reach+TL^2+spline(400,600))^2 psi(reach+TL) p(year*reach*pass+session*TL^2)}	28913.7	0.0	1.000	182	28540.4
2	{S(reach+TL^2+spline(400,600))^2 psi(reach+TL) p(year*reach*pass+TL^2)}	28954.0	40.3	0.000	178	28589.1
3	{S(reach+TL+spline(400,600)) psi(reach+TL) p(year*reach*pass+TL^2)}	28979.7	66.0	0.000	175	28621.1
4	{S(reach+TL) psi(reach+TL) p(year*reach*pass+TL^2)}	29147.0	233.4	0.000	173	28792.6
5	{S(reach+TL) psi(reach+TL) p(year*reach*pass+TL)}	29162.0	248.4	0.000	172	28809.8
6	{S(reach) psi(reach) p(reach*year*pass) test}	29317.7	404.1	0.000	169	28971.8
7	{S(reach+TL^2+spline(300)) psi(reach+TL) p(year*reach*pass+session*TL^2)}	29717.7	804.0	0.000	179	29350.7
8	{S(reach+TL) psi(reach+TL) p(year*reach+pass+TL)}	29729.2	815.5	0.000	78	29571.5
9	{S(reach+TL^2) psi(reach+TL) p(year*reach*pass+session*TL^2)}	29737.2	823.5	0.000	178	29372.3
10	{S(reach+TL^2) psi(reach+TL) p(year*reach*pass+TL^2)}	29757.1	843.5	0.000	174	29400.7
11	{S(reach+TL) psi(reach+TL) p(year*reach+TL)}	29799.9	886.2	0.000	76	29646.3
12	{S(reach+TL^2) psi(reach+TL) p(year*reach*pass+TL)}	29818.6	904.9	0.000	173	29464.2
13	{S(reach) psi(reach) p(year*reach)}	29958.1	1044.4	0.000	73	29810.6

Table 3. Abundance estimates, 95% confidence intervals, coefficients of variation (CV's, as %), and numbers of unique individuals captured (M_{t+1}) for adult (≥ 450-mm TL) Colorado pikeminnow in the Yampa River, Colorado, 2011–2013.

Life stage	Year	Abundance	SE	95% CI	CV	M_{t+1}
Adults						
	2011	85	18	61 – 137	22	41
	2012	123	100	33 – 504	81	6
	2013	48	28	19 – 144	58	7

Table 4. Abundance estimates, 95% confidence intervals, coefficients of variation (CV's, as %), and numbers of unique individuals captured (M_{t+1}) for adult (≥ 450-mm TL), recruit-sized (400–449-mm TL), and juvenile (<400 mm TL) Colorado pikeminnow in the White River, Utah and Colorado, 2011–2013.

Life stage	Year	Abundance	SE	95% CI	CV	M_{t+1}
Adults						
	2011	696	175	436 – 1143	25	77
	2012	274	44	205 – 382	16	84
	2013	365	81	243 – 569	22	59
Recruits						
	2011	84	42	34 – 216	51	5
	2012	12	8	4 – 42	67	2
	2013	51	24	23 – 127	48	5
Juveniles						
	2011	134	76	50 – 381	57	5
	2012	17	12	6 – 64	71	2
	2013	56	30	22 – 154	54	4

Table 5. Abundance estimates, 95% confidence intervals, coefficients of variation (CV's, as %), and numbers of unique individuals captured (M_{t+1}) for adult (≥ 450-mm TL), recruit-sized (400–449-mm TL), and juvenile (<400 mm TL) Colorado pikeminnow in the middle Green River, Utah, 2011–2013.

Life stage	Year	Abundance	SE	95% CI	CV	M_{t+1}
Adults						
	2011	449	96	303 – 689	21	80
	2012	422	111	259 – 711	26	48
	2013	981	372	487 – 2027	38	44
Recruits						
	2011	78	30	40 – 163	38	9
	2012	15	15	4 – 81	100	1
	2013	158	90	58 – 449	57	5
Juveniles						
	2011	159	75	69 – 389	47	11
	2012	67	56	17 – 283	84	2
	2013	39	41	8 – 213	105	1

Table 6. Abundance estimates, 95% confidence intervals, coefficients of variation (CV's, as %), and numbers of unique individuals captured (M_{t+1}) for adult (≥ 450-mm TL), recruit-sized (400–449-mm TL), and juvenile (<400 mm TL) Colorado pikeminnow in the Desolation-Gray Canyon reach of the Green River, Utah, 2011–2013.

Life stage	Year	Abundance	SE	95% CI	CV	M_{t+1}
Adults						
	2011	498	106	336 – 761	21	75
	2012	634	109	461 – 894	17	118
	2013	489	118	312 – 788	24	52
Recruits						
	2011	439	108	276 – 713	25	43
	2012	49	20	24 – 110	42	6
	2013	106	45	49 – 239	43	7
Juveniles						
	2011	601	198	326 – 1139	33	40
	2012	365	126	193 – 712	35	25
	2013	222	83	112 – 453	37	12

Table 7. Abundance estimates, 95% confidence intervals, coefficients of variation (CV's, as %), and numbers of unique individuals captured (M_{t+1}) for adult (≥ 450-mm TL), recruit-sized (400–449-mm TL), and juvenile (<400 mm TL) Colorado pikeminnow in the lower Green River, Utah, 2011–2013.

Life stage	Year	Abundance	SE	95% CI	CV	M_{t+1}
Adults						
	2011	356	62	259 – 508	18	91
	2012	335	70	229 – 508	21	63
	2013	244	101	115 – 536	41	15
Recruits						
	2011	369	70	260 – 541	19	67
	2012	45	21	21 – 110	46	5
	2013	163	85	64 – 430	52	6
Juveniles						
	2011	1789	602	968 – 3446	34	161
	2012	579	169	337 – 1022	29	41
	2013	475	264	175 – 1319	56	10

Table 8. Weighted regression models to estimates trends in adult Colorado pikeminnow abundance. Intercept-only (*I*), linear (*I, T*), or quadratic (*I, T, T^2*) regression relationship estimates of abundance for adult Colorado pikeminnow in reaches (Yampa = Yampa River, White = White River, M. Green = middle Green River, Deso-Gray = Desolation-Gray Canyon, Green River, L. Green = lower Green River) and total Green River basin (excludes 2000, including year 2000 increases the intercept and the negative slope value, as well as the weight (0.94) for the same model) of the Green River sub-basin, Colorado and Utah, 2000–2013, as a function of coefficients for *Time* (*T*, year, year 2000 = 1, year 2001 = 2, and so on) and *Time*^{2} *(T^2*, year squared); *I = Intercept*. For relationships with intercept only or linear (*T*) terms, that coefficient estimates the trend of the population for the entire period. Estimates are for adult fish (≥450 mm total length (TL) only); SE = standard error. Weights are the relative degree of support (larger proportion = greater support) each model has among other competing models and sum to 1 for each set of models.

River	Model	*df*	Intercept (SE)	Time (SE)	Time^2 (SE)	Weight
Yampa	*I*	1,9	107.1 (29.7)			< 0.01
	I, T	2,9	319.1 (43.3)	−20.3 (3.9)		0.14
	I, T, T^2	3,9	437.8 (48.0)	−54.6 (11.4)	2.0 (0.65)	0.85
White	*I*	1,9	425.5 (89.6)			0.04
	I, T	2,9	836.5 (134.8)	−42.7 (12.6)		0.56
	I, T, T^2	3,9	1197.7 (208.4)	−154.3 (55.3)	6.5 (3.2)	0.4
M. Green	*I*	1,9	877.2 (193.4)			< 0.01
	I, T	2,9	1544 (129.4)	−88.6 (13.7)		0.61
	I, T, T^2	3,9	1817.7 (174.0)	−216.1 (64.6)	8.6 (4.3)	0.39
Deso-Gray	*I*	1,8	577.1 (70.0)			0.81
	I, T	2,8	698.0 (126.0)	−15.6 (13.7)		0.18
	I, T, T^2	3,8	822.3 (225.0)	−58.5 (64.6)	2.7 (3.9)	0.01
L. Green	*I*	1,8	359.1 (42.5)			0.89
	I, T	2,8	344.2 (79.6)	2.3 (10.2)		0.08
	I, T, T^2	3,8	139.5 (129.4)	78.2 (41.8)	−4.9 (2.6)	0.02
Green R. basin	*I*	1,8	2690.1 (322.4)			< 0.01
(w/o year 2000)	*I, T*	2,8	3882.1 (222.8)	-156.9 (24.2)		0.92
	I, T, T^2	3,8	4266.0 (372.0)	-298.0 (114.4)	9.0 (7.2)	0.09

Table 9. Probabilities of capture for Colorado pikeminnow from the Green River sub-basin 2011–2013, for each sampling occasion, reach, and year.

River/reach	Sampling occasion	2011	2012	2013	mean
Yampa River	1	0.049	0.010	0.051	0.037
	2	0.069	0.005	0.012	0.029
	3	0.216	0.015	0.025	0.085
	means	0.111	0.010	0.030	0.050
White River	1	0.017	0.050	0.030	0.032
	2	0.010	0.054	0.026	0.030
	3	0.035	0.140	0.080	0.085
	means	0.021	0.081	0.045	0.049
Middle Green River reach	1	0.034	0.046	0.005	0.028
	2	0.047	0.031	0.129	0.069
	3	0.045	0.031	0.159	0.078
	means	0.042	0.036	0.098	0.059
Desolation-Gray Canyon reach	1	0.032	0.046	0.035	0.038
	2	0.036	0.081	0.026	0.048
	3	0.038	0.055	0.042	0.045
	means	0.035	0.061	0.034	0.043
Lower Green River reach	1	0.092	0.081	0.009	0.061
	2	0.065	0.055	0.020	0.047
	3	0.043	0.030	0.027	0.033
	means	0.067	0.055	0.019	0.047
Overall mean		0.055	0.049	0.045	0.050

Table 10. Abundance estimates, 95% confidence intervals, coefficients of variation (CV's, as %), and numbers of unique individuals captured (M_{t+1}) for adult (≥ 450-mm TL), recruit-sized (400–449-mm TL), and juvenile (<400 mm TL) Colorado pikeminnow in the Green River sub-basin, Colorado and Utah, 2011–2013.

Life stage	Year	Abundance	SE	95% CI	CV	M_{t+1}
Adults						
	2011	2083	239	1674 – 2619	11	364
	2012	1787	203	1440 – 2242	11	319
	2013	2128	413	1472 – 3117	19	177
Recruits						
	2011	973	145	732 – 1308	15	125
	2012	122	34	73 – 213	28	14
	2013	479	137	279 – 833	29	23
Juveniles						
	2011	2683	802	1541 – 4808	30	217
	2012	1028	274	623 – 1730	27	70
	2013	791	299	391 – 1630	38	27

Table 11.–Apparent survival probability estimates (*S*, 95% CI) from capture-recapture data for Colorado pikeminnow captured in the Green River sub-basin in four periods, 1991–1999, 2000–2003, 2006–2008, and 2000–2013; estimates for the earlier two periods were from Bestgen et al. (2007). Data for the intervals 1991–1999 were collected during a standardized monitoring program to estimate catch/effort indices for Colorado pikeminnow and were from about 23% of occupied habitat in the Green River sub-basin. Annual interval data from 2000–2003 were collected during a study to estimate abundance of adult and sub-adult Colorado pikeminnow throughout the Green River sub-basin; 2000 data were from only the middle Green, Yampa, and White rivers. Because no TL effects are included for 2006–2008, those estimates are for all fish captured. Survival estimates by river for 2000–2013 were from the top model without length effects because survival rates from the top model with splines were difficult to interpret.

Parameter	Period	*S*	95% CI
Survival	1991–1999	0.82	0.71 to 0.89
	2000–2003	0.65	0.59 to 0.71
	2006–2008	0.80	0.60 to 0.91
Yampa River	2000–2013	0.72	0.66 to 0.76
White River	“	0.75	0.71 to 0.77
Middle Green	“	0.68	0.65 to 0.72
Deso-Gray	“	0.70	0.66 to 0.74
Lower Green	“	0.78	0.74 to 0.81

Table 12. Annual transition probabilities (ψ_{ij}, movement to a different reach between years) for Colorado pikeminnow captured in the Green River sub-basin, Utah and Colorado, 2000–2013. River reaches are: Yampa R. = Yampa River (RK 192 to 74), White R. = White River (RK 167.4 to 0), middle Green R. = middle Green River reach (RK = 539.4 to 396.1), Deso-Gray = Desolation-Gray Canyon reach, Green River (RK 395.9 to 206.1), and lower Green R. = lower Green River reach (RK 193.2 to 0).

River reach	ψ	95% CI
White R. to Yampa R.	0.047	0.012 – 0.161
White R. to middle Green R.	0.243	0.106 – 0.465
White R. to Deso-Gray	0.278	0.131 – 0.496
White R. to Lower Green R	0.016	0.001 – 0.167
Yampa R. to White R.	0	
Yampa R. to middle Green R.	0.245	0.084 – 0.536
Yampa R. to Deso-Gray	0.069	0.009 – 0.381
Yampa R. to lower Green R.	0	
middle Green R. to White R.	0.109	0.046 – 0.236
middle Green R. to Yampa R.	0.149	0.066 – 0.301
middle Green R. to Deso-Gray	0.254	0.125 – 0.447
middle Green R. to lower Green R.	0.028	0.006 – 0.122
Deso-Gray to White R.	0.020	0.004 – 0.097
Deso-Gray to Yampa R.	0.228	0.115 – 0.401
Deso-Gray to middle Green R.	0.418	0.249 – 0.607
Deso-Gray to lower Green R.	0.170	0.076 – 0.339
lower Green R. to White R.	0.018	0.004 – 0.070
lower Green R. to Yampa R.	0.158	0.079 – 0.290
lower Green R. to middle Green R.	0.092	0.029 – 0.252
lower Green R. to Deso-Gray	0.566	0.400 – 0.718

Table 13. Mean annual transition probabilities (ψ, annual probability of movement to or from each reach, using only non-zero values) for Colorado pikeminnow captured in the Green River sub-basin, Utah and Colorado, 2000–2013. A positive net ψ indicated more fish moved into the reach than out, a negative net value of ψ suggested more fish moved out of the reach than into it; no adjustments were made for population size in each reach. River reaches are: Yampa R. = Yampa River (RK 192 to 74), White R. = White River (RK 167.4 to 0), middle Green R. = middle Green River reach (RK = 539.4 to 396.1), Deso-Gray = Desolation-Gray Canyon reach, Green River (RK 395.9 to 206.1), and lower Green R. = lower Green River reach (RK 193.2 to 0).

River reach	Mean ψ to:	Mean ψ from:	Net ψ
Yampa River	0.0484	0.1459	−0.0975
White River	0.1337	0.0786	0.0551
middle Green River	0.2493	0.1350	0.1142
Desolation-Gray Canyon, Green River	0.2918	0.2087	0.0831
lower Green River	0.0535	0.2085	−0.1549

Table 14. Annual sampling effort comparisons for each Green River sub-basin reach in three periods, 2000–2003 (2001–2003 for Desolation-Gray Canyon and lower Green River reaches), 2006–2008, and 2011-2013. Effort metrics are in terms of sampling passes through each reach (passes), days spent sampling, and electrofishing hours. For passes when total electrofishing hours were incomplete or not available, effort was estimated based on the mean hours of sampling for other passes conducted in that year. Fyke net sampling was not included in effort calculations. CPM = total fish captured.

	Sampling	1st period					2nd period				3rd period			
Reach	Metric	2000	2001	2002	2003	mean	2006	2007	2008	mean	2011	2012	2013	mean
Yampa R.														
	passes[1]	4	4	4	4	4	3	3	3	3	3	3	3	3
	days	34	33	30	35	33	58	60	72	63.3	39	38	41	39.3
	hours	92	185	166	231	169	360	417	498	425	423	399	430	417
	CPM	89	140	33	31	73.3	40	23	32	31.7	49	6	7	20.7
White R.														
	passes	3	3	3	3	3	3	3	3	3	3	3	3	3
	days	22	24	26	24	24	24	25	23	24	24	35	43	34
	hours	189*	204	180	175	186	146	133	140	140	199	382	427	336
	CPM	313	236	184	117	213	105	135	65	102	90	104	72	88.7
M. Green R.														
	passes	4	4	3	3	3.5	3	3	3	3	3	3	3	3
	days	29	31	25	31	29	23	23	18	21.3	25	35	25	28.3
	hours	205	251	183	194	208	148	127	126	134	161	180	204	182
	CPM	732	393	109	190	356	117	122	72	104	104	51	52	69

Deso-Gray													
	passes	3	3	4	3.33	3	3	3	3	3	3	3	3
	days	29	27	34	30	24	24	24	24	24	31	24	26.3
	hours	252*	230	268*	230	194	163	165	174	189	264	237	230
	CPM	281	137	178	199	201	146	92	146	165	155	75	132
L. Green R.													
	passes	4	3	3	3.33	3	3	3	3	3	3	3	3
	days	35	27	27	29.7	25	26	26	25.7	27	27	27	27
	hours	329	247	253	276	236	232	231	233	235	212	228	225
	CPM	249	160	208	206	597	332	127	352	342	116	31	163

[1] Yampa River effort, 2006-2008 consisted of 6-9 passes in some reaches, 3 in the remainder
*the majority or all of the effort (189 and 252) is estimated for pass 2 in each reach, or
(268), only pass 1 effort is not estimated, at least half of effort is estimated on the other 3 passes.

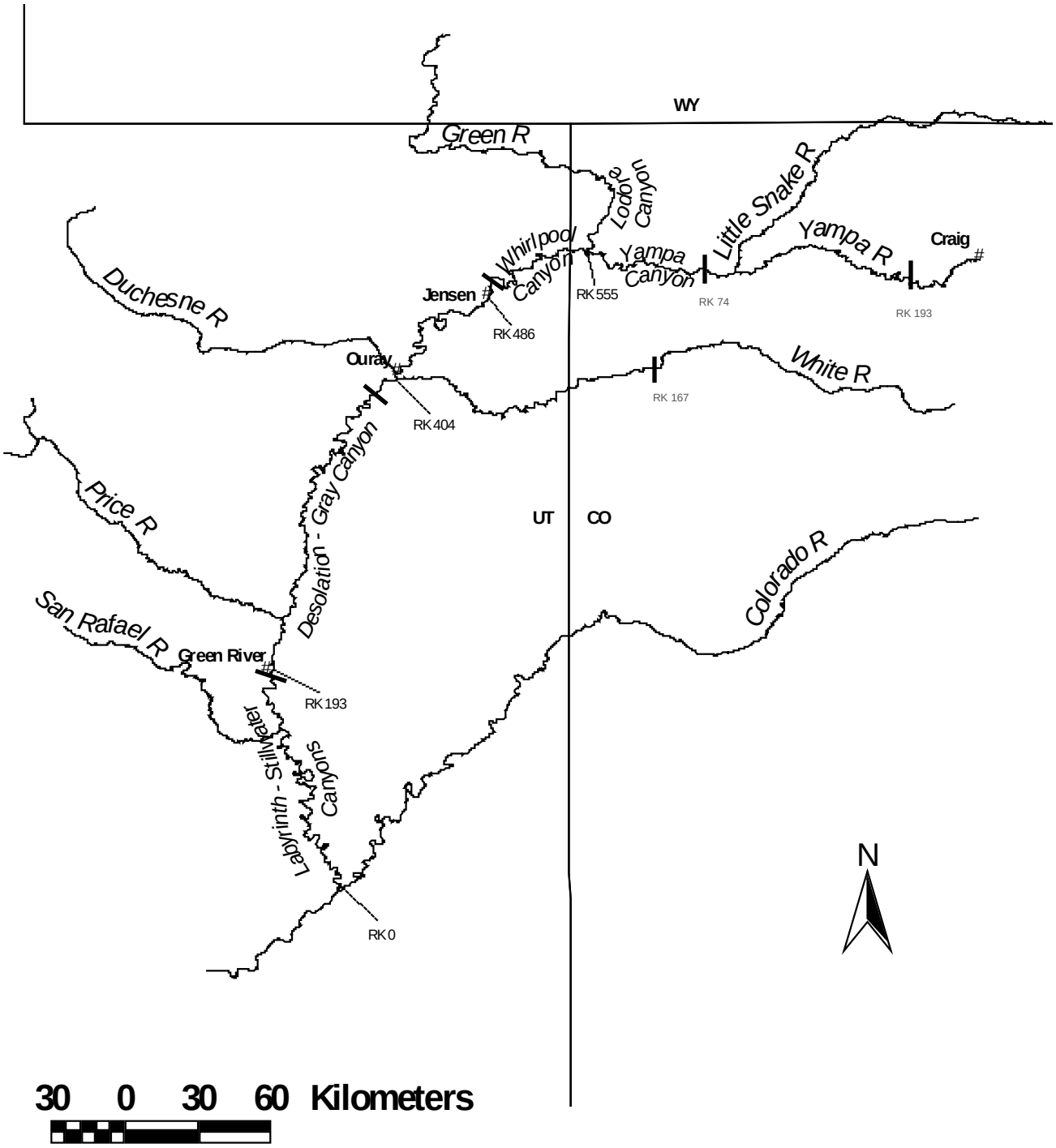


Figure 1. Map of Green River sub-basin study area. Heavy bars transverse to river denote study area segments in the Yampa River, the White River, and three segments of the Green River, the middle Green River, Desolation-Gray Canyon, and the lower Green River. No sampling occurred in Yampa Canyon or Whirlpool Canyon. Sampling also occurred in Island-Rainbow Park just downstream of Whirlpool Canyon, but not in Split Mountain Canyon.

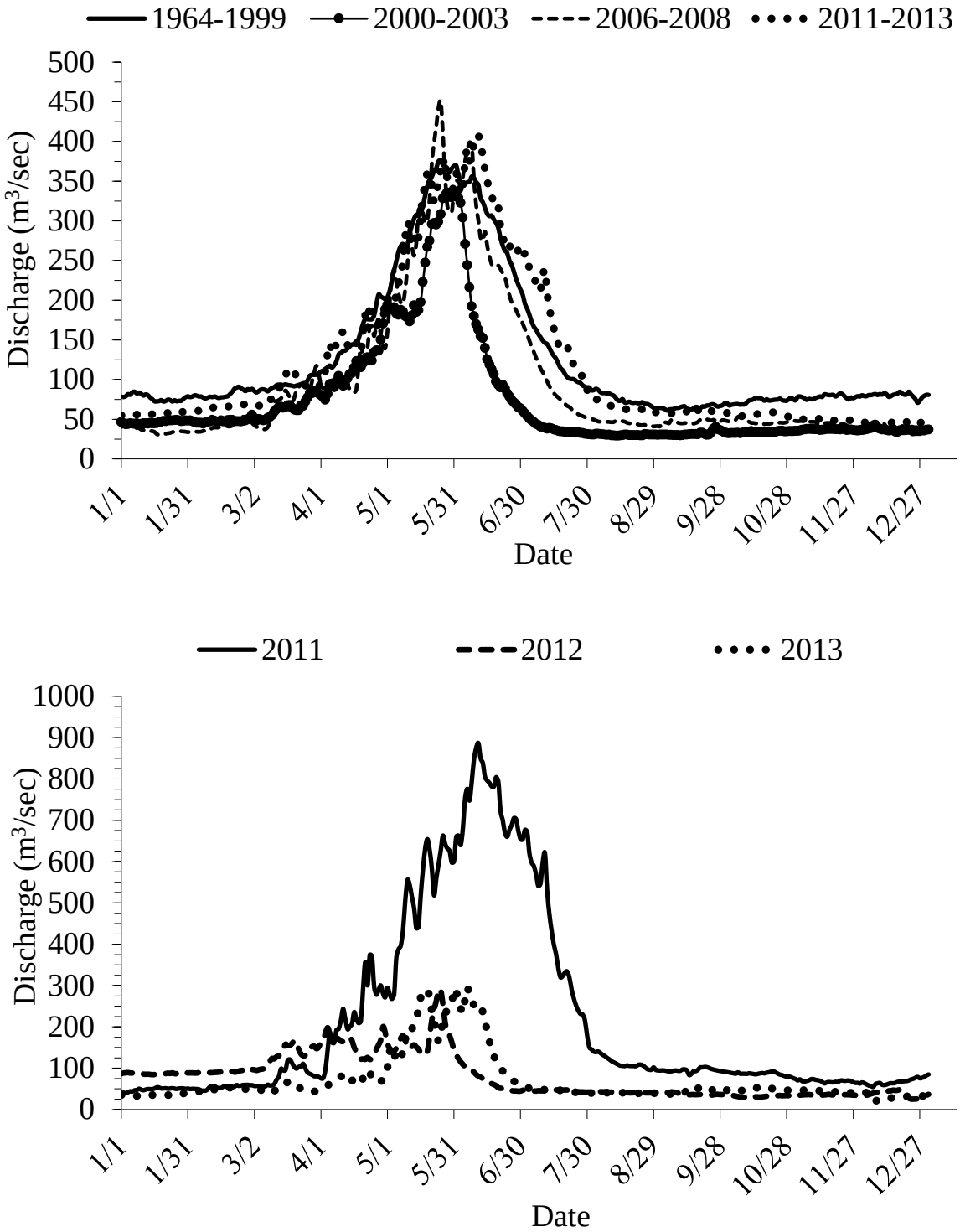


Figure 2. Mean daily discharge of the Green River, near Jensen, Utah (gauge # 09261000), for the period 1964–1999, and three abundance estimation periods, 2000–2003, 2006–2008, and 2011–2013 (top panel), and mean daily discharge for individual years 2011–2013 (bottom panel).

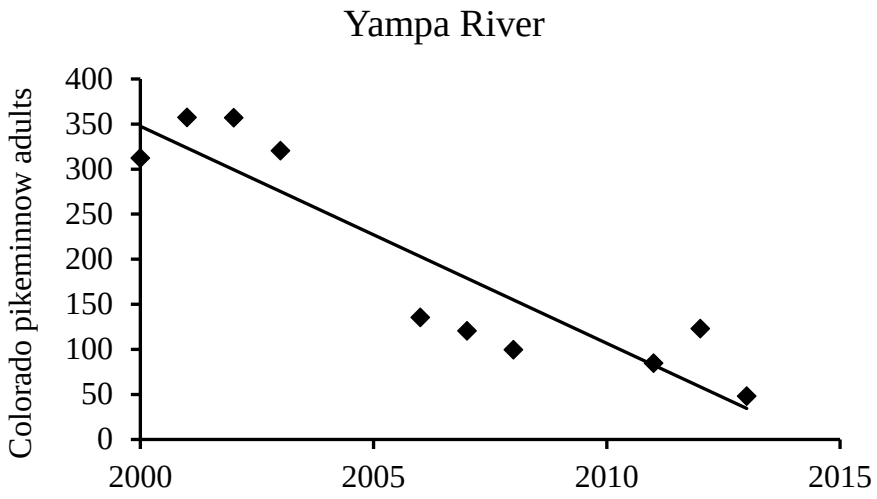


Figure 3. Abundance trend of Colorado pikeminnow adults (≥ 450-mm TL) in the Yampa River, Colorado, 2000–2003, 2006–2008, and 2011–2013. Regression relationship is shown in Table 8.

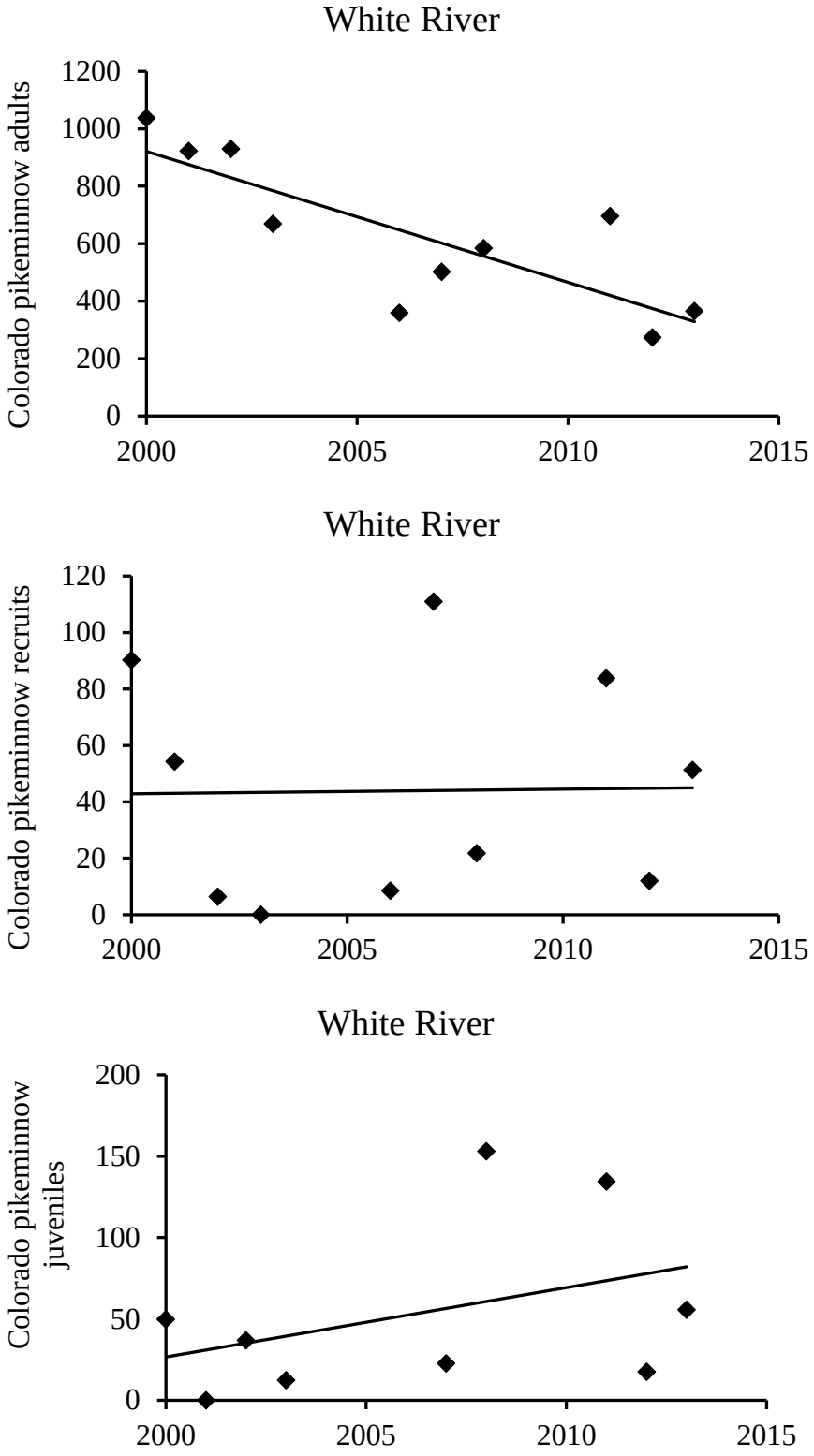


Figure 4. Abundance trends of Colorado pikeminnow adults (≥ 450-mm total length [TL]), recruits (400–449 mm TL), and juveniles (< 400 mm TL) in the White River, Utah and Colorado, 2000–2003, 2006–2008, and 2011–2013. Regression relationship for adults is shown in Table 8.

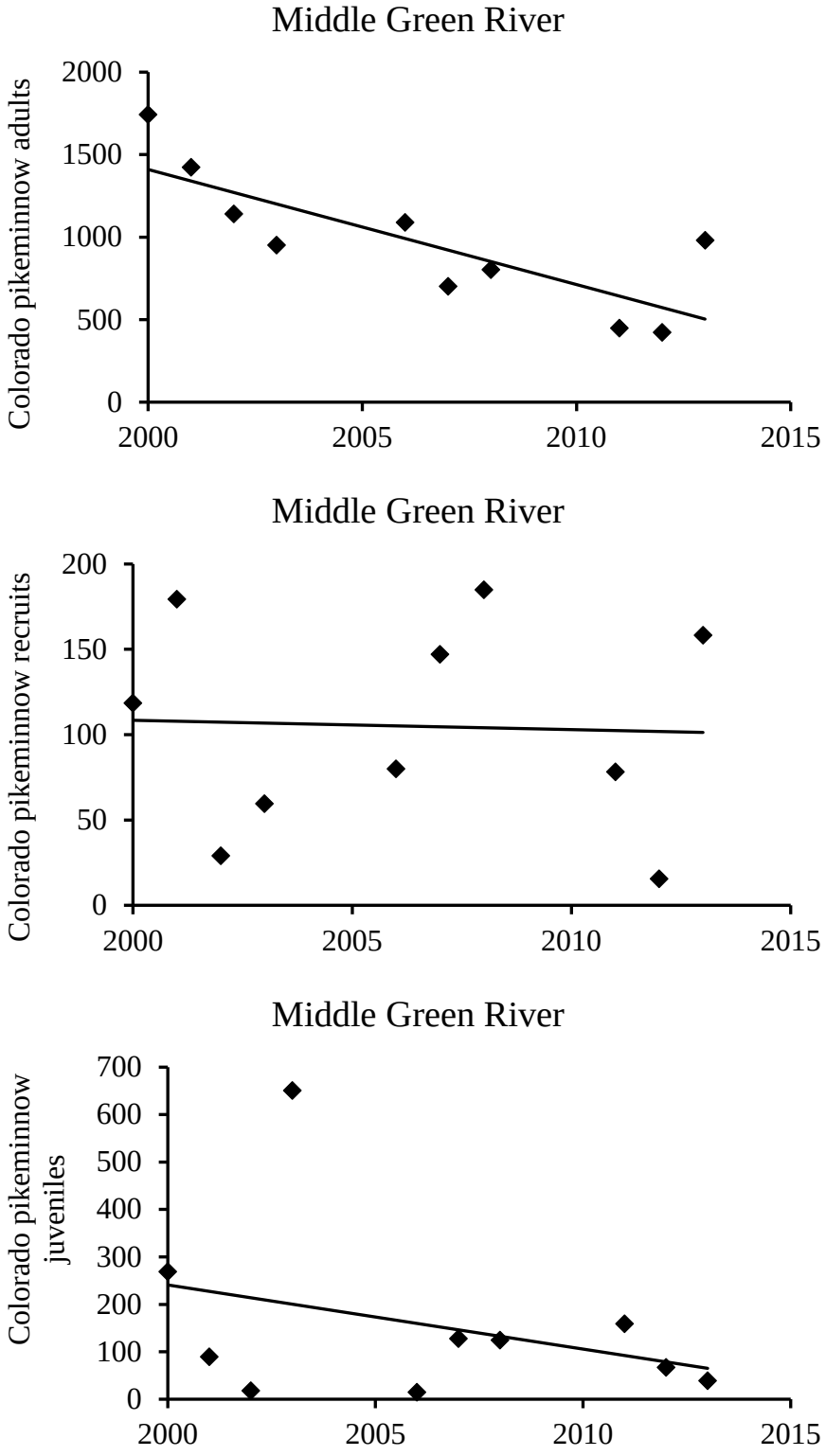


Figure 5. Abundance trends of Colorado pikeminnow adults (≥ 450-mm total length [TL]), recruits (400–449 mm TL), and juveniles (< 400 mm TL) in the middle Green River, Utah, 2000–2003, 2006–2008, and 2011–2013. Regression relationship for adults is shown in Table 8.

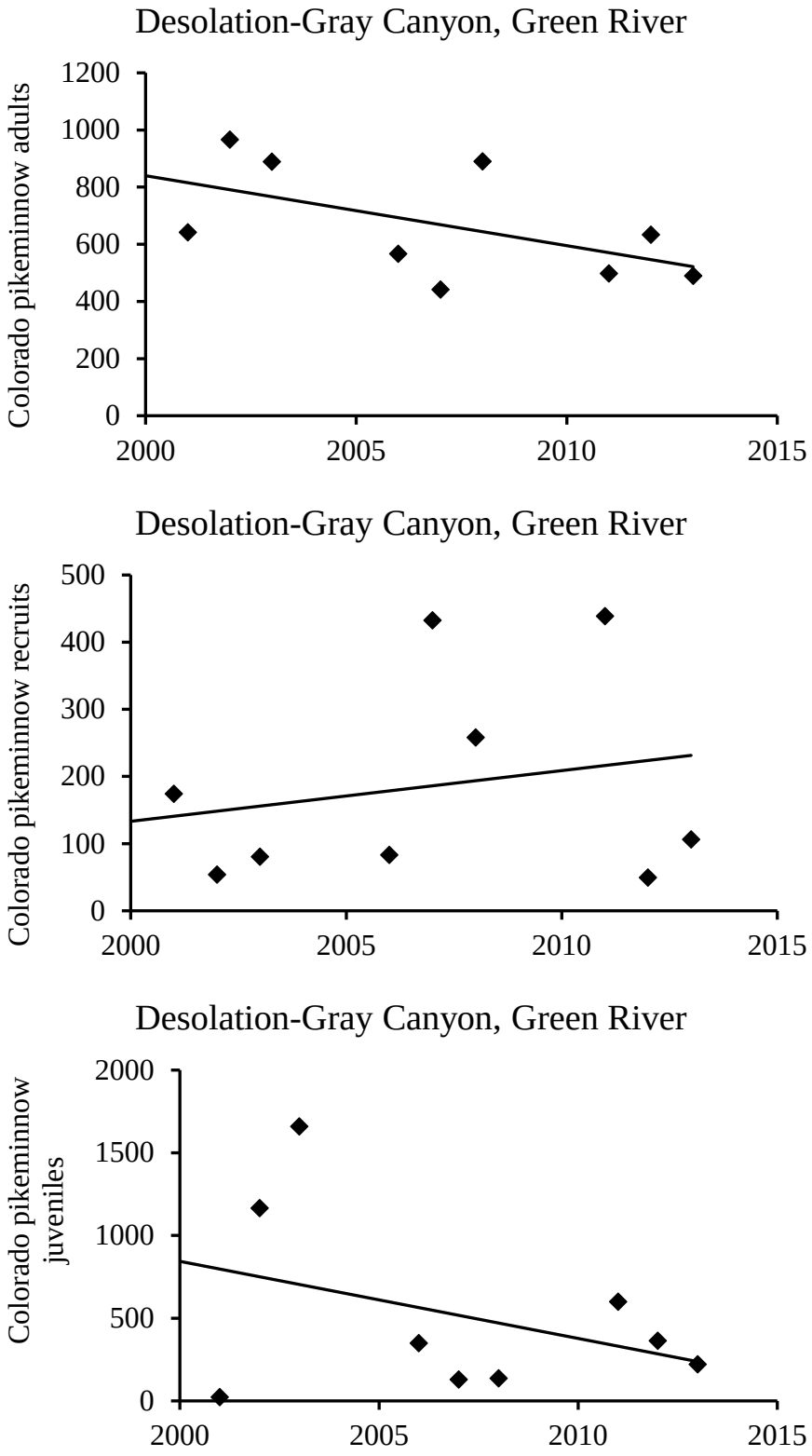


Figure 6. Abundance trends of Colorado pikeminnow adults (≥ 450-mm total length [TL]), recruits (400–449 mm TL), and juveniles (< 400 mm TL) in the Desolation-Gray Canyon reach of the Green River, Utah, 2001–2003, 2006–2008, and 2011–2013. Regression relationship for adults is shown in Table 8.

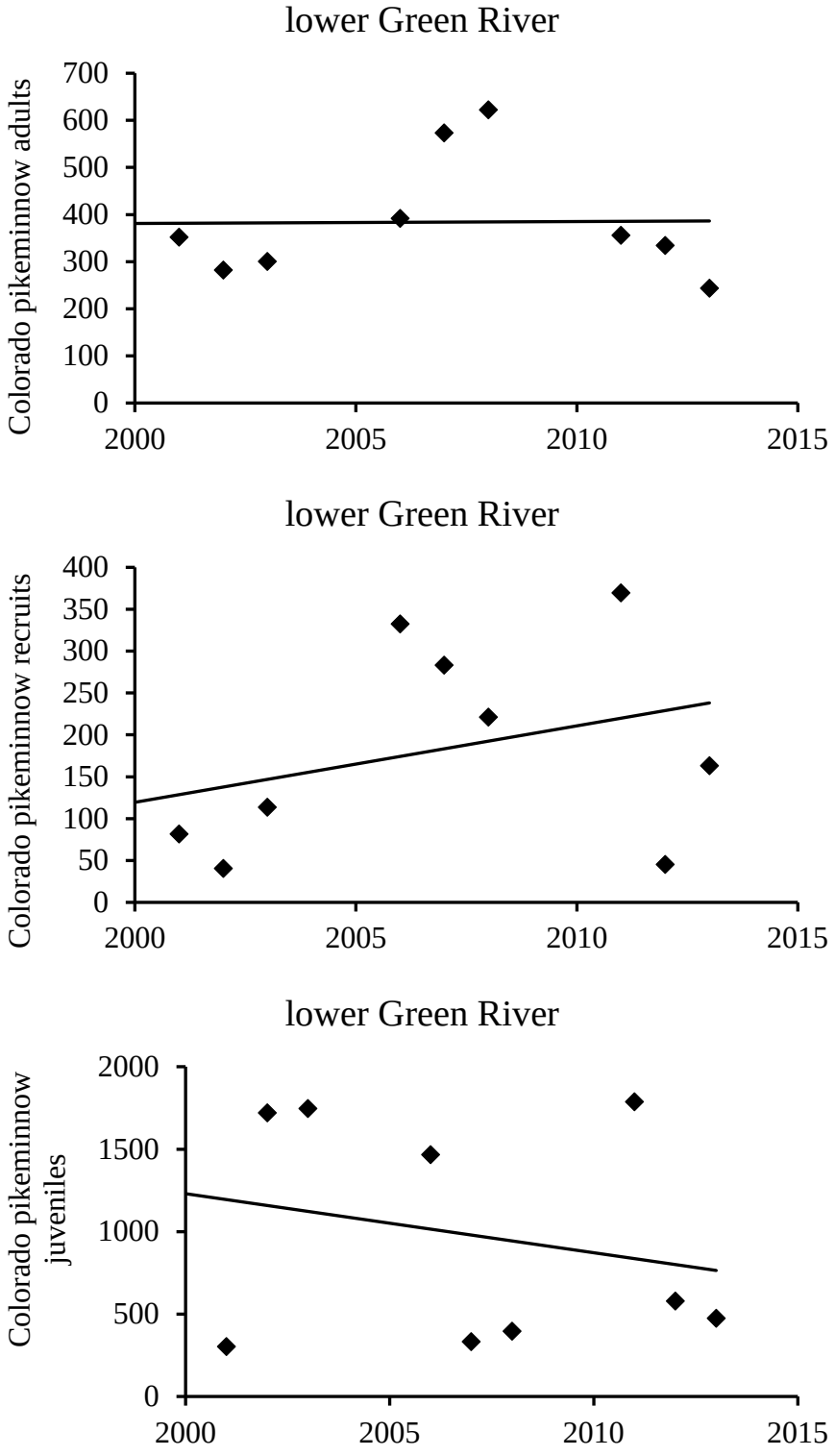


Figure 7. Abundance trends of Colorado pikeminnow adults (≥ 450-mm total length [TL]), recruits (400–449 mm TL), and juveniles (< 400 mm TL) in the lower Green River, Utah, 2001–2003, 2006–2008, and 2011–2013. Regression relationship for adults is shown in Table 8.

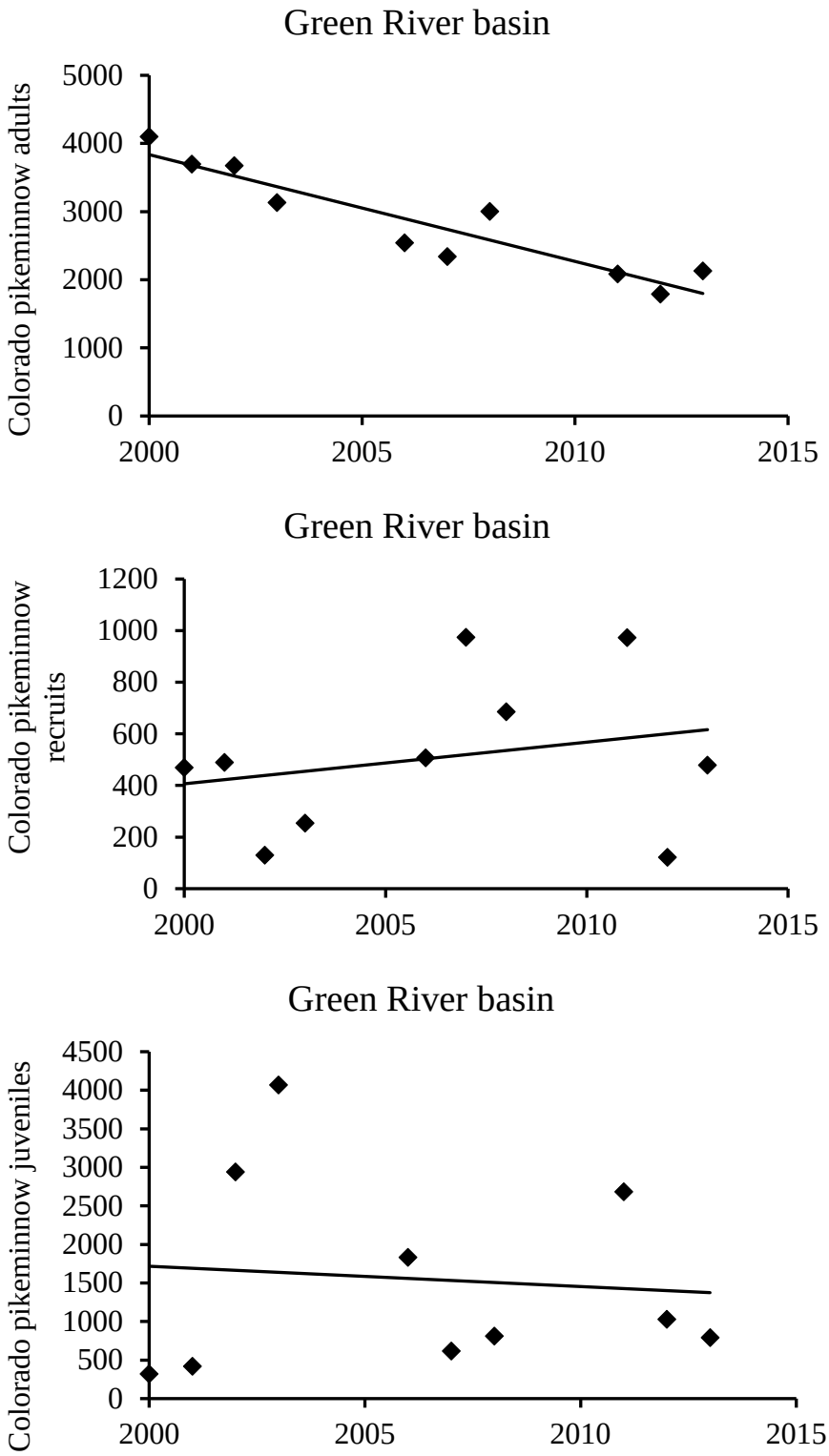


Figure 8. Abundance trends of Colorado pikeminnow adults (≥ 450-mm total length [TL]), recruits (400–449 mm TL), and juveniles (< 400 mm TL) in the Green River sub-basin, Utah and Colorado, 2000–2003, 2006–2008, and 2011–2013.

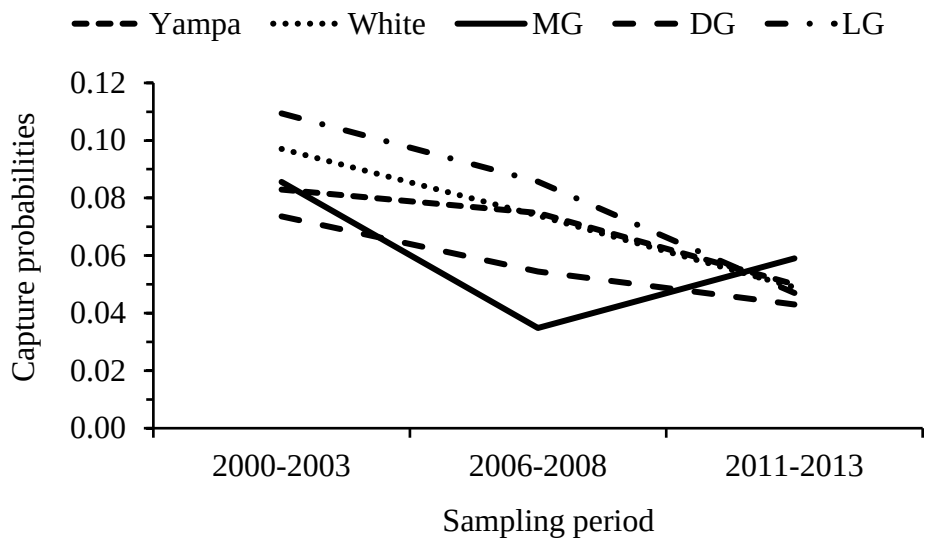


Figure 9. Mean capture probabilities in each major sampling period (2000–2003, 2006–2008, 2011–2013) for the Yampa River (Yampa), White River (White), middle Green River (MG), Desolation-Gray Canyon of the Green River (DG), and the lower Green River (LG).

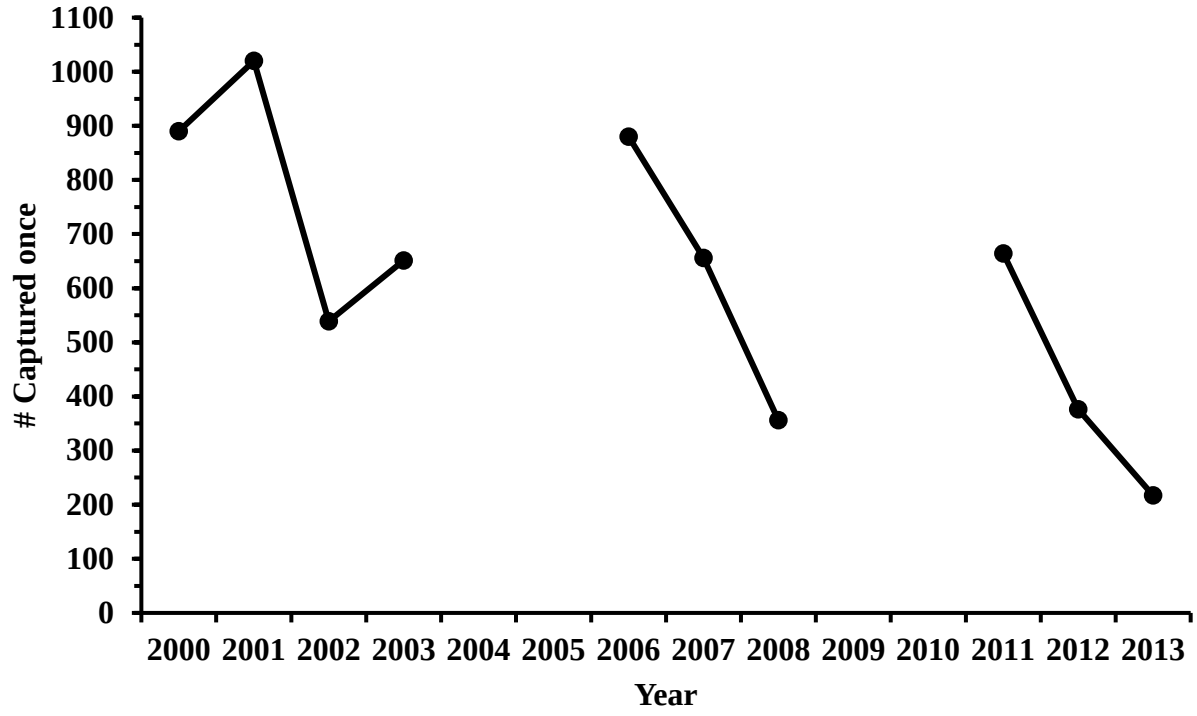


Figure 10. Number of fish captured only once during the year in three passes (encounter history could be 1 0 0, 0 1 0, or 0 0 1) during sampling for Colorado pikeminnow abundance estimation in the Green River subbasin, Colorado and Utah, 2000–2003, 2006–2008, 2011–2013. These represent 89-96% of all fish captured annually. Individuals could also be captured twice (encounter histories 1 1 0, 1 0 1, or 0 1 1), or during all three passes (1 1 1).

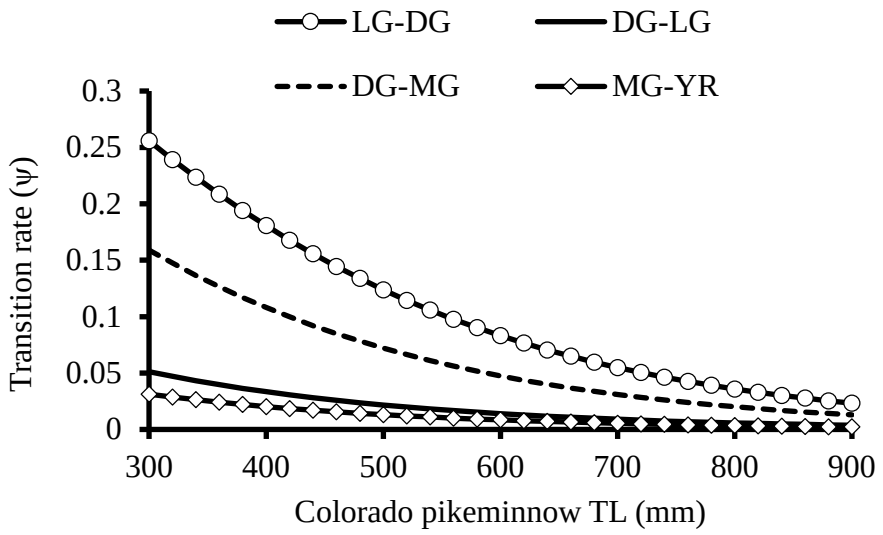


Figure 11. Transition rates between selected reaches (e.g., movement from LG to DG for the LG-DG combination depicted) as a function of Colorado pikeminnow total length (mm) for four reach combinations. LG = lower Green River, DG = Desolation-Gray Canyon reach of the Green River, MG = middle Green River, and YR = Yampa River.

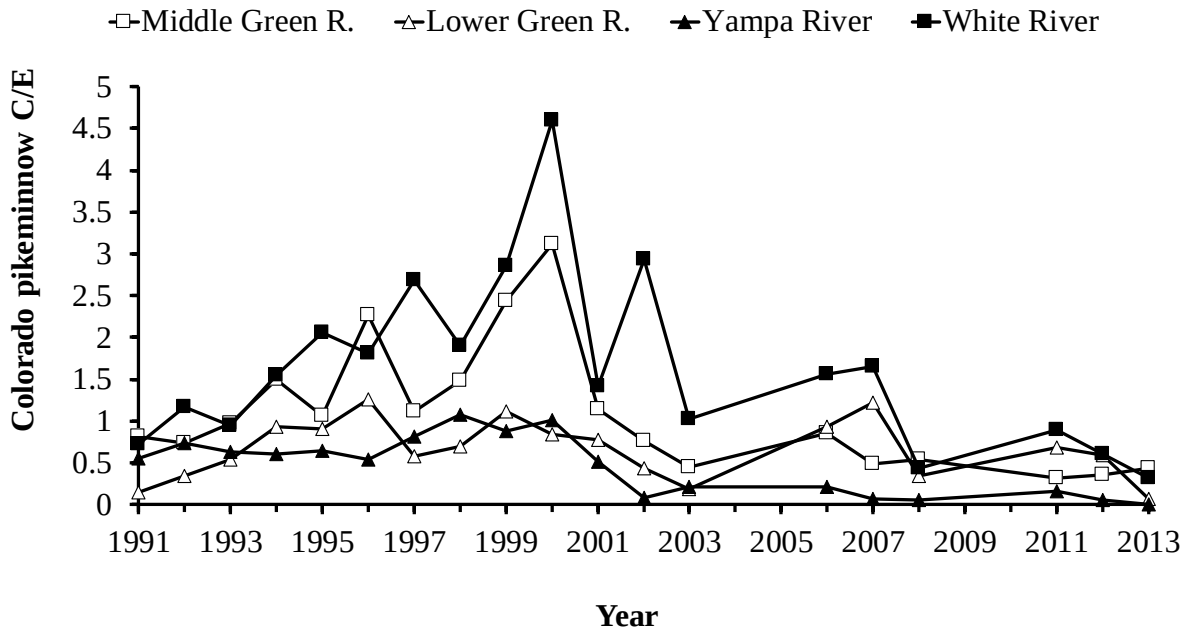


Figure 12. Interagency standardized monitoring program (ISMP) captures of sub-adult and adult Colorado pikeminnow per hour of electrofishing effort (C/E) in the Green River sub-basin, 1991–2003, 2006–2008, and 2011–2013.

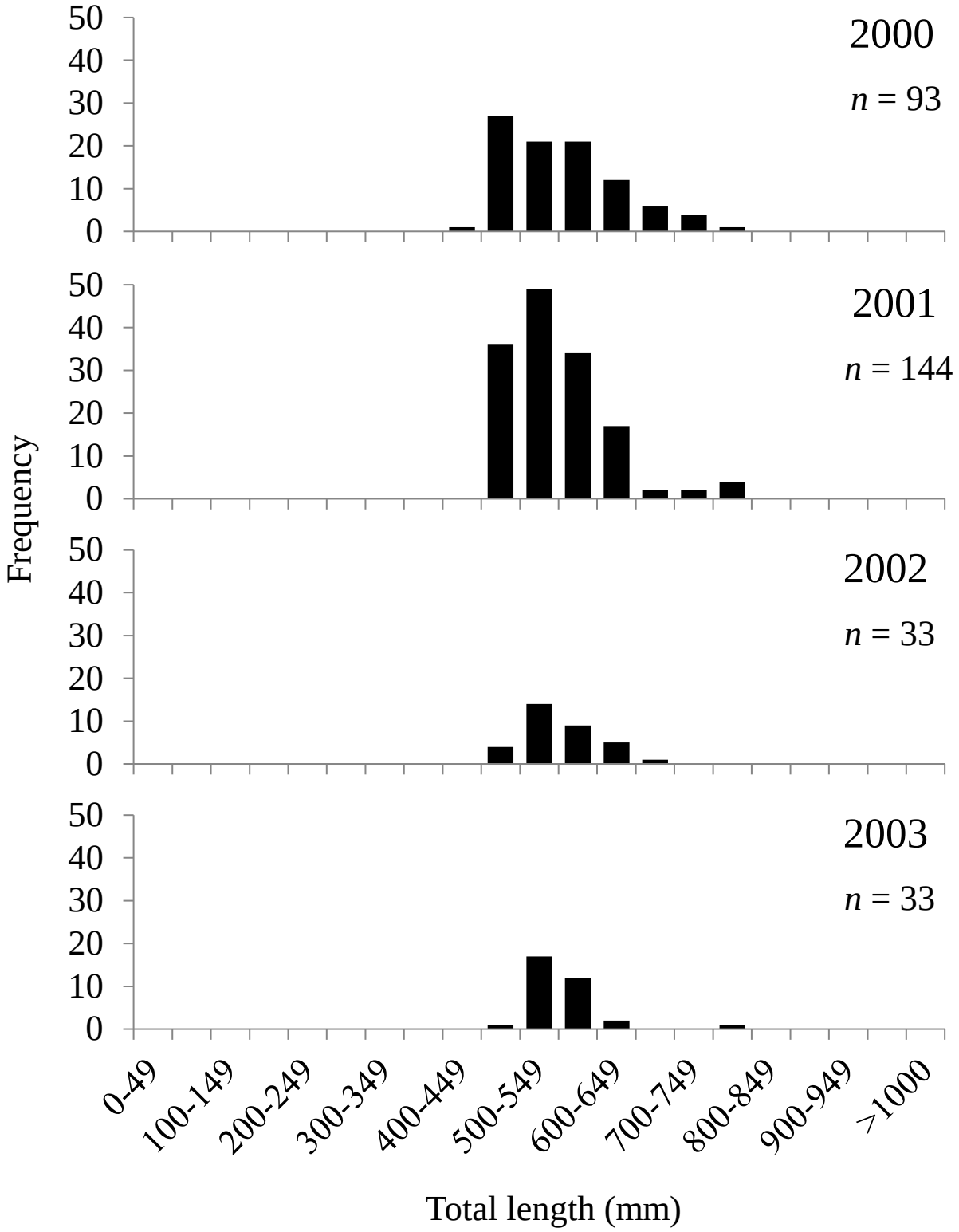


Figure 13. Length-frequency histograms for Colorado pikeminnow captured in the Yampa River, Colorado, in three periods from 2000–2013, during Green River sub-basin abundance estimation sampling.

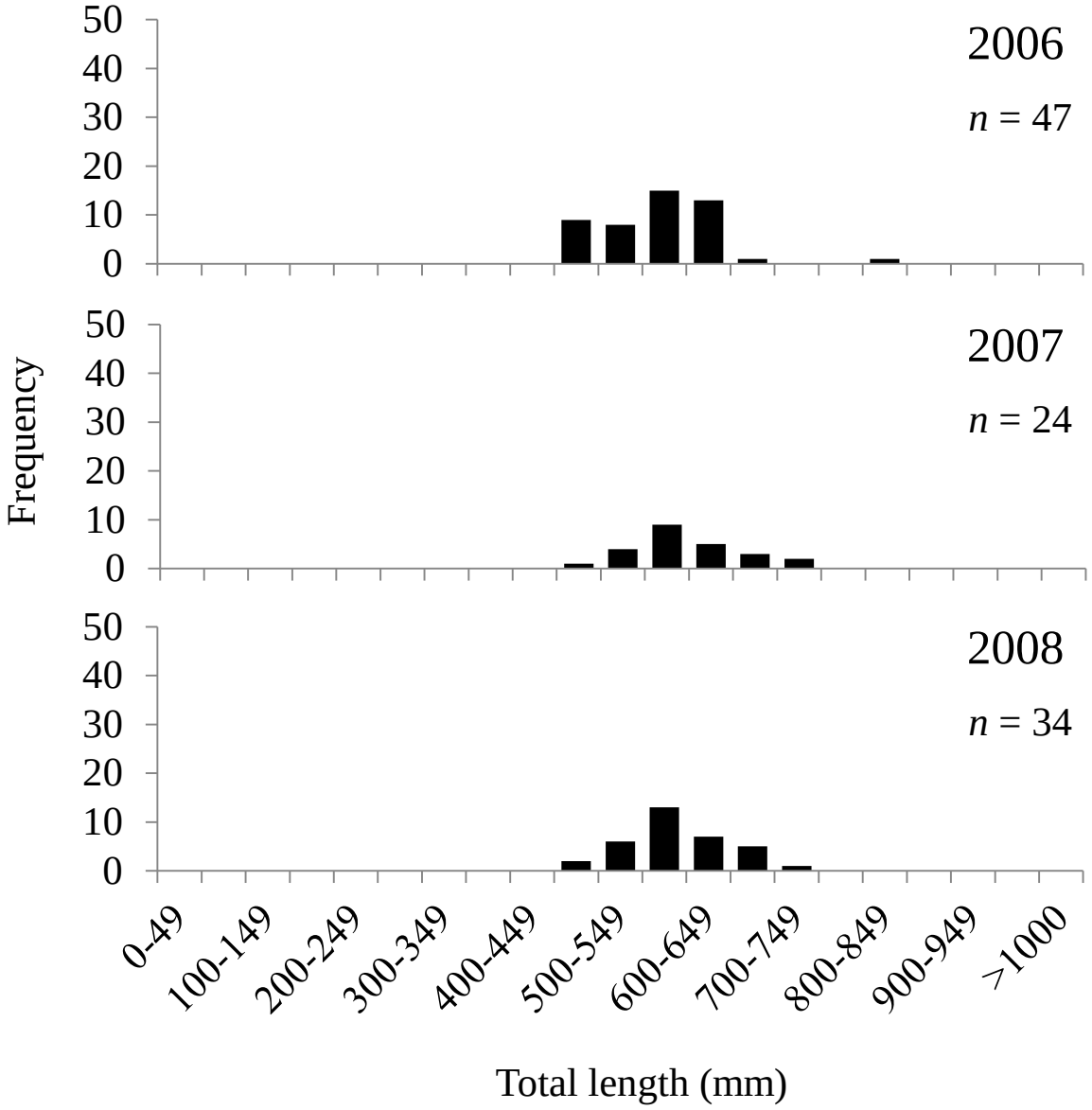
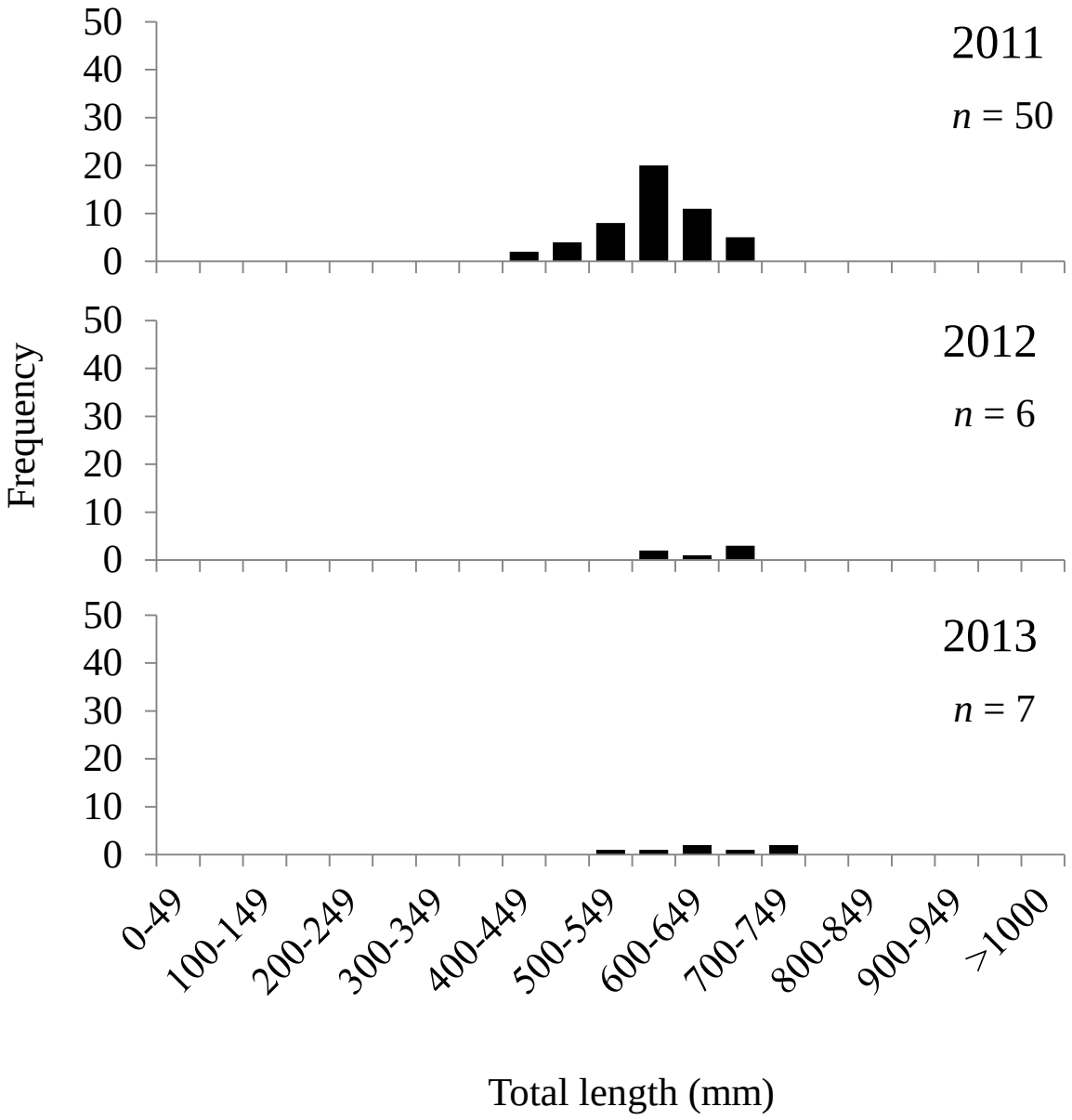


Figure 13. continued



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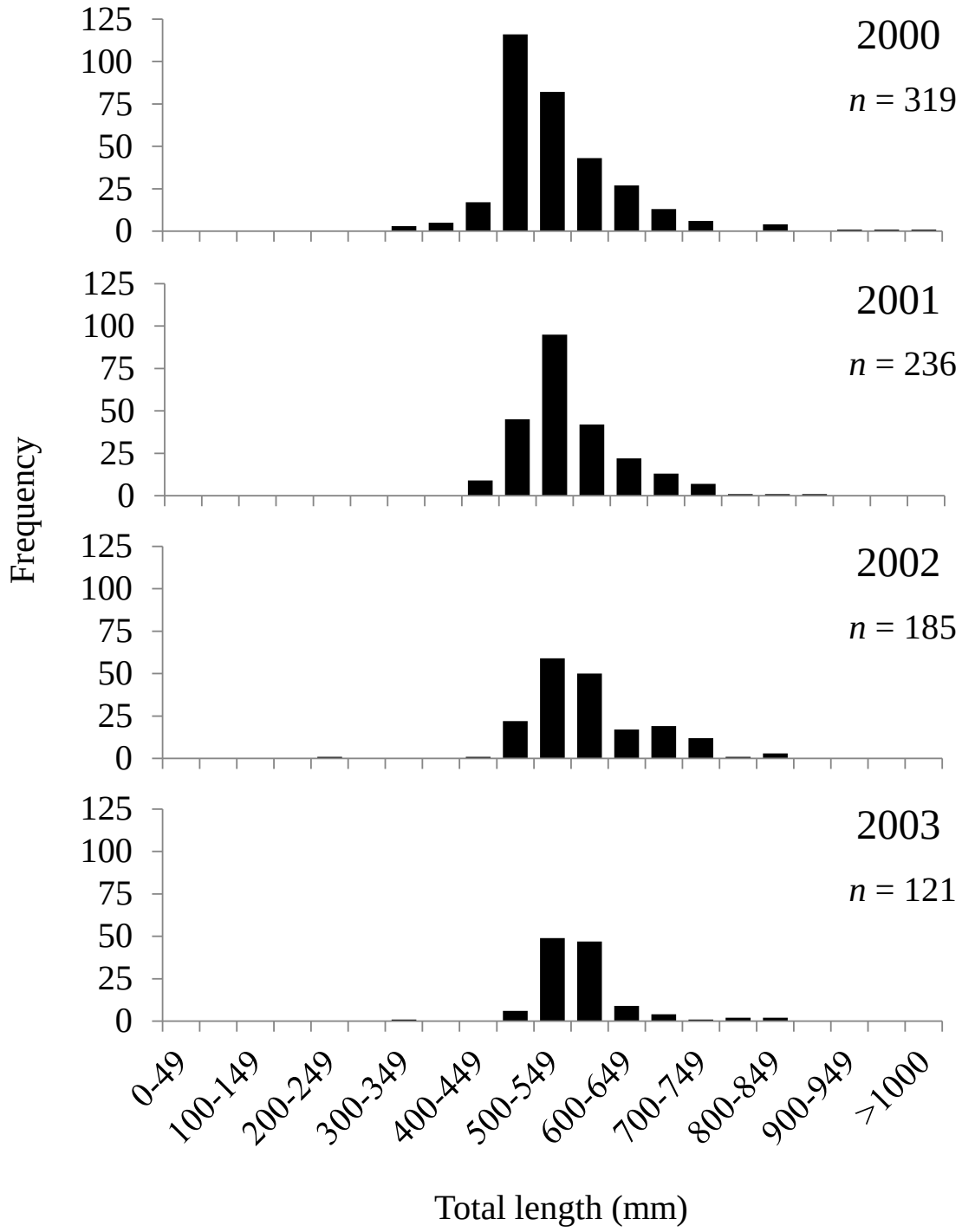
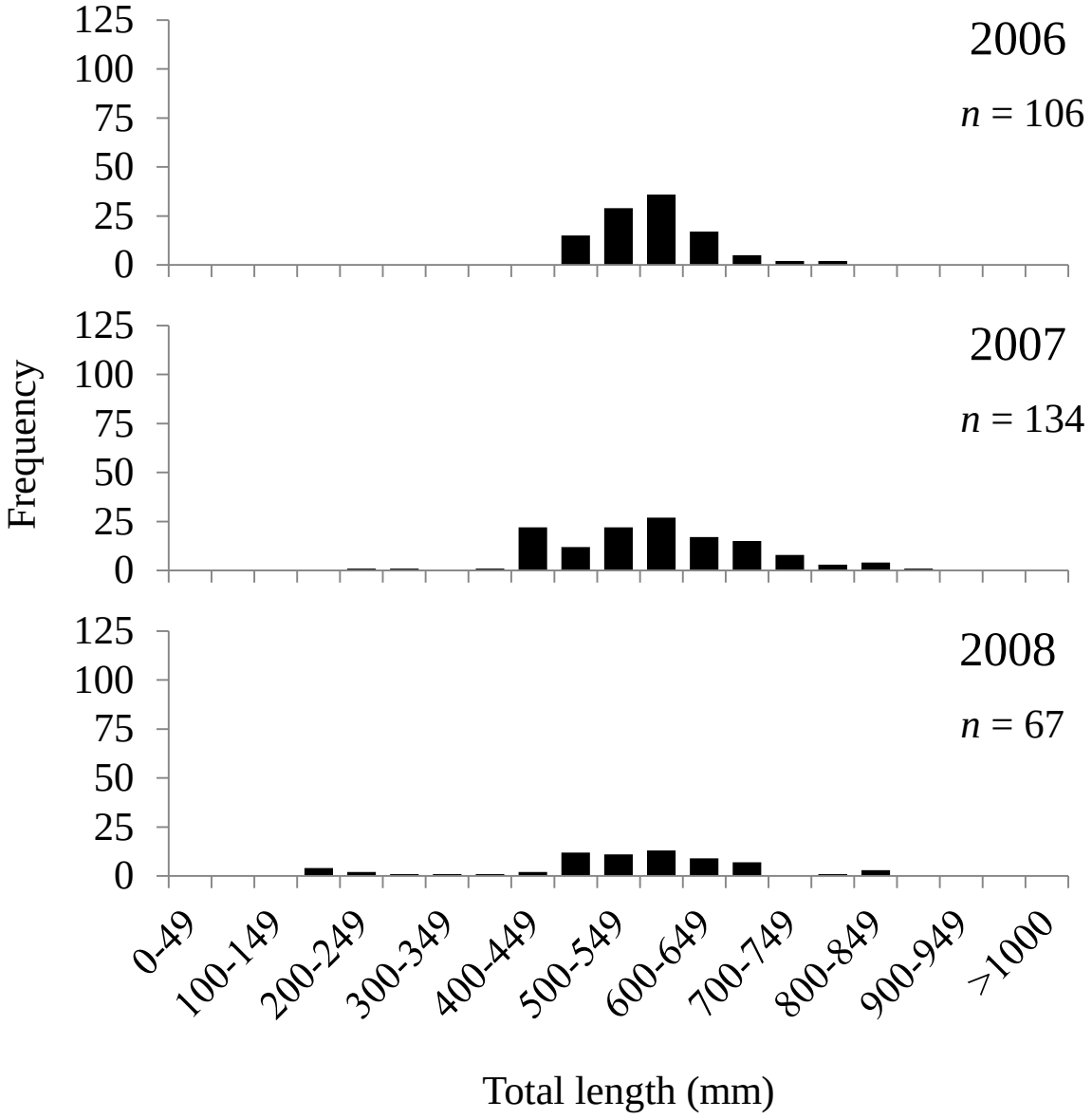


Figure 14. Length-frequency histograms for Colorado pikeminnow captured in the White River, Colorado and Utah, in three periods from 2000–2013, during Green River abundance estimation sampling.



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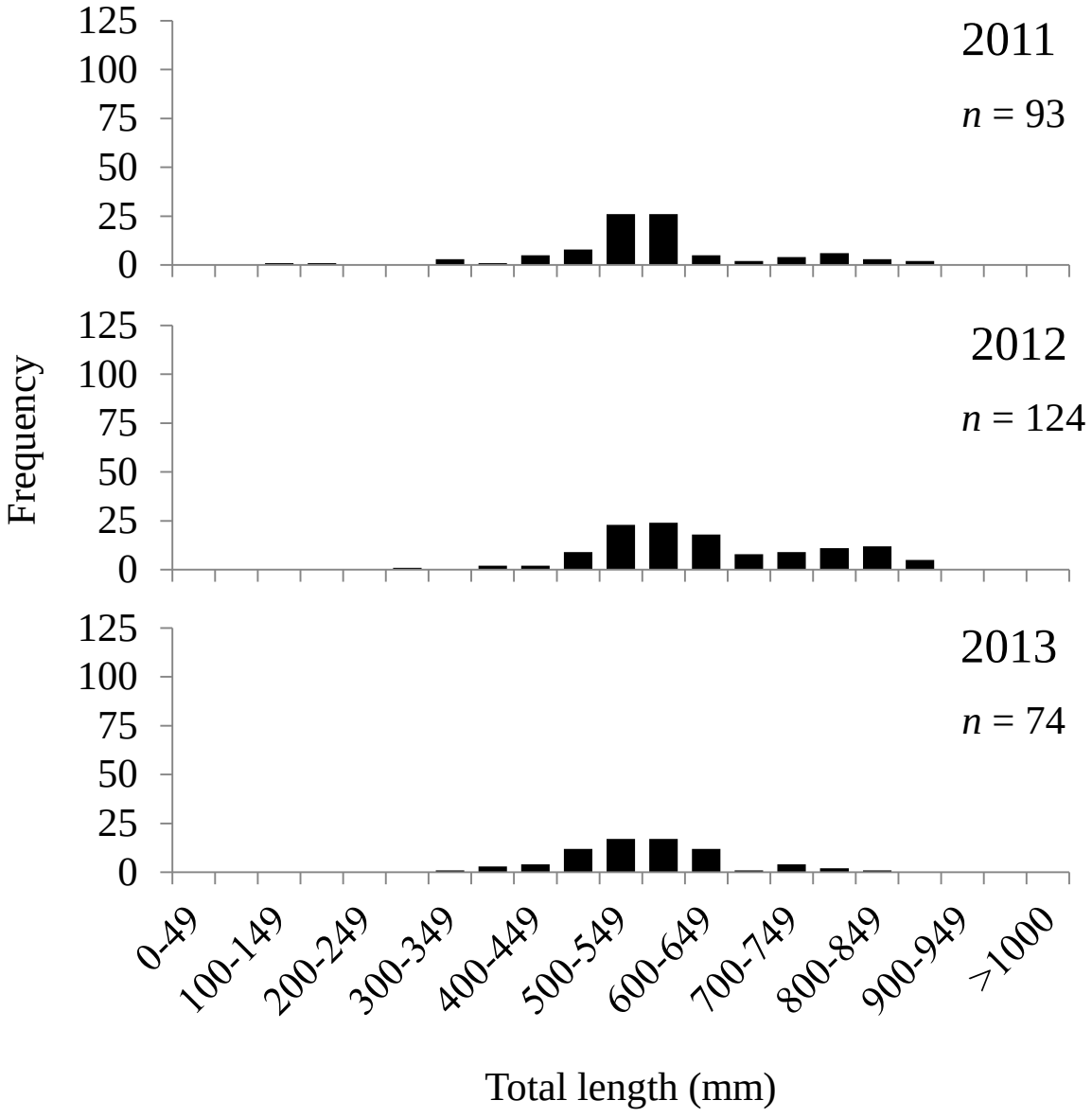

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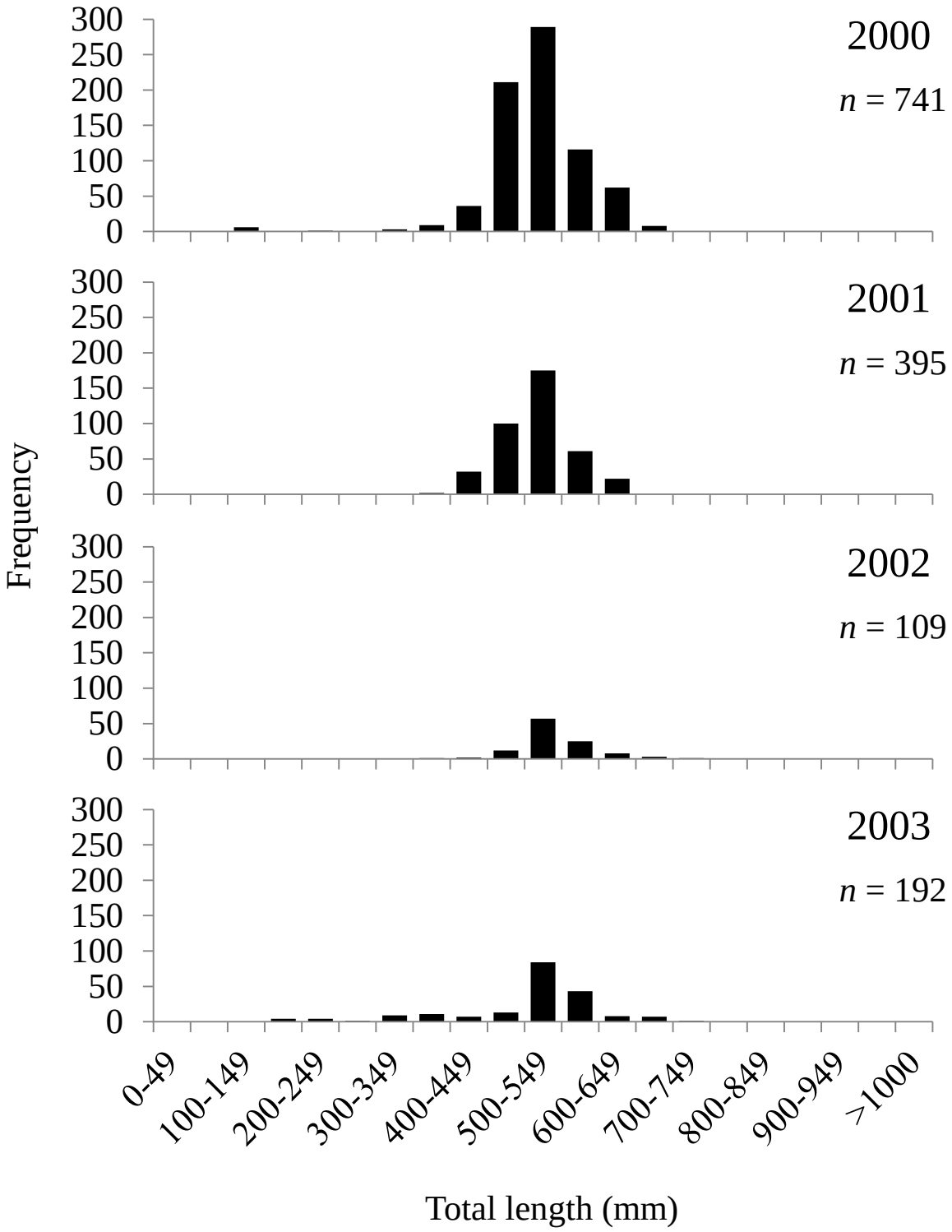
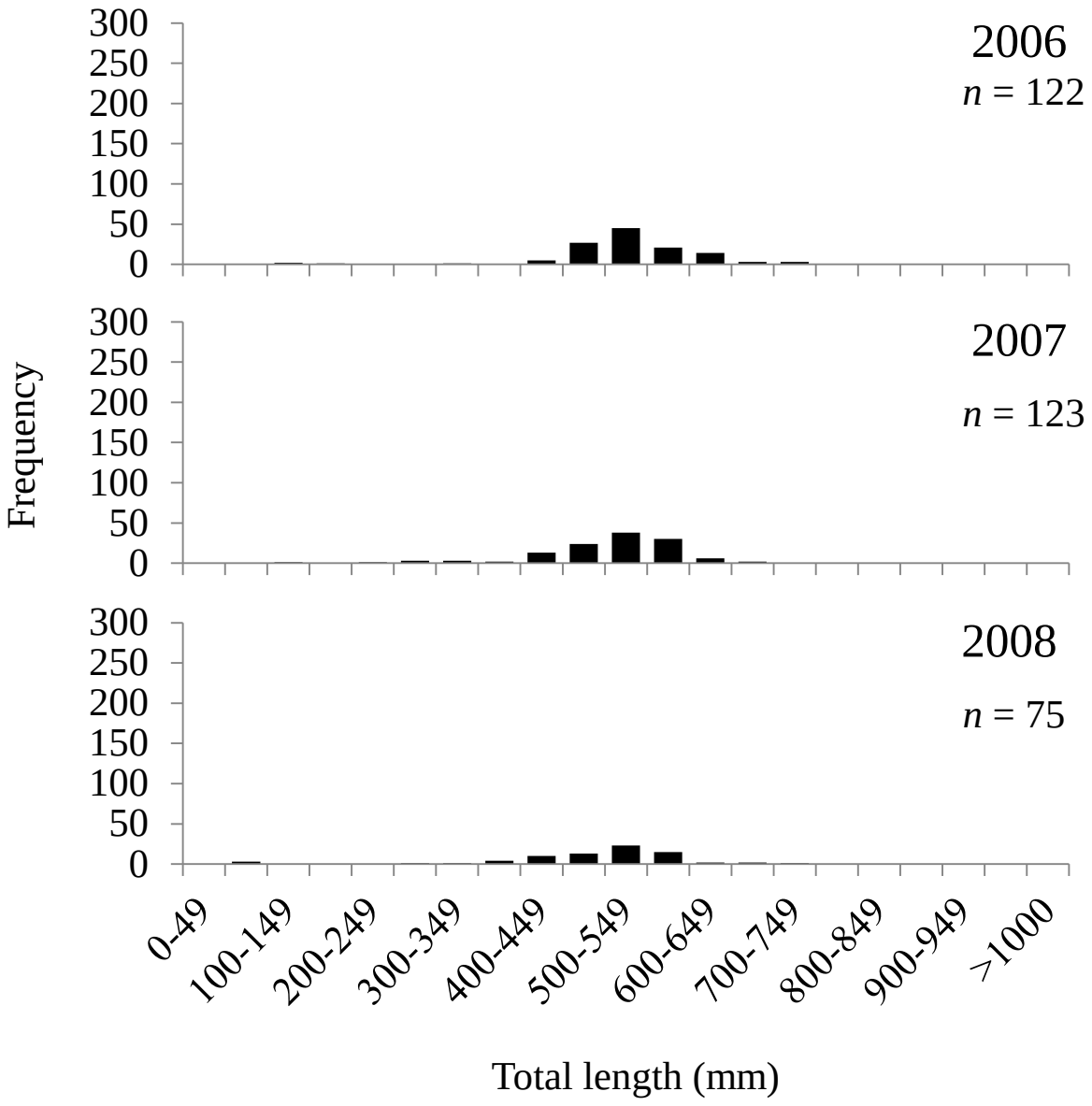


Figure 15. Length-frequency histograms for Colorado pikeminnow captured in the middle Green River, Utah, in three periods from 2000–2013, during Green River abundance estimation sampling.



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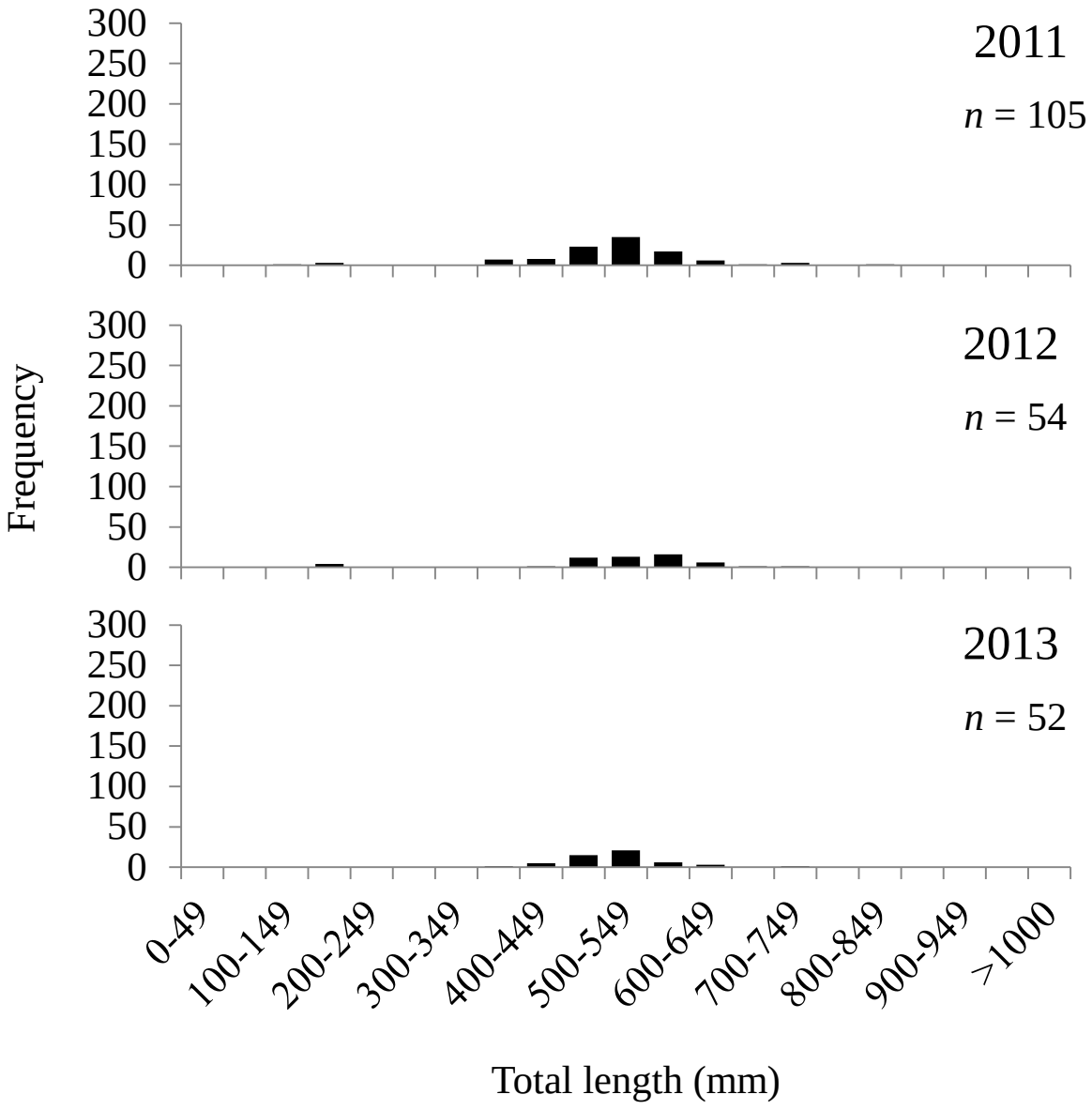

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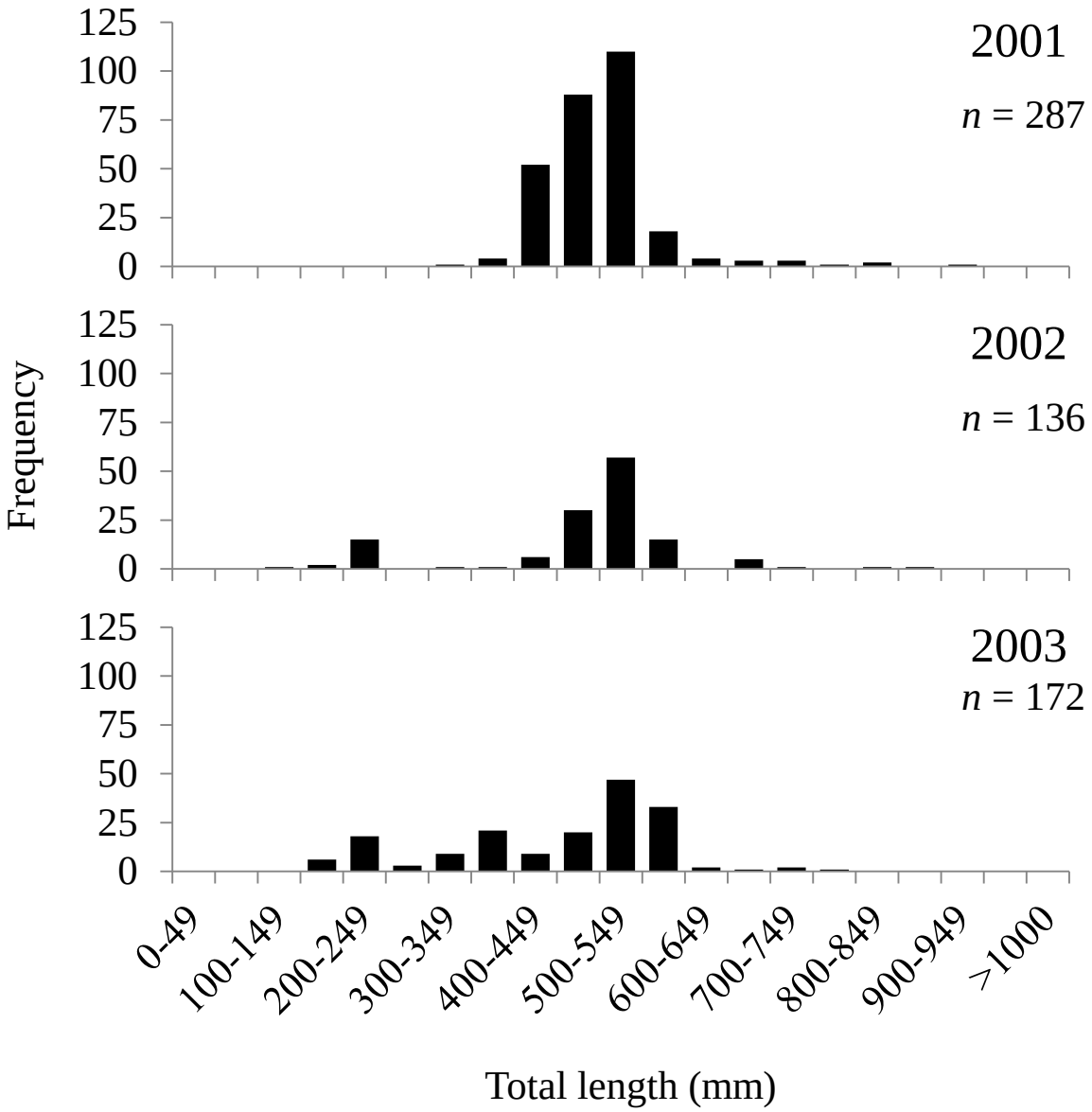
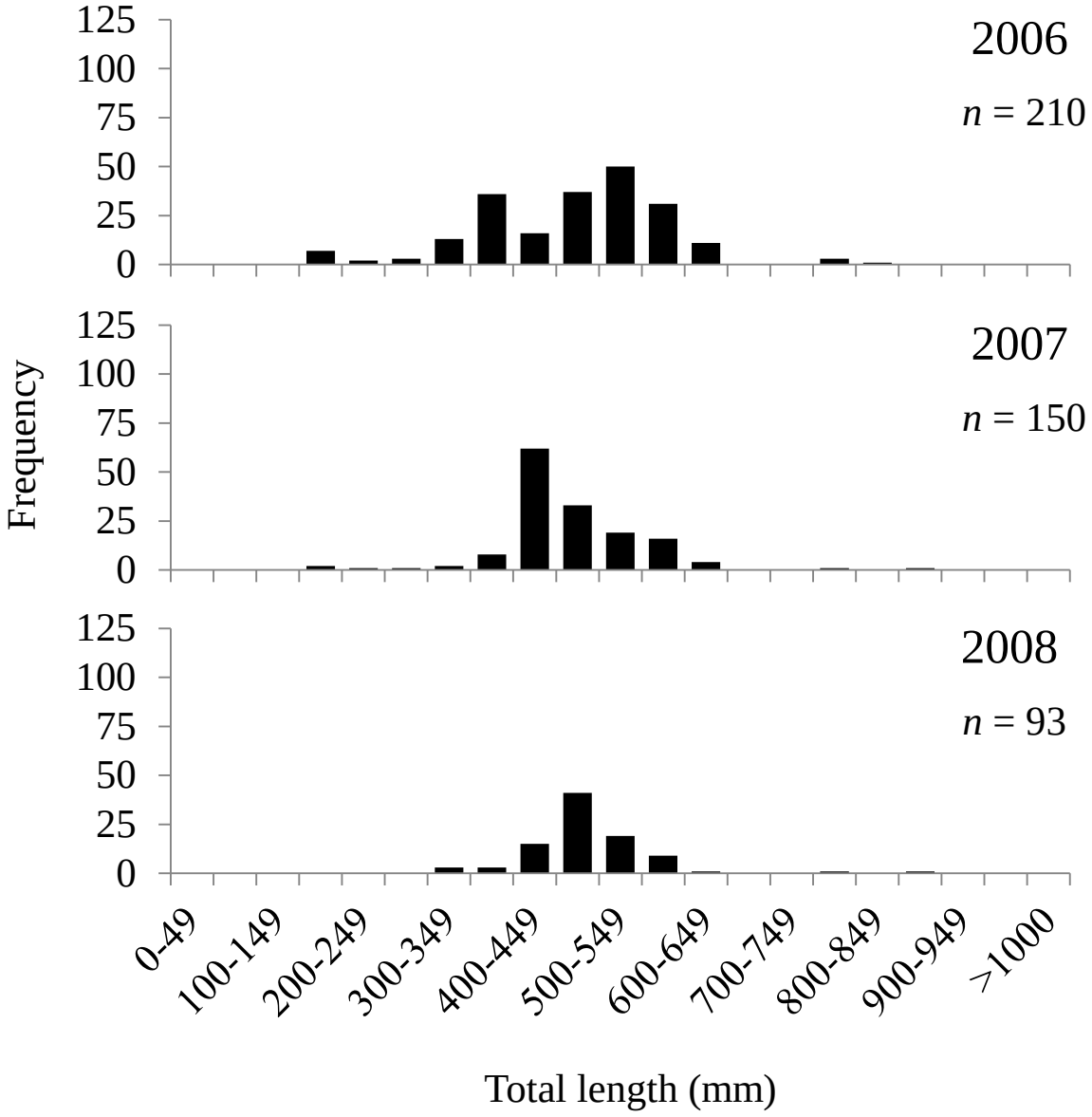


Figure 16. Length-frequency histograms for Colorado pikeminnow captured in the Desolation-Gray Canyon reach of the Green River, Utah, in three periods from 2001–2013, during Green River abundance estimation sampling.



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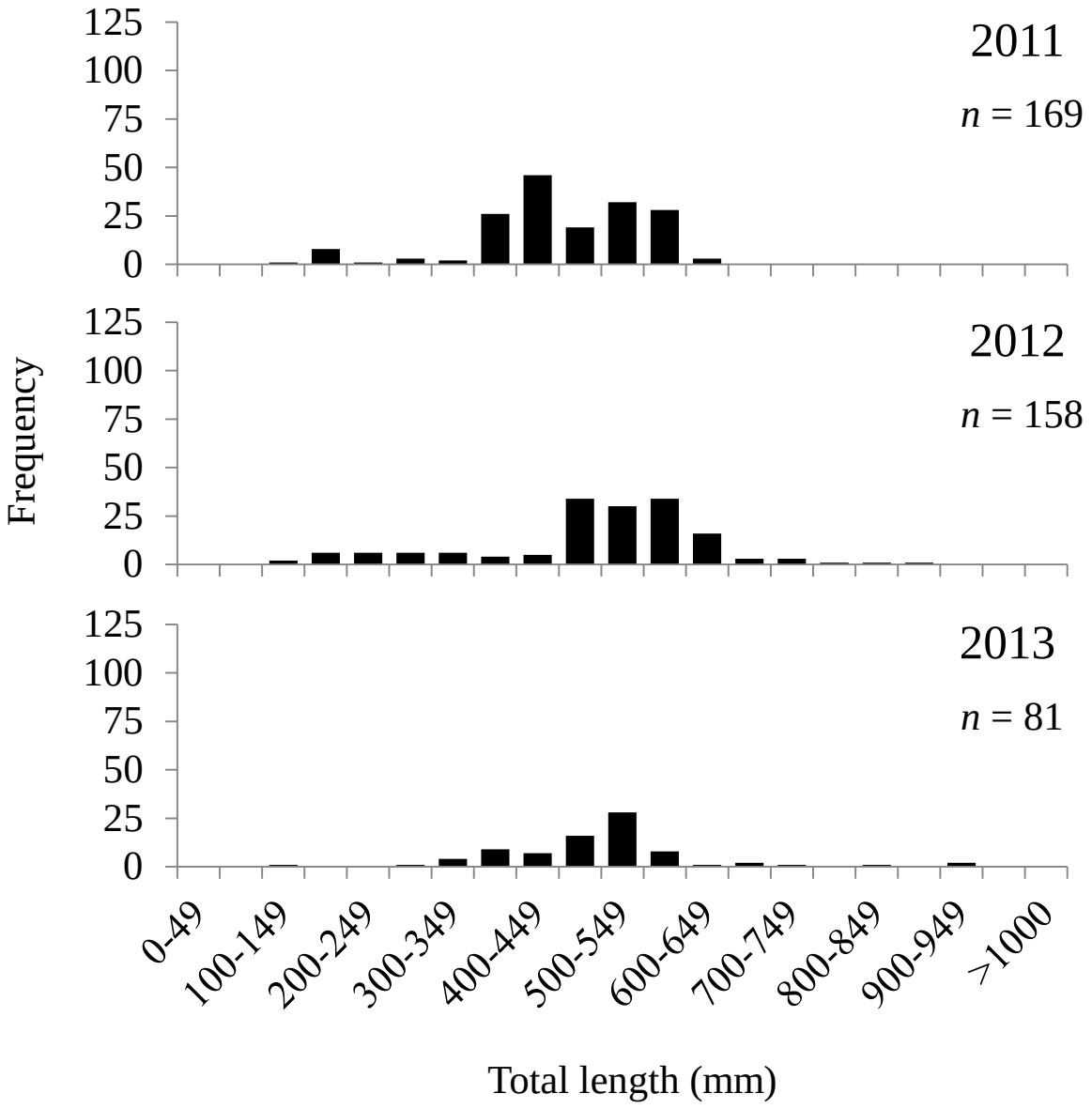

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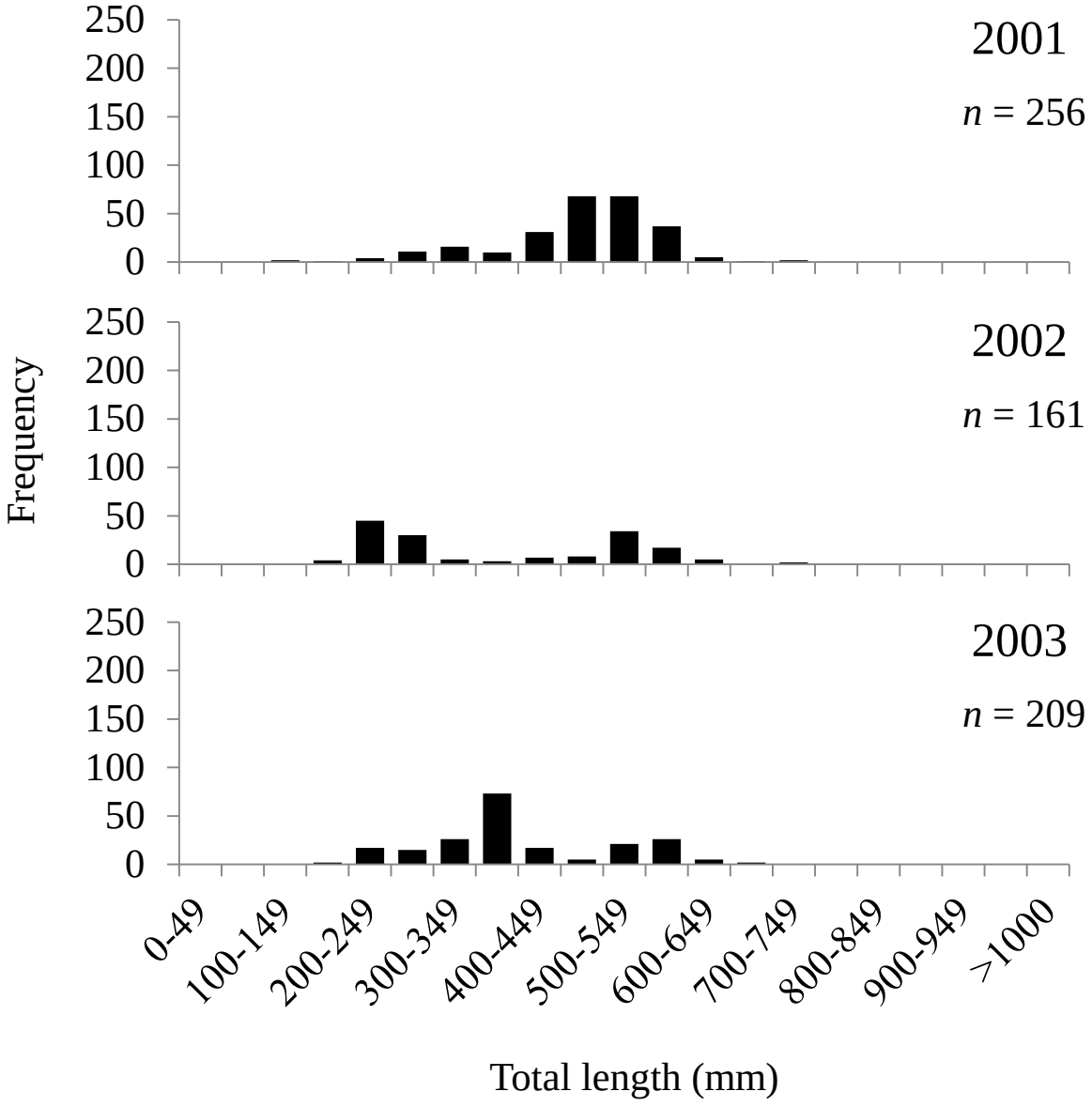
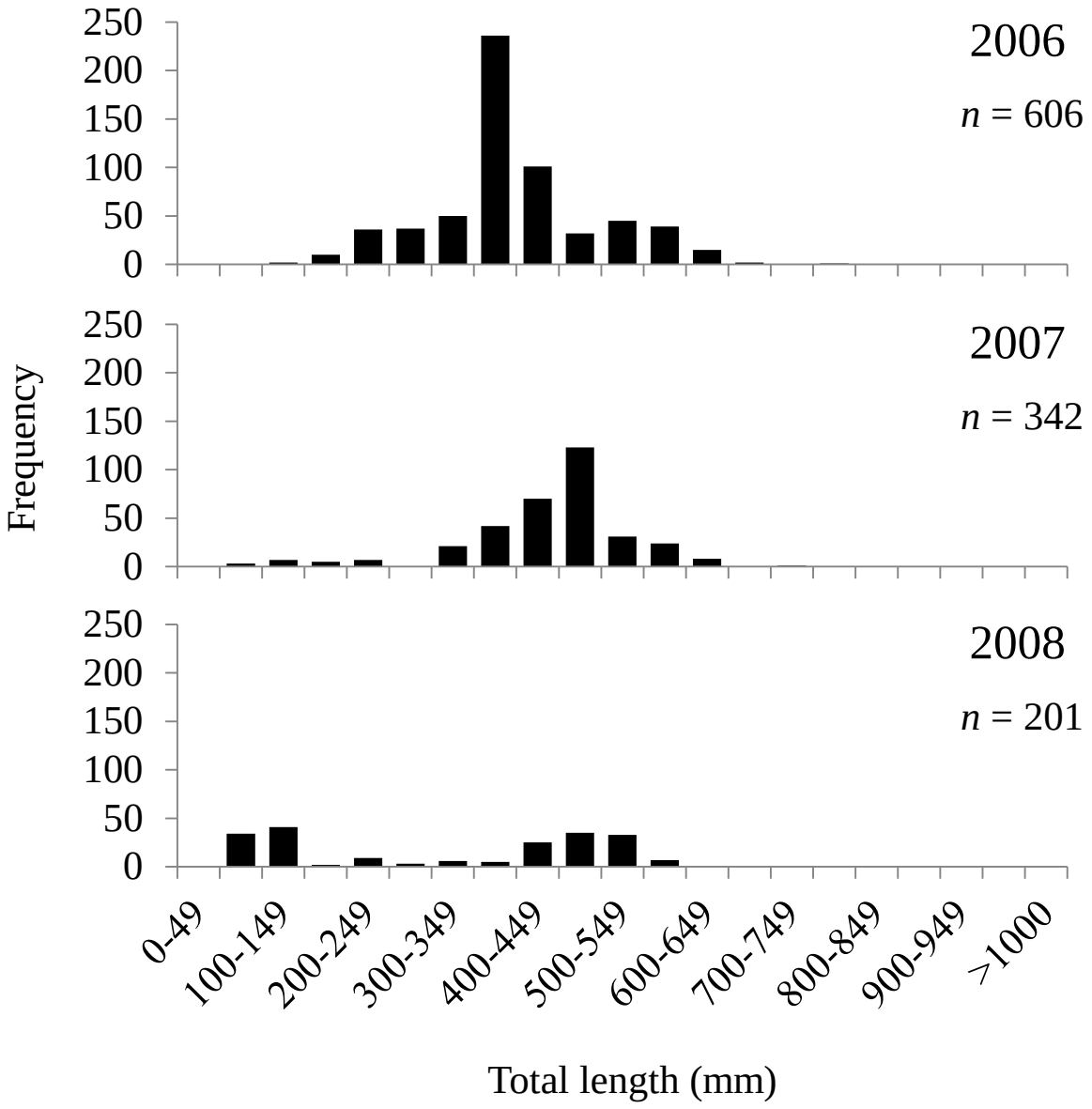


Figure 17. Length-frequency histograms for Colorado pikeminnow captured in the lower Green River reach, Utah, in three periods from 2001–2013, during Green River abundance estimation sampling.



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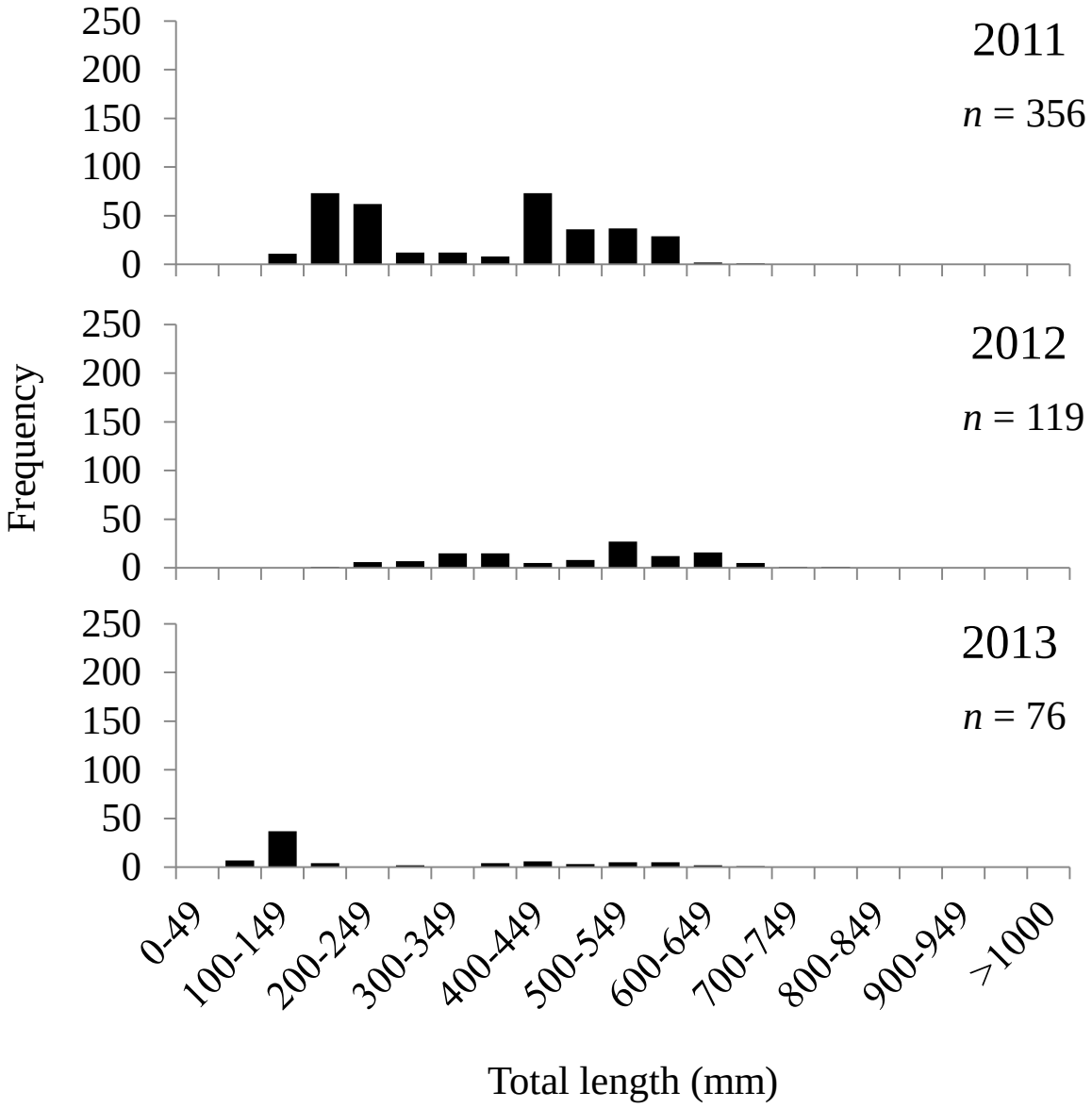


Figure 17. continued

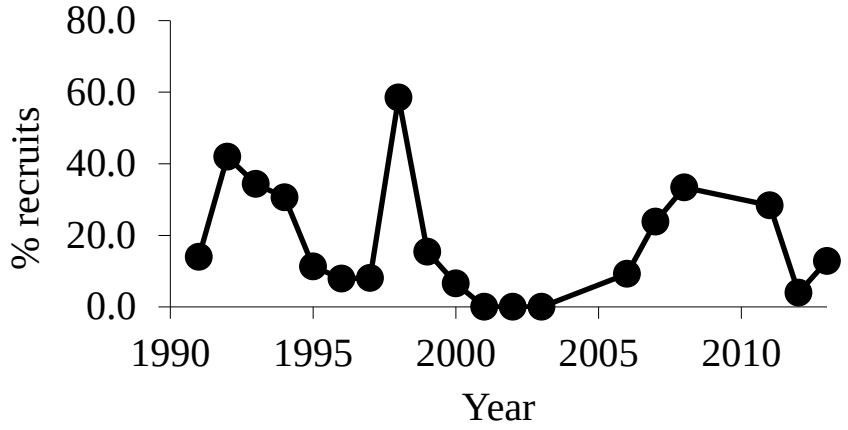


Figure 18. Percentage of recruit-sized (400 to 449 mm TL) Colorado pikeminnow relative to the number of adults (≥ 450 mm TL) in Interagency Standardized Monitoring Program samples collected from the Green River sub-basin, Utah and Colorado, 1991–2003, 2006–2008, and 2011–2013. In the 2011–2013 period, ratios were calculated based on the number of fish captured in the appropriate size class in all electrofishing reaches, excluding the Desolation-Gray Canyon reach, because it was not historically sampled by the ISMP program.

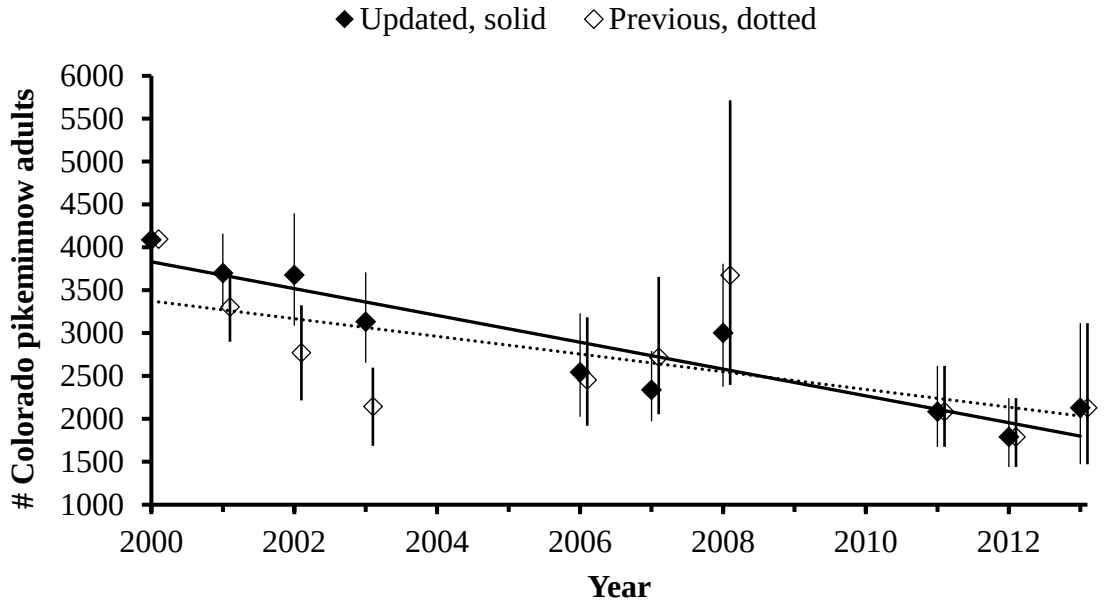


Figure 19. Colorado pikeminnow abundance estimates from 2000–2008 that were previously reported (open diamonds: Bestgen et al. 2007; 2010), compared to those estimated using the entire dataset, 2000–2013 (filled diamonds). The year 2000 value is a composite of estimates from 2000 and 2001 because estimates were not available for the Desolation-Gray Canyon and lower Green River reaches in year 2000. Vertical bars represent 95% confidence intervals.

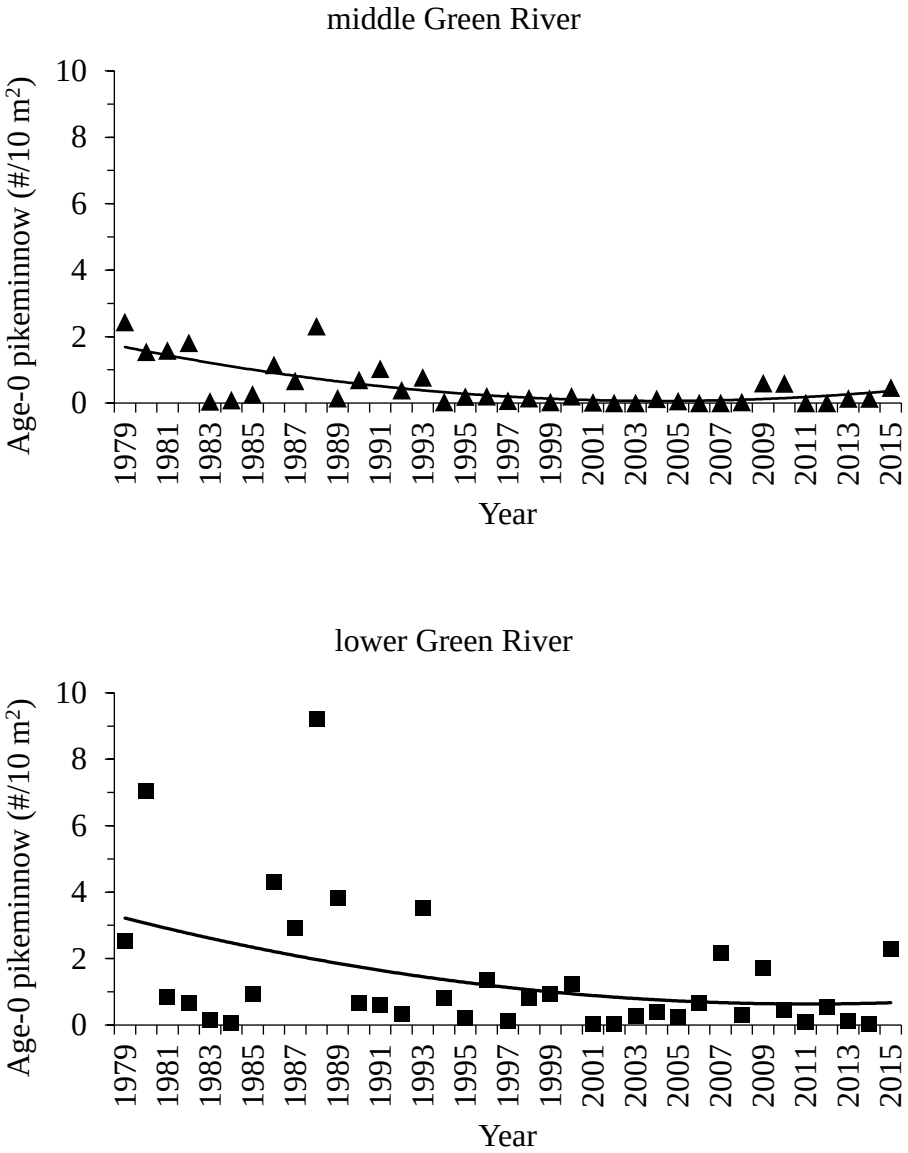


Figure 20. Abundance of age-0 Colorado pikeminnow in seine samples from backwaters in the middle (upper panel) and lower (lower panel) Green rivers, Utah, 1986–2015.

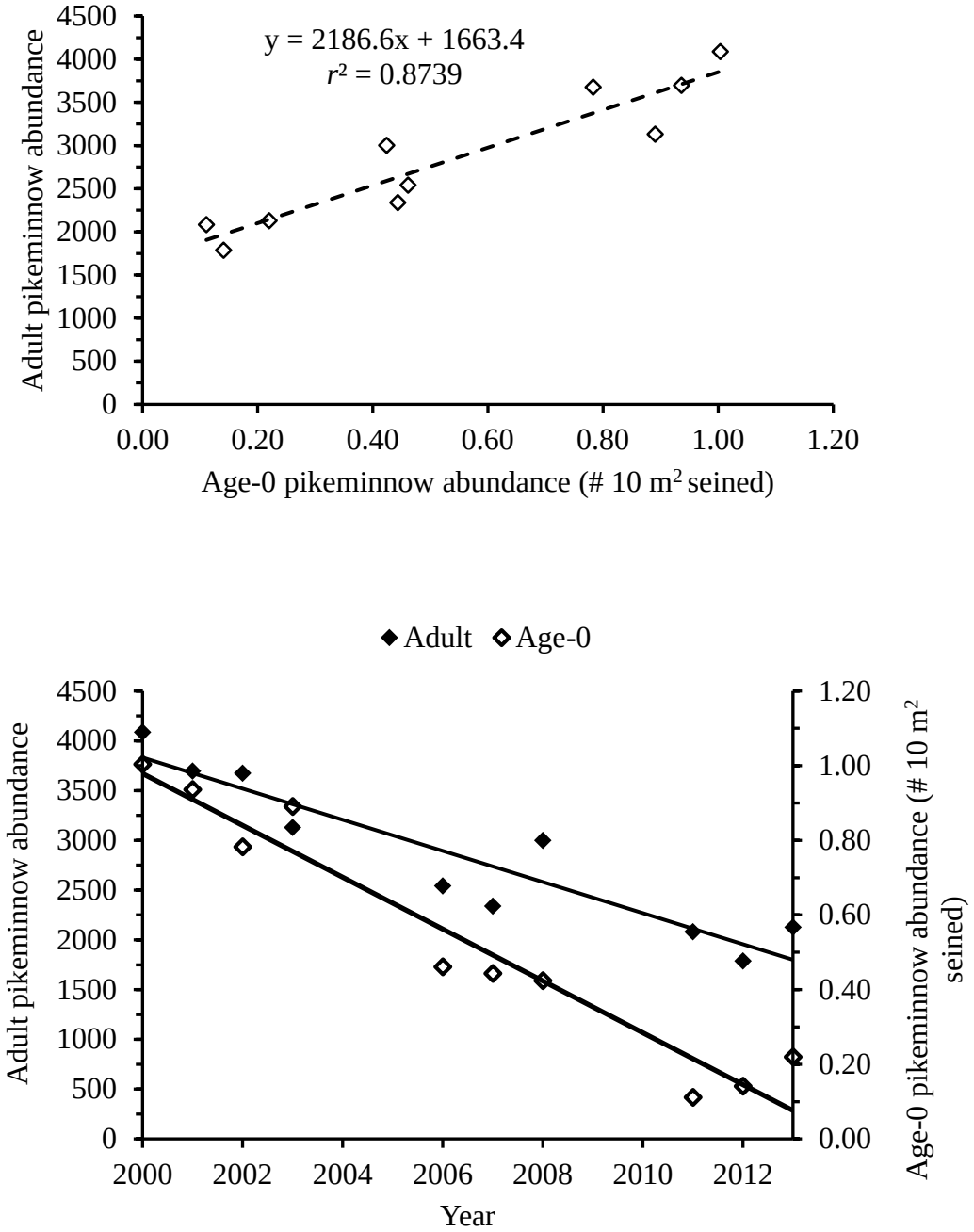


Figure 21. Abundance of adult Colorado pikeminnow from capture-recapture sampling as a function of mean abundance (# captured per 10 m^2 of sampling) of age-0 Colorado pikeminnow captured in Interagency Standardized Montioring samples collected 7, 8, 9 and 10 years prior (top panel) in the middle and lower Green River. Even though ISMP samples were not collected after 2000, we allocated electrofishing sampling data to particular reaches identified by ISMP protocols, so data could be compared equitably. The lower panel depicts the same adult and age-0 data as a function of time when adult abundance estimates were conducted.

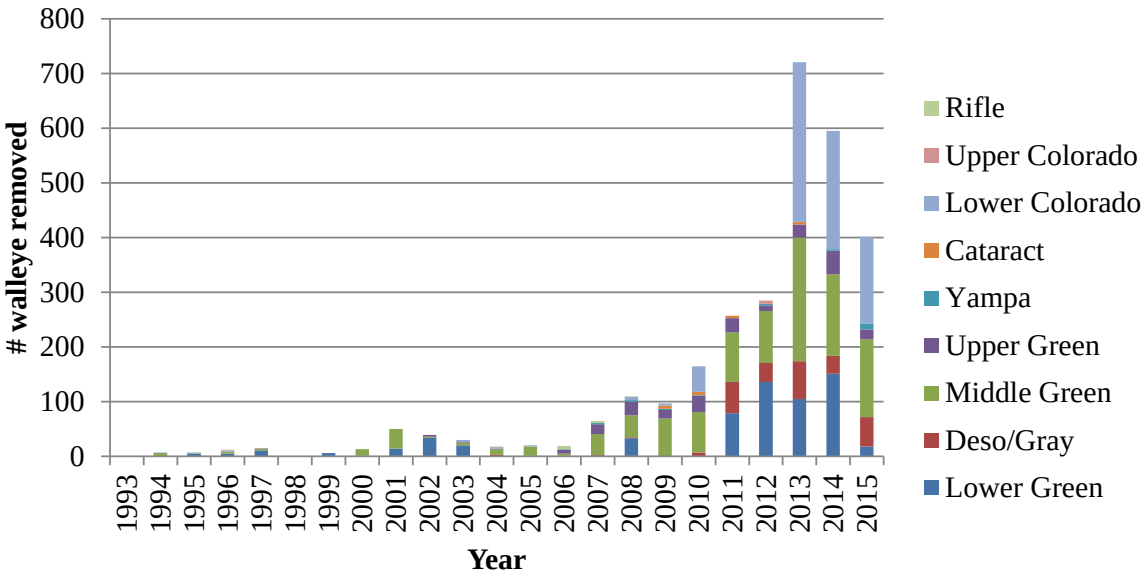


Figure 22. Number of walleye removed from various river reaches in the upper Colorado River basin, 1993–2015 (Figure courtesy of C. Michaud, Utah Division of Wildlife Resources, Moab, and T. Francis, U. S. Fish and Wildlife Service, Grand Junction, Colorado). Lower Green River numbers indicated a large increase in 2011 and after, which reflects abundance estimation (2011–2013) and removal sampling in that period. Intensive sampling was conducted from 2006–2008 during Colorado pikeminnow abundance estimation but little sampling occurred in 2009 and 2010.

Appendix I. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2000. Electrofishing effort includes main channel and backwater sampling associated with trammel nets. Effort data not available for some passes due to equipment failure.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 11 - 27	10	538-395	61	173	0
2	May 2 - 9	4	538-394	41	197	8
3	May 18 - June 1	8	537-396	55	263	52
4	June 6 - 16	7	538-396	48	99	28
Total		29		205	732	88
Yampa River						
Pass 1	April 18 - 27	9	192-80	30	14	0
2	May 6 - 14	9	192-82	18	23	2
3	May 22 - June 1	11	192-73	29	44	4
4	June 20 - 24	5	192-82	15	8	1
Total		34		92	89	7
White River						
Pass 1	April 24 - May 10	6	168-0	62	109	0
2	May 10 - 25	7	168-0	Not available	91	9
3	May 25 - June 9	9	168-0	64	113	17
Total		22		189	313	26

[1] All PIT tagged Colorado pikeminnow.

[2] Recaptured fish are those handled on previous sampling passes in 2000.

Appendix II. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2001. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 16 - 24	6	537-396	48	64	0
2	May 1 - May 11	9	537-396	69	86	2
3	May 14 - 24	9	537-396	75	158	14
4	May 29 - June 6	7	538-395	59	85	19
Total		31		251	393	35
Yampa River						
Pass 1	April 24 - May 2	8	192-82	50	51	0
2	May 11 - 19	9	192-73	47	36	8
3	May 27 - June 4	9	192-73	47	44	9
4	June 12 - 19	7	192-82	41	9	3
Total		33		185	140	20
White River						
Pass 1	April 16 - 27	8	167-0	73	79	0
2	May 8 - 23	8	167-0	62	94	10
3	May 30 - June 5	8	167-0	69	63	14
Total		24		204	236	24

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2001.

Appendix II continmued. Sampling dates, capture data, and effort for Desolation-Gray and lower Green River abundance estimation sampling for Colorado pikeminnow, 2001. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Desolation-Gray Canyon, Green River						
Pass 1	March 26 - April 9	10	396–207	91	104	0
2	April 17 - May 2	10	396–207	89 [3]	102	6
3	May 7 - 16	9	396–207	72	75	20
Total		29		252	281	26
Lower Green River						
Pass 1	March 12 - 21	8	193-0	77	42	0
2	April 1 - 11	9	193-0	83	53	4
3	April 22 - May 2	9	193-0	82	55	9
4	May 20 - 30	9	193-0	87	99	27
Total		35		329	249	40

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2001.
[3] Some effort estimated.

Appendix III. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2002. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 30 - May 15	8	536-396	55	36	0
2	May 16 - 30	9	536-396	69	43	2
3	May 31 - July 11	8	536-396	59	30	4
Total		25		183	109	6
Yampa River						
Pass 1	April 25 - May 3	8	192-73	46	11	0
2	May 11 - 19	8	196-73	52	11	0
3	May 26 - June 3	9	196-81	58	9	0
4	June 12 - 16	5	192-84	10	2	0
Total		30		166	33	0
White River						
Pass 1	April 15 - 23	8	167-0	61	64	0
2	April 26 - May 3	9	167-0	64	49	7
3	May 8 - 24	9	167-0	55	71	14
Total		26		180	184	21

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2002.

Appendix III continued. Sampling dates, capture data, and effort for Desolation-Gray and lower Green River abundance estimation sampling for Colorado pikeminnow, 2002. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Desolation-Gray Canyon, Green River						
Pass 1	March 23 - April 11	10	396–208	81	47	0
2	April 20 - May 7	8	396–207	80	41	1
3	May 11 - 17	9	396–207	69	49	6
Total		27		230	137	7
Lower Green River						
Pass 1	April 7 - 17	9	193-2	86	48	0
2	April 21 - May 1	9	193-0	88	68	3
3	May 5 - 15	9	193-0	73	44	4
Total		27		247	160	7

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2002.

Appendix IV. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2003. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 22 - May 12	10	538-396	67	41	0
2	May 13 - 27	10	538-396	65	65	3
3	May 28 - June 13	11	538-396	62	84	9
Total		31		194	190	12
Yampa River						
Pass 1	April 24 - May 3	9	193-80	48	4	0
2	May 12 - 20	8	192-80	58	5	0
3	May 28 - June 14	9	192-72	56	20	0
4	June 15 - 25	9	192-72	69	2	0
Total		35		231	31	0
White River						
Pass 1	April 21 - 30	8	167-0	61	55	0
2	April 29 - May 15	8	167-0	53	28	2
3	May 5 - 29	8	167-0	61	34	7
Total		24		175	117	9

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2003.

Appendix IV continued. Sampling dates, capture data, and effort for Desolation-Gray and lower Green River abundance estimation sampling for Colorado pikeminnow, 2003. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Desolation-Gray Canyon, Green River						
Pass 1	March 24 -April 2	9	396–207	62	49	0
2	April 14 - 23	9	396–207	72*	35	1
3	May 5 - 14	8	396–207	67*	44	2
4	June 2 - 6	8	396–207	67*	50	4
Total		34		190*	178	7
Lower Green River						
Pass 1	April 13 - 23	9	193-0	91	51	0
2	May 6 - 16	9	193-0	84	61	3
3	May 25 - June 4	9	193-0	78	96	8
Total		27		253	208	11

* Some effort not available due to lost data sheets and/or malfunctioning counters.
[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2003.

Appendix V. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2006. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 17 - 27	9	537-396	56	53	0
2	May 2 - June 1	7	537-396	50	39	4
3	June 5 - 14	7	537-396	42	25	2
Total		23		148	117	6
Yampa River						
Pass 1	April 18 - May 3	15	216-82	85	11	0
2	May 3 - 12	11	216-83	74	6	1
3	May 9 - June 20	32	216-80	201	23	2
Total		58		360	40	3
White River						
Pass 1	April 28 - May 5	8	167-0	50	37	0
2	May 9 - 18	8	167-0	49	38	2
3	May 19 - June 2	8	167-0	47	30	8
Total		24		146	105	10

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2006.

Appendix V continued. Sampling dates, capture data, and effort for Desolation-Gray and lower Green River abundance estimation sampling for Colorado pikeminnow, 2006. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Desolation-Gray Canyon, Green River						
Pass 1	March 27 - April 7	8	396–207	71	72	0
2	April 10 - 14	8	396–207	62	74	10
3	April 19 - 26	8	396–207	61	55	7
Total		24		194	201	17
Lower Green River						
Pass 1	May 3 - 10	8	193-0	76	232	0
2	May 24 - June 1	9	193-0	85	197	32
3	June 14 - 21	8	193-0	75	168	22
Total		25		236	597	54

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2006.

Appendix VI. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2007. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 11 - 27	9	538-396	43	22	0
2	April 30 - May 9	7	538-396	40	36	1
3	May 14 - 24	7	538-396	44	64	3
Total		23		127	122	4
Yampa River						
Pass 1	April 17 - 24	10	216-81	71	3	0
2	April 25 - May 8	14	216-81	107	6	0
3	May 15 - June 30	36	216-81	239	14	0
Total		60		417	23	0
White River						
Pass 1	April 30 - May 16	9	167-0	45	43	0
2	May 14 - 24	8	167-0	44	46	3
3	May 18 - June 6	8	167-0	44	46	6
Total		25		133	135	9

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2007.

Appendix VI continued. Sampling dates, capture data, and effort for Desolation-Gray and lower Green River abundance estimation sampling for Colorado pikeminnow, 2007. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Desolation-Gray Canyon, Green River						
Pass 1	April 3 - 7	8	396–207	55	66	0
2	April 11 - 15	8	396–207	53	48	2
3	April 16 - 26	8	396–207	55	32	4
Total		24		163	146	6
Lower Green River						
Pass 1	May 9 - 17	9	193-0	81	154	0
2	May 23 - 31	9	193-0	80	123	14
3	June 6 - 13	8	193-0	71	55	14
Total		26		232	332	28

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2007.

Appendix VII. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2008. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 21 - 29	6	538-396	39	9	0
2	April 30 - May 8	6	538-396	43	26	0
3	May 13 - 21	6	538-396	44	37	3
Total		18		126	72	3
Yampa River						
Pass 1	April 15 - 22	13	216-80	90	5	0
2	April 23 - May 6	13	216-81	102	7	0
3	May 7 - June 25	46	216-81	306	20	2
Total		72		498	32	2
White River						
Pass 1	April 14 - 19	8	167-0	59	38	0
2	May 16 - 23	7	167-0	37	14	0
3	June 2 - 23	8	167-0	44	13	1
Total		23		140	65	1

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2008.

Appendix VII continued. Sampling dates, capture data, and effort for Desolation-Gray and lower Green River abundance estimation sampling for Colorado pikeminnow, 2008. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Desolation-Gray Canyon, Green River						
Pass 1	April 24 -May 2	8	396–206	61	32	0
2	May 4 - 13	8	396–206	54	27	0
3	May 12 - 21	8	396–206	50	33	1
Total		24		165	92	1
Lower Green River						
Pass 1	April 22 - 30	9	193-0	82	42	0
2	May 6 - 14	9	193-0	80	45	4
3	May 20 - 27	8	193-11	69	40	4
Total		26		231	127	8

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2008.

Appendix VIII. Sampling dates, capture data, and effort for middle Green River, Yampa River, White River, Desolation-Gray, and lower Green River abundance estimation sampling for Colorado pikeminnow, 2011. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours) [1]	Fyke net (hours)	Pikeminnow Captured [2]	Pikeminnow Recaptured [3]
Middle Green							
Pass 1	April 11 – May 3	14	537-396	58	0	28	0
2	May 4 - 12	6	537-396	53	0	39	0
3	May 16 - 31	5	537-399	50	0	37	4
Total		25		161	0	104	4
Yampa River							
Pass 1	April 26 - May 11	11	216-77	129	0	8	0
2	May 4 - 15	8	216-79	85	0	11	1
3[5]	May 12 - June 29	19	216-76	201	0	30	6
Total		39		423	0	49	7
White River							
Pass 1	April 5 - 14	6	167-39	57	0	25	0
2	April 19 - 27	6	167-39	50	0	16	0
3[4]	May 2 – 20	12	167-0	92	0	49	2
Total		24		199	0	90	2

Appendix VIII continued

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)[1]	Fyke net (hours)	Pikeminnow Captured [2]	Pikeminnow Recaptured [3]
Desolation-Gray							
Pass 1	March 30 – April	8	396-206	67	0	51	0
2	April 12 - 26	8	396-206	64	0	55	2
3	April 28 – May 10	8	396-208	58	0	59	5
Total		24		189	0	165	7
Lower Green							
Pass 1	April 15 – 23	9	193-0	81	0	158	0
2	May 4 – 12	9	193-0	80	0	111	10
3	May 23 - 31	9	193-2	74	0	73	12
Total		27		235	0	342	22

[1] Some reaches had additional effort and/or passes that were combined with one of the three standard sampling passes.
[2] All PIT tagged Colorado pikeminnow.
[3] Recaptured fish are those handled on previous sampling passes in 2011.
[4] Three passes were completed on the White River, RM24-0 during the what would be the 3rd pass to make up for the lack of sampling through this reach during pass 1 and 2, we couldn't use those passes in that manner so all of it was grouped into pass 3 with the results being a lot of effort within pass 3 and several within pass recaptures.
[5] Some fish were captured later than June 20 but 2011 was a high water year.

Appendix IX. Sampling dates, capture data, and effort for middle Green River, Yampa River, White River, Desolation-Gray, and lower Green River abundance estimation sampling for Colorado pikeminnow, 2012. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours) [1]	Fyke net (hours)	Pikeminnow Captured [2]	Pikeminnow Recaptured [3]
Middle Green River							
Pass 1	March 5 – April 24	25	538-396	89	1546	22	0
2	April 30 – May 7	5	538-396	45	0	15	0
3	May 8 - 17	5	538-396	46	0	14	0
Total		35		180	1546	51	0
Yampa River							
Pass 1	April 17 - May 8	12	216-77	114	0	2	0
2	May 7 - 20	12	216-78	134	0	1	0
3	May 15 - June 7	14	216-77	151	0	3	0
Total		38		399	0	6	0
White River							
Pass 1	April 9 – 20	6	166-40	51	0	22	0
2	April 23 – 26	4	167-40	54	0	24	3
3	April 27 – June 7	25	167-38	277	0	58	13
Total		35		382	0	104	16

Appendix IX continued

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)[1]	Fyke net (hours)	Pikeminnow Captured [2]	Pikeminnow Recaptured [3]
Desolation-Gray							
Pass 1	March 27 – April 10	8	396-207	68	0	39	0
2	April 10 – May 14	16	396-207	134	0	68	2
3	May 17 – May 27	7	396-207	62	0	48	2
Total		31		264	0	155	4
Lower Green River							
Pass 1	May 6 – 14	9	193-0	66	0	57	0
2	May 22 – 30	9	193-0	70	0	37	3
3	June 6 - 14	9	193-0	76	0	22	3
Total		27		212	0	116	6

[1] Some reaches had additional effort and/or passes that were combined with one of the three standard sampling passes.
[2] All PIT tagged Colorado pikeminnow.
[3] Recaptured fish are those handled on previous sampling passes in 2012.

Appendix X. Sampling dates, capture data, and effort for middle Green River, Yampa River, White River, Desolation-Gray, and lower Green River abundance estimation sampling for Colorado pikeminnow, 2013. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours) [1]	Fyke net (hours)	Pikeminnow Captured [2]	Pikeminnow Recaptured [3]
Middle Green							
Pass 1	April 16 - 23	6	536-396	45	0	6	0
2	April 29 - May 10	6	536-396	51	0	7	0
3	May 13 - June 19	13	538-396	109	0	39	1
Total		25		204	0	52	1
Yampa River							
Pass 1	April 17 - May 15	18	216-76	157	0	4	0
2	May 6 - 21	12	216-76	140	0	1	0
3	May 27 - June 12	11	216-76	133	0	2	0
Total		41		430	0	7	0
White River							
Pass 1	April 8 - 18	8	167-39	85	0	16	0
2	April 23 - May 15	11	167-40	79	0	14	1
3[4]	May 16 – June 26	22	167-0	264	0	42	3
Total		43		427	0	72	4

Appendix X continued

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)[1]	Fyke net (hours)	Pikeminnow Captured [2]	Pikeminnow Recaptured [3]
Desolation-Gray							
Pass 1	April 11 - 19	8	396-206	76	0	26	0
2	April 23 - 29	7	396-207	80	0	19	1
3	May 7 – June 10	9	396-207	81	0	30	3
Total		24		237	0	75	4
Lower Green							
Pass 1	April 20 - 28	9	193-0	86	0	5	0
2	May 7 - 15	9	193-0	56	0	11	0
3	May 23 - 31	9	193-0	86	0	15	0
Total		27		228	0	31	0

[1] Some reaches had additional effort and/or passes that were combined with one of the three standard sampling passes.
[2] All PIT tagged Colorado pikeminnow.
[3] Recaptured fish are those handled on previous sampling passes in 2013.
[4] Some fish were captured later than June 20.

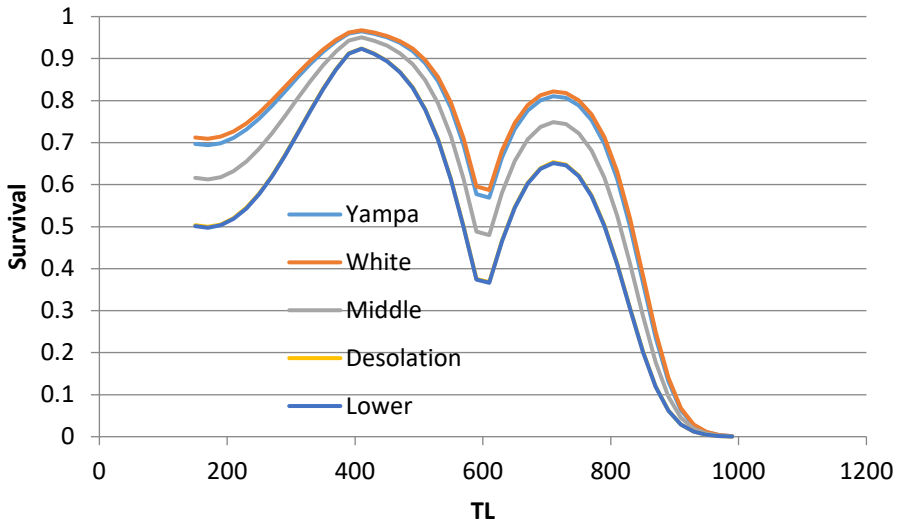
Appendix XI. Summary of abundance estimates for adult Colorado pikeminnow from Bestgen et al. (2010) and estimates updated for this report. Estimates from 2011-2013 are identical in each set of data. Differences reflect addition of fish to the data set, differences in analytical techniques, and declining capture probabilities over time, which affects estimates through time since data is borrowed to estimate capture probabilities over the duration of the study period.

Previous analysis, 2000-2013 estimates

Size Class	Year	Estimate	SE	LCI	UCI	CV	M(t+1)	LCLValues	UCLValues
	2000	3030	286.824	2467	3592	9.46721	910	563	562
>=450	2000	4093							
	2001	3303	206.074	2900	3707	6.23822	990	403	404
	2002	2771	282.689	2216	3325	10.2033	455	555	554
	2003	2142	232.705	1686	2598	10.8658	434	456	456
	2004								
	2005								
	2006	2454	319	1920	3185	12.9992	478	534	731
	2007	2718	404	2055	3656	14.8639	454	663	938
	2008	3672	828	2397	5715	22.549	279	1275	2043
	2009								
	2010								
	2011	2082.77	239.23	1674.11	2618.9	11.4862	364	409	536
	2012	1787.45	203.162	1440.11	2242.4	11.3661	319	347	455
	2013	2127.73	412.623	1471.53	3116.55	19.3927	177	656	989

Appendix XI continued.

Updated analysis, 2000-2013

Size Class	Year	Estimate	SE	LCI	UCI	CV	M(t+1)	LCLValues	UCLValues
	2000	3093.94	272.913	2621.42	3697.77	8.82088	921	473	604
>=450	2000	4088							
	2001	3697.52	218.274	3302.21	4159.98	5.90326	975	395	462
	2002	3675.88	332.81	3086.84	4396.86	9.05389	457	589	721
	2003	3130.84	268.047	2654.8	3709.62	8.56149	449	476	579
	2004			0	0			0	0
	2005			0	0			0	0
	2006	2542.37	304.663	2025.78	3229.96	11.9834	465	517	688
	2007	2339.17	208.097	1973.04	2792.57	8.8962	437	366	453
	2008	3000.41	362.989	2376.52	3809.17	12.098	271	624	809
	2009			0	0			0	0
	2010			0	0			0	0
	2011	2082.77	239.23	1674.11	2618.9	11.4862	364	409	536
	2012	1787.45	203.162	1440.11	2242.4	11.3661	319	347	455
	2013	2127.73	412.623	1471.53	3116.55	19.3927	177	656	989

Appendix XII. Survival of Colorado pikeminnow as a function of size, using the spline model, for each reach of river in the Green River system.