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Watershed nitrogen input and riverine export on the west coast of the US

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Abstract This study evaluated the sources, sinks, and factors controlling net export of nitrogen (N) from watersheds on the west coast of the US. We calculated input of new N to 22 watersheds for 1992 and 2002. 1992 inputs ranged from 541 to 11,644 kg N km^{-2} $year^{-1}$, with an overall area-weighted average of 1,870 kg N km^{-2} $year^{-1}$. In 2002, the range of inputs was 490–10,875 kg N km^{-2} $year^{-1}$, averaging 2,158 kg N km^{-2} $year^{-1}$. Fertilizer was the most important source of new N, averaging 956 (1992) and 1,073 kg N km^{-2} $year^{-1}$ (2002). Atmospheric deposition was the next most important input, averaging 833 (1992) and 717 kg N km^{-2} $year^{-1}$ (2002), followed by biological N fixation in agricultural lands. Riverine N export, calculated based on measurements taken at the furthest downstream USGS water quality monitoring station, averaged 165 (1992) and 196 kg N km^{-2} $year^{-1}$ (2002), although data were available for only 7 watersheds at the latter time point. Downstream riverine N export was correlated with variations in streamflow (export = 0.94 × streamflow − 5.65, $R^2 = 0.66$), with N inputs explaining an additional 16% of the variance (export = 1.06 × streamflow + 0.06 × input − 227.78, $R^2 = 0.82$). The percentage of N input that is exported averaged 12%. Percent export was also related to streamflow (%export = 0.05 × streamflow − 2.61, $R^2 = 0.60$). The correlations with streamflow are likely a result of its large dynamic range in these systems. However, the processes that control watershed N export are not yet completely understood.

Keywords Nitrogen budgets · Nutrient inputs · Riverine export · Watersheds · West coast

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Introduction

Excess loading of nutrients to the coastal zone is posited to be a primary cause of eutrophication-related problems. As nutrient loading (particularly nitrogen loading) increases, coastal marine systems show symptoms such as increased frequency and severity of algal blooms, decreased dissolved oxygen concentrations, and loss of submerged aquatic vegetation (Bricker et al. 2007). N export from watersheds to the coastal zone has been shown to be directly related to watershed input, such that increased input of new N results in a predictable increase in export to downstream receiving waters (e.g., Howarth et al. 1996; Boyer et al. 2006). Controls on the percentage of watershed N input that reaches the coast are less clear. Different studies have shown that percent N export can be related to streamflow (Dumont et al. 2005), temperature (Schaefer and Alber 2007), and residence time (Howarth et al. 2006).

Watershed nitrogen budgets have been constructed for a variety of different regions, including much of the US (Boyer et al. 2002; McIsaac et al. 2002; Schaefer and Alber 2007); China (Liu et al. 2006); and New Zealand (Parfitt et al. 2006), but to date there are no large-scale studies of the west coast of the United States. The climatology and geomorphology of US west coast watersheds differs significantly from those on the US east coast, yet water quality and land use data sets are collected by the same agencies, suggesting that a comparison of the two might yield insights into the factors affecting nitrogen processing in watersheds. In this study we estimated watershed N input and export of that N to the coastal zone for 22 west coast watersheds (Fig. 1) for two periods: the early 1990s, which is comparable to the period of budgeting exercises for the eastern US (Boyer et al. 2002; Schaefer and Alber 2007), and the early 2000s. We examined the relationship between watershed N input and export to the coast for these systems, and tried to elucidate the factors that explained both absolute and proportionate N export.

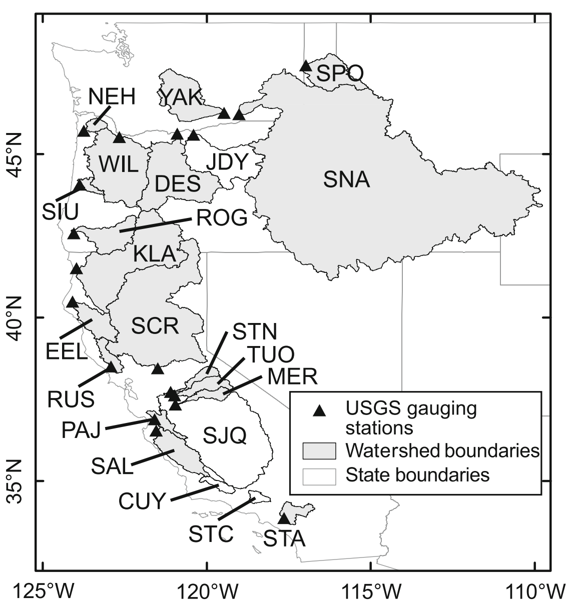

Fig. 1 US west coast watersheds considered in this study. Abbreviations are as in Table 1. Watersheds not shaded (CUY, JDY, SJQ, and STC) were not included in the analysis of export (see text)

Methods

Nitrogen budgets were constructed for the early 1990s (with a target year of 1992) and for the early 2000s (target year 2002) for 22 west coast watersheds (Fig. 1). The methodology used in constructing these budgets was very similar to that reported in Schaefer and Alber (2007), which was in turn based on the methods developed by Boyer et al. (2002) as part of the International SCOPE N project. We considered atmospheric deposition, fertilizer, net food and feed import, and biological nitrogen fixation as sources of new N to watersheds and compared these to riverine export at the most downstream USGS water quality monitoring station.

Atmospheric deposition

Wet and dry atmospheric N deposition were calculated by constructing Thiessen polygons from data collected at monitoring stations in the National Atmospheric Deposition Program/National Trends Network (NADP 2006) and the Clean Air Status and Trends Network (USEPA 1995), respectively. Organic N deposition was assumed to account for 30% of total atmospheric deposition (Neff et al. 2002), half of which was considered a new input (Boyer et al. 2002). 25% of N volatilized from animal manures and fertilizer (Battye et al. 1994) was assumed to be exported from each watershed and was subtracted from total atmospheric deposition (Boyer et al. 2002).

Fertilizer

Fertilizer use was calculated from county-by-county fertilizer sales data (Battaglin and Goolsby 1994; Ruddy et al. 2006) by weighting the amount of fertilizer sold in each county by the proportion of agricultural land in that county that was located within the watershed. Watershed totals were obtained by summing over all counties in the watershed. Land use was obtained from 1992 and 2001 national land cover data (USGS 1999a–c, 2000a–f; Vogelmann et al. 2001).

Net food and feed import

Net food and feed import is defined as total N consumption (by livestock and humans) minus total

N production (by crops and livestock). This quantity will be negative (and hence represent an export) when N production exceeds consumption. Crop production in each county (USDA–NASS 1992, 2002) was multiplied by N content (Lander and Moffitt 1996; USDA–NRCS 2005) and weighted by the proportion of agricultural land in that county that was inside the watershed, then summed over all counties to obtain a watershed estimate. This represents a deviation from the methodology of the SCOPE Project (Boyer et al. 2002), which assumes that agricultural land is distributed evenly throughout a county and therefore weights these data by the proportion of each county inside the watershed. On the west coast of the US, agricultural activity tends to be concentrated in valleys, such that weighting by the proportion of agricultural land within a watershed gives a more accurate estimate of crop and animal production. (Weighting by land area results in estimates ranging from 18 to 716% of the livestock N consumption and 15–554% of the crop production calculated by weighting by agricultural area.) Only crops accounting for 1% or more of harvested cropland in a watershed were considered, which could result in an underestimate of crop production in those watersheds where a wide variety of crops are grown. Vegetable crop yields were not available as part of the census of agriculture. However, the census did report crop acreages, which were multiplied by reported 1992 or 2002 vegetable yields per acre (CDFA 2002) in order to obtain estimates of vegetable production. Livestock production and consumption were similarly calculated by adjusting for the proportion of agricultural land inside the watershed and multiplying by published consumption and excretion factors (Van Horn 1998).

To estimate human consumption, Boyer et al. (2002) weighted county populations by the proportion of that county located inside the watershed and multiplied by a per-capita annual N consumption rate (5 kg N person^{-1} year^{-1}, Garrow et al. 2000). Because county sizes in the western United States tend to be substantially larger than those in the eastern US, we used the finer-scale data at the census tract level (USBoC 1990, 2000) to estimate population. Weighting by census tract results in human population estimates ranging from 4 to 760% of the estimates obtained from weighting by county; the largest differences were for smaller watersheds that include fewer whole counties. The Willamette watershed constituted a special case because the downstream boundary of this watershed intersects the city of Portland, Oregon. Portland is serviced in part by the Columbia Boulevard Wastewater Treatment Plant, which discharges downstream of the USGS gauging station used to calculate riverine export (see below). We therefore did not include the treatment plant's service area when calculating the population of this watershed.

Biological N fixation

Biological N fixation in agricultural land was calculated by multiplying acreages of leguminous crops in each watershed by published N fixation rates. Forest N fixation included both symbiotic and non-symbiotic components. Boyer et al. (2002) assumed that east coast species of alder cover 10% of wetland area as estimated from land cover data. We applied this same assumption to thinleaf alder (*Alnus incana* ssp. *tenuifolia*) on the west coast, with an N fixation rate of 5,000 kg N km^{-2} year^{-1} (Uliassi and Ruess 2002). Red alder (*Alnus rubra*) is an important nitrogen-fixing tree in coastal areas of the Pacific northwest that can contribute substantially to in-stream nutrient loads (Compton et al. 2003), especially where anthropogenic nitrogen inputs are small (Cairns and Lajtha 2005). We used the Forest Inventory and Analysis (FIA) Program's (USDA–FS 2006) "red alder" class to estimate the coverage of red alder in each watershed and assumed a fixation rate of 8,000 kg N km^{-2} year^{-1} (Binkley et al. 2002). Given that even low levels of alder coverage can result in elevated stream N exports (Cairns and Lajtha 2005), this may be an underestimate of the true input from biological nitrogen fixation due to red alder. There are a number of additional non-agricultural nitrogen-fixing plant species that grow in western North America, including plants of the genera *Ceanothus*, *Cercocarpus*, *Comptonia*, *Elaeagnus*, *Myrica*, *Purshia*, and *Shepherdia* (Torrey 1978). Given the difficulty of estimating their distribution and prevalence, and the generally small contribution of biological fixation in forest lands to total new nitrogen input, fixation by these species was not considered here. Non-symbiotic N fixation in forest soils was assumed to be 40 kg N km^{-2} year^{-1} (Boyer et al. 2002) and calculated from forest areas reported in the FIA (USDA–FS 2006).

Other sources and sinks of N

Pacific salmon spawning runs can be an important source of marine-derived nutrients to both terrestrial and aquatic environments in many western US stream ecosystems (Gende et al. 2002; Naiman et al. 2002). However, runs have declined by more than 95% from their historical highs (Gresh et al. 2000). An order-of-magnitude estimation for the Siuslaw River, one of the more important salmon streams included in this study, suggests that N derived from current salmon runs would be minimal. The Chinook salmon run is the healthiest run in this river, numbering approximately 11,000 individuals (Siuslaw Basin Council 2002). Based on an average weight of 3.76 kg per fish (Bigler et al. 1996) and an N content of 2.5% (Drake et al. 2006), Chinook salmon would contribute less than 1 kg N km^{-2} $year^{-1}$ to the watershed inputs. This would account for less than 0.1% of the total inputs. We therefore did not include marine-derived nutrients from spawning salmon in these budgets. Finally, we assumed that essentially all cotton grown in a watershed was exported and subtracted this as a non-food crop export. This is in keeping with our treatment of both tobacco and cotton in the southeastern US (Schaefer and Alber 2007).

Total N inputs

Data are presented as the annual average input (in kg km^{-2} $year^{-1}$) of each source of N to a watershed. In addition to the sum of all new N inputs (atmospheric deposition, fertilizer, net food and feed import, and biological N fixation), we also present gross N inputs, which includes net food and feed import only when it represents an import rather than an export. We also calculated an area-weighted value for each input by multiplying inputs by the area of the corresponding watershed and then dividing by the total area of all watersheds.

Riverine N export

N export to the coast was calculated from water quality data collected by the USGS National Water Information System (USGS 2006) at the most downstream water quality gauge. We used the USGS's LOADEST model (Runkel et al. 2004; Booth et al. 2007) to estimate loads. For the 1990s, we did not calculate export for four of the 22 watersheds: the Cuyama, John Day, and Santa Ana, due to insufficient water quality data, and the San Joaquin, due to the difficulty of accounting for N in the many water transfers in this basin. Unfortunately, water quality sampling in the 2000s was very limited and we were only able to calculate riverine export for seven watersheds (Sacramento, Salinas, Santa Ana, Snake, Spokane, Willamette, and Yakima).

We used measurements of unfiltered TKN to obtain estimates of dissolved organic N plus NH_4 for all watersheds. Because the monitoring program took filtered samples for NO_X analysis (USGS parameter 631) more often than unfiltered samples (parameter 630), we used data from filtered samples. Although this may result in an underestimate of NO_X-N loading, NO_X concentrations in filtered samples were often higher than those observed in unfiltered samples and the two were well correlated. Where only unfiltered samples were available (the Spokane River), these were used in the calculations.

Additional adjustments were necessary in three cases. Stream flow measurements were not available for the most downstream water quality station on the Snake River (USGS station no. 13353200; Snake River at Burbank, Washington), so we used stream flow data from a station located approximately 11 km upstream (USGS station no. 13353000; Snake River below Ice Harbor Dam, Washington). This distance should not result in a substantial change in flow, and therefore difference in N export, for a river as large as the Snake. Similarly, for the Merced River we used a streamflow station (USGS station no. 11272500; Merced River near Stevinson, CA) approximately 6 km upstream of the water quality station (USGS station no. 11273500; Merced River at River Road Bridge near Newman, CA). For the most downstream water quality station on the John Day River (USGS station no. 14048000; John Day River at McDonald Ferry, Oregon), stream flow measurements were only available beginning in April 1994. In order to be able to use water quality data taken prior to this, we developed a relationship between stream flow at this station and at the nearest upstream station (USGS station no. 14046500; John Day River at Service Creek, Oregon), which was then used to estimate stream flow for dates before April 1994 (McDonald Ferry flow $= 1.06 \times$ Service Creek flow $+ 34.59$, $R^2 = 0.95$, $P < 0.0001$).

Relationship between export and input

New N input is often considered the primary determinant of N export to the coast (e.g., Howarth et al. 1996; Boyer et al. 2002), although streamflow can also be important (e.g., Lewis 2002). Factors that have been suggested to control percent N export include streamflow (Dumont et al. 2005), temperature (Schaefer and Alber 2007), and residence time (Howarth et al. 2006). We compared both absolute and percent export from the watersheds to total new N input, average annual temperature, average annual streamflow, and average watershed slope (an indicator of residence time). These factors were selected to encompass the various explanations proposed to control N export. Although additional characteristics could also have been used in this analysis, many of them covary—for example, watershed population density and total N inputs; streamflow and precipitation. Streamflow was calculated as described above. Watershed temperatures were calculated for the 1990s using the DAYMET database (Thornton et al. 1997) and for the 2000s using PRISM data (PRISM Group 2008). Precipitation was also obtained (Thornton et al. 1997, PRISM Group 2008) to allow us to calculate the percentage of precipitation that runs off as streamflow as an additional characteristic of each watershed. Watershed slopes were calculated from a digital elevation model (USGS 1999d).

Results

Watershed characteristics

The watersheds included in this study ranged in size from 1,531 to 279,438 km^2 (Table 1) and were dominated by forest and shrub/grassland in 1992 (Table 2). Note that only 1992 land use is presented here, but there were only minor changes in land use in 2001. Northern watersheds tended to be dominated by forest, whereas southern watersheds tended to be dominated by shrub and grasslands. Together, these two categories on average accounted for 81.1% of land cover in western watersheds. The next most important land use was agriculture (area-weighted average = 13.8%), with the highest percentage observed in the San Joaquin (30.4%) and the Willamette (24.3%) River watersheds. Urban area generally accounted for only a small (≤4%) percentage of watershed area, except in the Santa Ana where it accounted for 19.7% of the watershed area. Human population density in 1992 ranged from very low (≤5 people km^{-2} in 10 of the 22 watersheds) to an extreme high of 432 people km^{-2} in the Santa Ana basin. Population densities were similar in 2002, though generally slightly higher. The area-weighted annual average watershed temperature across all watersheds was 8.5°C in 1992 and 9.2°C in 2002 (Table 1). Area-weighted annual average precipitation was 649 mm $year^{-1}$ in 1992 and 596 mm $year^{-1}$ in 2002, with the highest in the watersheds of the Nehalem, Willamette, and Eel Rivers. The average watershed slope was 11.7°.

Inputs

New N input to the 22 western US watersheds studied here ranged from 541 to 11,644 kg N km^{-2} $year^{-1}$ in 1992 and from 409 to 10,875 kg N km^{-2} $year^{-1}$ in 2002 (Table 3). The watershed with the highest input was the Santa Ana, followed by the San Joaquin. The high input to the Santa Ana was due to high imports of food and feed. This was primarily driven by the high number of dairy cattle and layer chickens in this watershed, which resulted in high animal production. Human N consumption was also high, as the greater metropolitan Los Angeles area takes up a large proportion of this watershed. The San Joaquin watershed had large livestock populations, resulting in high net food and feed import, but also very high fertilizer use due to the large proportion of agricultural area in that watershed. Inputs to all other watersheds were less than 5,000 kg N km^{-2} $year^{-1}$ in both years.

In both periods, fertilizer was the largest source of new N to the region, followed by atmospheric deposition and N fixation in croplands. Fertilizer accounted for 956 kg N km^{-2} $year^{-1}$ (38.6% of gross N inputs) in 1992 and 1,073 kg N km^{-2} $year^{-1}$ (43.6% of gross N inputs) in 2002. Atmospheric deposition averaged 833 kg N km^{-2} $year^{-1}$ (33.7% of gross N inputs) in 1992. In 2002, this source remained second in importance but had decreased to 717 kg N km^{-2} $year^{-1}$ (29.2% of gross N inputs). This was primarily the result of a decline in dry deposition, which was the major component of

Table 1 General characteristics of western US watersheds for 1992 and 2002

Watershed	Abbreviation	Area (km^2)	Temperature (°C)		Precipitation (mm $year^{-1}$)		Slope (°)	Persons km^{-2}	
			1992	2002	1992	2002		1992	2002
Spokane	SPO	9,932	6.3	7.0	1,135	870	19.2	7	10
Yakima	YAK	14,542	7.6	7.7	653	640	11.7	15	18
Snake	SNA	279,438	6.0	6.8	537	444	11.6	4	5
Nehalem	NEH	1,747	9.0	9.5	1,862	2,071	13.9	5	6
Deschutes	DES	27,787	7.2	7.6	549	422	6.9	4	6
John Day	JDY	19,764	7.3	8.2	447	349	13.3	1	1
Willamette	WIL	28,992	9.6	10.0	1,499	1,380	12.0	11	60
Siuslaw	SIU	1,531	10.7	11.8	1,584	1,524	19.1	4	4
Rogue	ROG	10,188	9.5	9.7	959	877	15.7	20	24
Klamath	KLA	40,356	8.1	8.9	786	789	13.0	3	3
Eel	EEL	8,058	10.9	12.1	1,205	1,420	18.2	4	4
Russian	RUS	3,470	13.6	14.8	932	1,045	13.8	86	102
Sacramento	SCR	68,332	11.5	12.2	802	854	10.1	28	32
Stanislaus	STN	2,485	10.0	10.0	822	861	14.4	5	19
San Joaquin	SJQ	72,129	13.7	14.0	417	432	10.1	31	38
Tuolumne	TUO	4,307	9.8	10.6	704	796	14.1	15	23
Merced	MER	2,876	10.5	11.8	697	747	15.5	4	7
Pajaro	PAJ	3,063	14.0	14.8	406	429	13.6	33	44
Salinas	SAL	10,568	13.9	14.9	478	378	13.5	10	12
Cuyama	CUY	2,279	13.4	13.8	497	313	16.2	3	1
Santa Clara	STC	1,694	15.5	16.3	460	343	17.4	96	125
Santa Ana	STA	3,881	15.2	15.7	536	372	12.0	432	518
Area-weighted average			8.5	9.2	649	596	11.7	14	19

atmospheric deposition in all watersheds. Atmospheric deposition was higher in southern than in northern watersheds. N fixation in croplands was the third-largest source of new N to the region in both years and was positively related to the amount of pastureland. This source accounted for an average of 628 kg N km^{-2} $year^{-1}$ (25.4% of gross N inputs) in 1992 and 613 kg N km^{-2} $year^{-1}$ (24.9% of gross N inputs) in 2002. N export due to volatilization was most important in watersheds located in southern California, particularly those of the Salinas, Pajaro, Cuyama, and Santa Ana Rivers.

Net food and feed import was often negative (indicating a net export) because crop production was high in many of the watersheds. Crop production tended to be highest in California, and was generally dominated by hay and pastureland. However, high crop production values did not necessarily result in low N import, since watersheds with high crop production also often had large populations of animals, and hence high consumption of N by animals. In 1992, net food and feed import averaged −578 kg N km^{-2} $year^{-1}$, with half the watersheds exporting N. By 2002, import had increased in many watersheds, primarily as a result of increases in animal production, with an average of −261 kg N km^{-2} $year^{-1}$.

Forest N-fixation generally accounted for only a small percentage of overall N input. The one exception was the Nehalem watershed, where forest N-fixation accounted for 57.5 and 67.7% of gross N inputs in 1992 and 2002, respectively. This was a result of the very high density of red alder in this area, which has a high rate of N-fixation (8,000 kg N km^{-2} $year^{-1}$, Binkley et al. 2002).

Table 2 Land use in western US watersheds for 1992

Watershed	Forest (%)	Shrub and grasslands (%)	Agriculture (%)	Urban (%)	Wetland (%)	Water (%)	Other (%)
SPO	81.2	6.1	3.7	1.0	0.1	2.0	5.9
YAK	36.4	41.9	15.2	1.8	0.2	0.8	3.8
SNA	27.2	55.6	12.6	0.3	0.6	0.7	3.0
NEH	93.6	0.2	1.1	0.1	0.0	0.2	4.8
DES	43.4	48.1	5.4	0.4	0.4	0.6	1.6
JDY	46.2	48.0	5.0	0.1	0.2	0.1	0.6
WIL	65.3	3.9	24.3	3.0	0.3	0.9	2.2
SIU	94.7	2.4	1.7	0.0	0.0	0.1	1.0
ROG	80.6	9.6	6.9	1.1	0.2	0.4	1.2
KLA	66.2	22.4	5.9	0.2	2.3	1.6	1.3
EEL	66.6	31.9	0.4	0.2	0.0	0.3	0.6
RUS	47.4	32.7	15.5	3.2	0.1	0.8	0.3
SCR	51.0	29.9	13.7	1.7	0.8	1.9	1.0
STN	64.1	25.9	4.8	1.2	0.1	1.7	2.3
SJQ	26.1	36.7	30.4	1.8	0.4	0.7	3.9
TUO	48.0	38.6	4.9	1.4	0.1	1.9	5.2
MER	53.1	36.5	5.6	0.4	0.7	0.6	3.0
PAJ	23.9	58.6	13.9	1.9	0.0	0.1	1.6
SAL	17.6	65.8	12.0	0.8	0.0	0.2	3.5
CUY	18.0	68.0	5.9	0.2	0.0	0.0	8.0
STC	15.4	74.9	1.9	4.0	0.0	0.8	3.0
STA	20.6	48.3	8.5	19.7	0.4	0.6	2.0
Area-weighted average	38.4	42.7	13.8	1.0	0.6	0.9	2.6

Export

Streamflow from the study watersheds ranged from 22 to 1,262 mm year^{-1} in 1992 (Table 4), and from 41 to 1,344 mm year^{-1} in 2002. Parts of the western US experienced a drought during the late 1980s and early 1990s, such that the 2000s were slightly wetter than the 1990s, with streamflow averaging 210 mm year^{-1} in 1992 and 278 mm year^{-1} in 2002. Streamflow was expressed as a percentage of precipitation as a measure of the flushing rate of water in these systems (with a high percentage indicating a shorter residence time). Streamflow ranged from values as low as 5% of precipitation in the Salinas to greater than 65% in the Siuslaw, Willamette, and Nehalem (Table 4). Low values may indicate high consumptive use or other losses from the watershed (e.g., evapotranspiration) that decrease runoff. High values were observed in systems that are either entirely (Siuslaw and Nehalem) or partially (Willamette) in the Oregon Coast Range.

Riverine N export ranged from 80 kg N km^{-2} year^{-1} in the Tuolumne to 1,670 kg N km^{-2} year^{-1} in the Nehalem, with an overall average of 165 kg N km^{-2} year^{-1} for the 18 watersheds with available export data in 1992 (Table 4). Export ranged from values less than 100 kg N km^{-2} year^{-1} in the Tuolumne, Merced, and Deschutes, to greater than 1,000 kg N km^{-2} year^{-1} in the Siuslaw, Nehalem, and Willamette. These watersheds with high export values are discussed further below. Although there were some differences between the two periods, 2002 export estimates agreed well with those from 1992 for the 7 watersheds for which measurements were available, averaging 165 kg N km^{-2} year^{-1} in 1992 and 195 kg N km^{-2} year^{-1} in 2002. We therefore did not analyze the 1990s and 2000s time periods separately, but rather included observations from both periods for those watersheds for which we had estimates of export in 2002.

Percent N export had an area-weighted average of 12% in 1992 (Table 4). The two Coast Range

Table 3 Inputs to watersheds on the west coast of the US in 1992 and 2002

Watershed	Atmospheric deposition		Fertilizer		Net food and feed import		Biological N fixation in agricultural lands		Biological N fixation in forest lands		Non-food crop export		Total	
	1992	2002	1992	2002	1992	2002	1992	2002	1992	2002	1992	2002	1992	2002
SPO	379	496	165	75	−82	−53	83	41	41	52	0	0	587	612
YAK	768	469	1,002	1,313	−255	−54	940	895	23	67	0	0	2,478	2,691
SNA	538	535	652	713	−907	−740	633	598	44	33	0	0	960	1,140
NEH	838	839	19	75	79	88	83	48	1,378	2,199	0	0	2,398	3,249
DES	716	555	265	240	−563	−655	547	542	37	22	0	0	1,001	704
JDY	604	497	114	67	−775	−787	637	614	19	18	0	0	597	409
WIL	723	548	1,932	1,787	78	341	399	154	270	362	0	0	3,402	3,192
SIU	689	480	32	204	33	28	40	13	153	208	0	0	947	933
ROG	647	511	119	120	111	100	264	175	44	107	0	0	1,185	1,012
KLA	789	513	207	188	−378	−498	458	511	160	52	0	0	1,236	766
EEL	1,650	598	59	99	−160	−80	199	73	66	67	0	0	1,815	757
RUS	1,566	501	388	1,346	1,281	592	513	1,204	34	34	0	0	3,782	3,676
SCR	1,112	627	972	1,214	−2,126	−945	561	544	21	40	0	−17	541	1,463
STN	1,255	1,157	401	620	382	524	439	396	26	37	0	−2	2,473	2,731
SJQ	1,392	1,607	2,962	3,219	1,044	1,933	1,006	1,152	10	18	−224	−335	6,190	7,594
TUO	1,263	1,176	510	711	642	917	270	343	20	32	0	−3	2,704	3,175
MER	1,314	1,193	338	721	153	639	164	440	68	27	−14	−56	2,023	2,963
PAJ	1,838	1,018	1,019	1,369	−573	−929	1,332	1,374	19	27	0	0	3,635	2,859
SAL	1,708	1,160	2,127	3,378	−1,337	−1,360	815	689	15	41	0	0	3,328	3,908
CUY	819	1,179	994	1,179	−350	−694	495	547	7	18	−5	0	1,961	2,229
STC	3,920	3,287	83	290	459	592	41	24	5	94	0	0	4,509	4,287
STA	3,967	3,064	658	949	5,711	6,266	1,286	597	25	7	−4	−8	11,644	10,875
Area-weighted average	833	717	956	1,073	−578	−261	628	613	57	57	26	41	1,880	2,160

All values in kg N km^{-2} $year^{-1}$

Table 4 N export and related characteristics for US west coast watersheds in 1992 and 2002

Watershed	Streamflow (mm $year^{-1}$)		Streamflow as a % of precipitation		Riverine N export (kg N km^{-2} $year^{-1}$)		Riverine N export as a % of input	
	1992	2002	1992	2002	1992	2002	1992	2002
SPO	516	550	45	63	117	106	20	17
YAK	183	209	28	33	194	185	8	7
SNA	136	209	25	47	93	137	10	12
NEH	1,262	1,344	68	65	1,670	–	70	–
DES	170	190	31	45	71	–	7	–
WIL	987	1,021	66	74	1,065	959	31	30
SIU	1,026	1,165	65	76	1,086	–	115	–
ROG	405	507	42	58	114	–	10	–
KLA	290	400	37	51	115	–	9	–
EEL	704	953	58	67	334	–	18	–
RUS	466	637	50	61	329	–	9	–
SCR	252	344	31	40	104	119	19	8
STN	205	382	25	44	106	–	4	–
TUO	133	281	19	35	80	–	3	–
MER	110	225	16	30	99	–	5	–
PAJ	34	71	8	17	460		13	
SAL	22	41	5	11	88	95	3	2
STA	77	90	14	24	512	501	4	5
Area-weighted average	235	291	30	47	165	195	12	12

'–' indicates that data were not available

watersheds (the Siuslaw and Nehalem) had extremely high percent export (115% and 70%, respectively). A value greater than 100% would be unsustainable over the long term and most likely reflects errors inherent in the calculation of both N input and export. Despite the potential error, however, it is apparent that percent export is much higher in these two watersheds than in any of the others we considered (all of which were calculated in the same manner). The Siuslaw and Nehalem are both particularly small watersheds that are primarily forested. As noted above, they receive a great deal of rainfall, a high percentage of which becomes streamflow. These systems may also be highly disturbed. Logging is common in the Coast Range (Ripple et al. 2000) and a high proportion of clearcut area has been shown to increase streamflows in the Western Cascades of Oregon (Jones and Grant 1996), which could result in increased export due to the landscape's inability to retain N for processing. When precipitation as a percentage of streamflow is plotted against percent N export, the Siuslaw and Nehalem are clear outliers (Fig. 2). We therefore present the following analysis of the relationships between inputs and riverine N export both with and without these watersheds.

Relationship between input and export

The best single predictor of N export was streamflow, which explained 66% of the variability in the observations (Fig. 3a; export = 0.94 × streamflow − 5.65, $R^2 = 0.66, P < 0.001$). When the Coast Range systems were excluded, streamflow was still the best predictor of export, but it explained only 41% of the variability (export = 0.62 × streamflow + 65.76, $R^2 = 0.41$, $P = 0.001$). Although N input alone was not important (Fig. 3b), including it in the regression with streamflow increased the predictive power of both relationships, but input was more important when the Coast Range systems were excluded (all watersheds,

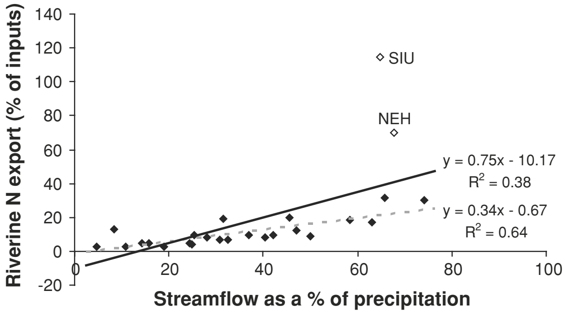

Fig. 2 Streamflow as a percentage of precipitation versus riverine N export as a percentage of N inputs for watersheds on the west coast of the US *Open symbols* Coast Range watersheds (SIU, Siuslaw; NEH, Nehalem). *Solid regression line* includes all data; *dashed regression line* excludes the Coast Range systems

export = 1.06 × streamflow + 0.06 × input − 227.78, $R^2 = 0.82$, $P < 0.001$; excluding Coast Range, export = 0.76 × streamflow + 0.06 × input − 149.29, $R^2 = 0.77$, $P < 0.001$). The other two variables (temperature and slope) were not related to N export (Fig 3c, d) when all watersheds were considered, but slope accounted for another 5% of variability when the Coast Range watersheds were excluded (export = 0.82 × streamflow + 0.05 × input − 22.29 × slope + 137.37, $R^2 = 0.82$, $P < 0.001$).

Streamflow was also the best predictor of percent nitrogen export from these watersheds (all watersheds, % export = 0.05 × streamflow − 2.61, $R^2 = 0.60$, $P < 0.001$; excluding Coast Range, % export = 0.03 × streamflow + 3.18, $R^2 = 0.77$, $P < 0.001$; Fig. 4a). In this case, none of the other factors (input, temperature, or slope) were significant alone (Fig. 4b–d) or improved the relationship with streamflow any further with or without Coast Range watersheds. Although precipitation was not used in this analysis, it is worth noting that regressions of both total N and %N export against streamflow explained more variance than regressions against precipitation.

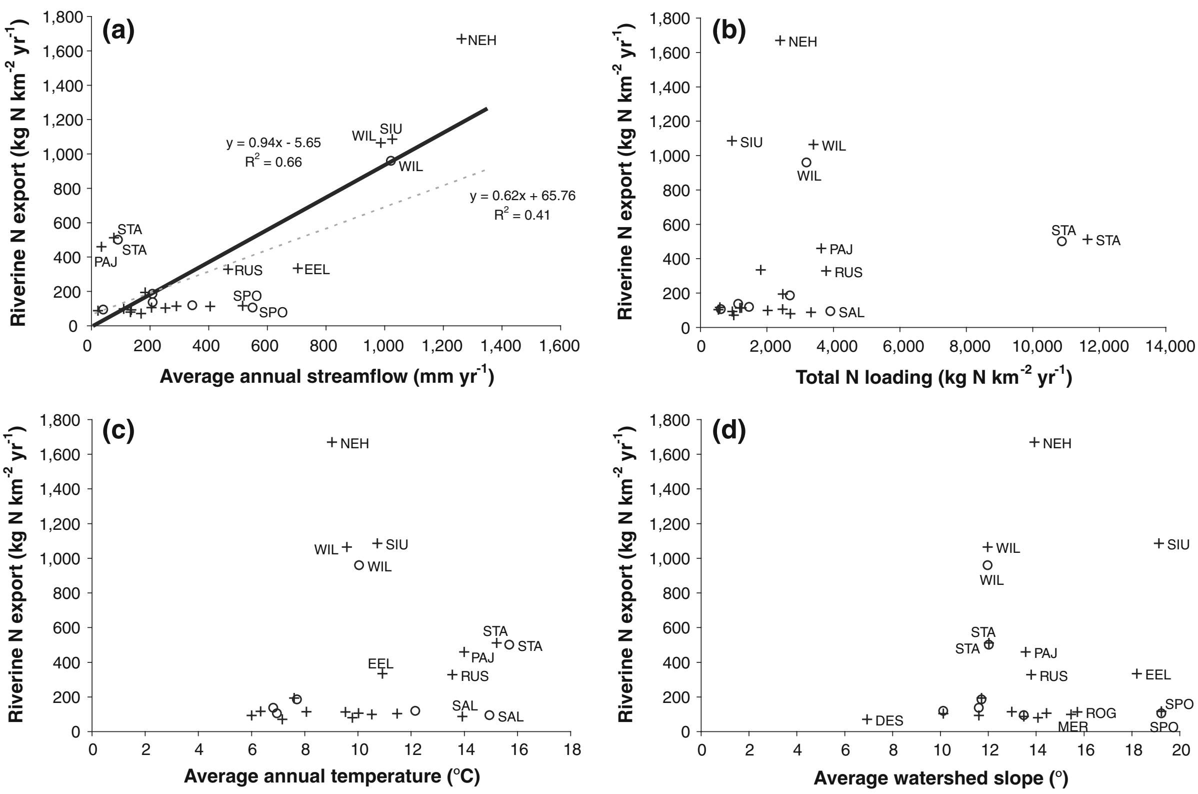

Fig. 3 **a** Average annual streamflow, **b** total N inputs, **c** average annual temperature, and **d** average slope of watersheds on the west coast of the US versus riverine N export at the most downstream USGS water quality gauging station. *Crosses* 1990s data; *circles* 2000s data. *Solid regression line* includes all data; *dashed regression line* excludes the Coast Range systems (Siuslaw and Nehalem). Abbreviations (as in Table 1) are provided for selected watersheds

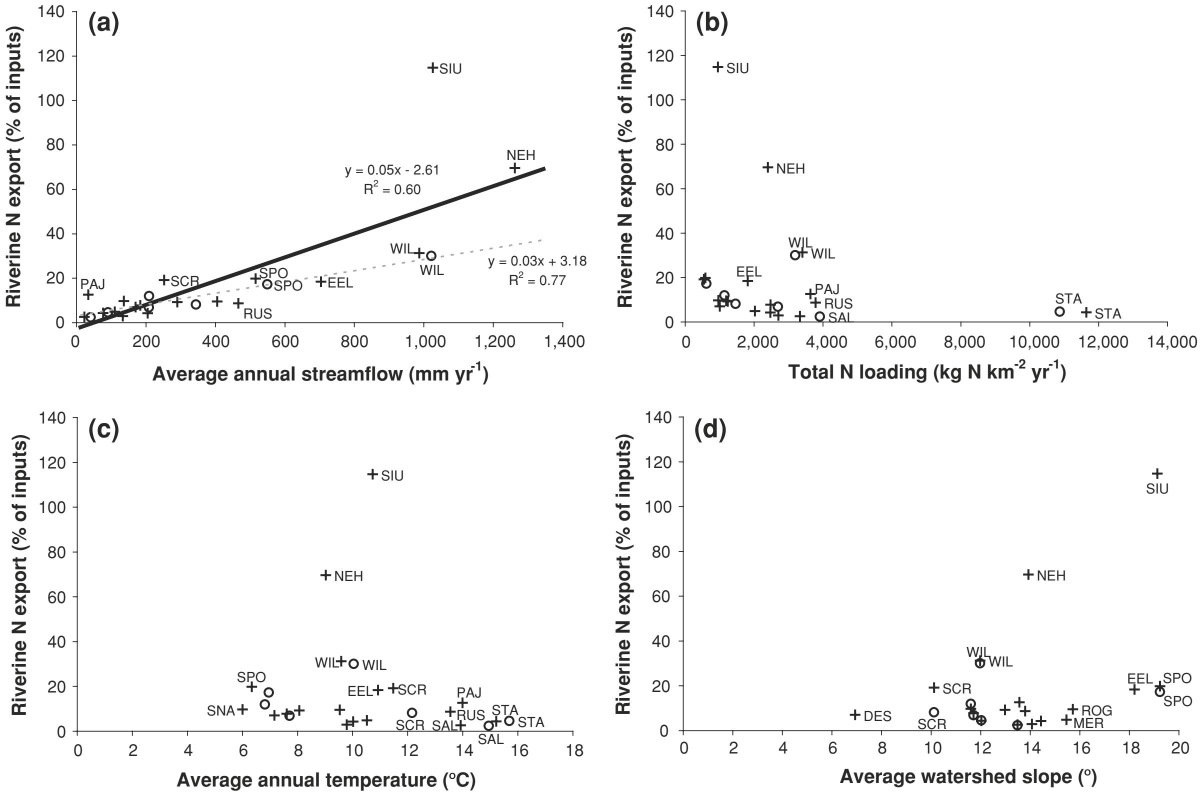

Fig. 4 **a** Average annual streamflow, **b** total N inputs, **c** average annual temperature, and **d** average slope of watersheds on the west coast of the US versus riverine N export expressed as a percentage of watershed input. *Crosses* 1990s data; *circles* 2000s data. *Solid regression line* includes all data; *dashed regression line* excludes the Coast range systems (Siuslaw and Nehalem). Abbreviations (as in Table 1) are provided for selected watersheds

Discussion

Area-weighted average N input to study watersheds was 1,870 kg N km^{-2} year^{-1} in 1992 (Table 3). Inputs were generally higher in southern than in northern watersheds. Inputs to most systems had increased by 2002, with an overall, area-weighted average of 2,158 kg N km^{-2} year^{-1}. However, 1992 inputs were well correlated with 2002 inputs ($R^2 = 0.94$), indicating that N input increased consistently across the entire study region.

Fertilizer was the most important source of N to the region in both decades, followed by atmospheric deposition. Fertilizer N inputs increased in importance from 1992 to 2002, accounting for 38.6 and 43.6% of gross inputs, respectively, whereas atmospheric deposition accounted for 33.7% of gross inputs in 1992 and 29.2% in 2002. A simultaneous increase in fertilizer use and a decline in atmospheric deposition resulted in fertilizer becoming an increasingly dominant N source in 2002. The reduction in atmospheric deposition was most likely a result of increasingly stringent emissions standards and cleaner-burning fuels mandated in California, which succeeded in reducing NO_X emissions substantially over the same time period (CARB 2008).

The relative importance of fertilizer as an N source to these watersheds is in agreement with observations in other regions of the world. However, fertilizer input to the western US is generally lower and atmospheric deposition is higher than in other areas. In the Mississippi River basin (McIsaac et al. 2002), the most important source of new N was fertilizer ($\sim$2,000 kg N km^{-2} year^{-1}), followed by agricultural N fixation ($\sim$1,500 kg N km^{-2} year^{-1}), whereas atmospheric deposition was approximately 500 kg N km^{-2} year^{-1}. In the Changjiang River basin in China, fertilizer N supplied approximately 2,000 kg N km^{-2} year^{-1} (86% of inputs) in 1990 and 4,500 kg N km^{-2} year^{-1} (91% of new N) in 2000, whereas atmospheric deposition was negligible (Liu et al. 2006). In New Zealand (Parfitt et al. 2006), the contribution of fertilizer N to watershed loading was comparable to that reported here (887 kg N km^{-2} year^{-1}) but atmospheric deposition was lower (599 kg N km^{-2} year^{-1}).

The 1992 observations of watershed N inputs can be compared directly to those on the east coast of the US, which were calculated for the same year using comparable methodologies (Boyer et al. 2002; Schaefer and Alber 2007). Although the range of N inputs on the east coast was lower (835–5,717 kg N km^{-2} year^{-1}), the area-weighted average N input was nearly 2-fold greater, 3,136 vs. 1,880 kg N km^{-2} year^{-1} in west coast watersheds. This difference in area-weighted input was largely the result of differences in crop production, which resulted in an average net *export* of 568 kg N km^{-2} year^{-1} in food and feed on the west coast compared to an import of 781 kg N km^{-2} year^{-1} on the east coast. Biological N fixation also contributed more new N on the east coast than on the west coast (agricultural N fixation, 716 vs. 628 kg N km^{-2} year^{-1}; forest land N fixation, 134 vs. 57 kg N km^{-2} year^{-1} on the east and west coasts, respectively). However, west coast watersheds received more N from both atmospheric deposition (833 vs. 790 kg N km^{-2} year^{-1}) and fertilizer (956 vs. 725 kg N km^{-2} year^{-1}). The greater fertilizer use is surprising, given that agricultural land use comprised an average of 13.8% of watershed area on the west coast (Table 2), compared to 21.2% on the east coast (calculated based on data in Boyer et al. 2002 and Schaefer and Alber 2007), and suggests that fertilizer use is more intensive on the west coast than on the east coast.

Riverine N export was better predicted by streamflow than by watershed N input (Fig. 3a). Streamflow has also been found to be a good predictor of N export in undisturbed watersheds, which experience a large range of annual runoff (Lewis et al. 1999; Lewis 2002). However, this finding contrasts with studies on the east coast of the US (Boyer et al. 2002; Schaefer and Alber 2007), in the watersheds surrounding the North Atlantic (Howarth et al. 1996), and in New Zealand (Parfitt et al. 2006), where N loading has been shown to be an excellent predictor of riverine N export. A possible explanation for this difference, at least in comparison to the east coast, is that west coast watersheds have a larger range of streamflow (annual averages ranged from 22 to 1,262 mm year^{-1}) than those on the east coast (275–672 mm year^{-1}, Boyer et al. 2002; Schaefer and Alber 2007). West coast watersheds also tend to have more pronounced seasonality in rainfall, such that most of the nitrogen export from these watersheds occurs during the wet season (fall/winter). Unfortunately the studies in the watersheds of the North Atlantic and New Zealand did not report comparable streamflow data which could be used to evaluate the dynamic range of streamflow in comparison to that of inputs.

Although export was best predicted by streamflow, the relationship improved when input was added to the equation (streamflow only, $R^2 = 0.66$; streamflow and inputs, $R^2 = 0.82$). This agrees well with the findings of Smith et al. (2005), who were able to predict riverine N loads from a combination of streamflow and population for 165 watersheds with a range of streamflows roughly comparable to those observed here. For the west coast, we suggest that export of nutrients may be limited primarily by the availability of water to transport them, with the magnitude of inputs playing a secondary role.

The percentage of N input exported to the coast ranged widely, from 2% (Salinas, 2002) to 115% (Siuslaw, 1992). This range is greater than that observed on the east coast, where percent export ranged from 5 to 40% (Boyer et al. 2002; Schaefer and Alber 2007). However, when the Coast Range systems were excluded, the remaining watersheds all exported less than 20% of the N inputs (the Willamette, which is partially in the Coast Range, exported 31% in 1992 and 30% in 2002). The watershed-area-weighted average export was 12% in 1992 (excluding the Coast Range watersheds, which are very small, changed this only slightly and still rounded to 12%). This value, which is substantially below the generally accepted global average of 25% (Galloway et al. 2004; Boyer et al. 2006), is largely a consequence of the fact that some of the largest watersheds in this study, such as the Snake and the Sacramento, tended to export smaller percentages of the load and so brought down the area-weighted average. Our results correspond well with the results of a modeling study by Dumont et al. (2005). Their Fig. 5 shows percent N export on the west coast of the US to generally be below 14% except in Coast Range watersheds, where percent export was between 27 and 59%.

Percent export was best predicted by streamflow, which could be a consequence of the very large range of streamflows in watersheds of the west coast. Watersheds with extreme values of streamflow may either (in the case of high streamflow) have such a short residence time that N is exported before any processing has taken place, or (in the case of low streamflow) water movement may be so slow that N is processed or stored in the watershed, so percent export is low. The large fraction of the load exported from Oregon Coast Range watersheds, in particular, may be the result of rapid flushing in these systems, which have high streamflows relative to precipitation. These watersheds are also quite small, which could further decrease the residence time of N in them. It would be instructive to know if more N is exported in other mountainous regions where watersheds are small and precipitation is high. Dumont et al. (2005), who also included watersheds with a wide range of streamflows, also found that percent N export was correlated with streamflow.

The west coast results presented here contrast with our east coast observations where we found that percent export was related to temperature (Schaefer and Alber 2007). As described above, US east coast watersheds are more homogenous with respect to streamflow than those on the west coast and thus the effect of temperature may be easier to discern in them. The temperature range on the east coast is also slightly greater (4.2–19.3°C; Boyer et al. 2002; Schaefer and Alber 2007) than on the west coast (6.0–15.5°C). Although the percentage of N exported from watersheds in the present study did not correlate with temperature, it is worth noting that percent export was lower and less variable at temperatures greater than 12°C (average = 6 ± 4%) as compared to lower temperatures (average = 22 ± 28%). This is in keeping with our east coast observations that percent N export is lower in warmer watersheds.

The apparent difference in the factors controlling N export from west coast watersheds compared to those in other regions suggests that our understanding of the relationship between input and export is incomplete. Export is not always predicted by input, and there is no single relationship that can be used to predict N export based on input for all watersheds. This was most obvious for the small mountainous watersheds of the Oregon Coast Range, which behaved differently from the rest of the region. Comparisons of N budgets for watersheds from other mountainous areas or across watersheds representing a wide range of streamflow may provide the perspective needed to develop an improved understanding of the relative importance of the environmental factors that control N export.

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