Ecological Impacts of Rainbow, Brown and Brook Trout in Japanese Inland Waters

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Abstract

Rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*) and brook trout (*Salvelinus fontinalis*) introduced to Japanese inland waters have significant impacts on native aquatic organisms such as white-spotted charr (*Salvelinus leucomaenis*), Dolly Varden charr (*Salvelinus malma*), masu salmon (*Oncorhynchus masou*) and Sakhalin taimen (*Hucho perri*), in coldwater habitats. Rainbow and brown trout have successfully established reproducing populations in Japan, and especially expanding their distribution in Hokkaido. Brook trout have shown relatively limited invasion in some spring-fed streams and ponds both in Honshu and Hokkaido. The introduced exotic trout have been implicated in reducing populations of native fishes, especially stream salmonids, through predation, competitive interaction for resources, and interspecific hybridization. Monitoring, management, including eradication, and evaluation of the effectiveness of these measures should be carried out to contain the ecological risks of trout invasion.

Key words: brook trout, brown trout, competition, hybridization, non-native species, predation, rainbow trout

1. Introduction

Invasion by non-native species is a serious threat to the conservation of freshwater ecosystems (Fuller *et al.,* 1999; Rahel, 2002). Of the non-native species invading aquatic ecosystems, salmonid fishes (subfamily salmoninae: genera *Oncorhynchus, Salmo* and *Salvelinus*) are among the globally most widespread taxa (Welcomme, 1988). Many species of salmonids have been introduced for recreational and commercial purposes to regions throughout the world where they did not occur naturally, with little regard to the effects on native species (Fausch, 1988). In most cases, salmonid introductions have been widely implicated in declines of native biota (*e.g.,* Polhemus, 1993; Lassuy, 1995). In northern hemisphere freshwater ecosystems, such as in North America and Europe, which generally support one or more native salmonids, the potential for impact of non-native salmonids on native species are widely reported (*e.g.,* Allendorf & Leary, 1988; Behnke, 1992). Because non-native salmonids are biologically similar to native salmonids, there is evidence of strong interspecific interactions for resources (Fausch, 1988) and hybridization (Leary *et al.,* 1995). Also in the southern hemisphere, such as New Zealand and Australia, where no native salmonids naturally occur, impact of introduced salmonids on native fish and invertebrates is widely recognized (*e.g.,* Townsend, 1996; Moyle & Light, 1996).

By the early 1990s, three salmonids, rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*) and brook trout (*Salvelinus fontinalis*), were among 12 fish species introduced to more than 30 countries (Welcomme, 1992). The former two salmonids are the species with the biggest impact on biological diversity, being listed in '100 of the World's Worst Invasive Alien Species' by the IUCN (2000). Rainbow trout, whose native range stretches along the Pacific coast of North America and the Kamchatka Peninsula, have been introduced to 87 countries worldwide (Welcomme, 1992) and all U.S. states outside their native range (Fuller *et al.,* 1999), primarily to establish populations for recreational angling. Establishment of reproducing populations was highly successful in the Southern Appalachians of North America, moderately successful in the Central Rocky Mountains of North America, the Andes Mountains in South America, as well as in New Zealand and northern Japan, but failed in Scandinavia and central Europe (Fausch *et al.,* 2001). The rainbow trout hybridized with other, more rare trout species, such as inland cutthroat trout (*Oncorhynchus clarki*), thereby affecting their genetic integrity (*e.g.,* Allendorf & Leary, 1988;

Weigel *et al.,* 2003). Stocking of hatchery rainbow trout in rivers has led to introduction of whirling disease into open waters in some parts of the United States (Fuller *et al.,* 1999). Brown trout have a large native range that encompasses the natural boundaries of Europe, extending south to North Africa and east to the Ural Mountains and the Caspian Sea (Elliott, 1994). The earliest known introduction beyond its native range was made in Tasmania and New Zealand in the 1860s (MacCrimmon & Marshall, 1968). They have been implicated in extirpating an endemic grayling *Prototroctes oxyrhynchus* in New Zealand (MacDowall, 1990) and in reducing native salmonid populations, through predation, displacement, and food competition in North America (Taylor *et al.,* 1984). Brook trout are native to northeastern North America, but have become one of the most widespread non-native salmonid species in western North America (Dunham *et al.,* 2002) and have been introduced worldwide as a popular sport fish (Scott & Crossman, 1973). Introduced brook trout have replaced native cutthroat trout and golden trout (*Oncorhynchus aquabonita*) in some streams in western North America (Moyle, 1976; Behnke, 1992). Hybridization between native bull trout (*Salvelinus confluentus*) and introduced brook trout is widespread in North America (Howell & Buchanan, 1992; Leary *et al.,* 1993).

Numerous studies have investigated the impact of introduced trout on native biota (reviewed by Fausch, 1988; Moyle & Light, 1996; Townsend, 1996; Dunham, 2002). However, most studies have been conducted only in a few regions, primarily North America, Australia and New Zealand. Studies of other geographical regions with different biotic and abiotic conditions are needed for a general understanding of the impact of introduced trout.

In Japan, translocations of non-native salmonid fishes from overseas began in the late 1800s for utilization as commercial or recreational fishery resources (Yuma *et al.,* 1998). Rainbow and brook trout were first introduced into Japanese waters in 1877 (Kawanabe, 1980; EAGJ, 1982), and brown trout were introduced in 1892 (Elliott, 1989). Since 1926, when regulations for salmon and trout enhancement came into enforcement by the Japanese government, substantial efforts were put into importation and hatching of their fry, and this has continued until recent years (EAGJ, 1982). For instance, a total of more than 10^6 eggs of rainbow trout were imported from the United States from 1877 to 1934 (Maruyama *et al.,* 1987). A large number of fry, juveniles and adults were introduced each year for decades, or escaped from fish hatcheries into Japan's waters. Production and distribution of eggs or fry of rainbow, brown and brook trout by trout hatcheries still continue throughout Japan (Maruyama *et al.,* 1987). Since these intensive introductions have resulted in the establishment of reproducing populations in Japanese inland waters, concerns have emerged about the impact of introduced trout on native biota involving endemic Asian salmonids such as masu salmon (*Oncorhynchus masou*), white-spotted charr (*Salvelinus leucomaenis*) and Sakhalin taimen (*Hucho perri*), stream communities and ecosystems.

In this paper, I begin by reviewing the patterns and causes of invasion of the three trout species, and the potential impact of exotic trout on native fauna. Following this review, I offer suggestions for managing the risk of exotic trout invasion and its impact on Japanese inland waters.

2. Invasion of Rainbow Trout

There are records of rainbow trout occurrence from Kyushu, Shikoku, Honshu and Hokkaido (Fig. 1(a)). Donor stocks of rainbow trout introduced from North America to Japan are of mixed lineage, including stream resident and anadromous races, and hatchery and wild stocks (*e.g.,* various strains by the name of Donaldson, Westalian and Steelhead trout are included: Maruyama *et al.,* 1987; Fausch *et al.,* 2001). Rainbow trout were first introduced to Honshu, but this resulted mostly in failure (Kawanabe, 1980; Fausch *et al.,* 2001), despite frequent stocking in many locations by commercial fishermen's unions and by the public during the last 50 years (*e.g.,* 20×10^6 juveniles in 1988; see Yuma *et al.,* 1998). Evidence of only a few cases of natural reproduction have been obtained in habitats in cold lakes with inlet systems or cold low gradient streams in Honshu (Kato, 1985; Nakamura & Maruyama, 1994; Kitano *et al.,* 2003). Limited invasiveness presumed attributable to high angling pressure, bird predation at the time of release, high water temperatures and/or flood disturbance at the time of fry emergence (Kawanabe, 1980). In contrast, the rainbow trout invasion of the island of Hokkaido was a significant success (Fausch *et al.,* 2001), with records of occurrences gradually increaseing since 1970, ultimately resulting in a distribution of 72 sites, including every major river system, by 1996 (Takami & Aoyama, 1999). Most of these populations appear to be self-sustaining (Aoyama *et al.,* 1999b; Taniguchi *et al.,* 2000). Rainbow trout attain sexual maturity at 11 to 37 cm FL (fork length) at ages of 1 to 5^+ in males and 17 to 33 cm FL at ages 2 to 4^+ in females in spring-fed streams in Hokkaido (Kitano *et al.,* 1993). Rainbow trout typically spawn in late winter and early spring, the date varying among populations. In Hokkaido, they spawn from April to June (range of water temperature 5 to 12°C: Aoyama *et al.,* 1999b) in upper Shiribetsu River, but from January to April in Horonai Creek (4 to 10°C: see Kitano *et al.,* 1993; Taniguchi *et al.,* 2000). In central Honshu, spawning takes place in April to June in the upper Shinano River (Kitano *et al.,* 2003) and in Lake Nozori (Nakamura & Maruyama, 1994), but in December in the upper Tama River system (Kato, 1985).

Rainbow trout prey primarily upon aquatic and terrestrial invertebrates, but eggs and larvae of the native river sculpin (*Cottus nozawae*) constitute 10% of their diet in Horonai Creek, Hokkaido (Kitano *et al.,* 1993). They also prey on the eggs and fry of chum salmon (*Oncorhynchus keta*), the fry of masu salmon (*O. masou*) and, on rare occasions, voles in streams in Hokkaido (Hikita *et al.,* 1959; Taniguchi *et al.,* 2002).

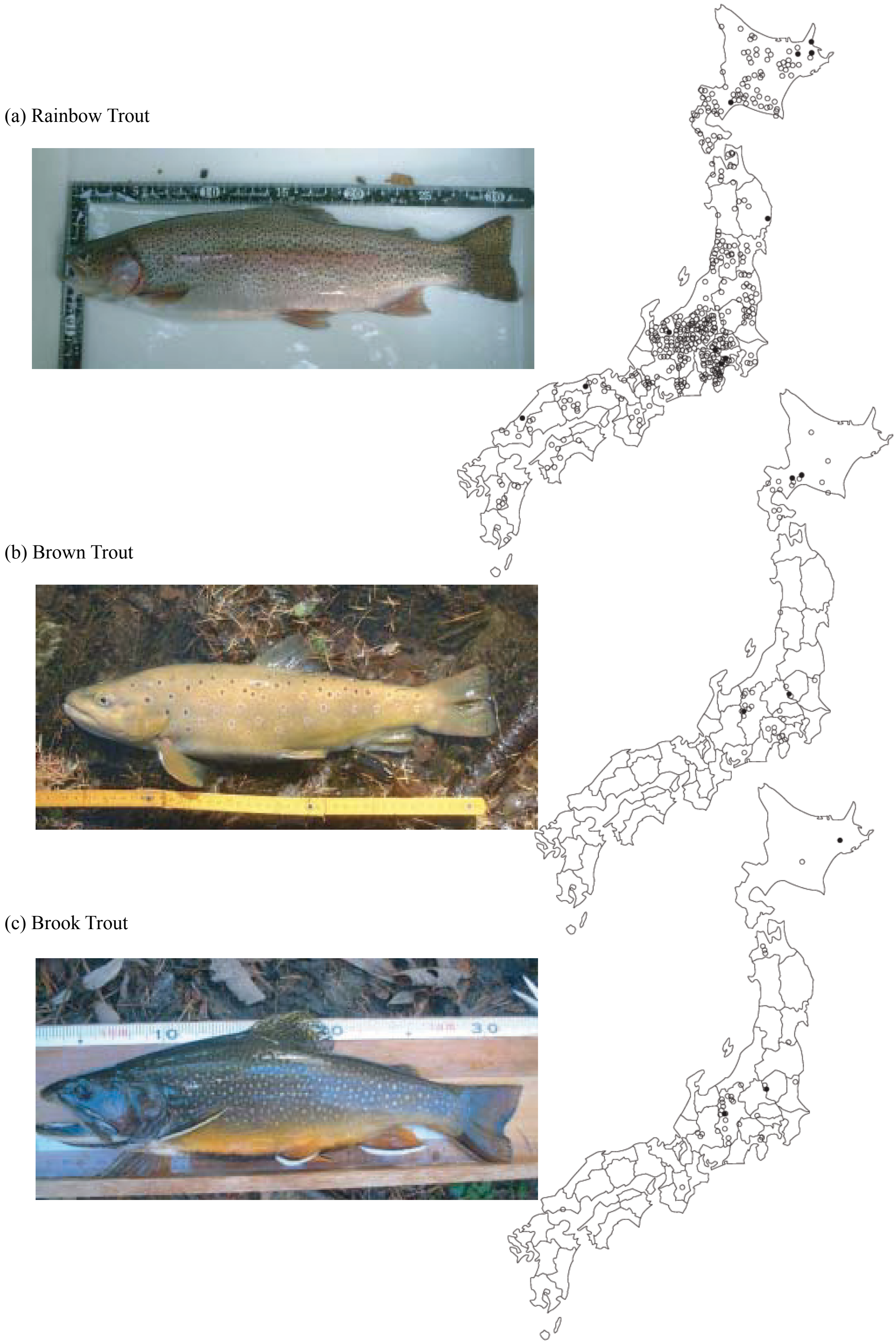

Fig. 1 Recorded location of occurrence (open circles) and natural reproduction (solid circles) of introduced (a) rainbow trout, brown trout (b) and brook trout (c). Occurrence data were obtained from the MEGJ (2002) survey largely conducted from1960 to 2000. See text for reports of natural reproduction by introduced trout.

The fry of white-spotted charr (*S. leucomaenis*) were also found in the diet of trout in the Honshu stream (Kitano *et al.,* 2003). Rainbow trout occupy undercut banks that native fish normally use for refuge (Kitano *et al.,* 1993; Urabe & Nakano, 1998), and may be displacing native fish from preferred microhabitats and pushing them into open water, making them vulnerable to predation. Larger rainbow trout dominate smaller masu salmon by aggressive interference, relegating them to less favorable foraging positions downstream and reducing their foraging frequency and growth in an experimental stream channel (Taniguchi *et al.*, 2002). The trout have been implicated in reducing native Dolly Varden charr (*Salvelinus malma*) on the Shiretoko Peninsula (Morita *et al.,* 2003). Because habitat conditions of spawning sites are quite similar among salmonid fishes (i.e., gravel beds in shallows), competition for spawning space may occur between rainbow trout and native salmonids. Spring-spawning rainbow trout reduce survival of eggs and alevins of fall-spawning salmonids (white-spotted charr and Dolly Varden charr) by dislodging the spawning redds (Taniguchi *et al.,* 2000). They may potentially superimpose on the redds of the endangered Sakhalin taimen (*Hucho perryi*) as an earlier spring-spawner in Shiribetsu River, Hokkaido (Aoyama *et al.,* 1999b).

3. Invasion of Brown Trout

Brown trout were first introduced into Japan from the United States, together with the eggs of rainbow and brook trout in the late 1800s (Maruyama *et al.,* 1987). Recently brown trout are distributed in Honshu and Hokkaido (Fig. 1(b)). Natural reproduction has been reported in upper Azusa Creek (EAGJ, 1982) and in the inlets of Lake Chuzenji (Wakabayashi *et al.,* 2002, 2003) in central Japan, and also in Lake Shikotsu and its outlet stream in Hokkaido (Kaeriyama, 2002; Aoyama *et al.*, 2002), but is not evident for most stocks in Japan. In Hokkaido, the release of brown trout by sport anglers has caused a rapid increase in records of occurrences since 1980, ultimately reaching 48 sites distributed in 36 river systems (Takami & Aoyama, 1999; Kaeriyama, 2002). In addition, the trout may extend their distribution by means of sea-run migration (anadromous form) in Hokkaido (Aoyama *et al.,* 1999a; Arai *et al.,* 2002; Morita *et al.,* 2003). Like other salmonids, brown trout stocked in inlet-lake systems have fluvial-lacustrine (lake-run form) life histories (Misawa *et al.,* 2001; Wakabayashi *et al.,* 2002). The trout have been known to grow to over 1 m in length and to live up to 18 years (McGinnis, 1984). The maximum total length is 84 cm in Lake Shikotsu (Takayama *et al.,* 2002) and 70 cm in Lake Chuzenji (Wakabayashi *et al.,* 2002). The trout attain sexual maturity at 12 to 36 cm FL (ages 1 to 3^+) in males and 20 to 38 cm FL (ages 2 to 4^+) in females in a Hokkaido stream, with a growth pattern similar to that in its native region (Aoyama *et al.,* 2002). Spawning takes place during mid-October to December in inlets of Lake Chuzenji (Wakabayashi *et al.,* 2002) and during December to January in inlets of Lake Shikotsu (Kaeriyama, 2002).

Brown trout have displaced native white-spotted charr in a tributary of the upper Ishikari River in Hokkaido over the last 15 years (Takami *et al.,* 2002). The trout have been implicated in reducing the abundance of native goby (*Rhinogobius* sp. OR) in the shallow areas of Lake Shikotsu during the last decade (Takayama *et al.,* 2002). In Lake Chuzenji, originally a fish-less lake, brown trout prey upon aquatic invertebrates in spring, terrestrial insects in summer, and fish (Salmonidae, Cyprinidae and Gobiidae) throughout the year (Shiraishi & Tanaka, 1967). The trout, showing a piscivorous nature, consume threespine stickleback (*Gasterosteus aculeatus*), kokanee salmon (*Oncorhynchus nerka*) and white-spotted charr in Lake Shikotsu (Kaeriyama, 2002), newly emerged masu salmon fry in Chitose River (Mayama, 1999) and a goby (*Gymnogobious* sp.) in a stream on Shiretoko Peninsula (Morita *et al*., 2003). Fall-spawning (or winter-spawning) brown trout have been implicated in the destruction of formerly spawning masu salmon, thereby reducing the breeding success of that species (Wakabayashi *et al.,* 2002). Although it rarely occurs, brown trout are known to hybridize with native white-spotted charr in natural habitats of northern Honshu (Sugiyama, 1997).

4. Invasion of Brook Trout

Occurrences of brook trout have been recorded in 14 prefectures of Honshu and Hokkaido (Fig. 1(c)). Judging from the records of occurrences, stocking of brook trout is not so popular compared with that of the other two trouts in Japan. Establishment of reproducing populations has been reported in Nijibetsu Creek in Hokkaido (Hikita *et al.,* 1959), inlets of Lake Chuzenji (Wakabayashi *et al.,* 2002) and Lake Yunoko (Shiraishi & Takagi, 1955), and in upper Azusa Creek (EAGJ, 1982) in central Honshu, sites characterized by spring branches of low gradient streams or cold mountain lakes. Brook trout spawn in early November to December, attaining sexual maturity at 11 to 26 cm FL (Kitano & Uehara, 2002).

Brook trout are carnivorous, and feed upon a wide range of organisms (Kitano, 2002). Brook trout feed upon benthic invertebrates more intensively than do rainbow trout in Lake Yunoko (Shiraishi & Takagi, 1955), and upon eggs and fry of chum salmon in Hokkaido (Hikita *et al.,* 1959). Brook trout have hybridized with white-spotted charr, a congeneric native charr in an inlet of Lake Chuzenji (Suzuki & Kato, 1966) and in upper Azusa Creek (EAGJ, 1982). Asymmetric hybridization in which male brook trout cross with female white-spotted charr has been implicated in reduction of native white-spotted charr (Kitano, 2002). Redd superimposition may also have detrimental effects on the breeding success of native charr (Kitano & Uehara, 2002).

5. Factors Affecting Invasion Success and Ecological Impacts of Trout

The successful invasion of non-native trout may be primarily associated with environmental factors such as temperature, habitat size, stream flow, and human influences in Japan, as already discussed in the case of other countries (Dunham *et al.,* 2002). Among Japan's three exotic trouts, rainbow trout are particularly germane to the analysis of the relationship between success of invasion and environmental characteristics, because of more intensive stocking attempts nationwide than for any other species. Rainbow trout have been successful in Hokkaido, but have failed in most of Honshu. Differential vulnerability to disturbance is often invoked as an explanation for the success or failure of non-native fish invasions (Moyle & Light, 1996). Fausch *et al.* (2001) concluded that flood disturbance regimes strongly influence the success of rainbow trout invasions based on empirical evidence from five Holarctic regions, including Honshu and Hokkaido, with suitable water temperatures. Highly successful trout invasions are observed in regions where trout fry emerge during a period of low flood probability as in Hokkaido, whereas a high probability of floods produced by summer monsoon rains followed by fall typhoons was apt to wash away emergent trout fry in Honshu streams. Similar mechanisms may explain the successful invasion of brown and brook trout, although such an analysis is difficult to apply due to lack of broad, quantitative data. Given that such mechanisms are real, Japanese stream environments, altered by damming during these several decades, have become hospitable to invasion by exotic trout. In mountainous regions, small, rapid streams have often been changed into significantly slower ones by the construction of small dams for irrigations and flood control (see Yuma *et al.*, 1998). Storage reservoirs have also been built in the middle to upper reaches of most of Japanese rivers for power production, agricultural, industrial water use and flow regulation. These alterations may increase the invasive success of exotic trout because storage reservoirs generally reduce peak flow (Raymond, 1988).

The number of introduced propagules, frequency of introduction, characteristics of the donor populations as in term of genetic composition, and angling pressure may also influence the success of invasion (*e.g.*, Simberloff, 1989). Intensive introduction and relatively low fishing pressure may relate to the rapid expansions of rainbow and brown trout in Hokkaido. The distribution of non-native trout has increased since the 1970s when sports fishing using lures became popular in Japan, with detailed information on stockings by private individuals unavailable (see Takami & Aoyama, 1999). Sea-migratory habits have been suggested as another means of dispersion of brown trout in Hokkaido, even though the strains introduced into Japan are considered to be non-migratory (Aoyama *et al.*, 1999a). Regardless of original strain, transition from non-migratory to sea-migratory has often been reported in North America (Dymond, 1963) and the Falkland Islands (McDowall *et al.*, 2001). It is still unclear whether introduced rainbow and brown trout are reproducing naturally even in Hokkaido, except in some streams. However, regardless of establishment of self-reproducing populations, large and long-lived trout can have detrimental effects on native species for a long period.

Based on the available ecological information, I conclude the three exotic salmonid fishes have significant impacts on native fauna in Japan, especially on native freshwater fishes. However, the degree of invasive success and the processes and mechanisms of ecological impact differ among trout species and among regions. Predation on native fishes and interspecific competition with native salmonids has been evident for the three exotic trout, but hybridization with native species is almost specific to brook trout. Native salmonid fishes with the potential to interact with introduced trout differ between Honshu and Hokkaido. In Honshu, landlocked masu salmon and white-spotted charr are native and may potentially interact with exotic trout in cold water habitats, generally isolated areas in upper reaches or headwaters. In Hokkaido, four salmonids including anadromous forms: masu salmon, white-spotted charr, Dolly Varden, and Sakhalin taimen, have the potential to interact with introduced trout in low- to high-altitude streams and lakes.

The non-native trout have potential effects on native fish species through predation and competition. Serious impacts of brown trout have been noted on white-spotted charr (Takami *et al.*, 2002) and native goby (*Rhinogobius* sp. OR) in Hokkaido (Takayama *et al.,* 2002), although extinction of native fish as a result of invasion of these non-native trout has not been evident in Japan. Intensive predatory and competitive impacts by brown trout have been implicated for North America, New Zealand and Falkland Islands (*e.g.,* Taylor *et al.,* 1984). For instance, invasive brown trout preyed directly on native fishes and were responsible for the local extinction and population fragmentation of certain species of the family Galaxiidae in New Zealand (McIntosh *et al.,* 1992) and in the Falkland Islands (McDowall *et al.*, 2001). Introduced rainbow trout also exerted a major negative effect on the endangered humpback chub (*Gila cypha*) through predation in the Colorado River (Marsch & Douglas, 1997). Fausch and White (1981) revealed that adult brown trout displaced native brook trout from the best habitats through competition in a Michigan stream. Cutthroat trout have been displaced from much of their native ranges in the Rocky Mountains of the western United States by introduced brook trout, probably due to competitive interaction (Gresswell, 1988). Competition for spawning resources (i.e., redd superimpositions or dislodging by later-spawning species) seems to be crucial for Japanese salmonids, because non-native salmonids tend to spawn later than native species (*e.g.*, Taniguchi *et al.*, 2000).

Asymmetric hybridization is suspected to occur between introduced brook trout and native white-spotted charr in a headwater stream in central Japan (EAGJ, 1982; Kitano, 2002). Introduced brook trout have been displacing resident bull trout, an endangered salmonid species, in parts of northwestern North America through asymmetric hybridization (Leary *et al.,* 1993). According to mtDNA analysis, male brook trout were thought to mate with female bull trout, yet allozyme data indicated that about 97 % of detected hybrids were first generation individuals. Because brook and bull trout hybridization produces mainly sterile progeny and no individuals beyond the backcrosses have been detected, this hybridization does not constitute a threat of introgression. Even without substantial mixing, however, this hybridization can have serious consequences to the conservation of bull trout, because the more numerous brook trout may have an advantage by wasting the smaller reproductive potential of the bull trout with hybrid production. On the other hand, hybridization between rainbow trout and native salmonids has not been reported in Japan, most likely due to differences in spawning season, whereas introgressive hybridization with rainbow trout have often resulted in loss of diversity of native cutthroat trout in western U.S. watersheds (Allendorf & Leary, 1988; Weigel *et al.,* 2003).

There is also no doubt that native species suffer more from the presence of two or more introduced species in the same stream. Brown and brook trout occur with native white-spotted charr in sympatry in upper Azusa Creek (EAGJ, 1982). Similarly, brown and rainbow trout occur in inlets of Lake Shikotsu (Kikuchi *et al.*, 2001) and in other Hokkaido lakes (Takami & Aoyama, 1999). Since competitive interaction between introduced trout generally leads to differential resource utilization between them (see Kikuchi *et al.,* 2001), inferior native species may be forced to utilize more depleted resources as the introduced trout species increase (Nakano *et al.,* 1998; Nakano *et al.,* 1999b; Taniguchi *et al.*, 2002).

Parasite or disease transmission is another possible influence on native species, but evidence for this mechanism is rarely available in Japan. However, since viral, bacterial and fungal diseases have frequently induced great losses in salmon and trout hatcheries in Japan, diseases transmission could have certain negative effects on native fishes (Nagasawa, 1989). For instance, Yoshimizu *et al.* (1989) reported infectious hematopoietic necrosis (IHNV) in wild chum and masu salmon in Hokkaido, which was thought to have been imported with salmon eggs from North America. This viral disease has become widely distributed among most of the hatcheries from Hokkaido to Kyushu (Nagasawa, 1989). Thus, transplantation of eggs and fishes may potentially transmit disease nationwide. Inversely, whirling disease parasites (*Myxobolus cerebralis*) in the native European range of brown trout are believed to be an important factor in their resistance to rainbow trout invasion (Lever, 1996).

Indirect effects are a common feature in animal communities (Sih *et al.,* 1985; Pimm, 1991). The impacts of invasive species on individual species are expected to be propagated through other species in the food-web. In relatively species-poor aquatic communities such as headwater streams, ‘top-down’ trophic cascades are likely to occur (Strong, 1992). Introduced brown trout profoundly affect the biotic interactions in stream communities, reducing the abundance of grazing invertebrates and altering their grazing behavior so that algal biomass increases (Flecker & Townsend, 1994; McIntosh & Townsend, 1994). More recently, Nakano *et al.* (1999a) have suggested that invading rainbow trout also have strong effects that could cascade through aquatic-terrestrial food linkages and potentially affect forest birds living near a Hokkaido stream. They showed that rainbow trout actively selected terrestrial prey over aquatic prey, because of the larger size of the terrestrial prey and their peak flux into streams during the evening. Consequently, rainbow trout consumed 77% of the total input of terrestrial prey into a stream reach during mid-summer, and this constituted 73% of their daily ration. Thus, if the input of terrestrial prey is reduced by modification of riparian habitat, rainbow trout will be forced to forage more intensively on aquatic invertebrates. Moreover, when drifting prey are scarce, native Dolly Varden charr shift foraging modes to benthos feeding (Fausch *et al.,* 1997; Nakano *et al.,* 1999b). In either case, stream salmonids have a potential for strong effects on aquatic invertebrates, their emergence as winged adults and, ultimately, the flux of aquatic prey that subsidizes forest birds (Fausch *et al*., 2002).

6. Implications for Practical Management of Trout

Japan’s domestic laws and regulations are insufficient to avoid ecological risks posed by exotic trout. The rainbow trout is one of the most popular fish species in Japanese inland fisheries, being officially released to inland waters of 31 prefectures throughout Japan (Fig. 2(a)). In contrast, legislation or regulations prohibiting stocking of trout are limited to only three prefectures (Fig. 2(b)). The government of

Hokkaido, where rapid expansion of non-native trout has been recognized, has prohibited stocking of brown and brook trout (but not rainbow trout) by regulations with penalties of a maximum of six months' penal servitude and 100,000 yen since November 2003. Under existing law, however, there are no regulations to controlling the trout populations previously stocked to the waters. Because catch-and-release fishing is common for sport anglers, stock depletion would not be expected even where angling intensity is high. There would seem to be an urgent need for additional regulations encouraging catch-and-keep fishing of non-native trout in special conservational areas such as national parks or waters protected for fisheries resources. Furthermore, establishment of systematic processes of screening, monitoring and feedback will be required in order to contain ecological risks (Ham & Pearson, 2001). Native salmon and charr should be utilized as commercial resources more often than non-native trout, since eggs and fry of native species have become available recently at a reasonable cost.

In Japanese cold water streams and lakes, there are several endemic salmonid species or subspecies endangered due to human impacts such as habitat degradation or overfishing (MEGJ, 2003). For instance, Sakhalin taimen, Dolly Varden charr and Miyabe charr (*Salvelinus malma miyabei*) in Hokkaido are listed as '*Critically Endangered taxa,'* and the southernmost populations of Yamato charr (*S. leucomaenis japonicus*) and Gogi charr (*S. l. imbrius*) in Honshu are currently listed among '*Threatened Local Populations.'* Yamamoto *et al.* (2004) have indicated that white-spotted charr contain more pronounced genetic variation at a population level based on molecular phylogenetic analyses of mtDNA. Habitats with endangered species or with populations of genetic uniqueness should have a management priority.

When there are adverse impacts from established populations of exotic trout, direct control can be applicable for their management. For instance, removal by electrofishing, selective angling, or toxicants has been used to control brook trout in non-native areas of the United States (*e.g.,* Bettoli & Maceina, 1996). Eradication of invasive trout by electrofishing is more likely to be effective in smaller streams, but not in large rivers or lakes. Toxicants can be applicable to complete eradication of invasive trout, and are sometimes used to control invasions in the United States (*e.g.,* Gresswell, 1991). Dispersal barriers are installed at the down-stream end of the treated section of streams to prevent re-invasion by non-native trout (Thompson & Rahel, 1996; Dunham *et al.,* 2002; Novinger & Rahel, 2003). There are, however, few case studies about such direct control of invasive trout in Japan. Eradication is most feasible for brook trout with distribution restricted to headwater area, but is difficult for rainbow and brown trout inhabiting wider streams or lakes. Since spawning trout usually enter small tributaries from larger streams or lakes and spawn in shallow areas with fine gravel suitable to trout, a precise detection of spawning sites and seasons may lead to effective management of brown and rainbow trout.

Eradication of invasive trout may, on the other hand, have short- and long-term unpredicted consequences for the native fauna and ecosystem. Strong non-selective eradication may be detrimental not only to invasive species but also to native species in terms of loss of genetic diversity (*e.g.,* Avise & Hamrick, 1996). In cases that invasive trout play a major role in an aquatic community, rapid loss of invasive trout may seriously affect the viability of non-target native species. For example, parasitic larvae of an endangered freshwater mussel (*Marga-*

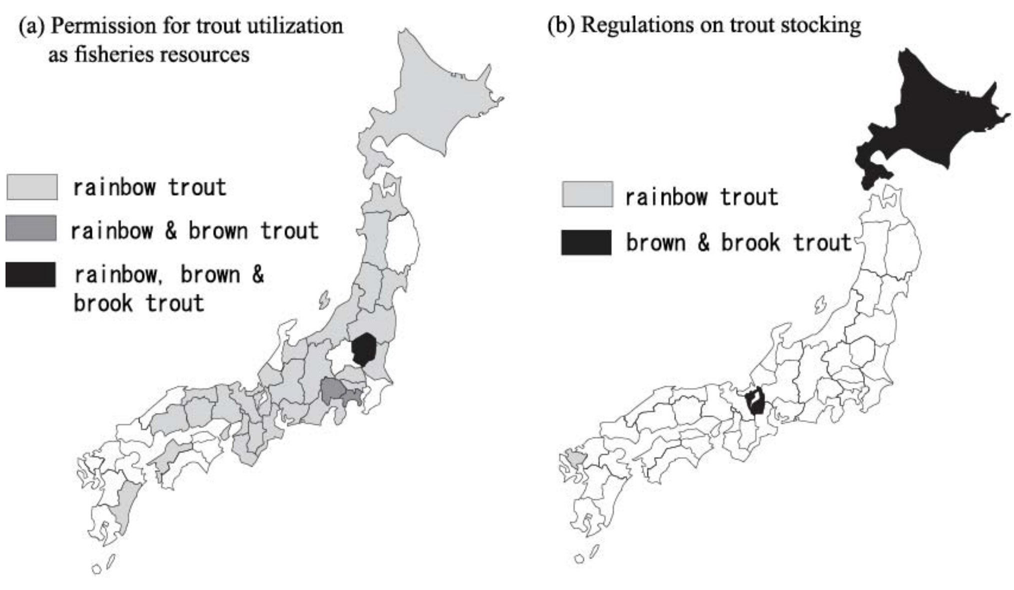

Fig. 2 Areas with permission to utilize the exotic trout as fisheries resources and (a) with regulations on trout stocking (b). This information was provided by the Fisheries Agency, Government of Japan, dated 2 December, 2003.

ritifera laevis), utilizing invasive brook trout as hosts instead of scarce native white-spotted charr (Kondo *et al.,* 2000), may be threatened by the drastic removal of the invasive trout. Similarly, the piscivorous Japanese water shrew (*Chimarrogale platycephala*) would be influenced by low food availability immediately after trout eradication (see Abe, 2003). To consider the full range of impacts associated with direct control, managers can evaluate short-term threats by non-native trout and long-term considerations for persistence of native populations and communities.

Most recently, the number of artificial trout fishing ponds and streams connected to natural streams have been increasing from southern to northern regions of Japan (*e.g.*, 98 sites were listed in the fishing guidebook edited by Murata, 2003). They have stocked various types of exotic trout including a triploid type of rainbow trout, hybrid trout (between brown trout and brook trout or between brook trout and white-spotted charr) and arctic grayling (*Thymallus arcticus*) in addition to rainbow, brown and brook trout. Escapes of fish from the facilities may cause novel ecological issues regarding the conservation of Japanese freshwater fishes. In fact, accidental stocking of arctic grayling, originally cultured for the fishing ponds, to reservoirs has been detected in central Japan (Kitano *et al.*, 2004). Management of exotic trout stocking sources is also important in controlling the likelihood of stocking mishaps, thereby preventing the problem from increasing.

Finally, our knowledge of invasive trout is still limited in Japan. We need to know more about the invasion process: how they arrive, how their arrival can be blocked, how to handle problems when they arise and how to evaluate the overall effectiveness of our management programs. The feedback process of research, monitoring, management action and evaluation may develop more robust theories for predicting invasion success.

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