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Current status of natural spawning of chum salmon *Oncorhynchus keta* in rivers with or without hatchery stocking on the Japan Sea side of northern Honshu, Japan

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Abstract

Information on the status of natural spawning is needed on the Japan Sea side of northern Honshu, Japan for ecosystem-based sustainable management of chum salmon resources. We conducted on-site visual surveys in October–December of 2015 and 2016 that targeted spawning chum salmon redds in all rivers > 5 km long (total 94 rivers) in Akita, Yamagata, Niigata (including Sado Island), and Toyama prefectures. The ratio of rivers found to host natural reproduction to the total number of surveyed rivers was 93.6% (44/47) in stocked rivers and 74.5% (35/47) in non-stocked rivers. These results show that there is a wide occurrence of natural reproduction of chum salmon in these rivers, regardless of the history of hatchery stocking. The density of spawning redds (number of redds/1000 m^2) as an indicator of chum salmon escapements did not differ ($P = 0.54$) between stocked rivers (mean 3.5, $N = 49$) and non-stocked rivers (mean 2.4, $N = 36$),when rivers where no redds were observed were excluded from the analysis. These results suggest that chum salmon escapements into non-stocked rivers may not be negligible. Conservation measures for wild fish are needed in stocked and non-stocked rivers to promote enhancement programs based on natural reproduction.

Keywords Chum salmon · Natural spawning · Escapement · Wild fish · Hatchery program · Northern Honshu

Introduction

Hatchery programs involving the mass stocking of cultured fish have been conducted widely to increase fisheries harvests (Morita et al. 2006; Salvanes and Braithwaite 2006).

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The number of coastal captured Japanese chum salmon *Oncorhynchus keta* increased dramatically during the last quarter of the twentieth century following a drastic increase in the number of hatchery cultured fry stocked, coupled with the development of improved hatchery techniques (e.g., initiation of fry feeding and optimal release time) (Kaeriyama 1999; Kobayashi 1980). It has been generally accepted that most Japanese stocks of chum salmon have been sustained by hatchery programs (Hiroi 1998; Kaeriyama 1999; Kaeriyama and Edpalina 2004; Kobayashi 1980; Nogawa 2010), although the fraction of total catch that are hatchery fish has never been quantitatively estimated. Along this same line of thought, it has also been considered that chum salmon originating from natural spawning (i.e., wild fish) are a seldom occurrence in Japan (wild fish in this article are considered to be fish that have reproduced naturally for more than one generation, regardless of parental origin [hatchery fish or wild fish]; Morita and Ohkuma 2015). As a result, the primary aim of hatchery programs in Japan is to manage chum salmon resources, and little or no consideration has been given to the conservation of wild fish (Morita and Ohkuma 2015; Morita et al. 2006).

The total annual catch of chum salmon (i.e., coastal and river catch) on the Japan Sea side of northern Honshu (hereafter, JSSNH; Fig. 1) at the southern limit of the chum salmon distribution (Salo 1991) is 860,000, which is only 2% of that of Hokkaido (Fig. 1), the principal fishing ground of chum salmon in Japan (1999–2008 average; Fisheries Research Agency 2015). However, a conservation program (Tanegawa-no-sei) for wild chum salmon started in the mid-seventeenth century in the Miomote River, Niigata Prefecture (Kaeriyama and Edpalina 2004) recognized the importance of chum salmon on the JSSNH as a fishery resource (Takahashi et al. 2006).

Changing perspectives have made it necessary to change the management policy for chum salmon resources on the JSSNH. First, the role of hatchery programs has recently become controversial due to the negative impacts of hatchery programs on the fitness of stocked and wild fish and to increasing evidence of the potential for reducing genetic variation (Araki and Schmid 2010). The Japanese government has directed that salmonid enhancement programs (whereby enhancement refers stocking rivers with chum salmon fry reared in hatcheries) also consider the conservation of wild fish to conserve the ecosystem (Ministry of the Environment: http://www.biodic.go.jp/biodiversity/about/initiatives/; accessed 10 Dec 2015). Second, the future of operating hatcheries on the JSSNH has become tenuous because of funding shortages, coupled with an aging workforce (see Introduction in Iida et al. 2017). In fact, the number of hatchery chum salmon fry stocked in rivers on the JSSNH decreased from 186 million in 1998 to 150 million in 2010, whereas the number stocked in Hokkaido (one billion) and on the Pacific Sea side of northern Honshu (657 million) remained stable (Fisheries Research Agency 2015). Moreover, the number of hatcheries in Akita Prefecture (Fig. 1) decreased from 13 in 2010 to six in 2014 (Akita Prefectural Government, personal communication, 2015). It is necessary to maintain hatchery programs, but a new strategy is needed in which enhancement programs are implemented which are based on the natural reproduction of chum salmon for sustainable use of chum salmon resources in the JSSNH (Kaeriyama et al. 2012; Morita 2014; Morita and Ohkuma 2015; Nagata et al. 2012).

Information on the ecology of wild chum salmon spawning (e.g., location of spawning grounds) is critical for conservation of this resource (Gallagher et al. 2007; Miyakoshi et al. 2012; Nagata et al. 2012) because this information enables conservation measures to be implemented preferentially in rivers where chum salmon reproduce naturally. To this end it is necessary to confirm the existence of natural reproduction not only in rivers where chum salmon fry have been stocked, but also in rivers where chum salmon fry have never been stocked. However, although a few naturally spawning chum salmon have been observed in some rivers in the southwest region where the chum salmon population size is extremely small (Fujiwara et al. 1983; Kato 2007; Sakai et al. 2011), information on the distribution of naturally spawning populations in the JSSNH is extremely scarce. In addition, although it is critical to evaluate abundance for resource management (Nose et al. 1988), there is no information available on chum salmon abundance in non-enhanced rivers.

The objectives of this study were to provide baseline information on the spawning ecology of chum salmon in the JSSNH. We conducted on-site visual surveys targeting spawning redds in all rivers > 5 km long in Akita, Yamagata, Niigata (including Sado Island), and Toyama prefectures. In addition, the density of spawning redds, which is an index of chum salmon escapement, was compared between enhanced and non-enhanced rivers.

Materials and methods

Evaluation of the distribution of naturally spawning chum salmon

Chum salmon mainly run into rivers located north of Toyama Prefecture on the JSSNH (Fujiwara et al. 1983; Nogawa 1992). Chum salmon runs occur between October and January, with a peak in November–December (Saito et al. 2015). We conducted visual surveys in rivers in Akita, Yamagata, Niigata (including Sado Island), and Toyama prefectures between 8 October and 14 December 2015 and between 24 October and 21 December 2016 to assess the distribution of naturally spawning chum salmon (Fig. 1). We did not survey rivers in Aomori Prefecture (north of Akita Prefecture) due to a workforce shortage. Datasets on the lengths of rivers and watershed areas in the JSSNH were obtained from the prefectural governments of Akita, Yamagata, Niigata and Toyama. Missing data on watershed areas were determined using the planimetry function in the Q geographic information system (QGIS; version 2.4.0; http://www.qgis.org; accessed 2 Sept 2014), based on watershed boundary data obtained from National Land Numerical Information (http://nlftp.mlit.go.jp/ksj/index.html; accessed 25 Jan 2018). We targeted all rivers that were > 5 km long (except the Shimazaki River in Niigata Prefecture, the Hamo and Ogochi Rivers on Sado Island, and the Kamisho River in Toyama Prefecture) as water levels in smaller rivers may have been inadequate to allow upstream runs of chum salmon (Miyakoshi et al. 2012). Rivers < 5 km long were also surveyed if they had been enhanced by hatchery fish stocking in the past. Referring to Miyakoshi et al. (2012), we divided the surveyed rivers into three categories based on

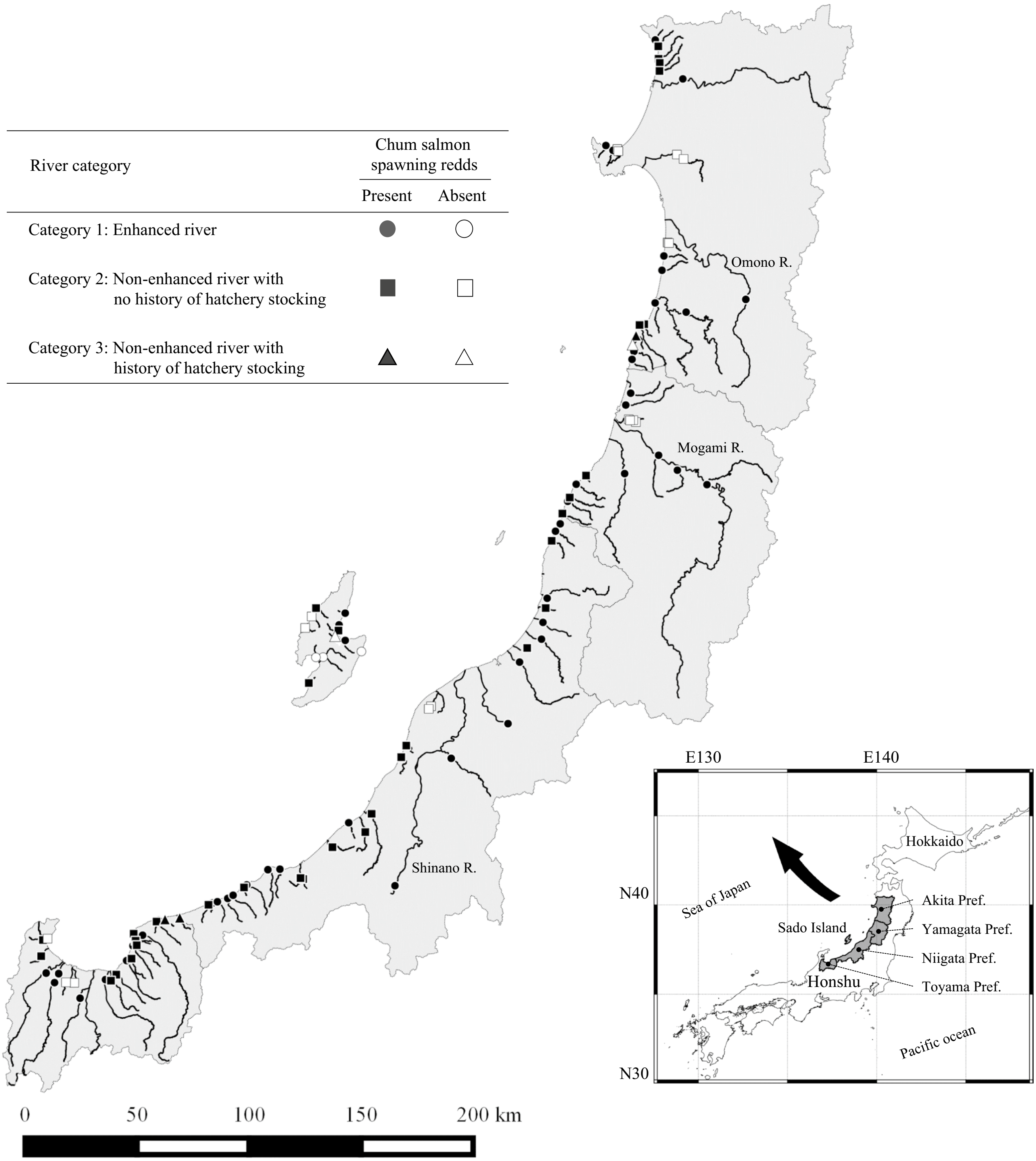

Fig. 1 Locations of the survey sites for detecting chum salmon (*Oncorhynchus keta*) spawning redds in Akita, Yamagata, Niigata (including Sado Island), and Toyama prefectures in 2015 and 2016. The river categories are classified by symbols (circles, squares, and triangles). Black lines with filled symbols and black lines with open symbols indicate rivers where chum salmon spawning redds were observed and not observed, respectively. Enhancement refers to rivers receiving chum salmon fry reared in hatcheries. Land symbols referenced in the text are shown on the map. Information on the location of hatcheries is available at the Hokkaido National Fisheries Research Institute homepage (http://salmon.fra.affrc.go.jp/zousyoku/mapH22/rvr_hty_map_h22.htm; accessed 16 Nov 2017)

the history of hatchery stocking (Fisheries Research Agency 2015): (1) rivers where chum salmon fry reared in hatcheries are stocked almost every year; (2) rivers where chum salmon fry have never been stocked; (3) rivers where chum salmon fry had been stocked in the past, but which are not currently stocked. Chum salmon have the ability to home (i.e., spawn in their natal rivers) (Salo 1991), and it is estimated that the straying rate of Japanese chum salmon averages 0.03% (Fukuzawa 2016). Thus, we assumed that a Category 1 river is one in which both hatchery and wild chum salmon spawn, and Category 2 and 3 rivers are those in which wild chum salmon that reproduce naturally at least more than one generation spawn. The median (range) watershed area was 107 km^2 (3–11,900 km^2; $N = 47$) in Category 1 rivers and 41 km^2 (5–1140 km^2, $N=47$) in Categories 2 and 3 rivers. Watersheds differed significantly between Category 1 rivers and Categories 2 and 3 rivers (Mann–Whitney U test, $P < 0.001$).

One to four survey reaches were established, mainly in the lower reaches, in each surveyed river. In rivers where a hatchery weir (i.e., screen to catch almost all returning adults for hatchery broodstock) (Kobayashi 1980) was installed, the survey reaches were established downstream from the weir or in a tributary flowing into the lower reach from the weir. In large-scale rivers, survey reaches were established in the middle or upper reaches because of the high discharge at lower reaches, which made on-site surveying difficult (Fig. 1). Chum salmon prefer spawning in a riverbed in which silt and fine sand are not dominant (Salo 1991). The survey reaches were established to avoid the river section containing a large amount of fine sediments. The length of the survey ranged from 25 to 2892 m. Because we made an effort to find at least one spawning redd, the median length of survey reaches in rivers where spawning redds were not observed (663 m; $N=23$) was significantly longer than that of rivers where spawning redds were observed (210 m; $N=85$) (Mann–Whitney U test, $P = 0.001$). Surveys were timed to avoid conditions of high water level and turbidity to enable clear observation of the riverbed. Chum salmon spawning redds and carcasses were counted visually in each survey reach by observers with polarizing sunglasses. Salmonids construct false redds that are abandoned before the eggs are deposited to test the suitability of a location (Gallagher et al. 2007). Thus, a site without the typical gravel-bed feature consisting of a mound and pit structure were regarded as “false redds” and were not counted. Spawning adults and carcasses of masu salmon *Oncorhynchus masou*, which spawn in the upstream areas of the main stem or tributaries in the JSSNH (Kato 1991), were not observed in any of the survey reaches; therefore, we regarded all spawning redds in our survey as those of chum salmon. Starting and ending locations of the surveys and locations where chum salmon redds were observed were recorded by mobile GPS (GPSMAP62SCJ; Garmin, Kansas City, KS, USA). All information on the locations was managed using the QGIS.

Assessment of spawning redd density in surveyed reaches

The number of spawning redds in a river is an indicator of chum salmon escapements in that river (Gallagher et al. 2007). The density of chum salmon spawning redds (number of redds/1000 m^2) was determined in each survey reach by dividing the number of spawning redds observed by the area of the river bed observed. The observed area was roughly obtained using the planimetry function in the QGIS, based on a satellite photograph of the surveyed river on which the starting and ending locations were marked. The density of chum salmon redds in the study reaches was compared between enhanced and non-enhanced rivers (i.e., Category 1 vs. Categories 2 and 3) to evaluate the population size of wild chum salmon in non-enhanced rivers. Rivers in which no redds were observed were excluded from the analysis. A generalized linear model (GLM) with a quasi-Poisson distribution (Kasuya 2012) was used in which the number of spawning redds observed was used as the response variable and the river category (enhanced rivers/non-enhanced rivers) was used as the explanatory variable. The GLM was offset by the observed area, which was log-transformed. The significance of the explanatory variable for predicting the response variable was determined by the F test (Kasuya 2012); statistical significance was accepted at $P < 0.05$. All statistical analyses were performed in R 3.4.3 (R Core Team 2017). Detailed information on the study reaches (e.g., latitude/longitude, observed area) are shown in Electronic Supplementary Material (ESM) 1.

Results

Existence of natural spawning chum salmon by river category

The ratio of surveyed rivers with observed chum salmon spawning redds to the total number of surveyed rivers was 93.6% (44/47) in Category 1 rivers, i.e., rivers where chum salmon fry reared in hatcheries are stocked every year, 76.2% (32/42) in Category 2 rivers, i.e., rivers where chum salmon fry have never been stocked, and 60% (3/5) in Category 3 rivers, i.e., rivers where chum salmon fry had been stocked, but are not currently stocked (Table 1). All three Category 1 rivers where chum salmon spawning redds were not observed were on Sado Island, and only 50% (3/6) of the Category 1 rivers had spawning redds (Fig. 1).

Table 1 Summary of the results of a visual survey to identify the presence of chum salmon spawning redds on the Japan Sea side of Northern Hoshu (including Sado Island), Japan in 2015 and 2016

River category[a]	Number of rivers surveyed	Number of rivers chum salmon redds present
1	47	44 (93.6)
2	42	32 (76.2)
3	5	3 (60)

Number in parentheses are percentages of rivers that had chum salmon redds

[a] Category 1, enhanced river; Category 2; non-enhanced river with no history of hatchery stocking; Category 3; non-enhanced river with history of hatchery stocking. Enhancement refers to rivers receiving chum salmon fry reared in hatcheries

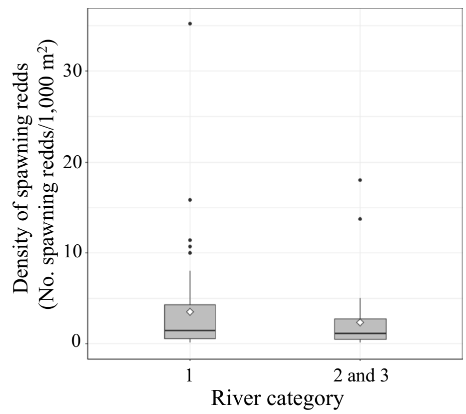

Fig. 2 Density of chum salmon spawning redds observed in the survey reaches (excluding reaches where no spawning redds were observed) in Category 1 (stocked rivers; $N=49$) and Categories 2 and 3 rivers (non-stocked rivers; $N=36$) in 2015–2016. Dark horizontal lines in boxes, diamonds and boxes depict the median, mean and interquartile range, respectively. Whiskers show the highest value within 1.5-fold the interquartile range beyond the 25th and 75th percentile. Circle indicates any value beyond the whiskers

Comparison of the density of spawning redds between enhanced and non-enhanced rivers

The median (range) length and area of the surveyed reaches where chum salmon spawning redds were observed were 201 (30–1292) m and 4567 (313–29,020) m^2, respectively, in Category 1 (enhanced) rivers and 233 (25–1400) m and 2785 (406–17,590) m^2, respectively, in Categories 2 and 3 (non-enhanced) rivers. The median length and area of the surveyed reaches were not significantly different between enhanced rivers and non-enhanced rivers (Mann–Whitney *U* test, $P=0.68$ in length, $P=0.22$ in area). When rivers in which no redds were observed were excluded from the analysis, the mean density of spawning redds (number of redds/1000 m^2) in surveyed reaches was 3.5 (range 0.1–35.2; $N=49$) in Category 1 (enhanced) rivers and 2.4 (range 0.1–18.0, $N=36$) in Categories 2 and 3 (non-enhanced) rivers (Fig. 2). The GLM did not detect significant effects of presence of hatchery programs on the density of spawning redds in the surveyed reaches ($F=0.37$, $P=0.54$). The number and density of spawning redds observed are shown in ESM 1.

Discussion

It is generally accepted that most Japanese stocks of chum salmon have been sustained by hatchery programs and that wild chum salmon in Japan are practically non-existent (Hiroi 1998; Kaeriyama 1999; Kaeriyama and Edpalina 2004; Kobayashi 1980; Nogawa 2010). Within this framework, the status of natural chum salmon spawning has been confirmed in Category 1 rivers, i.e., rivers where chum salmon fry reared in hatcheries are stocked every year (e.g., Miyakoshi et al. 2012). In our survey, chum salmon spawning redds were observed in almost all Category 1 rivers (44/47) surveyed in Akita, Yamagata, Niigata (including Sado Island), and Toyama prefectures (Fig. 1; Table 1), suggesting that the chum salmon stocks in Category 1 rivers may include both hatchery and wild fish. Using the mass mark and recapture method, Morita et al. (2013) recently estimated that the proportion of wild fish to total catch of chum salmon in Category 1 rivers in Hokkaido averaged 28.3% (Fig. 1); in contrast, the proportion of wild fish to total catch of chum salmon in Category 1 rivers in the JSSNH has remained unknown due to a lack of similar research in this area. However, unlike the situation in Hokkaido where hatchery weirs are installed at the river mouths to collect hatchery broodstock, small operations, such as casting net or hooking, which do not block the upstream migration of chum salmon, are used in approximately half the rivers from which hatchery broodstock are collected in the JSSNH (Miyamoto et al. 2009; M. Iida, unpublished data). Available space to spawn in Category 1 rivers in the JSSNH may be relatively large compared to that in Hokkaido, as evidenced by our observation of spawning redds in both the middle and upper reaches of Category 1 rivers without hatchery weirs installed at their river mouths (e.g., Omono, Mogami, and Shinano Rivers; Fig. 1). Similar to Hokkaido (Morita et al. 2013), the contribution of wild fish to the total catch of chum salmon in Category 1 rivers could be substantial in the JSSNH. It is therefore essential to obtain quantitative information on the contribution of wild fish to the chum salmon resource in the JSSNH and compare it to that of hatchery fish. In Japan, the importance of rivers as spawning and nursery habitats for salmonids has been disregarded relative to the progress in improved hatchery programs (Kaeriyama and Edpalina 2004). As a result, river management based on natural reproduction of salmonids is extremely rare (Mayama 1993). The scale of the hatchery programs in the JSSNH is expected to shrink because the number of chum salmon fry stocked will decrease due to management issues. It is therefore necessary to review the importance of rivers as a spawning habitat and to conduct conservation programs (described later in text) for wild chum salmon in Category 1 rivers for sustainable use of the chum salmon resource.

Our survey revealed that only 50% of the Category 1 rivers on Sado Island had spawning redds (Fig. 1). The number of chum salmon fry stocked annually per river on Sado Island averaged 49,000 (range 8000–270,000), which was much lower than that stocked (average 3.2 million, range 66,000 to 23 million) in Akita, Yamagata, Niigata, and Toyama prefectures (2008–2010 average; Fisheries Research Agency 2015). It was assumed that the size of chum salmon populations originating from Category 1 rivers on Sado Island was small, and this may be why the ratio of rivers with spawning redds observed was low.

Chum salmon spawning redds were observed in 74.5% (35/47) of surveyed non-enhanced rivers (Categories 2 and 3) (Table 1). Because Japanese chum salmon have a strong homing ability (Fukuzawa 2016), these results suggest that populations of natural-origin chum salmon are established in non-enhanced rivers. In the surveyed reaches where chum salmon spawning redds were observed, the median area (length) was not significantly different between enhanced and non-enhanced rivers. Similar research efforts were given to both enhanced and non-enhanced rivers. The median density of spawning redds did not differ between enhanced and non-enhanced rivers (Fig. 2). These results suggest that escapement of chum salmon in non-enhanced rivers may not be negligible. However, it is important to recognize the following limitation. Salmonid spawning redds are not uniformly distributed in a river but tend to concentrate in suitable sites, such as island heads (sandbank head) (Coulombe-Pontbriand and Lapointe 2004; Okamoto et al. 1993). If suitable sites for salmonid spawning were biased toward the survey reaches of either river division (enhanced river/non-enhanced river), there is a possibility that the density of spawning redds in the river division was overestimated. To preclude this possibility, it is necessary to evaluate the geomorphic forms of the survey reaches and to match the suitability of the spawning grounds between survey reaches in enhanced and non-enhanced rivers. The strategy of visually observing chum salmon spawning redds should be improved in the future. Determining the escapements of chum salmon in non-enhanced rivers is indispensable for managing the resource. However, the escapements of chum salmon have never been counted in non-enhanced rivers in the JSSNH. It will therefore be necessary to establish a system to monitor escapements of chum salmon (e.g., installing automatic fish counters) (Gonda et al. 2014) in the non-enhanced rivers in the future.

The results of this study show that natural reproduction of chum salmon widely exists in the sampled rivers regardless of their stocking history and that the size of chum salmon populations in non-enhanced rivers may be substantial. It is necessary to implement conservation measures for wild chum salmon (e.g., installing fishways [Nakamura and Komiyama 2010], improving the riverbed substrate [Merz and Setka 2004], and introducing river meandering [Nagata et al. 2002]) not only in enhanced rivers but also in non-enhanced rivers to promote enhancement programs based on natural reproduction. It will be essential to share information and establish a river management system across jurisdictions, such as fisheries, civil engineering, and forestry.

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