Ecological and water quality consequences of nutrient addition for salmon restoration in the Pacific Northwest

Jana E Compton[1*], Christian P Andersen[1], Donald L Phillips[1], J Renée Brooks[1], Mark G Johnson[1], M Robbins Church[1], William E Hogsett[1], Michael A Cairns[1], Paul T Rygiewicz[1], Brenda C McComb[2], and Courtney D Shaff[3]

Salmon runs have declined over the past two centuries in the Pacific Northwest region of North America. Reduced inputs of salmon-derived organic matter and nutrients (SDN) may limit freshwater production and thus establish a negative feedback loop affecting future generations of fish. Restoration efforts use the rationale of declining SDN to justify artificial nutrient additions, with the goal of reversing salmon decline. The forms of nutrient addition include introducing salmon carcasses, carcass analogs (processed fish cakes), or inorganic fertilizers. While evidence suggests that fish and wildlife may benefit from increases in food availability as a result of carcass additions, stream ecosystems vary in their ability to use nutrients to benefit salmon. Moreover, the practice may introduce excess nutrients, disease, and toxic substances to streams that may already exceed proposed water quality standards. Restoration efforts involving nutrient addition must balance the potential benefits of increased food resources with the possible harm caused by increased nutrient and toxin loads.

***Front Ecol Environ* 2006; 4(1): 18–26**

The decline in salmon populations has tremendous economic, cultural, and social implications for the Pacific Northwest (PNW) of North America (Lichatowich 1999). The marine-derived organic matter and nutrients supplied by salmon (here termed SDN; Figure 1) also play an important ecological role in riparian and freshwater ecosystems (Naiman *et al.* 2002; Schindler *et al.* 2003). It has been hypothesized that declines in SDN from historically large salmon runs have negatively impacted freshwater production, reducing smolt survival and subsequent run size. Findings that support this hypothesis include declines in SDN contributions to many watersheds during the past century (Gresh *et al.* 2000), increases in juvenile salmon growth following nutrient enrichment of streams in British Columbia (Johnston *et al.* 1990), and demonstrated incorporation of SDN into freshwater ecosystems using a stable isotope approach (Bilby *et al.* 1996). These findings have led PNW scientists and managers to call for nutrient addition as a component of salmon restoration. For decades, managers in British Columbia fertilized lakes and streams to improve fish production (Slaney *et al.* 2003). Recent restoration projects in Oregon and Washington State place hatchery salmon carcasses directly in streams. Oregon's program has distributed over 158 000 salmon carcasses to 36 watersheds in western Oregon since 1995 (ODFW 2004), while Washington's program currently includes protocols for adding salmon carcasses, carcass analogs (processed cakes composed of ocean fish), and inorganic nutrients (WDFW 2004).

In a nutshell:

- Adding salmon carcasses or inorganic nutrients to a stream is a restoration tool in the Pacific Northwest, yet the effects are not well studied across the region
- Inorganic nutrient addition may not increase aquatic production in many small streams and, ultimately, may not benefit salmon
- We recommend expanded monitoring of the nutrient enhancement programs in order to determine where streams may benefit or where water quality problems may arise

The restoration goal of nutrient addition is to increase growth and survival of juvenile salmon; ideally this practice would increase returns of adult salmon through a positive feedback. However, along with important nutrients and energy, salmon carcasses carry toxins and sometimes pathogens. Nutrient enrichment should therefore be viewed in a broader ecosystem context, including the possible effects on other fish and wildlife, implications for water quality, and the potential spread of pathogens and toxins. Understanding the consequences of nutrient addition is particularly important for the Oregon Coast Range (OCR), which supports threatened populations of coho salmon (Ruckelshaus *et al.* 2002). While OCR streams are unconstrained by dams that restrict salmon migration, suggesting that recovery potential is relatively high, habi-

---

[1] *US Environmental Protection Agency, National Health and Environmental Effects Laboratory, Western Ecology Division, 200 SW 35th St, Corvallis, OR 97333 *(compton.jana@epa.gov); [2] Department of Natural Resources Conservation, University of Massachusetts, Amherst, MA 01003; [3] Environmental Science Graduate Program, Oregon State University, Corvallis OR 97331*

© The Ecological Society of America

tat degradation impedes restoration in many areas (Lichatowich 1999). Despite this, there has been little research concerning SDN in the region. Here we review the literature on sources and outcomes of stream nutrients, focusing on potential effects of nutrient enhancement. Our review identifies scientific uncertainties surrounding nutrient addition for salmon restoration, with an emphasis on implications for ecological function, water quality, and spread of diseases and toxins.

Figure 1. *Chinook salmon carcass in Oregon's North Umpqua River.*

■ Nutrient supplies to PNW streams

Understanding terrestrial and aquatic linkages is particularly critical to nutrient management. We consider the relative importance of both terrestrial and marine nutrient sources, focusing on nitrogen (N) and phosphorus (P), the key limiting nutrients for primary production in PNW streams (Welch *et al.* 1998).

In undisturbed PNW watersheds, nutrients are derived from atmospheric and geologic sources (Figure 2). Triska *et al.* (1984) showed that N inputs to a stream reach in an old growth watershed in Oregon's Cascade Mountains were dominated by dissolved organic N from groundwater (69% of inputs), with litterfall and precipitation playing smaller roles. Vegetation, geological features, and disturbance appear to yield high and variable N and P concentrations in OCR streams (Wigington *et al.* 1998). N_2-fixing red alder (*Alnus rubra*) is a major source of dissolved N in streams (Compton *et al.* 2003; Figure 3). Geology is complex and some bedrock types yield high stream P (Ice and Binkley 2003). This regional variability suggests that nutrient addition will be difficult to manage without knowledge of the nutrient status of individual streams.

Nutrient inputs to streams have shifted in quantity and composition over time, with implications for the potential fate and effects of artificial additions. Towns and farms are usually found along river valleys and estuaries, whereas forests dominate upper watersheds in the OCR (Wimberley and Ohmann 2004). Agricultural and urban activities generally increase N and P delivery to streams via soil disturbance, increased runoff, sewage inputs, and fertilization (Welch *et al.* 1998). The effects of logging on stream nutrient concentrations vary with nutrient form, site, and harvest method, with moderate to strong increases after logging (McClain *et al.* 1998). Logging increases soil-derived sediment loads to streams and decreases riparian litter inputs (McClain *et al.* 1998). Historic logging practices that expanded alder cover on the landscape increased nitrate loading to streams (Compton *et al.* 2003), although alder expansion may be reversing in some areas (Wimberley and Ohmann 2004). We therefore conclude that human activities generally have increased nutrient transfer from terrestrial to aquatic ecosystems and altered nutrient forms in the OCR.

The return of anadromous fish acts as a source of nutrients for freshwater ecosystems, yet animal migration is not included in most watershed models. Drastic reductions in run sizes over the past two centuries, together with declines in average fish size, have reduced watershed N and P inputs via returning salmon to only 6–7% of historic levels in coastal California, Oregon, and Washington (Gresh *et al.* 2000). Terrestrial nutrient sources are substantially different

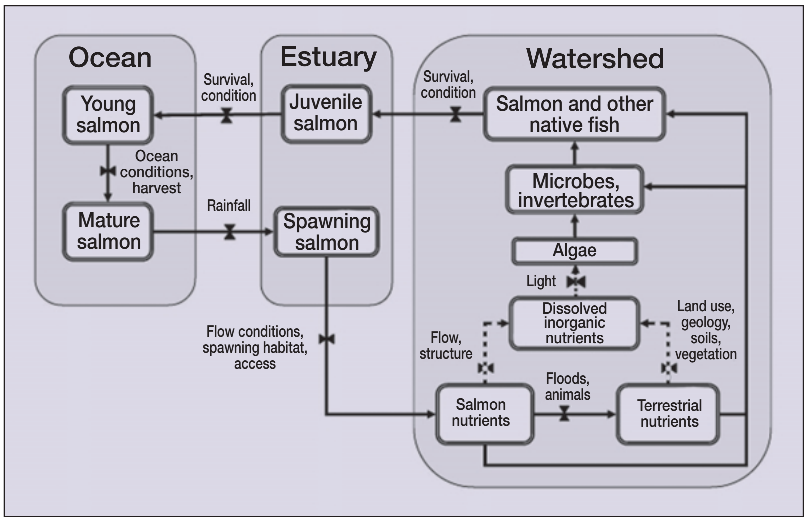

Figure 2. *Simplified nutrient and organic matter flows within a Pacific Northwest watershed, and transfers to the ocean and estuary by salmonids. Solid lines indicate transfers of materials or organisms. Dotted lines indicate movement of dissolved inorganic nutrients. Hourglass symbols indicate controls on a given flow. Inorganic nutrients can only be incorporated into stream food webs by primary production or fungal and bacterial growth, since secondary producers like fish and insects do not use these forms.*

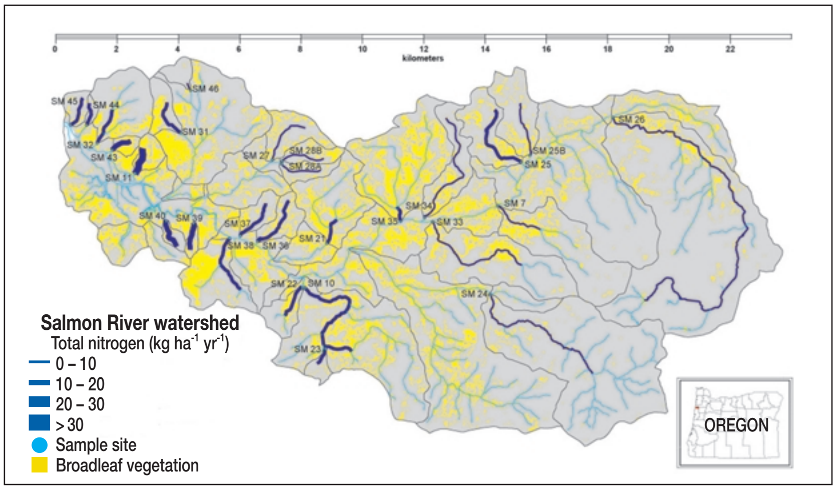

Figure 3. *Diagram showing the spatial relationships between stream N export and red alder cover. Width of dark blue lines is proportional to stream total nitrogen fluxes from watersheds in the Salmon River watershed. Yellow shading indicates the land area occupied by broadleaf forest cover, which is strongly dominated by red alder (94% of basal area on average). Data from Compton* et al. *(2003).*

from marine salmon inputs in form, timing, and distribution (Table 1). Sediment, fertilizers, and sewage are dominated by inorganic or mineral-associated forms (Carpenter *et al.* 1998), while carcasses are dominated by organic forms. Carcass flesh and eggs can be directly consumed by invertebrates, fish, and wildlife, while inorganic and mineral-associated nutrients have little direct food value for invertebrates and fish.

Watershed retention of SDN has probably declined during the past century. Woody debris retains carcasses in stream channels (Cederholm *et al.* 1989); splashdams and removal of large wood from rivers and streams during the past century (Sedell and Froggatt 1984) probably reduced carcass retention (Figure 4). Beaver (*Castor canadensis*) ponds retain organic matter and alter nutrients (Naiman *et al.* 1988), so beaver trapping may have reduced SDN retention compared to historic levels. Many animals consume salmon carcasses (Willson and Halupka 1995) and are therefore vectors for SDN dispersal and subsequent retention on land (eg river otters [*Lontra canadensis*] and raccoons [*Procyon lotor*] near streams). Bald eagles (*Haliaeetus leucocephalus*), turkey vultures (*Cathertes aura*), ravens (*Corvus corax*), and gulls (*Larus* spp) may move carcasses some distance away from the stream (Figure 5). Human activities that affect animal populations and stream structure thus limit the distribution and storage of SDN within watersheds.

Table 1. Contrast between terrestrial and marine sources of organic matter and nutrients to streams

Source	*Form*	*Timing*	*Location*
Terrestrial – dissolved	Inorganic macro/micronutrients dissolved organic	Continuous, peak in winter	Water column
Terrestrial – particulate organic	Cellulose, lignin, lipids, protein, macro/micronutrients	Pulsed, peak in fall	Patchy
Terrestrial – sediment bound	Humus, mineral particles	Pulsed, peak during storms	Patchy
Marine – adult salmon	Protein, fats, carbohydrates, macro/micronutrients	Pulsed, peak in fall*	Patchy in-stream riparian

*Spawning in the Oregon Coast Range historically occurred throughout the year, but human activities have generally concentrated spawning time and location (Lichatowich 1999).

Ecological considerations for nutrient addition

Salmon carcasses are a seasonal source of organic matter and are incorporated into stream food webs via two dominant pathways: primary production, or uptake by stream algae after decay into inorganic forms; and secondary production, or the consumption of eggs and flesh by heterotrophic microbes, invertebrates, fish, or mammals (Figure 2). The pathways of incorporation can have widely divergent implications for streams (eg increasing juvenile salmon production versus contributing to harmful algal blooms).

Effects on primary production

Inorganic nutrients are not expected to increase primary production in small, forested OCR streams, given that these streams often contain high nutrient concentrations and are shaded. Inorganic nutrient additions can increase primary production in nutrient-poor streams with open canopies (Perrin *et al.* 1987), which in turn stimulates insect and fish production (Slaney *et al.* 1986; Johnston *et al.* 1990). Ashley and Stockner (2003) proposed limiting P concentrations to 1 µg soluble reactive P L^{-1}, but most OCR streams exceed this concentration (Wigington *et al.* 1998). Mass ratios of dissolved N:P often exceed 20:1 (Welch *et al.* 1998; JE Compton and MR Church unpublished), which is greater than the critical 7:1 ratio for algal growth (Redfield 1958). Light limitation or other limiting factors may preclude an increase in primary production associated with inorganic additions.

The response of primary production to salmon carcass addition has varied from no increase (Minshall *et al.* 1991), to an increase in primary production only (Richey *et al.* 1975), and to increased primary production as one of many responses (Wipfli *et al.* 1998). Bilby *et al.* (1996) found that primary production accounted for only a small proportion of SDN incorporation in a western Washington stream; main pathways

© The Ecological Society of America

were direct consumption by insects and juvenile fish, sorption to the streambed, and uptake by secondary producers.

Nutrient additions should be considered in a broader temporal and spatial context in order to avoid undesirable effects. Added nutrients in small streams could stimulate algal production downstream as light availability increases. Nutrients are of particular concern in estuaries, which can be more strongly nutrient limited than streams (Cloern 2001). A watershed view of nutrient enrichment in which downstream condition is considered should therefore be adopted. Timing is also important, as most algal production is expected to occur during the spring and summer (Rounds and Woods 2001), while carcass addition is driven by fall salmon runs. If SDN added in the fall are retained in the streambed (Bilby *et al.* 1996) and released the following spring or summer, this could stimulate algal production in open stream reaches. If not, nutrients added in the fall may not cause algal blooms. The timing and persistence of SDN additions is an important component of nutrient management that needs further study.

Courtesy of US EPA

Figure 4. *Stream structure has been altered by human activities in many parts of the OCR. (a) Areas where the substrate is bedrock only (West Fork Smith River); (b) areas where wood and rocks provide structure (Elk Creek, Coquille River).*

Effects on secondary production

Experimental evidence in other areas of the PNW generally suggests that salmon carcass addition to streams will increase juvenile salmonid growth and density. Salmon carcasses can increase biomass and growth of aquatic invertebrates (Wipfli *et al.* 1998), which could indirectly increase fish production. Incorporation of SDN into stream food webs largely occurs via consumption of eggs and flesh by invertebrates and juvenile fish (Chaloner *et al.* 2002). Experiments have shown that carcass addition increased growth, condition, and density of salmonids in some PNW streams (Bilby *et al.* 1998; Wipfli *et al.* 2003). More and larger juvenile salmon result in better survival over the winter (Quinn and Peterson 1996) and in the ocean (Ward and Slaney 1988); carcass addition could potentially lead to a positive feedback between adult returns and juvenile growth. In contrast, Wilzbach *et al.* (2005) found that juvenile trout did not respond to salmon carcass addition but instead responded to increased light associated with removal of the riparian canopy.

Unanswered questions about salmon carcass placement remain: will streams with higher background nutrients respond to carcass addition? Will shaded channels respond to nutrients? How long are carcass-derived nutrients retained (ie will they affect nutrient availability the following spring or summer?) Furthermore, while other native fish may respond to increased food availability resulting from carcass addition, we could not find any PNW studies that examined the effects on fish other than salmonids. The nature of responses to additions may also depend on the watershed nutrient and energy status, and the timing, quantity, and retention of the addition. As both biological and physical habitat structure fish communities (Reeves *et al.* 1998), carcass addition alone may not improve fish production in streams with poor physical environments.

Effects on riparian ecosystems

Salmon carcasses are an important food resource, influencing all trophic levels of PNW watersheds (Willson and Halupka 1995), and organisms that directly consume salmon are expected to benefit from carcass addition (Figure 5). Terrestrial scavengers and carnivores link the aquatic and terrestrial components of watersheds by physically transporting carcass material onto land. Flooding can also deposit salmon remains in riparian areas. Examination of stable N isotope ratios provides evidence that returning salmon contribute to forest nutrient pools. Because adult salmon returning from the ocean are enriched in ^{15}N relative to terrestrial sources, δ^{15}N of different ecosystem pools has been used to trace N from SDN. Using stable isotopes, SDN have been detected far away from streams in Alaska (Helfield and Naiman 2001). But there are limitations to the stable isotope approach. While incorporation of marine-derived ^{15}N into stream food webs demonstrates uptake, it does not demonstrate limitation by SDN availability. Isotopic ratios of trees, soils, and stream biota can also shift through processes that discriminate against the heavier

© B Babusis/www.LightscapeGallery.com

Figure 5. *Many organisms benefit from salmon returns, such as this bald eagle feeding on salmon in the Chilkat River Bald Eagle Preserve near Haines, Alaska.*

isotope (Pinay *et al.* 2003). It is therefore difficult to definitively estimate the proportion of SDN in riparian vegetation without considering differential fractionation. Nevertheless, comparisons of spawning to non-spawning sites provide compelling evidence that salmon N is used in terrestrial systems and that the presence of spawning salmon may even contribute to an increase in riparian tree growth (Helfield and Naiman 2001). This research suggests that the benefits of salmon carcass addition extend well beyond the streambank.

Other environmental concerns

Water quality and nutrient addition

The Clean Water Act (CWA) regulates pollutants in US water bodies by designating their beneficial use (eg drinking water, fisheries, or recreation), then setting criteria to protect that use. Criteria to protect sources of drinking water are long established; current EPA-proposed criteria for nutrients are the result of concerns about eutrophication (US EPA 2000). Since Oregon has not yet developed nutrient criteria for coastal streams to protect their use as fisheries, we use EPA's proposed criteria as a guide (Table 2).

Vegetation and underlying geology in many PNW watersheds can yield stream N and P levels that exceed EPA standards. When compared to proposed criteria (Table 2), stream P concentrations were five times greater in a small, old-growth watershed at the HJ Andrews Experimental Forest (Blue River, Oregon; Ice and Binkley 2003), and stream N concentrations were an order of magnitude greater in coastal Oregon (Compton *et al.* 2003). Despite minimal human impact, these watersheds would be considered "impaired" based on these standards, revealing a potential weakness of the criteria. Although nutrient levels can be high, problems associated with excess nutrients (eg harmful algal blooms or low dissolved oxygen levels) may be constrained by flow regimes, cool temperatures, and light limitations typical of many of western Oregon's forested streams.

If many OCR streams currently exceed proposed nutrient criteria, what effects will salmon carcass addition or restoration of salmon runs have on these streams and their CWA compliance? Stream ammonium increased following large returns of Alaskan salmon (Jauquet *et al.* 2003). Runs of Oregon salmon are generally an order of magnitude lower than in Alaska, but could still alter stream chemistry. Nutrient additions may exacerbate algal blooms if nutrients persist into spring and summer. Inherently high nutrients do not raise eutrophication concerns in many streams due to physical limitations such as light and scour, but the inconsistency remains that salmon carcasses are added with the intention of fertilizing streams that already have inherently high N and P concentrations. These issues should be resolved before developing nutrient criteria and management strategies. Since the proposed criteria may not take into account natural sources of N and P, comparing pre-treatment water chemistry with guidelines for nutrient addition in other areas of the PNW (Ashley and Stockner 2003) will help inform restoration.

Table 2. Proposed water quality criteria for western forested mountains, based on the 25th percentile of stream samples collected (US EPA 2000)

	Western forested mountains[1]		*Oregon and Washington coastal forested mountains*[2]	
Nutrient parameter	N*	25th percentile	N*	25th percentile
Total P ($\mu g\ L^{-1}$)	1380	10.0	134	10.25
Total N ($mg\ L^{-1}$)	239	0.12	21	0.13
$NO_2 + NO_3$ ($mg\ N\ L^{-1}$)	1061	0.014	137	0.09

[1] Ecoregion II [2] Ecoregion II, Level III ecoregion I *Number of streams used to generate the criteria.

Potential pathogen spread associated with salmon carcass placement

Pathogens could influence the health of juvenile salmon, as well as other organisms that may become infected after feeding on carcasses. This concern is addressed by rules in the Hatchery Management and Disease Control Plans governing carcass placement (Washington State Fisheries Co-Managers 1998; ODFW 2003). These plans prohibit placement of carcasses across major watersheds and require testing for evidence of regulated pathogens, including:

(1) infectious hematopoietic necrosis virus (IHNV); (2) infectious pancreatic necrosis virus; (3) North American viral hemorrhagic septicemia virus; (4) viral pathogens not known to exist in Washington state; and (5) whirling disease (*Myxobolous cerebralis*). While we found no documented infection of juvenile salmon from planted salmon carcasses, the potential for infection exists. Meyers (1998) found that virus-free sockeye smolts returned from the ocean as adults with a very high percentage of the fish infected with IHNV (99% in females and 40% in males). This finding emphasizes the importance of ongoing efforts to monitor carcasses and prevent the spread of pathogens.

Another concern with carcass placement is infection of domestic and wild animals with salmon poisoning disease (SPD). This disease was recognized in the 19th century in the PNW and occurs in canids (dogs, foxes, coyotes, and wolves) that consume salmon infected with trematodes carrying the rickettsia organism *Neorickettsia helminthoeca* (Knapp and Millemann 1981). SPD results in > 90% mortality without treatment in all canids, but recovery is high if treated. Many carcasses are frozen before planting, which reduces the spread of SPD, since freezing or cooking salmon inactivates *N helminthoeca*. Preventing infection of hatchery fish is another option, but concerns have been raised regarding the distribution of fish treated with antibiotics. Until now, controlling access of pets to salmon carcasses has been sufficient to reduce the frequency of SPD.

Toxin inputs from salmon carcasses

Anadromous fish transport toxins as well as nutrients from marine to freshwater and terrestrial environments. Toxins carried by salmon include metals such as mercury, arsenic, and cadmium, and organic compounds such as polychlorinated biphenyls (PCBs), pesticides, compounds found in fire retardants, and dioxins (Krummel *et al.* 2003; Hites *et al.* 2004). Since the occurrence of these toxins in the environment has increased over the past century, restoring historical run size and/or enhancing nutrients by carcass addition may inadvertently increase toxin loads to some streams. We focus on mercury and PCBs as examples of compounds of concern.

PCBs, which bioaccumulate at higher trophic levels, concentrate in lipid-rich tissues such as muscle (O'Neill *et al.* 1998). Salmon may retain more than half of their lifetime dietary PCBs (Madenjian *et al.* 2002), which often reach concentrations several million-fold higher in body lipids than are found in the surrounding ocean water (Krummel *et al.* 2003). PCB concentrations in salmon muscle tissue in the Columbia River Basin varied from 1–88 $\mu g\ kg^{-1}$ (US EPA 2002), which is well below the FDA interstate commerce limit (2000 $\mu g\ kg^{-1}$). O'Neill *et al.* (1998) calculated a mean PCB body burden of 130 μg for Chinook salmon returning to the Duwamish River, one of the most polluted rivers around Puget Sound. At this level, 10 000 returning spawners or carcass additions per year would deliver 1.3 g of PCBs to a watershed.

Most mercury in salmon occurs as methyl mercury (MeHg), which also biomagnifies at higher trophic levels (Zhang *et al.* 2001). These authors estimated mercury concentration factors of 52 000 and 32 000 for Chinook and coho muscle tissue, respectively, compared to the water column. Mercury concentrations in Columbia River Basin Chinook and coho measured nearly 100 $\mu g\ kg^{-1}$ (US EPA 2002), which is below the FDA limit of 200 $\mu g\ kg^{-1}$ of MeHg for human consumption (based on consumption rates of 1 kg fish week^{-1}). If 78% of the total mercury occurs in the form of MeHg (Zhang *et al.* 2001), then average size spawners in coastal Oregon streams (4 kg coho, 7 kg Chinook; ODFW 2002) would have MeHg body burdens nearing 310 μg and 550 μg, respectively. At these levels, 10 000 returning spawners or carcass additions would add 3.1–5 g of MeHg to a watershed, depending on the species, compared to 500 g for the Kvichak River watershed in southwest Alaska, with mean yearly returns of 6 million sockeye (Zhang *et al.* 2001).

Although reported toxin concentrations in salmon are generally below FDA limits for human consumption, carcass placement has the potential to increase watershed toxin loads to some extent. PCBs transported by salmon to remote areas in Alaska far exceed atmospheric inputs (Krummel *et al.* 2003). While numbers of fish would be much smaller for Oregon than Alaska, increased loading should be considered when making management decisions about the consequences of carcass addition, particularly in areas where toxins are already a concern.

■ Conclusions and implications

Managers are currently conducting an unstudied experiment in Oregon and Washington streams, without full consideration of ecological and water quality consequences. Volunteer groups have conducted nearly all of these efforts, and minimal monitoring or research has occurred as part of this restoration. In the OCR, lack of research on stream nutrient limitation and variability in watershed conditions leaves many questions unanswered. Based on scientific evidence from other areas, salmon carcass additions are expected to improve food resources for fish and wildlife. Current practices protect juvenile fish from disease, but watershed loads of toxins and nutrients will increase, with potentially negative consequences.

To balance salmon restoration with water quality issues, some questions should first be addressed: does nutrient addition increase production and survival of juvenile salmon in the OCR? Will these practices spread diseases and toxins? What are the consequences of additions within a whole watershed framework? We recommend that more comprehensive evaluation and monitoring programs, such as those suggested by Kiffney *et al.* (2005), accompany nutrient enhancement projects, to provide

Courtesy of Scott Lentz, US Forest Service (b): Courtesy of Matt Wallis/Skagit Valley Herald

Figure 6. *Methods of salmon carcass application range from targeted helicopter drops to volunteer manual labor. (a) Loading of a helicopter bucket. (b) Aerial application of salmon carcasses to the Baker River in Washington. (c) Salmon carcasses placed from a bridge into Elk Creek, Oregon, display the clumped distribution common to such means of introduction.*

insight into these issues. Streams with ongoing juvenile monitoring may also provide an opportunity to investigate the effects of carcass planting. Prior to nutrient enhancement, stream nutrient concentrations should be compared with water quality and ecological requirements. Determining stream nutrient levels and ratios may prove important, given the regional variability in nutrient status.

If nutrient addition is a viable tool in salmon recovery, how can we maximize benefit and minimize harm? It is important to distinguish the effects of nutrient forms. Salmon carcasses deliver organic nutrients, potentially increasing growth and survival of both aquatic insects and juvenile salmon. Added inorganic nutrients will probably not be incorporated in the relatively nutrient-rich streams of the OCR, and could have detrimental downstream effects. We suggest that freshwater salmon production is limited by some combination of physical habitat and food availability; therefore, increased supply of inorganic nutrients is unlikely to improve salmon production in this region. Stream nutrients are often greater than proposed water quality criteria, revealing a potential conflict between salmon restoration and water quality regulations. Placing this management tool in a watershed context could help. One serious concern is that nutrients added in small, light-limited forested reaches might have negative impacts on nutrient-limited algae in downstream reaches and estuaries.

The timing and location of carcass additions within a watershed have important consequences for their net effect (Figure 6). Few studies document long-term impacts of carcass addition. Placement efforts must be considered relative to algal blooms, reproductive cycles of mammals, and the retention of nutrients across seasons. Ben-David *et al.* (1997), studying the timing of reproduction in mink, found that lactation onset was closely aligned with the arrival of spawning salmon. Carcass addition projects usually follow natural runs, but addition of frozen carcasses or artificial materials that differs from the current timing of spawning could disrupt these ecological connections. Enrichment programs should mimic natural spawning both spatially and temporally, since many terrestrial and aquatic organisms benefit from carcass placement. Although further research is needed, using limited SDN resources in areas with good physical habitat could maximize benefits.

There are many unresolved issues surrounding nutrient enhancement in salmon restoration, particularly in the OCR. Decisions about salmon restoration must balance the benefits for aquatic and terrestrial organisms with the potentially harmful effects of increased nutrient and toxin loads. We hope further clarification of these issues will result in better scientific understanding and management of PNW watersheds.

■ Acknowledgements

We thank R Bilby, H Michael, R Lackey, and J Orme-Zavaleta for comments on this manuscript. This article has been subjected to the EPA's peer and administrative review, and approved for publication as an EPA document.

■ References

Ashley KI and Stockner JG. 2003. Protocol for applying limiting nutrients to inland waters. In: Stockner JG (Ed). Nutrients in salmonid ecosystems: sustaining productivity and biodiversity. Bethesda, MD: American Fisheries Society.

Ben-David M, Hanley TA, Klein TR, and Schell DM. 1997. Timing of reproduction in wild mink: the influence of spawning Pacific salmon. *Can J Zool* **75**: 376–82.

Bilby RE, Fransen BR, and Bisson PA. 1996. Incorporation of nitrogen and carbon from spawning coho salmon into the trophic system of small streams: evidence from stable isotopes. *Can J Fish Aquat Sci* **53**: 164–73

Bilby RE, Fransen BR, Bisson PA, and Walter JK. 1998. Response of juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead (*Oncorhynchus mykiss*) to the addition of salmon carcasses to two streams in southwestern Washington, USA. *Can J Fish Aquat Sci* **55**: 1909–18

Carpenter SR, Caraco NF, Correll DL, *et al.* 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol Appl* **8**: 559–68.

Cederholm CJ, Houston DB, Cole DL, and Scarlett WJ. 1989. Fate of coho salmon (*Oncorhynchus kisutch*) carcasses in spawning streams. *Can J Fish Aquat Sci* **46**: 1347–55.

Chaloner DT, Wipfli MS, and Caouette JP. 2002. Mass loss and macroinvertebrate colinisation of Pacific salmon carcasses in south-eastern Alaskan streams. *Freshwater Biol* **47**: 263–73.

Cloern JE. 2001. Our evolving conceptual model of the coastal eutrophication problem. *Mar Ecol–Prog Ser* **210**: 223–53

Compton JE, Church MR, Larned ST, and Hogsett WE. 2003. Nitrogen export from forested watersheds of the Oregon Coast Range: the role of N_2-fixing red alder. *Ecosystems* **6**: 773–85.

Gresh T, Lichatowich J, and Schoonmaker P. 2000. An estimation of historic and current levels of salmon production in the Northeast Pacific Ecosystem. *Fisheries* **25**: 15–21.

Helfield JM and Naiman RJ. 2001. Effects of salmon-derived nitrogen on riparian forest growth and implications for stream productivity. *Ecology* **82**: 2403–09.

Hites RA, Foran JA, Schwager SJ, *et al.* 2004. Global assessment of polybrominated diphenyl ethers in farmed and wild salmon. *Environ Sci Technol* **38**: 4945–49.

Ice G and Binkley D. 2003. Forest streamwater concentrations of nitrogen and phosphorus: comparison with EPA's proposed water quality criteria. *J Forest* **101**: 21–28.

Jauquet J, Pittman N, Heinis JA, *et al.* 2003. Observations of chum salmon consumption by wildlife and changes in water chemistry at Kennedy Creek during 1997–2000. In: Stockner JG (Ed). Nutrients in salmonid ecosystems: sustaining productivity and biodiversity. Bethesda, MD: American Fisheries Society.

Johnston NT, Perrin CJ, Slaney PA, and Ward BR. 1990. Increased juvenile salmonid growth by whole-river fertilization. *Can J Fish Aquat Sci* **47**: 862–72.

Kiffney PM, Bilby RE, and Sanderson BL. 2005. Monitoring the effects of nutrients enrichment on freshwater ecosystems. In: Roni P (Ed). Monitoring stream and watershed restoration. Bethesda, MD: American Fisheries Society.

Knapp SE and Millemann RE. 1981. Salmon poisoning disease. In: Davis JW, Karstad LH, and Trainer DO (Eds). Infectious diseases of wild mammals. Ames, IA: Iowa State University Press.

Krummel EM, Macdonald RW, Kimpe LE, *et al.* 2003. Delivery of pollutants by spawning salmon. *Nature* **425**: 255–56.

Lichatowich J. 1999. Salmon without rivers: a history of the Pacific salmon crisis. Washington, DC: Island Press.

Madenjian CP, O'Connor DV, Stewart DJ, *et al.* 2002. Field estimate of net trophic transfer efficiency of PCBs to Lake Michigan Chinook salmon from their prey. *Environ Sci Technol* **36**: 5029–33.

McClain ME, Bilby RE, and Triska FJ. 1998. Biogeochemistry of N, P, and S in Northwest rivers: natural distributions and responses to disturbance. In: Naiman RJ and Bilby RE (Eds). River ecology and management: lessons from the Pacific coastal ecoregion. New York, NY: Springer-Verlag.

Meyers TR. 1998. Healthy juvenile sockeye salmon reared in virus-free hatchery water return as adults infected with infectious hematopoietic necrosis virus (IHNV): a case report and review of controversial issues in the epizootiology of IHNV. *J Aquat Anim Health* **10**: 172–81.

Minshall GW, Hitchcock E, and Barnes JR. 1991. Decomposition of rainbow trout (*Oncorhynchus mykiss*) carcasses in a forest stream inhabited only by nonanadromous fish populations. *Can J Fish Aquat Sci* **48**: 191–95.

Naiman RJ, Bilby RE, Schindler DE, and Helfield JM. 2002. Pacific salmon, nutrients, and the dynamics of freshwater and riparian ecosystems. *Ecosystems* **5**: 399–417.

Naiman RJ, Johnston CA, and Kelley JC. 1988. Alteration of North American streams by beaver. *BioScience* **38**: 753–62.

ODFW (Oregon Department of Fish and Wildlife). 2002. Salmon and trout enhancement program. Portland, OR: Oregon Department of Fish and Wildlife. Annual Progress Report.

ODFW (Oregon Department of Fish and Wildlife). 2003. Oregon fish hatchery management policy. Portland, OR: Oregon Department of Fish and Wildlife. OAR 635-007-0547.

ODFW (Oregon Department of Fish and Wildlife). 2004. Hatchery fish carcass placements in Oregon streams: final reports 1997–2004. Portland, OR: Oregon Department of Fish and Wildlife.

O'Neil SM, West JE, and Hoeman JC. 1998. Spatial trends in the concentration of polychlorinated biphenyls (PCBs) in Chinook (*Oncorhynchus tshawytscha*) and coho salmon (*O kisutch*) in Puget Sound and factors affecting PCB accumulation: results from the Puget Sound Ambient Monitoring Program. In: Strickland R (Ed). Puget Sound research '98 proceedings. Seattle, WA: Puget Sound Water Quality Action Team.

Perrin CJ, Bothwell ML, and Slaney PA. 1987. Experimental enrichment of a coastal stream in British Columbia: effects of organic and inorganic additions on autotrophic periphyton production. *Can J Fish Aquat Sci* **44**: 1247–56.

Pinay G, O'Keefe T, Edwards R, and Naiman RJ. 2003. Potential denitrification activity in the landscape of a western Alaska drainage basin. *Ecosystems* **6**: 336–43.

Quinn TP and Peterson NP. 1996. The influence of habitat complexity and fish size on over-winter survival and growth of individually marked juvenile coho salmon (*Oncorhynchus kisutch*) in Big Beef Creek, Washington. *Can J Fish Aquat Sci* **53**: 1555–64.

Redfield AC. 1958. The biological control of chemical factors in the environment. *Am Sci* **46**: 205–21.

Reeves GH, Bisson PA, and Dambacher JM. 1998. Fish communities. In: Naiman RJ and Bilby RE (Eds). River ecology and management: lessons from the Pacific coastal ecoregion. New York, NY: Springer-Verlag.

Richey JE, Perkins MA, and Goldman CR. 1975. Effects of kokanee salmon (*Oncorhynchus nerka*) decomposition on the ecology of a sub-alpine stream. *J Fish Res Board Can* **32**: 817–20.

Rounds SA and Wood TM. 2001. Modeling water quality in the Tualatin River, Oregon, 1991–97. Portland, OR: US Geological Survey. Water Resources Investigations Report 01–4041.

Ruckelshaus MH, Levin P, Johnson JB, and Kareiva PM. 2002. The Pacific salmon wars: what science brings to the challenge of recovering species. *Ann Rev Ecol Syst* **33**: 665–706.

Schindler DE, Scheuerell MD, Moore JW, *et al.* 2003. Pacific salmon and the ecology of coastal ecosystems. *Front Ecol Environ* **1**: 31–37.

Sedell JR and Froggatt JL. 1984. Importance of streamside forests to large rivers: the isolation of the Willamette River, Oregon, USA, from its floodplain by snagging and streamside forest removal. *Verh Int Vereinigung Limnol* **22**:1828–34.

Slaney PA, Perrin CJ, and Ward BR. 1986. Nutrient concentration as a limitation to steelhead smolt production in the Keogh River. *P Annu Conf West Assoc Fish Wildlife Agen* **66**: 146–57.

Slaney PA, Ward BR, and Wightman JC. 2003. Experimental nutrient addition to the Keogh River and application to the Salmon River in coastal British Columbia. In: Stockner JG (Ed). Nutrients in salmonid ecosystems: sustaining productivity and biodiversity. Bethesda, MD: American Fisheries Society.

Triska FJ, Sedell JR, Cromack KJ, *et al.* 1984. Nitrogen budget for a small coniferous forest stream. *Ecol Monogr* **54**: 119–40.

US EPA (US Environmental Protection Agency). 2000. Ambient water quality criteria recommendations information supporting the development of state and tribal nutrient criteria: rivers and streams in nutrient ecoregion II. Washington, DC: US EPA. Report 822-B-00-015.

US EPA (US Environmental Protection Agency). 2002. Columbia River basin fish contaminant survey 1996–1998. Seattle, WA: US EPA. Report 910-R-02-006.

Ward BR and Slaney PA. 1988. Life history and smolt-to-adult survival of Keogh River steelhead trout (*Salmo gairdneri*) and the relationship to smolt size. *Can J Fish Aquat Sci* **45**: 1110–22.

Washington State Fisheries Co-Managers. 1998. Salmonid disease control policy. www.nwifc.wa.gov/enhance/. Viewed September 2004.

WDFW (Washington Department of Fish and Wildlife). 2004. Protocols and guidelines for distributing salmonid carcasses, salmon carcass analogs, and delayed release fertilizers to enhance stream productivity in Washington State. Seattle, WA: Washington Department of Fish and Wildlife.

Welch EB, Jacoby JM, and May CW. 1998. Stream quality. In: Naiman RJ and Bilby RE (Eds). River ecology and management: lessons from the Pacific coastal ecoregion. New York, NY: Springer-Verlag.

Wigington PJ, Church MR, Strickland TC, *et al.* 1998. Autumn chemistry of OCR streams. *J Am Water Resour As* **34**: 1035–49.

Willson MF and Halupka KC. 1995. Anadromous fish as keystone species in vertebrate communities. *Conserv Biol* **9**: 489–97.

Wilzbach MA, Harvey BC, White JL, and Nakamoto RJ. 2005. Effects of riparian canopy opening and salmon carcass addition on the abundance and growth of resident salmonids. *Can J Fish Aquat Sci* **62**: 58–67.

Wimberly MC and Ohmann JL. 2004. A multi-scale assessment of human and environmental constraints on forest land cover change on the Oregon (USA) coast range. *Landscape Ecol* **19**: 631–46.

Wipfli MS, Hudson JP, and Caouette JP. 1998. Influence of salmon carcasses on stream productivity: response of biofilm and benthic macroinvertebrates in southeastern Alaska, USA. *Can J Fish Aquat Sci* **55**: 1503–11.

Wipfli MS, Hudson JP, Caouette JP, and Chaloner DT. 2003. Marine subsidies in freshwater ecosystems: salmon carcasses increase the growth rates of stream-resident salmonids. *T Am Fish Soc* **132**: 371–81.

Zhang X, Naidu A, Kelley JJ, *et al.* 2001. Baseline concentrations of total mercury and methylmercury in salmon returning via the Bering Sea (1999–2000). *Mar Pollut Bull* **42**: 993–97.