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Restocking of salmonids—opportunities and limitations

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Abstract

Stocking can be a cost effective method of enhancing salmonid populations, in particular where the aim is to restore populations or mitigate against developments. There are risks associated with any intervention and it is suggested that all stockings undergo risk screening in order to identify the high risk areas. The main concern regarding stocking relates to the impact on the genetic fitness of the wild population, and proposals to minimise the impact while still maintaining a fishery are made. To ensure that the greatest benefit from a stocking programme is realised, stocking rates should be optimal for the type of habitat being stocked. How this can be determined is presented together with guidelines for stocking different types of habitat. Benefit, in terms of cost of adult return or per adult fish caught, enables comparisons to be made with other management options. Information on survival rates of wild and hatchery-reared fish, unit cost of production and the economic value of fish and fishing is summarised enabling simple estimates of cost: benefit to be determined.

Keywords: *Salmo salar*; *Salmo trutta*; Stocking; Enhancement

1. Introduction

Stocking is defined as "the repeated injection of fish into an ecosystem in which a population of that species already exists from one external to it, i.e. a stocked species may be either already native to the recipient water body or exotic to it but previously introduced" (Cowx, 1998). In the case where the species is exotic to a particular water body it is usually not the intention that the species become self-sustaining in the recipient water body. Stocking can benefit recreational fisheries in a number of ways (Postle and Moore, 1996); by increasing the capital value of the fishery, anglers may catch more fish, more desirable, better quality fish and the numbers of anglers fishing a particular site may increase. There are risks associated with any introduction and they include; that the stocking may not be successful (Riddell, 1993); it may give rise to competition and/or predation (Kennedy and Strange, 1980; Harcup et al., 1984; Berg and Jorgensen, 1991; Näslund, 1992); and it could impact on other organisms, which may have conservation value (Saura et al., 1990). There is also the risk that interbreeding might cause a reduction in fitness which for some populations has been considered a contributing factor to their decline (Hindar et al., 1991; Utter et al., 1993; Reisenbichler and Rubin, 1999; Waples, 1999).

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In any stocking programme it is imperative that the objective is clearly set out. It may be to use artificial propagation to mitigate, restore, enhance and conserve populations within the scope of natural production or it may be to increase the population beyond that which could be supported by the natural carrying capacity of the habitat, in order to increase the harvest. The objective of the former is to facilitate the long-term self-sustaining capacity of the population being managed. The second type of intervention is one for which the limitations of natural production are exceeded in order to expand production and as a consequence to possibly replace a situation of self-sustainability with one which must be artificially maintained. The biological considerations of these two types of intervention are different and for the most part these objectives are mutually exclusive. A programme that is well suited to harvest augmentation may not conserve natural population structure. If the aim is to maximise local abundance by creating a self-sustaining population, then it is important to conserve the genetic and phenotypic variability, to ensure that mean individual fitness remains unchanged (Youngson and Verspoor, 1999). Alternatively if the objective is to optimise local production by selecting for particular genotype frequencies or phenotypic characteristics, then it is important to ensure that the capacity of the wild population to evolve would not be impaired (Youngson and Verspoor, 1999). Effectively this comprises trying to ensure that the wild and artificial populations did not interbreed.

This paper aims to illustrate the reasons for stocking and show how the risks can be effectively managed. The paper also deals with the costs of the programme so that comparisons can be made with other forms of enhancement. It does not aim to provide an extensive review of salmonid stocking or the production of a user manual on how to undertake a stocking programme—this aspect has been well documented by Egglishaw et al. (1984), and the processes involved by the Salmon Advisory Committee (1991), Cowx (1994), Harris (1994) and Welcomme (2001).

2. Reasons for restocking

The greatest benefit of stocking when carried out correctly is that it is more efficient at producing returning adults than natural spawning, in the case of salmon (*Salmo salar* (Linnaeus, 1758)) and sea trout (*Salmo trutta* (Linnaeus, 1758)). Marshall et al. (1994) showed from studies on the Saint Johns River that stocking with 0+ parr was about three times more efficient, and smolts approximately eight times more efficient than natural spawning, in terms of converting eggs into returning adults. The main reasons for stocking can be summarised as follows:

(a) *Mitigation*: Stocking that is conducted to mitigate lost production due to a scheme or activity, which cannot be prevented or removed.

Mitigation stockings can be categorised as follows:

- *Statutory and contractual scheme specific mitigation*—where there is a legal or contractual requirement to mitigate against lost production.
- *Non-statutory and non-contractual scheme specific mitigation*—where there is no legal nor contractual requirement to mitigate against lost production, and where it can be identified to a particular scheme.

A useful example of mitigation stocking is that associated with the impact of two hydro-developments on the River Blackwater (Scotland). In 1957, two hydro dams were constructed, these dams effectively excluded fish from much of the spawning habitat of the Blackwater as no fish passage facilities were provided. Downstream of the dams the gradient of the Blackwater is steeper, consisting mainly of cobbles and boulders making ideal nursery habitat.

Broodstock are collected from a trap situated approximately 15 km downstream of the dams, throughout the migration period providing a wide and diverse gene pool. The fish are stocked at the eyed egg and unfed fry stages, ensuring that they are exposed to natural selection for as long as possible in fresh water. The resulting smolts are regarded as indigenous, and well adapted to their habitat. Over the years the trap catch of returning adults, though fluctuating, has been maintained at between 1000 and 2000 fish per year. This represents a return rate from eyed egg/unfed fry to the trap of 0.19% and has meant the continuation of the fishery on the Blackwater, which has averaged 150 salmon per year (1979–1999).

Another example is that of the River Tyne where a mitigation programme compensates for the loss of 11.2 km of salmon spawning and nursery habitat caused by the construction of Kielder reservoir. The fish are stocked mainly as 0+/1+ parr and have shown return rates to the river of up to 5.12% (J. Shelley, pers. comm., Environment Agency, UK).

(b) *Restoration*: Stocking which is carried out after the removal or reduction of a factor which has been limiting or preventing natural production.

Restoration stocking includes the rehabilitation of stocks following water quality and/or habitat improvements, and the replacement of fish following a fishkill, land drainage operations and other activities, some of which may involve legal or contractual obligations.

An example is the restoration of salmon to the River Taff (South Wales). The objective of the stocking programme was first to restore a salmon population to the river, and second to monitor the impact of a barrage at its mouth at Cardiff Bay. The Taff used to support prolific runs of salmon and sea trout which died out during the last century as a result of a combination of over-fishing, abstraction, obstructions and pollution, mainly from the coal industry (Mawle, 1991). By the early 1980s, there had been major improvements in water quality due to the economic recession and improved pollution control, and it appeared feasible that the Taff could once again support salmon.

The stocking programme started in 1983 and was designed as a pump priming exercise. Since then the number of returning salmon has increased steadily until 1994 (Fig. 1); the decline after 1994 reflects the reduction in trapping activity. The data will also be helpful in assessing the impact of the Cardiff Bay Barrage, the aim being to compare the return rate of hatchery-reared smolts back to the river. Prior to completion of the barrage in 1999 the recapture rate of smolts to the river was 0.79%, with a return rate to the river of about 2%, and about 3% if captures in offshore fisheries are taken into account (Jones, 1994).

Other examples include the restoration of the River Morrell (Canada) where in 8 years the salmon runs increased from between 4 and 45 fish per year, to between 360 and 1263 (Bielak et al., 1991). On the River Mawddach (Wales) the return rate of sea trout smolts, stocked following a major pollution incident, to the river was estimated to be 6.75% (Jones, 1994).

The objective for such programmes is to work within the scope of natural production, to maintain diversity and in the case of restoration to achieve in the long-term a self-sustaining population. This can be obtained by sourcing the broodstock from a stream geographically near and ecologically similar to the target patch as opposed to the hatchery stocks as the latter are subject to a high degree of domestication. To minimise any reduction in fitness in the newly established population, broodstock should be taken throughout the spawning season and the residency time in the hatchery prior to stocking should be kept to a minimum to reduce the impact of domestication. Ideally the fish should be planted out as ova or swim-up fry. The whole process is likely to be more

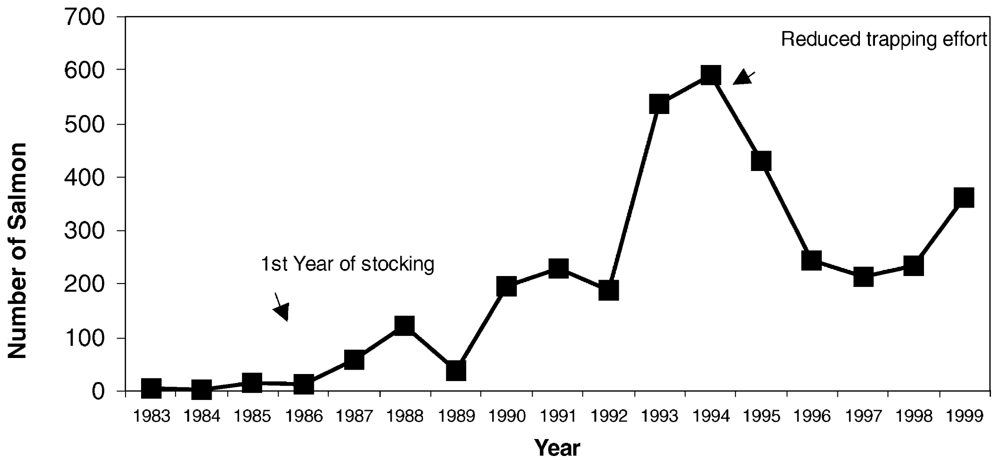

Fig. 1. Catch of salmon in the River Taff (Wales) using all methods from 1983 to 1999.

successful if repeated over a number of years and with a large number of colonists. It is obviously important that the number of adults removed for breeding and recolonisation should never threaten the persistence of the source population.

(c) *Enhancement*: Stocking which is carried out to supplement an existing stock where the production is less than the water body could potentially sustain.

Enhancement stocking can be categorised as follows:

- Stocking undertaken to compensate for the affects of adverse natural factors, which manifest themselves on a periodic basis. For example flow which for salmonids can affect spawning success and the distribution of spawners within a catchment.
- Stocking migratory salmonids above natural barriers and salmonid ranching.
- Stocking which is carried out to compensate for lost production where the loss is a result of diffuse activity, for example where there has been large scale degradation of habitat (physical and chemical) due to urbanisation, channelization, acidification and land use changes.
- Where stocking is carried out to maintain an artificial fishery such as a put and take fishery.

The main purpose of the programme is to optimise local production while ensuring that the viability and diversity of the natural population is not impaired. In such cases, a fraction of the wild parental fish from an extant population is brought into the hatchery for artificial reproduction and the offspring are released into the natural habitat as fry, parr, smolt or adult life stages where they mix with the wild fish. This can also include kelt (post-spawned fish) reconditioning programmes where all or a fraction of the kelts from an extant population are retained in fresh water or sea water rearing facilities. The fish are held to maturity and their offspring subsequently released into the wild.

The idea is to overcome a real or perceived temporary bottleneck (egg to fry mortality, fry to parr, parr to smolt, egg to smolt, egg to adult, smolt to adult). The aim is to ensure that no exogenous genes are introduced into the population. In this type of programme there must be habitable space for the population to expand into, and be linked to a regularisation of exploitation. The key genetic consideration is to minimise artificial selection; the longer the fish are in the hatchery the greater will be the risk. In addition, the impact of broodstock removal from the wild population and relative success on the 'enhanced' fish will need to be balanced against the risk of damage.

The salmon ranching carried out in the rivers Bush (Northern Ireland), Burrishoole (Ireland) and Baltic are examples of this form of stocking. In the River Bush, Crozier et al. (1997) reported return rates of hatchery-reared smolts of up to 8.6% to the coast and 3.0% to the river; equivalent figures for the Burrishoole were 6.83 and 2.25%. In the Finnish Rivers Kemijoki and Kokemaenjoki the return rates of hatchery smolts have been 10.0 and 12.75%, respectively (Kallio-Nyberg and Koljonen, 1997; Salminen and Erkamo, 1998). In the Baltic Sea approximately 90% of the salmon caught are of hatchery origin (Määttä, 1999).

Fresh water release programmes for recreational brown trout fisheries are widespread throughout the British Isles. One concern is that the released fish will interbreed with local natural stocks altering their genetic composition (McMeel and Ferguson, 1997), with a risk of reducing genetic diversity and population viability (Laikre et al., 1999). The best way to minimise the risk is not to introduce hatchery stocks into the wild. However, sterilised fish, most commonly rendered infertile by a process of triploidisation, offer a useful alternative to introducing reproductively competent trout into the wild. In some instances rainbow trout (*Oncorhynchus mykiss* (Walbaum, 1792)), where except for a few rare instances are not thought to breed in the wild (Welton et al., 1997), can be used to supplement commercial trout fisheries. In certain circumstances, it may be deemed appropriate to stock rainbow trout into rivers, for example where there has been a long history of stocking rainbow trout at a particular location. This does have one advantage in that the stocked fish will be more easily identifiable when compared to wild fish, but the potential risks of increased competition, predation and disease still exist. If rainbow trout are to be stocked to support the fishery then they should be all female or sterile stock.

(d) *Creation of new fisheries*: Stocking which aims to transfer fish into new water bodies or when new species are introduced into existing fisheries.

(e) *Research and development*: Stocking which aims to address particular fisheries management issues.

As an example, see Section 4.1, assessment of carrying capacity.

(f) *Conservation*: Stocking which aims to conserve the stock of fish.

Stocking has been used to conserve both lake and river salmonids; examples include *Oncorhynchus apache*, *O. gilae* (Rinne, 1990), *S. salar* m. *sebago* (Westman and Kallio, 1987) and *S. trutta* m. *fario* and *S. trutta* m. *lacustris* (Gjedrem, 1981; Skaala et al., 1991).

3. Risk management

Stocking is a legitimate management tool. However, some of the effects are irreversible and there is strong pressure to regulate such activity and explore alternative solutions in order to reduce the risk of damage to the environment (Welcomme, 2001). To any particular problem there will be a number of solutions; each will be associated with its own costs, benefits and risks. For each potential solution there will be a need to identify the biological and social consequences. Ideally, the solution to the particular management problem should aim to achieve best environmental practice.

The risk assessment element identifies possible consequences and their likelihood of occurrence, whereas risk management uses this information to evaluate and steer decision alternatives. The first stage in any risk analysis should be to define the risk scenario whereby the objectives and constraints of the fishery system are quantified, and the variables, both controllable and uncontrollable, are described (Hickley and Aprahamian, 2000). Risk screening should be used to separate low priority risks from high priority risks. For complex, high priority risks a tailored assessment is likely to be necessary whereas for less complex risks a generic assessment may be adequate.

It is essential at the start to identify, set and agree the standard by which the risk will be judged, otherwise risks will be assessed against different standards (Lackey, 1994). The approach by Pearsons and Hopley (1999) was to set objectives for non-target species and following an assessment of the species value and status an acceptable level of impact could be identified. The positive and negative impacts and their strengths are then assessed together with the level of uncertainty. These are then peer reviewed before discussion with interested parties. To assist the process a decision table (Table 1) showing a summary of the biological alternatives, management alternatives and risks should be

Table 1
An example of a risk management decision table to assist with evaluation of alternative management actions and discussions between interested parties

	Probability (H/M/L)	Consequence (H/M/L)	Effect of risk occurring	Uncertainty (H/M/L)	Method of control
Generic risks					
Unforeseen conditions					
Inadequate consultation					
Inaccurate estimates					
Inappropriate design					
Adverse publicity					
Others					
Project specific risks (completed separately for each management action, e.g. stocking, reduction in exploitation, improved access, habitat improvement)					
Availability of fish					
Effect on genetic integrity					
Degree of species interaction					
Risk of disease/parasites					
Others					

constructed and used to help in the dialogue between fishermen and managers.

4. Stocking density

4.1. Assessment of carrying capacity

The implication of the term "carrying capacity" is that there is an inherent maximum number of fish that can be supported by a given area (Solomon, 1985). There is evidence for both flat-topped (Watt and Penney, 1980; Chadwick, 1985) and domed (Elson and Tuomi, 1975; Elliott, 1984) stock-recruitment curves (Milner et al., 2003). Thus, the ideal situation for the manager is to manipulate the numbers of fish through natural reproduction or artificial stocking to achieve carrying capacity. If juvenile stocks are below the carrying capacity then the habitat is perceived to be under-utilised, whereas attempting to increase populations beyond the carrying capacity represents wasted effort (time or money) since higher mortality and/or emigration will occur.

However, carrying capacity is essentially a static measure at a single point in time. Carrying capacity will vary with factors such as flow regime, food availability and temperature, none of which can be predicted in advance. Furthermore, carrying capacity may also be related to the fish themselves, which can show ontogenetic changes in habitat use or feeding, creating more or less useable habitat as they grow (Bohlin et al., 1994).

One of the simplest hypotheses is that territoriality in juvenile salmonids places an upper limit on carrying capacity (Chapman, 1966; Allen, 1969; Elliott, 1984). Grant and Kramer (1990) performed an analysis of studies on territory size on a range of salmonid species. They found a strong relationship between fish size and territory size for a total of 23 studies:

$$\log_{10}(\text{territory size}) = 2.61\log_{10}(\text{fork length}) \quad (r^2 = 0.87).$$

If the total area of suitable habitat for juvenile salmonids of a particular size is known then optimum stocking densities could readily be calculated from the above formula (Grant et al., 1998). However, recent work suggests that the simple model of stream-dwelling salmonids holding exclusive territories with restricted movement may not be correct (Gowan et al., 1994; Gowan and Fausch, 1996; Armstrong et al., 1999).

Some assessment of carrying capacity can be obtained from experimental studies. Such work usually involves stocking at a range of densities and then surveying at some later stage (Fig. 2). Problems with the empirical approach are that there can be considerable, unexplained variation from year-to-year (Fig. 2) and site-to-site. There may be severe problems in applying criteria developed at one location to a different location. Thus, experimental stocking has to be performed many times under many different regimes, which is often not feasible.

4.2. Habitat models

Habitat models have been used to assess the carrying capacity of streams for salmonids. HABSCORE estimates the carrying capacity of different age-classes of salmon and trout for a particular physical habitat, assuming water quality and recruitment are not limiting in streams <15 m in width (Wyatt and Barnard, 1995; Milner et al., 1998). It is based on empirical models of fish density against combinations of site and catchment features measured using a standard protocol (Barnard and Wyatt, 1995). Using just altitude and stream order, Wyatt and Barnard (1997) estimated the carrying capacity for 0+ and >0+ salmon (Tables 2 and 3). The estimates are considered to represent the summer (July–September) carrying capacity under pristine water quality conditions over a range of habitat sites, where recruitment was not limiting.

Table 2
The density of 0+ salmon parr (number 100 m^{-2}) estimated empirically from altitude and stream order (Wyatt and Barnard, 1997)

Altitude (m)	Stream order (1:50,000)			
	1	2	3	4
0–49	9.65	14.11	18.73	22.58
50–99	4.79	12.06	19.62	20.62
100–149	5.09	17.04	34.15	40.94
150–199	8.77	27.27	50.20	54.68
200–299	26.38	30.34	14.83	3.08
300–399	44.64	1.56	–	–

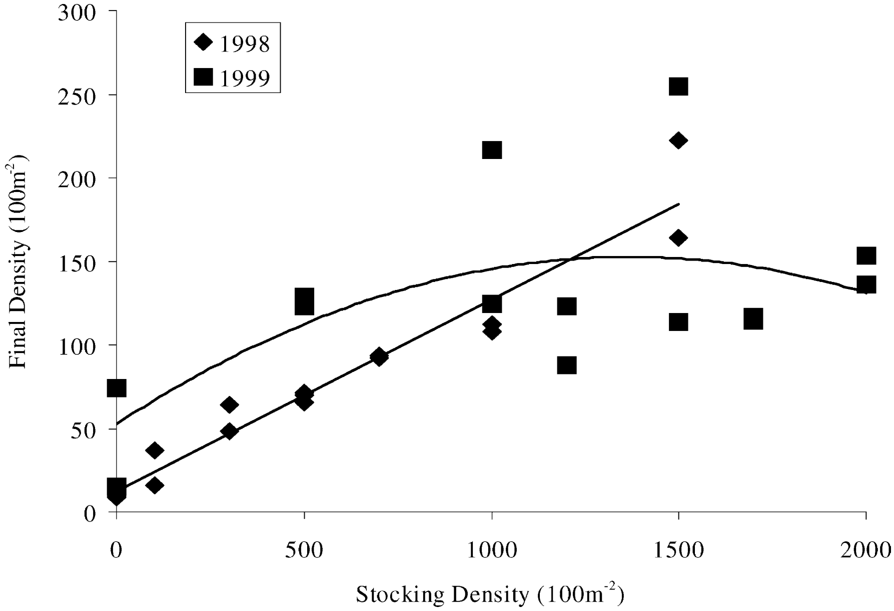

Fig. 2. The relationship between the starting and final density of salmon stocked into the River Tombane.

Assessments of carrying capacity can also be made from the analysis of time series data and, where these do not exist, through comparisons with other sites of similar biological, physical and chemical characteristics. The latter can be carried out partly by using the Fisheries Classification Scheme (Mainstone et al., 1994) which compares fish stocks with those found at sites of similar width and gradient.

4.3. Still waters

For large (>0.5 ha) still waters fish production can be determined using the morpho-edaphic index (Ryder, 1965), enabling current yields to be assessed against potential fish production.

Table 3
The density of >0+ salmon parr (number $100\,m^{-2}$) estimated empirically from altitude and stream order (Wyatt and Barnard, 1997)

Altitude (m)	Stream order (1:50,000)			
	1	2	3	4
0–49	1.87	3.49	3.93	2.66
50–99	3.33	5.33	6.39	5.73
100–149	6.39	7.27	7.70	7.59
150–199	11.51	8.87	7.93	8.21
200–299	18.06	9.70	8.93	11.68
300–399	7.02	7.40	–	–

4.4. Guidelines

Stocking densities for eyed ova and unfed fry of salmon within the British Isles have ranged from 1 to $20\,m^{-2}$, depending on the productivity of the water and the standing stock of fish in relation to carrying capacity (Egglishaw and Shackley, 1973; Crisp, 1995, 1996; Armstrong et al., unpublished data). For sea trout, stocking densities for fed fry have ranged from 0.4 to $1.50\,m^{-2}$ (Wyatt, 1989; Hoggarth et al., 1992; Hoggarth, 1992). For sea trout fry (age 0+) stocked in September, Scott et al. (1997) recommended trickle stocking at a density of $0.75\,m^{-2}$, which would give an output of ca. 0.03 smolts m^{-2}.

For older parr (1+) stocking has been carried out at densities of $1.0–2.0\,m^{-2}$ for sea trout (Berg and Jorgensen, 1991) and at $5.0\,m^{-2}$ for brown trout (Zalewski et al., 1985).

Recommendations for stocking densities for wider applications have been reported by Egglishaw et al. (1984) and Harris (1994) (Tables 4 and 5).

The question of stocking density for smolts does not arise in the same way as it does for the younger

Table 4
Recommended stocking densities (m^{-2}) for two different habitat types producing 0.06 and 0.09 smolts m^{-2} (modified from Egglishaw et al., 1984)

Habitat class: medium ($0.06\,m^{-2}$)			Habitat class: good ($0.09\,m^{-2}$)		
Width (m)	Altitude (m)	Density	Width (m)	Altitude (m)	Density
All	>450	2.0	<10	<450	10.0
<25	<450	5.0	>10	<450	5.0
>25	<450	2.0			

Table 5
Recommended stocking densities (m^{-2}) for stocking with different life stages of salmon to produce maximum smolt output for three different types of habitat quality (modified from Harris, 1994)

Life stage	Habitat class (smolts m^{-2})		
	Good ($0.09\,m^{-2}$)	Medium ($0.06\,m^{-2}$)	Poor ($0.03\,m^{-2}$)
Eyed eggs	4.5	3.3	1.7
Unfed fry	4.0	3.0	1.5
Fed fry (4 weeks)	1.8	1.2	0.6
0+ parr (autumn)	0.4	0.25	0.15
1+ parr (spring)	0.2	0.1	0.05

life stages of salmon and sea trout except when smolts are stocked into smolt release (SR) ponds. These are specially designed ponds attached to the target river, whereby fish can be allowed to migrate on their own volition (Table 6). These ponds can vary in size but are typically of the order of 30 m long × 4 m wide by 1.5 m deep and stocked with 40–50 fish m^{-3}.

Similar to SR ponds are semi-natural (SN) rearing ponds, which are designed for more long-term holding and rearing than the SR pond. Fish are usually stocked into the pond as 1+ parr (5–10 fish m^{-3}) and reared through to S2 smolts using only a small ration of artificial food (15–20%). Fish emigrating from these ponds would already be adapted to feeding on wild food enhancing their ability to survive in the wild when compared to tank reared fish (Shustov et al., 1980).

Table 6
Survival rates for salmon and recovery rates for sea trout from smolts stocked directly into the river and into SN ponds (Bielak et al., 1991) or SR pond (Jones, 1994)

Salmon (2+ smolts)			Sea trout (1+ smolts)		
Year	Percentage of sea survival		Year	Percentage of recovery	
	Direct	SN pond		Direct	SR pond
1985	1.5	8.3	1990	0.233	0.613
1986	6.1	11.3	1991	0.280	1.350
1987	2.8	7.0	1992	0.053	0.255

5. Costs and benefits

5.1. General

To estimate the cost and benefit of any stocking operation information is required on the cost of production, both in terms of the capital as well as the revenue costs, the rates of survival in the hatchery and once released into the wild and the capital value of the fishery. In this paper only the revenue costs are considered.

5.2. Costs

Labour costs make up a large part of the expense of running a hatchery. Some savings can be made by the use of volunteer labour but there should be an experienced hatchery worker in charge of operations. As an example, the annual costs of running a salmon hatchery designed to produce 4 million eyed ova/unfed fry is £ 26,835, made up as follows: general husbandry (22.3%), stripping (24.0%), rearing (27.4%), stocking out (13.7%), maintenance (1.9%) and overheads (10.7%), a cost of £ 0.0067 per individual (McKelvey, pers. comm., Conon Fishery Board, UK).

The unit cost of production of eyed ova, unfed fry and other life stages as estimated from three Environment Agency fish farms is summarised in Table 7.

Table 7
Unit cost of producing various life stages of salmon

Life stage	Unit cost (£)
Eyed ova	0.01789
Unfed fry	0.03654
6-week fed fry	0.10
12-week fed fry	0.16
30-week fed fry	0.36
1+ parr/S1 smolt	0.85
S2 smolt	1.70

5.3. Survival rates

Survival of hatchery-reared fish once stocked is generally lower than that of equivalent wild fish. For the stocking to be viable, hatchery survival must be great enough to offset the lower rates experienced by hatchery fish once they have been released into the wild. The main sources of mortality once stocked are predation from birds (Kennedy and Greer, 1988; Anthony, 1994), by fish (Bakshtansky et al., 1983); delay in adapting to wild food (Shustov et al., 1980; Bakshtansky et al., 1983) and inappropriate behaviour (Dickson and McCrimmon, 1982).

5.3.1. Variability in survival/return rate

The variability in survival rates will reflect density dependent factors, variation in the rearing environment and to temporal difference in environmental conditions (Locke, 1998). For example discharge at the time of smolt release can have a significant effect with higher returns at higher discharges (Hosmer et al., 1979; Hvidsten and Hansen, 1988; McKinnell and Lundqvist, 2000). Other causes include the following:

- *Time of stocking*. Stocking time can have a substantial effect on survival rate (McKinnell and Lundqvist, 2000) and on recapture rates of takeable-sized fish (Cresswell, 1981). For trout being stocked for angling Cresswell (1981) reported that recapture rates were higher for brown trout stocked during the spring or angling season (23%) than during the autumn (14%). In order to maximise returns the closer the fish are stocked, in terms of time, to the start of the angling season the greater the yields (Cresswell and Williams, 1982).
- *Location of stocking*. The location of release is important for smolts for though, in general, higher return rates are achieved the lower down the catchment the fish are released, there is some evidence to suggest that the returning adults have a tendency not to penetrate further upstream than the release site (Piggins, 1971). Browne (1984) (cited by Solomon, 1993) found a sixfold increase in the survival of hatchery-reared salmon smolts when released at the head of tide.
- *Preconditioning and acclimatisation*. There are two aspects which need to be considered; first there is the adjustment from hatchery food to natural food and second the transfer from a still water to a riverine environment. It is important to remember that the hatchery environment is very different from that of a river and the fish may need preconditioning before stocking to improve the viability of the stocking programme (Cresswell and Williams, 1983). For fish being stocked into running water, preconditioning the fish to such conditions enables fish to build up red muscle and can result in better survival (Wendt and Ericson, 1972), lower dispersion and higher recapture rates (Cresswell and Williams, 1983).
- *Broodstock selection*. As there is a strong genetic component to the age at which salmon and trout mature (Table 8) (McGinnity et al., 1997; Ferguson, 1999), the use of MSW parents would produce a lower return rate than 1 SW fish as the former will have an additional year of mortality.

Table 8
Proportion of MSW salmon among returning females derived from pedigree grilse and MSW parents (Wilkins et al., 1999)

Release year	Proportion of MSW salmon among returning females	
	Grilse lines (%)	MSW lines (%)
1993	1.4	16.3
1994	7.3	18.4
1995	20.5[a]	36.5

[a] The high percentage of MSW female salmon was the result of ranching 50,000 all female smolts out of a total of 100,000.

5.3.2. Salmon

Survival rates between various life stages both of wild and hatchery-reared salmon have been published by Locke (1998) together with survival rates in Carlo hatchery; these data together with some additional data are presented in Table 9.

5.3.3. Sea trout

For sea trout, survival rates from unfed fry and from fry stocked in September to smolt (total output from a cohort) were between 4 and 9% (Saura et al., 1990) and 4 and 10% (Scott et al., 1997). Mills et al. (1985, 1990) reported recapture rates of 0.5% for hatchery-reared 1+ smolts and 3.7% for 2+ smolts. On the River Mawddach (Wales), Jones (1994) estimated the return rate of hatchery-reared smolts to the river of be 6.75%.

Table 9
Survival rates mean (range) for wild Atlantic salmon, from Locke (1998) with additions

Life stage	Wild-reared fish		Hatchery-reared fish		Mean (range) percent survival in hatchery
	Mean (range) percent survival in wild	Reference	Mean (range) percent survival in wild	Reference	
Survival from fertilised egg to:					
Eyed egg			89 (85–95)	MacKenzie and Moring (1988)	93 (91–96)
Hatching			31 (7–61)	Pauwels and Haines (1994)	89 (88–90)
			74 (45–88)	MacKenzie and Moring (1988)	
Summer 0+	2 (1–3)	Jessop (1984)	>2	Shearer (1961)	82 (76–88)
	7 (5–8)	Jessop (1984)	4	Kennedy and Strange (1981)	
	7 (6–8)	Elson (1957)			
	8	Elson (1957)			
	10 (9–11)	Meister (1962)			
	12 (7–20)	Jessop (1984)			
	15 (11–18)	Jessop (1984)			
Summer 1+	5 (4–6)	Elson (1957)			70 (61–78)
2-year smolt	3 (1–6)	Symons (1979)			65 (55–76)
Survival from eyed egg to:					
Emergence	6	Gustafson-Marjanen and Moring (1984)	5 (3–7)	Gustafson-Marjanen and Moring (1984)	94 (81–98)
Summer 0+			19	Kennedy and Strange (1981)	90 (84–95)
Autumn 0+			13 (12–14)	Egglishaw and Shackley (1973)	79 (70–91)
			– (17–19)	Kennedy and Strange (1981, 1986)	
Survival from unfed fry to:					
Autumn 0+			8 (1–30)	Mills (1969)	71 (68–74)
			20 (9–30)	Egglishaw and Shackley (1973)	
			26 (18–34)	Orciari et al. (1994)	
			42 (5–53)	McMenemy (1995)	
Survival from summer age 0 to:					
Autumn 0+			– (6.7–22.7)	Elson (1957)	89 (84–96)
			– (7.8–41.3)	Farooqi and Aprahamian (1995)	
			– (10.0–42.3)	Milner (1993)	
			13 (11–15)	McCrimmon (1954)	
Summer 1+	17 (1–29)	Côté and Pomerleau (1985)	– (4 to <33)	Elson (1957)	87 (81–94)
	– (14–32)	Kennedy and Strange (1981)			
	47	Kennedy and Strange (1986)			
	50 (41–59)	Meister (1962)			
	51 (22–88)	Egglishaw and Shackley (1980)			
	53 (45–68)	Orciari et al. (1994)			

2-year smolt	>5	Meister (1962)	– (3–12)	Elson (1957)	81 (71–91)
	20	Elson (1957)	8	Elson (1975)	
	38	Elson (1975)			
Survival from summer age 1 to:					
2-year smolt	19 (14–23)	Orciari et al. (1994)	– (2–30)	Elson (1957)	93 (89–97)
	45 (14–79)	McMenemy (1995)	26.2 (14.7–43)	Jokokokko and Jutila (1998)	
Survival from 1-year smolts to:					
1 SW adult			1 (0.1–2.9)	Crozier and Kennedy (1993)	
Survival from 2-year smolts to:					
1 SW adult	0.7 (0.5–2)	Chadwick (1986)	0.05 (0.01–0.1)	Baum (1983)	
	6 (1–12)	Chadwick (1986)	1 (0.3–3)	Harvie and Amoro (1996)	
	6 (1–17)	Jessop (1984)	1 (0.4–4)	Harvie and Amoro (1996)	
	7 (3–12)	Chadwick (1986)	2 (0.4–5)	Harvie and Amoro (1996)	
	8.2 (3.9–12.0)	Crozier and Kennedy (1993)	2.3 (0.6–8.2)	Crozier and Kennedy (1993)	
			4 (1–6)	Isaksson (1979)	
2 SW adult	0.6 (0.3–0.9)	Chadwick (1986)	0.1 (0–0.7)	Crozier and Kennedy (1993)	
	0.6 (0.4–1)	Chadwick (1986)	0.1 (0.03–0.2)	Harvie and Amoro (1996)	
	1.1 (0.4–1.9)	Crozier and Kennedy (1993)	0.2 (0–0.5)	Isaksson (1979)	
			0.5 (0.1–1.5)	Harvie and Amoro (1996)	
			0.7 (0.2–1.3)	Baum (1983)	
			0.7 (0.2–3)	Harvie and Amoro (1996)	
1–3 SW adult	4	Piggins (1979)	– (0.004–0.36)	Meyers (1994)	
	8 (4–13)	Piggins (1979)	0.07 (0.008–0.17)	Stolte (1994)	
			0.45	Piggins (1979)	
			2.4 (1–4)	Piggins (1979)	
			2.7 (0.5–7)	Piggins (1979)	
			2.3	Piggins (1979)	
Survival from 1- to 2-year smolts to:					
2 SW adult			0.1 (0.0–0.7)	Crozier and Kennedy (1993)	
1–2 SW adult	– (2–6)	Shearer (1961)	0.035	Rideout and Stolte (1988)	
	10 (2–16)	Carlin (1967)	0.33	Rideout and Stolte (1988)	
	21	Isaksson (1979)	0.06 (0.001–0.16)	Rideout and Stolte (1988)	
	23 (20–26)	Österdahl (1969)	– (0.2–2)	Shearer (1961)	
			– (0–11)	Carlin (1967)	
			1–2	Isaksson (1979)	
			2	Isaksson (1979)	
			8	Isaksson (1979)	
			10 (6–13)	Österdahl (1969)	

Table 10
Percentage survival of hatchery-reared brown trout stocked in Sweden (Näslund, 1998)

Age	Month stocked	Percentage survival after			
		2 months	10 months	12 months	24 months
0+	October		5–23	5–26	0–5
1+	June	20–43		0–3	0–1
1+	October		0–1	0	0
2+	June	8–21		0–3	0–1

5.3.4. Brown trout

For trout, Näslund (1998) reported survival rates for fish age 0+ to 2+ stocked into small Swedish streams in summer and autumn (Table 10). It is evident that except for the 0+ age group the survival rate over the first year was very low.

The recapture rate for brown trout stocked as take-able-size fish (250–300 mm) was on average 27.2% (range: 5.0–39.8%) in the River Ribble and 18.4% (range: 7.0–29.2%) in the River Lune (Clifton-Dey and Walsingham, 1996). In the Ribble the majority of re-captures (54%) occurred within the first 5 weeks and 88% within the first 10 weeks (Clifton-Dey and Walsingham, 1996).

5.4. Cost per adult return

The cost per adult return can be calculated using data on the unit cost of production (Table 7) and on survival rates in the hatchery and after release into the wild (Section 5.2). Harris (1994) estimated for salmon that the cost per adult return ranged from £ 143 for unfed fry to £ 32 for 0+ parr. In contrast, studies on the River Conon in Scotland indicated a cost of £ 3.52 per adult return for fish stocked as eyed ova/unfed fry. In the case of smolts Harris (1994) over-estimates the cost of a returning adult as no account is taken of the extra benefit derived from surplus fry production grown for smolt (1+) programmes. Taylor (1999) estimated that if the surplus production was taken into account then this reduces the cost per fish by approximately half from £ 100 to £ 43.50.

In those cases where the donor stock is below its conservation level and where the spawning and nursery habitat is of good quality then it is important that net benefit be determined. The net benefit takes into account the number of adult salmon that would have been produced if the broodstock had been allowed to spawn in the wild. If this cost is taken into account then Harris (1994) estimated that stocking with green ova, eyed ova and unfed fry resulted in a negative benefit in that more fish would have returned if the fish had been allowed to spawn naturally. For the other life stages the net cost per adult return ranged from £ 388.88 for fed fry to £ 35.01 for 0+ parr.

When calculating the benefit in terms of rod caught fish, account needs to be taken of exploitation rate in the cost per fish caught. For example, if the exploitation rate was 15% then the cost per adult fish caught for fish stocked as 0+ parr is £ 214.47 or £ 233.40 if nett benefit is to being considered using the figures from Harris (1994).

5.5. Economic value

The benefit in terms of economic value can be calculated from the number of fish caught multiplied by their capital value. The capital value of a salmon was calculated to be £ 5925 (1995 prices) by Postle and Moore (1996) and represents the economic value of one extra rod caught salmon each year to the fishery. Scott et al. (1997) estimated the benefit:cost ratio of stocking with 0+ sea trout to range from 25.6:1 to 64.2:1. In their study, benefit was defined as the change in capital value of the fishery.

The change in economic rent can be determined, if the rent is a fixed proportion of the capital value, for example 10% equating to £ 593 per rod caught fish. For sea trout, the economic value can be assumed to equate to 0.25 of the capital value of salmon.

For trout fisheries an upper and lower estimate of economic value can be estimated. The upper value can be determined using the average permit or site licence fees paid by anglers, the cost being; stocked waters (£ 11.30), wild fisheries in lowland rivers (£ 10.20) and wild fisheries in upland waters (£ 4.10) (Postle and Moore, 1996). The economic value can be determined once the number of extra fishing days has been estimated.

The lower estimate of economic value can be determined from an anglers' willingness to pay which for trout ranges from £ 2.05 to £ 5.65 per angler day. This needs to be multiplied by the number of extra angler days achieved to determine the overall economic value.

5.6. Other considerations

In assessing the benefit it is important to consider the chance that the stocking may fail, for example because of a pollution or flood event. If, for example, 5% of all stockings fail then this needs to be taken into account when determining the overall benefit, which in this case would be benefit $\times$ 0.95. Similarly, if periodically a significant proportion of the stock in the hatchery is lost, for example once every 20 years because of excessively high levels of suspended solids, then this loss will need to be built into the cost and benefit calculations.

6. Conclusions

Stocking can be regarded as a useful management technique for improving stocks of salmonids. However, artificial reproduction will not lead to recovery unless the fundamental problems that cause the population to decline are addressed (Jonsson et al., 1999) and it may place the population at greater risk than it would have been if it had been left alone (Waples and Do, 1994). Stocking of salmon can be considered a very cost effective option if carried out responsibly, with costs per returning adult as low as £ 3.50, though there are large disagreements between authors. There are however significant risks associated with stocking, most notably the genetic impact on the resident/wild stock. This and other risks need to be managed. This can best be achieved by formalising the risk assessment process. For each management action the probability, consequences and uncertainty of meeting the operational goals need to be assessed and then discussed with the interested parties the implications of these actions and whether these risks are acceptable. It is important that fisheries managers and owners are aware that their actions can have repercussions outside the boundaries of their particular fisheries, but with responsible management and risk minimisation stocking can be a very beneficial and cost effective tool.

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