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Potential threat of introduced rainbow trout *Oncorhynchus mykiss* to native salmonids in the western part of Hokkaido, Japan

Genki Sahashi[1] · Kentaro Morita[2]

Abstract We obtained the following five results in 10 rivers while elucidating the potential threat of introduced rainbow trout to native salmonids. First, native salmonid density decreased with increasing trout density. Second, four environmental variables, namely altitude, distance from the sea, river width, and river depth, did not significantly affect trout density. Third, the distribution of trout expanded, and trout were the dominant species in an unconfined river. Fourth, the trout invasion has changed salmonid faunas over the last 20 years. Lastly, smolt trout were collected from a river. Therefore, the potential threat to native salmonids due to trout introduction is continuously increasing.

Keywords Exotic fish · Private stocking · Replacement · Salmonid fishes · Smolt

Introduction

Rainbow trout, *Oncorhynchus mykiss*, is the most widely introduced salmonid fish species worldwide (Welcomme 1992); however, the introduction of rainbow trout negatively affects native species and ecosystems (e.g., Dunham

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et al. 2004; Fausch 2007). The introduction of rainbow trout has also additionally occurred widely in Japan (Kitano 2004), and thus a number of studies have reported on natural reproduction and establishment of rainbow trout (e.g., Hokkaido, Aoyama et al. 1999; Nara, Kato and Yanagawa 2000). In Japan, rainbow trout is included in the top 100 of the worst invasive alien species in Japan (Murakami and Washitani 2002) and has been given a rank of "A2" in the Hokkaido Blue List (Hokkaido 2010). On Hokkaido Island, where the impact of rainbow trout on native species is a concern, the private stocking of rainbow trout is believed to be a major cause of their recent expansion. However, few studies have described the current status of the privately stocked rivers and the potential threat posed by privately stocked rainbow trout to native salmonids.

Several studies have examined the regulated factors for the establishment of trout and the interspecific relationship between the trout and native salmonids (Taniguchi et al. 2000; Fausch et al. 2001; Taniguchi et al. 2002; Inoue et al. 2009). Additionally, previous studies have suggested that the density of rainbow trout is affected by several environmental factors, such as flow disturbance, flow variability, altitude, and river gradient (Fausch et al. 2001; Inoue et al. 2009; Kitanishi et al. 2010). However, ecological information for the established rainbow trout population is still scarce to establish an adequate measure of rainbow trout management.

In this study, we examined the following four points to elucidate the potential threat posed by the introduced rainbow trout to native salmonids in 10 rivers in which rainbow trout had been privately stocked: 1) the effect of the density of rainbow trout on the density of native salmonids, 2) the effect of four environmental variables on the density of rainbow trout, 3) the longitudinal distribution of

salmonid fishes, and 4) a comparison of the status of salmonid fauna between previous and present years. Our objective was to sound the alarm on the private stocking of rainbow trout by describing the current status of the privately stocked rivers.

Materials and methods

Study area. The present study was conducted in 10 rivers, where information of the inhabitation status of rainbow trout was obtained in advance, on 12-28 May 2015 (Fig. 1a). In the studied rivers, rainbow trout stocking had
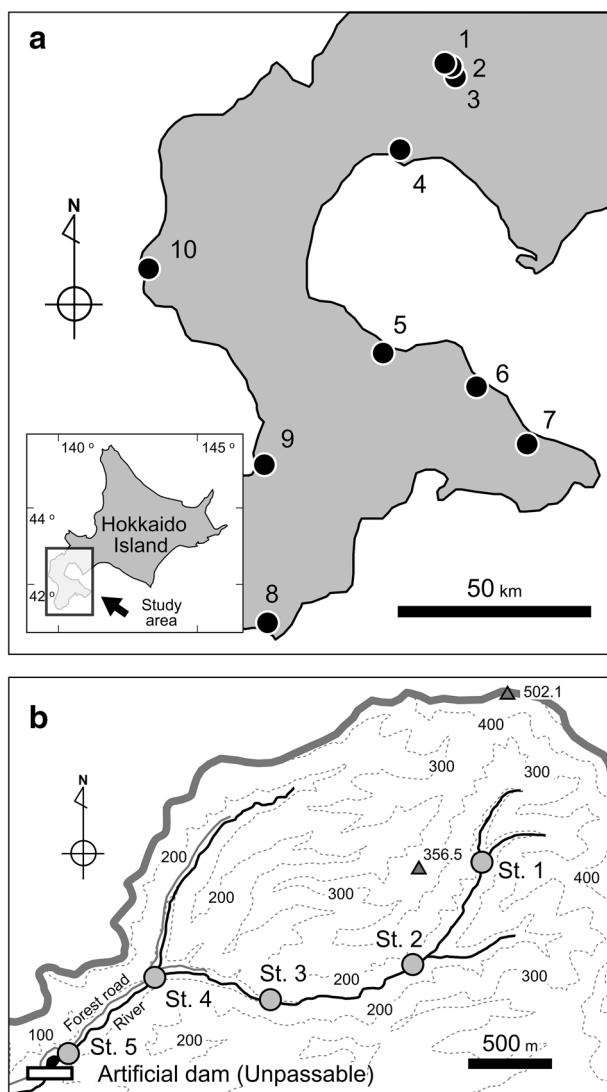
Fig. 1 a Study rivers at the southern part of Hokkaido, Japan. The Todo River is labeled as River 9. The names of the other rivers are given in Table 1. **b** Study stations along the Todo River. *Dotted lines* show contours and *bold gray line* shows boundary lines of the watershed. Densities of rainbow trout and native salmonids, and associated environmental variables are described in Table 1 and ESM Table S1

never been conducted by public institutions. To estimate the density of fish and to measure environmental variables, study stations were established in each river (reach length of the station: 40 m; number of the stations in each river: two to five; distance between the stations: $\geq$300 m; [Electronic Supplementary Material (ESM) Table S1]. In the river 2, 4, 5, 6, 9, and 10, impassable physical barrier (i.e., natural waterfall or erosion control dam) exists below the study stations, thus salmonid fishes cannot access the study stations from the mainstream and sea. The erosion control dams do not have reservoirs. In the Todo River, we established five study stations to investigate the longitudinal distribution of salmonid fishes (Fig. 1b). An impassable artificial dam exists below the study stations located at the Todo River (Fig. 1b); however, no physical barriers for fish migration or extreme water temperature gradient between the study stations existed.

Sampling of fishes. The fishes were sampled using an electrofisher (200–300 V DC, model 12B Smith-Root, Inc., Vancouver, Washington, USA) with a dip net (30 cm in width, 3-mm mesh). The densities of the rainbow trout and native salmonids (i.e., white-spotted charr *Salvelinus leucomaenis*, Dolly Varden charr *Salvelinus malma*, and masu salmon *Oncorhynchus masou*) at each station were estimated using the two-pass removal method (model M(b), program CAPTURE, available at http://www.mbr-pwrc.usgs.gov/software/index.html). In certain rivers, 0+ juveniles of the white-spotted charr and masu salmon were collected; however, they were excluded from density estimation because quantitative collection is difficult for the 0+ juveniles during spring due to their small body size.

Measurement of environmental variables. To investigate the effects of environmental variables on the densities of rainbow trout, we measured the following four environmental variables as indices of environmental conditions for each station: altitude, distance from the sea, river width, and river depth (Table S1). The environmental variables were selected to evaluate the effect of study site location in a river system and its environmental suitability on the densities of rainbow trout. The altitude was measured for each station using a portable GPS receiver (GPSMAP62SJ, Garmin, Olathe, KS, USA). The distance from the sea was measured for each station using the GPS receiver and 1:25,000 scale topographic maps (http://www.gsi.go.jp/). River width was measured at 5-m intervals at each study station. River depth was measured at 5-m intervals with three evenly spaced transects (1/4, 1/2, and 3/4 of the river width).

Data analyses. To test the effect of density of rainbow trout on the density of native salmonids, we used a linear mixed model (LMM). In the LMM, the density of native

Table 1 The number of samples, density of rainbow trout and native salmonids, and the proportion of trout at 24 study stations (40-m long) in 10 rivers

No	River	Date	St. No.	Rainbow trout (n)	Native salmonids (n)	Density of the trout (no. m^{-2})	Density of native salmonids (no. m^{-2})	Proportion of trout (%)
1	Daini-Kashunbetsu (Makkari)	2015/5/28	St. 1	8	23	0.078	0.225	25.8
			St. 2	16	13	0.164	0.143	53.3
2	Daiichi-Kashunbetsu (Makkari)	2015/5/28	St. 1	0	10	0.000	0.160	0.0
			St. 2	32	3	0.278	0.026	91.4
			St. 3	46	0	0.500	0.000	100.0
3	Mohanrin (Makkari)	2015/5/28	St. 1	11	25	0.121	0.274	30.6
			St. 2	7	10	0.075	0.107	41.2
4	Rebunge	2015/5/12	St. 1	54	0	0.293	0.000	100.0
			St. 2	15	0	0.094	0.000	100.0
5	Katsura	2015/5/12	St. 1	22	9	0.089	0.033	72.7
			St. 2	21	6	0.092	0.026	77.8
6	Shikabe	2015/5/19	St. 1	25	0	0.142	0.000	100.0
			St. 2	24	5	0.140	0.029	82.8
7	Kakkumi	2015/5/19	St. 1	10	25	0.054	0.135	28.6
			St. 2	37	21	0.199	0.087	69.6
8	Komatazawa (Oyobe)	2015/5/20	St. 1	3	18	0.018	0.128	12.5
			St. 2	8	13	0.058	0.094	38.1
9	Todo	2015/5/21	St. 1	9	3	0.137	0.046	75.0
			St. 2	17	2	0.179	0.021	89.5
			St. 3	9	0	0.095	0.000	100.0
			St. 4	55	4	0.364	0.026	93.2
			St. 5	56	1	0.291	0.005	98.3
10	Raruishi	2015/5/13	St. 1	17	0	0.173	0.000	100.0
			St. 2	43	0	0.365	0.000	100.0

salmonids was treated as a response variable, the density of rainbow trout was treated as an explanatory variable, and the river was treated as a random intercept. We additionally used an LMM to test the effect of the environmental variables on the density of rainbow trout. The density of rainbow trout was treated as a response variable, the environmental variables (i.e., altitude, distance from the sea, river width, or river depth) were treated as explanatory variables, and the river was treated as a random intercept in the LMM. The significance of the explanatory variables in the LMMs was evaluated using the F test. All statistical analyses were performed using RStudio Version 0.98.1103.

Results

A total of 545 rainbow trout and 191 native salmonid individuals (i.e., white-spotted charr, Dolly Varden charr, and masu salmon) were collected in the study stations (Table 1). Most of the sampled rainbow trout were mature fish or

immature parr; however, two fishes, which were collected at the Rebunge River, were identified as smolts (ESM Fig. S1). The smolts were classified at the smolt stage of pre-seaward migration, during which body color is silver and the color of the tip of the dorsal fin is black (ESM Fig. S1). Rainbow trout were collected at all but one of the study sites (i.e., 23/24), whereas native salmonids were not identified at approximately 29 % of the study sites (i.e., 7/24) (Table 1).

The density of native salmonids significantly decreased with increasing density of rainbow trout ($F = 6.033$, $P = 0.026$; Fig. 2). All of the four environmental variables showed no significant relationship with the density of rainbow trout (altitude: $F = 1.317$, $P = 0.283$; distance, $F = 0.214$, $P = 0.655$; width: $F = 1.970$, $P = 0.177$; depth: $F = 0.751$, $P = 0.397$).

The proportions of rainbow trout in the fish assemblage were higher than 75 % at all five study stations along the Todo River (Table 1). In the river, native salmonids were not the dominant species, even at the upstream study stations (Table 1).
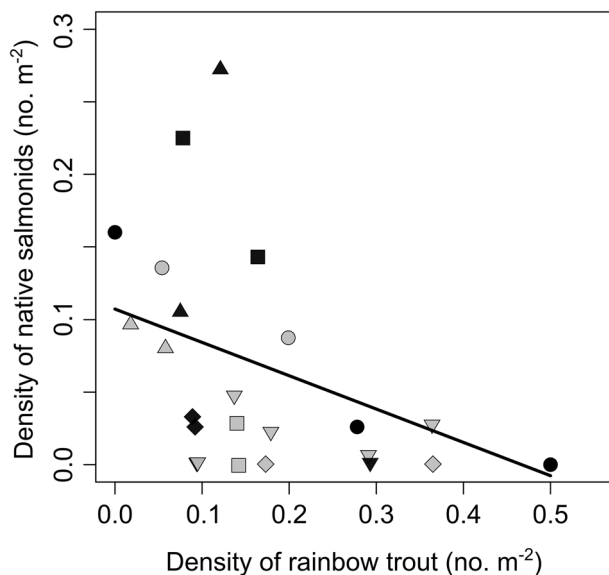
Fig. 2 Relationship between the density of rainbow trout and native salmonids at 24 study stations in 10 rivers. Each symbol represents a river: *black square* River 1; *black circle* River 2; *black triangle* River 3; *black inverted triangle* River 4, *black diamond* River 5; *gray square* River 6; *gray circle* River 7; *gray triangle* River 8; *gray inverted triangle* River 9; *gray diamond* River 10

Considering the results of the present study (Table 1) with the references to previous results of salmonid fauna (ESM Supplement A), rainbow trout invaded the Komatazawa and Todo rivers in the last 20 years. The native salmonid faunas at the Todo and Raruishi rivers have experienced a considerable change from the dominance by native salmonids to dominance by rainbow trout (Table 1, ESM Supplement A). In particular, this change in the Todo River has occurred in the last 20 years.

Discussion

In the present study, the density of native salmonids decreased with increasing density of rainbow trout. Previous studies have similarly shown that the abundance of native salmonids decrease with increasing density of rainbow trout (Morita et al. 2004; Baxter et al. 2007; Inoue et al. 2009). Rainbow trout are competitively superior to white-spotted charr (Hasegawa et al. 2004) and induce interspecific competition between sympatric native salmonids, white-spotted charr, and masu salmon (Hasegawa and Maekawa 2006). The introduction of rainbow trout induces an appreciable reduction of terrestrial prey in the diet and growth of native Dolly Varden charr (Baxter et al. 2007). Therefore, the density of native salmonids might be decreased through interspecific competition between the native salmonids and rainbow trout.

The present study examined the relationship between four environmental factors and the density of rainbow trout to assess the effect of study site location within a river system and the environmental suitability of the study site. In particular, rainbow trout occupy locations that have deeper water and are closer to cover than are masu salmon (Inoue et al. 2009). Thus, the river depth and width may affect the rainbow trout density. However, our results illustrated that the density of rainbow trout was not significantly related to the four environmental variables, implying that the invasion and presence of rainbow trout are not affected by the four environmental variables. However, caution is needed when interpreting our results, because the effect of other environmental factors on the density of rainbow trout was not controlled by the study. For example, the unconsidered factors, such as food availability and the number of visual barriers, may affect the density of rainbow trout by altering inter- or intra-specific competition. Thus, further studies should independently evaluate the effect of the four environmental factors on rainbow trout density.

A number of previous studies have shown that longitudinal variation in the distribution of native and exotic salmonids and, in many cases, the abundance of native salmonids increases from downstream to upstream (e.g., Dunham et al. 2002; Morita et al. 2004; Baxter et al. 2007). However, in the present study, rainbow trout were widely distributed in a single river and native salmonids were not the dominant species, even at the upstream study stations. In upstream river reaches where native salmonids have become the dominant species, physical barriers or a water temperature gradient are the critical factors limiting the upstream invasion of exotic salmonids (e.g., Dunham et al. 2002). However, in the present study, both of these factors would not have affected the distribution of rainbow trout, since physical barriers and an extreme temperature gradient are not present in the Todo River. Thus, the present study suggests that the effect of an expansion of rainbow trout distribution in a river occurs when physical barriers or a temperature gradient is absent.

In Hokkaido, the distribution of rainbow trout has increased widely from 1970 to 2012 (1970, five river systems; 1996, 72 systems; 2012, more than 120 systems) (Takami and Aoyama 1999; Shimoda 2012). In addition, at our study sites, rainbow trout have been recently introduced in at least two rivers in the last 20 years. In particular, the invasion by upstream migration by rainbow trout in the Todo River is thought to be impossible due to the unpassable dam that was constructed at the lower reach. Thus, the extension of the distribution of rainbow trout would only be continued by private stocking. Moreover, the current study showed that the invasion of rainbow trout has largely changed the salmonid fauna in the last 20 years. Nagasawa et al. (2009) showed that the proportion of native salmonids in the Shoro River system has decreased

in conjunction with the invasion of rainbow trout over the last 30 years. Thus, the invasion of rainbow trout would rapidly change salmonid faunas in the river.

Not only resident rainbow trout, but also outmigrating smolt fish were collected at the studied river. A part of the rainbow trout (i.e., steelhead) population exhibits partial migration in which anadromous fish undergo marine migration and complete their life cycle in freshwater (Kendall et al. 2015). The alternative migratory tactics of the partial migration have been reported in an introduced population (Pascual et al. 2001). However, in Japan, most previous studies focused on resident populations of rainbow trout in streams, and no studies have reported on the presence of rainbow trout smolt. Even if the smolting rate is low, smolts often emerge above the migration barrier (e.g., Morita et al. 2000). Similarly, a rainbow trout population keeps the potential of smolt emergence even after 100 years of isolation above an unpassable waterfall (Phillis et al. 2016). Our result suggests that introduced rainbow trout populations in Japanese rivers have the potential to produce anadromous fish, and this potential has been retained in populations confined above physical barriers. Thus, further studies are required to examine the existence of anadromous fish in Japanese rivers to precisely quantify the potential threat posed by introduced rainbow trout.

In conclusion, the private stocking of rainbow trout has been continued in the rivers of Japan to this day, and salmonid faunas have consequently undergone rapid changes in these sites. Currently in Japan, there is no legal control applied to rainbow trout stocking, and thus the establishment of a legal control or a license system is urgently required for the management of rainbow trout.

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