Supplementary Materials: Nutrient Retention in Restored Streams and Rivers: A Global Review and Synthesis

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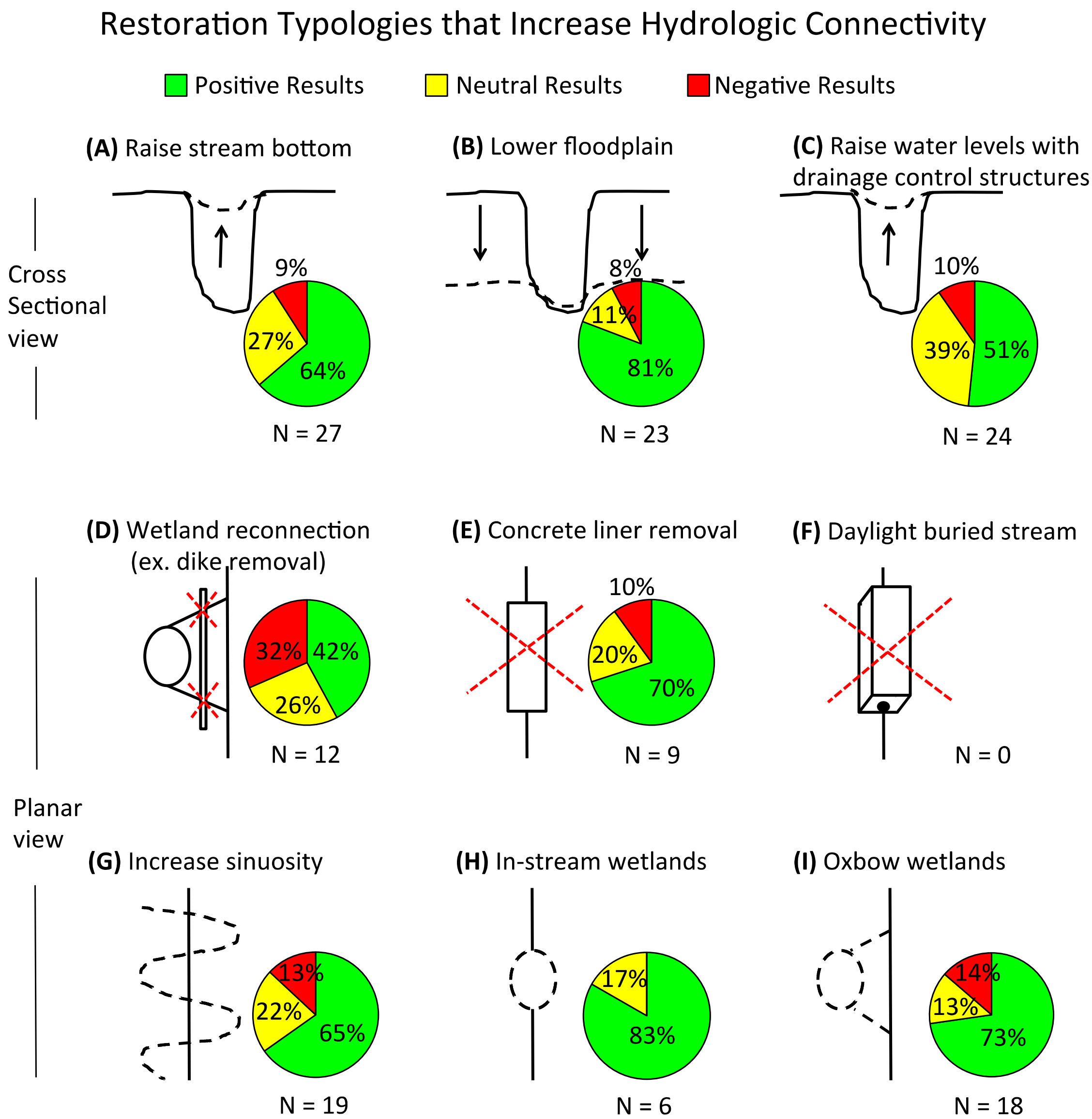

Figure S1. Restoration projects were divided into 9 typologies: (**A**) raise stream bottom, (**B**) lower floodplain, (**C**) raise water levels with drainage control structures, (**D**) reconnect wetlands, (**E**) remove concrete liner, and (**F**) daylighting urban streams buried in pipes, (**G**) increase sinuosity, (**H**) add in-stream wetlands, and (**I**) reconnect oxbow wetlands. Positive results (green) indicate that restoration either increased nutrient retention or decreased nutrient concentrations compared to pre-restoration or reference condition. Neutral results (yellow) indicate that restoration did not change nutrient retention or concentrations. Negative results (red) indicate that restoration either reduced nutrient retention or increased concentrations.

Table S1. Method, land use (LU), typology (from Figure 2), management action, rating, summary of results, location and citation for 79 empirical nutrient case studies.

Method	LU	Type	Management Action	(Rating)—Summary of Results	Location and Citation
Nutrient Spiraling, Mass balance, Denit.	Urb	**AB E H**	Stream restoration & stormwater management	(Positive)—Inline stormwater management decreased total dissolved N concentrations & there were high rates of denitrification in both restored floodplains & stormwater management.	Baltimore LTER, Maryland, USA [1]
Nutrient Spiraling	Ag	**A**	Experimental manipulations: removal of vegetation and CWD followed by addition of flow baffles	(Positive)—NH_4^+ and PO_4 uptake velocity (V_f) decreased after CWD removal by 88% and 38%, respectively. After baffles were installed, NH_4^+ and PO_4 V_f increased dramatically.	North Carolina coastal plain, USA [2]
Nutrient Spiraling	Ag	**A**	Addition of experimental substrate deflector packs (control, mud, sand, & cobble)	(Neutral)—Adding substrate deflector packs doubled the size of the transient storage zone but did not significantly influence total NH_4^+ and PO_4 uptake. This may be because of the small reach size (20 m long by 60 cm wide) and relatively small initial transient storage. Also, NH_4^+ uptake coefficient was 1.6× higher than PO_4 in mud packs. In contrast, PO_4 uptake coefficients were 50× higher than NH_4^+ in sand and cobble packs.	Irrigation canal 60 km north of Barcelona, Spain [3]
Nutrient Spiraling	Ag	**A G I**	Channel relocated using natural channel design & the former channel was left in place as a remnant oxbow	(Positive)—Stream restoration decreased flow velocity and reduced downstream transport of nutrients. N and P uptake rate coefficients were 30- & 3-fold higher, respectively, within restored relative to pre-restoration.	Wilson Creek stream restoration in Kentucky, USA [4]
Nutrient Spiraling	Ag Urb	**A**	Constructed riffles & a step	(Positive)—Constructed riffles & step increased hyporheic exchange & N removal in hyporheic zone. A 40 m constructed riffle removed 50%–99% of NO_3^- that entered the hyporheic zone which was similar to the natural reach.	Toronto, Southern Ontario, Canada [5]
Nutrient Spiraling	Log	**A**	Headwater stream restored by building a 10 m sediment trap & lining banks with boulders & logs parallel to direction of flow	(Positive/Neutral)—Restored reaches had higher gas exchange and transient storage. There was a significant positive relationship between rock (gravel + cobble + boulder) coverage and nutrient uptake. However, nutrient uptake & community respiration rates were different between reaches at only one site.	Ontonagon River basin of Lake Superior in Michigan, USA [6]
Nutrient Spiraling	Base	**A**	Coarse woody debris was added to increase structural complexity. In 100 m stream sections, 10 logjams were arranged in a zigzag pattern	(Positive)—Within a month of adding coarse woody debris, transient storage doubled (measured as A_S, A_S/A, Rh, and F_{med}^{200}) and NH_4^+ uptake rates (V_f and U) increased significantly. V_f increased by 23%–154% and U increased 61%–235% in streams with coarse woody debris additions.	Fort Benning Military Installation, Georgia, USA [7]
Nutrient Spiraling	Mine	**AC**	Natural channel design with cross-vanes and j-hooks.	(Neutral)—Restoration did not change NH_4^+ uptake in a highly disturbed, acid mine drainage impacted stream.	Appalachian coalfield, Virginia, USA [8]
Nutrient Spiraling, Denit.	Mine	**HI**	AMD remediated using limestone diversion wells, vertical flow wetlands, and settling ponds for metal precipitates	(Positive/Negative)—Stream remediation restored ammonium uptake, restored phosphorus uptake to near normal rates, and partially restored nitrification in the bituminous (but not the anthracite) region, and reduced nitrate uptake to an undetectable level. Denitrification was not detected in any stream.	Bituminous and anthracite coal mining regions of Pennsylvania, USA [9]
Nutrient Spiraling	Urb	**AB**	Stream restoration as mitigation projects for highway construction	(Positive)—NH_4^+ uptake lengths were significantly (2.5–3 times) shorter in restored stream due to greater biofilm development on large substrates (boulder, cobble, & gravel) and less canopy cover. Denitrification was high, representing approximately 45% of N loading in North Buffalo Creek.	Greensboro, North Carolina, USA [10]
Nutrient Spiraling	Urb	**A**	Installation of rocky riffles & raised channel bed elevations	(Positive)—Otis model simulation predicted higher denitrification & in-stream NO_3^- retention in restored stream based on increased subsurface residence time.	Truckee River, Nevada, USA [11]

Table S1. *Cont.*

Method	LU	Type	Management Action	(Rating)—Summary of Results	Location and Citation
Nutrient Spiraling	Urb	**C** **G**	5 stream restoration projects ranging from 200 to 1800 m that included designs like riffle/step/pool sequences using large wood J-hooks, boulder cross-vanes, and floodplain reconnection	(Positive/Neutral)—V_f of NO_3^- (0.02–3.56 mm/min) and PO_4^- (0.14–19.1 mm/min) was similar to other urban restored streams and higher than forest reference streams. Nitrate uptake was highest in older sites possibly due to greater channel stability and establishment of microbial communities. Phosphate uptake was greater in newly restored sites, which was attributed to algal assimilation.	5 restored streams in Charlotte and Raleigh, North Carolina, USA [12]
Nutrient Spiraling	Urb	**A**	Natural channel design stream restoration project	(Positive/Neutral)—In summer, restored reaches had substantially higher NO_3^- uptake than unrestored or forested reaches. In winter, uptake rates did not vary by stream type. Temperature & canopy cover explained 80% of variation.	Piedmont area of North Carolina, USA [13]
Nutrient Spiraling	Urb For	G I	New, longer meandering channel was excavated and it included 2 backwater oxbows, 2 deep pools & 3 short riffles, fixed large woody debris with root wads, large boulders, and native riparian vegetation	(Positive/Neutral)—After restoration, nutrient demand for $NH_4^+$and SRP temporarily increased to levels that have rarely been reported. Rapid periphyton accrual dramatically increased NH_4^+ V_f. Within 35 days periphyton biomass began to senesce and nutrient demand for both N and P recovered to background levels. Peak P demand occurred 2 weeks after peak N demand due to different controlling factors.	Wilson Creek, a 3rd-order stream, forest headwaters in Okanogan-Wenatchee National Forest of Central Washington, USA [14]
Nutrient Spiraling and Denit.	Ag	**AB** **G**	Excavation of stream banks & re-structuring with a 2-stage ditch design, increased sinuosity, plus logs were used for stabilization of channel & stream bed	(Positive/Negative)—Restored & forest reaches had shorter NH_4^+ uptake lengths & larger mass transfer coefficients than channelized reaches. $NH4^+$ uptake positively correlated with transient storage in restored & forest reference. Potential denitrification lowest in restored reaches	Weinviertel in north east Austria [15]
Nutrient Spiraling, Denit.	Urb	**AB** **E** **G**	Stream restoration raised stream bottom, lowering stream banks	(Positive)—Approximately 40% of daily NO_3^- load removed via denitrification over 220.5 m in restored reach that was reconnected to its floodplain	Minebank Run & Spring Branch, MD, USA [16]
Denit.	Ag	**D**	Stream restoration through bank stabilization & riparian buffer plantings	(Positive)—Denitrification removal in sediments with macrophytes was equivalent to 43% of the nitrate stream load (463.7 kg N day^{-1}) during spring and nitrification in sediments with macrophytes was equivalent to 247% of summer ammonium load (3.5 kg N·day^{-1}).	Black Earth Creek, Wisconsin, USA [17]
Denit.	Ag	**CD**	Reflooding a leveed Midwestern floodplain to create open water floodplain pond and wet meadows	(Neutral)—A drained floodplain used for row crop agriculture for >50 years was sampled 1-year pre and 2-years post restoration. The floodplain soils had the potential to support denitrification (from 0.00 - 15.0 µg N_2O-N [kg soil]$^{-1}$·h^{-1}, mean: 1.4 ± 2.0), but restoration did not immediately increase rates.	Baraboo River floodplain in Wisconsin, USA [18]
Denit.	Ag	**B**	Two-stage ditch floodplain connection	(Positive/Neutral)—1-year pre and 2-years post restoration, denitrification measurements along the floodplain showed the restoration contributed significantly to NO_3^- retention during storm events. However, during storms <10% of load was removed due to high NO_3^- concentrations.	Shatto Ditch, tributary of Tippecanoe River, Indiana, USA [19]
Denit.	Ag	**B**	Two-stage ditch floodplain connection	(Positive)—On vegetated floodplains, denitrification rates were enhanced during inundation. The floodplain was inundated 12 times per year. Scaling up rates showed that the restoration tripled retention during storms.	Shatto Ditch, tributary of Tippecanoe River, Indiana, USA [20]
Denit.	Ag	**D**	Levee breached to restore connection between main channel & historic floodplain	(Positive/Neutral)—Floodplain restoration increased N retention through denitrification. Scaling up showed the restored floodplain could remove 118 kg-N/yr (~24% of annual river load) in the dry year when it was flooded 24% of the time and 850–6,150 kg-N/year (0.6%–4.4% of annual load) during the wet year when it was flooded 43% of the time	Lower Cosumnes River, California, USA [21]

Table S1. *Cont.*

Method	LU	Type	Management Action	(Rating)—Summary of Results	Location and Citation
Denit.	Ag	**D**	Wetland reconnection through experimental levee breach	(Negative)—2 years after restoration, the restored site had significantly higher bulk density and lower total C, total N, microbial biomass, PMN and ~50 times lower potential denitrification than the natural reference site. Differences were linked to organic matter loss during 50 years of isolation.	Redman point bar, Mississippi River, Arkansas, USA [22]
Denit.	For	**I**	13-yr-old restored forested wetland amended with cotton gin trash as C source to enhance N retention	(Positive)—Denitrification in the restored forested wetland was limited by organic carbon availability. Cotton gin trash amendment increased denitrification rates in the restored forest soils to the level of the natural forest soils.	Panther Swamp National Wildlife Refuge, Northwestern Mississippi, USA [23]
Denit. P min.	For Ag	**BC**	Creation of 12.9-ha floodplain wetland & upland buffer complex	(Positive)—Reconnecting the floodplain to the stream channel increased terrestrial inputs and stimulated soil N and P cycling that likely led to greater retention of sediment and nutrients in created and natural wetlands. P mineralization increased with sedimentation and sediment-N loading rate.	Piedmont physiographic province of Virginia, USA [24]
Denit.	Mix	B	Floodplain reconnection	(Positive)—Increasing the floodplain's hydrological connection to the main river channel increased N retention. Denitrification was out-competed by assimilation (estimated to use ≤ 70% of available NO_3^-). Denitrification was higher in the restored site (5.7 ± 2.8 mmol $N{\cdot}m^{-2}{\cdot}h^{-1}$ compared to the disconnected site (0.6 ± 0.5 mmol $N{\cdot}m^{-2}{\cdot}h^{-1}$).	Lower Lobau & Orth floodplains, Alluvial Zone National Park, Danube River, Austria [25]
Denit.	Mix	**D** **I**	Floodplain and side arm channel reconnection through partial levee breach	(Positive/Negative)—Denitrification potential was lower in the reconnected floodplain than the isolated floodplain. The authors suggested that floodplain reconnection changed conditions like temperature, dissolved oxygen, and macrophyte distribution, which should increase N and C cycling efficiency.	Lower Lobau & Orth floodplains, Danube River, Austria [26]
Denit.	Ag Mix	**A** **G**	Floodplain reconnection	(Positive)—The reconnected floodplain supported both denitrification and DNRA. Both processes were limited by organic carbon availability. Denitrification rates (0.4–4.2 mmol $N{\cdot}g^{-1}$ dry soil d^{-1}) were ~10× greater than DNRA.	2 km stretch of River Cole floodplain, Coleshill, Oxfordshire, United Kingdom [27]
Denit.	Urb	**AB** **E** **G**	Stream restoration through natural channel design	(Positive)—In the riparian zone, restored sites had highest denitrification potentials but the difference was not statistically significant. The highest rates were in the top 10 cm of soil, which was linked to high levels of soil organic matter and root biomass. Increasing riparian water tables fosters interaction of groundwater NO_3^- with near-surface soils with higher denitrification potential.	Baltimore LTER, Maryland, USA [28]
Denit.	Urb	**AB** **E** **G** **I**	Constructed & relict oxbow wetlands	(Positive)—High rates of denitrification found in urban wetlands in both summer and winter. Sediment denitrification rates could remove between 23%–28% of the NO_3^- standing stock in the overlying water column (8%–11% of daily stream load). A residence time of ~4 days would result in complete removal of any NO_3^- that enters these wetlands.	Baltimore LTER, Maryland, USA [29]
Denit.	Urb	**AB** **E** **G**	Stream restoration raised stream bottom, lowered stream banks, and added cross vanes and riffles	(Neutral)—Restoration did not dramatically change the distribution of geomorphic features (pools, riffles, debris dams) so degraded sites and restored sites had similar laboratory rates. Reach scale denitrification rates were lower than net nitrification rates suggesting that these stream features are both a sink for N and a net nitrate source. Denitrification potential rates were positively related to microbial biomass N and % sediment organic matter.	Baltimore LTER, Maryland, USA [30]

Table S1. *Cont.*

Method	LU	Type	Management Action	(Rating)—Summary of Results	Location and Citation
Denit.	Urb	**AB E G**	Stream restoration raised stream bottom, lowered stream banks, and added cross vanes and riffles	(Positive)—Mean rates of denitrification were significantly greater in the restored reach of the stream than the unrestored reach (77.4 ± 12.6 *vs.* 34.8 ± 8.0 μg N·kg^{-1}·d^{-1}, respectively). N retention increased with hydrologic retention time. Not all areas of the restoration performed equally; reaches with low connected stream banks had higher denitrification rates than high banks.	Minebank Run, Baltimore, Maryland, USA [31]
Denit.	Urb	**AB E G**	Stream restoration	(Negative/Neutral)—Denitrification potential rates in hyporheic sediment were significantly higher in unrestored than restored streams when grass clippings were used as a carbon source. In contrast, when other materials (such as periphyton, leaves, and stormwater runoff) were used as the carbon source restored and unrestored streams were not significantly different but they were both significantly higher than forest reference streams. Denitrification in the restored streams was carbon limited.	Baltimore LTER, Maryland, USA [32]
Mass balance	Urb	**E G**	Stream restoration	(Positive)—The restoration reduced NH_4^+ and NO_3^-, which was linked to higher amounts of hydrophytes.	Zhuanhe River, Beijing, China [33]
Mass balance	Ag	**G**	River & floodplain restoration	(Positive)—Enhanced NO_3^- retention in restored reach compared to upstream reference reach during 3 months of flooding after restoration completion.	River Brede, Denmark [34]
Mass balance	Ag	**G**	4 river restorations that included restoration of riparian wetlands	(Positive)—Among 4 river restoration projects, restored riparian wetlands retained 0.13–10 kg·ha^{-1}·year^{-1} of P and 52–337 kg P ha^{-1}·year^{-1} of N.	Denmark [35]
Mass balance	Ag	**CD**	Riparian wetland restoration	(Positive/Negative)—There were high rates of N removal & low rates of P release within wetlands	Island of Funen, Denmark [36]
Mass balance	Ag	**I**	0.07 ha diversion oxbow wetland	(Positive)—Diversion wetland reduced NO_3^- during storm pulses	Olentangy River Wetland Park, Ohio, USA [37]
Mass balance	Ag	**BC I**	Wetland creation	(Positive)—Wetlands continued to retain NO_3^- 10 years after creation	Olentangy River Wetland Park, Ohio, USA [38]
Mass balance	Ag	**B**	Constructed pond between agricultural field & creek	(Positive)—Model predicted that restoration of ponds at a density of 5% of agricultural area would reduce riverine N export by up to 25% in regions with impermeable lithology.	Seine River Basin, France [39]
Mass balance	Ag	**CD G**	Replaced drainage canals with floodplain meadows & wetlands and increased sinuosity	(Positive)—Restored area retained 10% of total N load.	Skjern River, Denmark [40]
Mass balance	Ag	**CD**	Ditch blocking and displacement of drainage pipes to restore stream wetland complex	(Positive/Negative)—Despite re-wetting measures, during the growing season the restored wetland exported all N and P species except for NH_4^+. Nitrate retention occurred during summer flood & low flow.	Northeast of Hamburg in Schleswig-Holstein, Northern Germany [41]
Mass balance	Ag	**BC**	2.8-ha multi-function constructed wetland	(Positive)—More than 77% of total coliforms (TC), 78% of biochemical oxygen demand (BOD), 88% of total nitrogen (TN), and 96% of ammonia nitrogen were removed via the constructed wetland system	Linlo Constructed Wetland, Pingtung County, Taiwan [42]
Mass balance	For	**B**	Substratum excavation to wash away fine materials	(Positive)—100 days after restoration there was a significant decline in hyporheic NO_3^-, NO_2^-, and NH_4^+	River Moosach, a highly regulated subalpine calcareous stream, Bavaria, Germany [43]
Mass balance	Ag	**CD**	Wetland restoration & reconnection	(Positive/Negative)—Within wetlands there was typically NO_3^- & NH_4^+ retention & organic N release. TN budgets were variable.	Pohnsdorfer Stauung, Northern Germany [44]

Table S1. *Cont.*

Method	LU	Type	Management Action	(Rating)—Summary of Results	Location and Citation
Mass balance	Urb	**AB** **H**	Floodplain lowered, streambed elevated, & in-stream wetland creation	(Positive)—Average of 18% total N mass removal within created wetlands	Liza's Bottom, Chowan County, North Carolina, USA [45]
Mass balance	Urb	**AC**	Natural channel design & stream-wetland complexes	(Positive/Neutral)—2 of 6 restored reaches were clearly effective at reducing TN export & only 1 was effective during stormflow conditions	Wilelinor project, Coastal Plain of Maryland, USA [46]
Mass balance	Urb	**I**	Relict oxbow wetlands	(Positive/Negative) - 2 oxbows received 1.6%–7.4% of cumulative stream flow during storm events, and retained runoff from 0.2 to 6.7 days, during which 23%–87% on N was retained (0.25–2.7 g N/m^2/day) and during the storms a small amount of dissolved P was released (0.23–24.8 mg P/m^2/day).	Baltimore LTER, Maryland, USA [47]
Mass balance	Urb	**I**	*In-situ* remediation engineering, ex-situ remediation engineering and constructed wetland engineering based on the different environmental characteristics of the river was applied to treat low concentration sewage	(Positive)—The average values of chemical oxygen demand, biochemical oxygen demand, ammonia nitrogen, total phosphorus and total nitrogen in the same monitoring point of the river were all decreased from 244.45, 84.95, 28.75, 2.28 and 36.05 mg/L in 2009 to 28,67, 8.58, 6.92, 0.38 and 13.40 mg/L in 2012, respectively.	Xinyunliang River in Kunming City, Yunnan Province, China [48]
Mass balance	Urb	**A**	stream channel is transformed into a stormwater management structure designed to reduce peak flows and enhance hydraulic retention of stream flow with the goals of reducing bank erosion and promoting retention of nutrients and suspended sediments	(Positive/Neutral)—Net annual removal of N was insignificant in the Wilelinor project despite a long restored reach and an extensive floodplain. The "best-case scenario" for reducing N was found in the Howard's Branch sand-seepage project which also has an extensive flood-plain. Because stormflow accounts for up to 70% of the annual discharge in these small urbanized streams, load reduction during stormflow conditions is essential to the effectiveness of the system.	Wilelinor project, Coastal Plain of Maryland, USA
Mass balance	Urb	**BC** **H**	3-phase floodplain restoration, storm water wetland complex & surface treatment wetland to increase stream wetland connection	(Positive)—There was a 64% reduction in load due to effects of all three-restoration phases.	Sandy Creek, a headwater stream for Cape Fear River, North Carolina, USA [49]
Mass balance	Urb	**AB** **E** **G**	Stream restoration: raising stream bottom, lowering stream banks	(Positive)—In restored streams, mass balances showed net TDN retention and DOC release across reaches. In contrast there was net TDN release and DOC retention in unrestored streams suggesting an influence of the restoration.	Baltimore LTER, Maryland, USA [50]
Mass balance, Denit.	Ag	**D** **H**	Wetland restoration	(Positive)—N retention efficiency close to 100% except for DON: denitrification rates at 0%–12% of incoming DIN.	Ebro River Delta, northeast Spain [51]
Other	Ag	**C** **H**	Runoff attenuation features	(Neutral)—Removal of NO_3^- was negligible, probably due to short residence time in feature.	Belford Burn catchment, England [52]
Other	Ag	**B**	Removal of river embankments	(Positive)—Embankment removal increased how frequently surface water reached the floodplain thus enabling the possibility of greater processing of high nitrate river water (6.2 mg/L) by floodplain sediments containing low nitrate groundwater (0.5 mg/L).	River Glaven, England [53]
Other	Ag	**A** **G**	Stream restoration with cross vanes	(Positive)—Cross vanes had strong downwelling zones, high DO levels, streambed chemistry similar to surface water, and sulfate and NO_3^- reduction occurring in streambed (but not in reference reach); at restored sites, hyporheic NO_3^- concentrations always equal to or less than overlying stream water NO_3^- concentrations and strongly correlated with concentrations of DO.	Restored streams Owego Creek & Ninemile Creek, Catskills region of Central New York, USA [54]

Table S1. *Cont.*

Method	LU	Type	Management Action	(Rating)—Summary of Results	Location and Citation
Other	Ag	**C**	Stream restoration with cross vane structures	(Neutral)—Restoration structures did promote low magnitude hyporheic exchange around steps in water surface profile and secondary pool and riffle bed forms. Cross-vanes in studied systems did not process significant amounts of nutrients or pollutants for whole-stream system.	Central New York, USA [55]
Other	Ag	**I**	River restoration	(Positive)—During storms N rich water flowed from Danube River into oxbow side channel where concentrations significantly declined after storms	Danube-Auen National Park, Danube River, Vienna, Austria [56]
Other	Ag	**C**	Small log dam restoration structures	(Positive)—Log dams can create hot spots of biogeochemical activity.	Red Canyon Creek, Wyoming, USA [57]
Other	Ag	**A** **G**	Stream restoration	(Neutral)—Total N and NO_3^- concentrations not significantly different between restored, reference, and channelized stream reaches.	Jutland, Denmark [58]
Other	Ag	**C** **H**	Wetlands constructed by building low earthen berm with outflow passing through control device	(Positive)—etlands removed up to 68% of NO_3^- and 43% of P from drainage water; % removal varied considerably with highest removal in wetlands with 1–2 week retention times & large surface area to drainage area ratio	Case studies in Maryland, Illinois, & Iowa, USA [59]
Other	Ag For	**C** **I**	Backwater oxbow rehabilitated by constructing two weirs in its lower limb (one of which was used to create wetland)	(Neutral)—The diversion of polluted runoff and the use of water control structures to maintain greater water depth were observed to be effective management tools, but the former reduces the water supply to habitats that tend to dry up and the latter reduces connectivity.	Yazoo River Basin Northwestern Mississippi, USA [60]
Other	Ag Urb	**G**	Floodplain restoration	(Negative)—Low N release from sediments deposited on restored floodplain	Odense River, Denmark [61]
Other	For	**D**	Wetland tree island restoration through levee removal	(Neutral)—Tree islands distinct in structure & biogeochemical properties from surrounding marsh: higher organically bound P & N, but lower inorganic N. NH_4^+ dominant N constituent & it was low at both island types (3.97 mM).	Florida Coastal Everglades LTER, southern Florida, USA [62]
Other	For	**A**	Added 25 aspen logs (each 2.5 m length × 0.5 m diameter) to 100-m reaches in 3 streams	(Negative)—In a low nutrient, wood-poor stream, restoration through wood addition increased nitrate concentrations (associated with faster leaf decomposition rates)	Upper peninsula of Michigan, USA [63]
Other	Mix	**I**	Floodplain reconnection "partly restored hydrological exchange patterns"	(Positive)—A dynamic exchange allowed the river to benefit from floodplain production under connected conditions	Regelsbrunn floodplain, Danube River, Austria [64]
Other	Mix	**I**	River restoration reconnection to side channels	(Neutral)—Nutrient concentrations in restored side channels *vs.* reference side channels were not significantly different.	Rhine River floodplain, France & Germany [65]
Other	Unk	**I**	Side arm oxbow channel reconnection	(Neutral)—Side channel was connected for 44% of study period; The timing and duration of connection varied between years. N and P concentrations were highest during flood pulses but decreased during connectivity phases when water age increased. During isolation phases, concentrations rose again, but declined after isolation periods exceeding 37 days.	Danube River in National Park Donauauen, Regelsbrunn, Austria [66]
Other	Urb	**B**	Removal of sediments to reconnect floodplain	(Positive)—Stable isotope $\delta^{15}N$ value of riparian plants increased, suggesting enhanced uptake of river water N by floodplain plants	Chikuma River, Japan [67]
Other	Urb	**I**	Engineered wetlands	(Positive)—The flow diverter bed system, which transported stream water to an aerobic wetland & then an anaerobic wetland, significantly decreased N concentrations	Kyungan Stream at central western part of Korea [68]

Table S1. *Cont.*

Method	LU	Type	Management Action	(Rating)—Summary of Results	Location and Citation
Other	Urb	**C**	Erosion control structures	(Neutral)—Structures retained organic matter and decreased NO_3^- (50.3 *vs.* 56.9 mg/L) and ammonia concentrations but difference was not significant	Wastewater dominated drainage (Wash) in Las Vegas, Nevada, USA [69]
Other	Urb	**I**	Created Rio Bosque Wetlands	(Positive/Negative)—The wetlands reduced NO_3^- concentrations; however, agricultural water diversions left wetland dry & without macrophytes in summer limiting ability to retain N	El Paso–Ciudad Jua'rez metroplex, Rio Grande River, United States & Mexico [70]
Other	Urb	**C**	River restoration: water aerated 3 dams constructed 5 km apart	(Positive)—Engineering and biological techniques dramatically improved water quality: NH_4^+ decreased from 27 to 4 mg/L, and total suspended solids decreased from 270 to 40 mg/L, among other parameters.	Dihe River is located in Changyi, Shandong Province, northern China [71]
Other	Urb Ag	**C**	River diversion & wetland drainage followed by wetland restoration	(Positive/Neutral)—Before restoration, the river diversion and wetland drainage increased turbidity and NO_3^- levels. After restoration, the wetland decreased turbidity (N wasn't measured after restoration).	Northwestern Arabian Gulf, Asia [72]
Other	Urb Ag	**C**	Wetlands restored by closing main drainage ditches	(Positive)—Wetland effectively reduces NO_3^- concentration entering Alegria River from storms	Vitoria-Gasteiz, North Spain [73]
Other	Unk	**AB**	Natural channel design to increase stream floodplain hydrologic connectivity	(Positive)—N concentrations and transport were reduced by 20%–70% with in-stream and constructed storm water wetlands.	Chowan Golf Course, North Carolina, USA [74]
Other	Unk	**I**	Oxbow lakes left after river channelization	(Positive)—Oxbow lakes had significantly lower NO_3^- concentrations than adjacent river channel	Łyna & Drweca Rivers, N Poland [75]
Other	Unk	**C** **I**	Two-stage baffled surface-flow constructed wetland 7400 m^2 demonstration project	(Positive)—Mean removal rates of total N, total phosphorus, NH_4^+, chemical oxygen demand (CODcr), suspended solid were about 75%, 78%, 85%, 40%, 80% respectively in summer & autumn. While it decreased in winter, average removal rates were respectively about 30%, 73%, 45%, 25%, 78%.	Jialu River, Hinterland of central China [76]
Other	Unk	**C**	Controlled drainage in canal to restore water levels	(Neutral)—Monthly monitoring showed higher N concentrations in reach with controlled drainage than uncontrolled canal	Tull Creek, North Carolina, USA [74]
Other	Ag	**D**	Wetland reconnection	(Neutral/Negative)—Total C, total N, and P was lower at all sites compared to the natural reference site. Although hydrology has been restored to the wetlands, functionality may take a considerable amount of time to be detectable.	Redman Point-Loosahatchie Bar Restoration Project, Tennessee, USA [77]
Other	Ag	**C**	Floodplain restoration	(Neutral)—Both sites shifted from reducing to more oxidizing environments, based on changes in soil redox potential.	St. Joseph Wetland, Illinois, USA [78]

Method abbreviations: denit. (denitrification), min. (mineralization), and other (indicates an alternative method was used). Land use abbreviations: ag (agriculture), urb (urban), for (forest), log (logging), mine (mining), base (military base), and unk (unknown). Type refers to the typologies developed in Figure 2: (**A**) raise stream bottom, (**B**) lower floodplain, (**C**) raise water levels with drainage control structures, (**D**) reconnect wetlands, (**E**) remove concrete liner, and (**F**) daylighting urban streams buried in pipes, (**G**) increase sinuosity, (**H**) add in-stream wetlands, and (**I**) reconnect oxbow wetlands.

1. Examination of Common Methods used to Monitor Restoration Projects

Changes in water chemistry: Most studies (96%) examined changes in water chemistry (pre and post restoration and/or compared restored and degraded streams), and there was considerable variety in how changes in streamwater chemistry were examined. N species monitored included one or more of the following: nitrate, nitrite, ammonium, inorganic nitrogen, organic nitrogen, total dissolved nitrogen, particulate nitrogen, total Kjeldahl nitrogen, and total nitrogen. If P was monitored, it was one or more of the following: total phosphorus, total dissolved phosphorus, and soluble reactive phosphorus (SRP). Some studies compared concentrations pre-restoration to post-restoration [18,36,40,55,67,68,71]. Other water chemistry studies compared restored and reference reaches. Reference reaches were usually either in neighboring watersheds or a reach upstream of the restoration. References were either "natural" reaches (which are nearby streams of similar size and geology that are considered to be in good ecological condition) [22,24,54,74] or unrestored, degraded reaches [6,10,26,62]. Some studies compared concentrations in restored reaches with concentrations in both natural and unrestored degraded reference reaches [1,30,32,58,65]. Additionally, several studies used a before-after-control-impact (BACI) design to evaluate changes in water chemistry [4,7,34,46]. Lastly, another approach was to examine changes in water chemistry through detailed mapping of hyporheic porewater dynamics around individual restoration structures [5,57]. Most water chemistry studies examined surface water dynamics, but there were several that examined porewater and groundwater as well [53–55].

Mass Balance: Mass balances were conducted in 22% of the studies. Mass balance complexity ranged from measuring inlet and outlet flux [38,39,41,44,51,74,79] to projects across broader spatial scales that incorporated longitudinal sampling, groundwater, and tributaries [1,49,50]. A limitation of the mass balance approach is that it represents a "black box" approach where it is difficult to distinguish between N plant uptake (temporary removal unless vegetation is harvested) and denitrification. This differentiation requires moving beyond mass balance approaches and conducting process level measurements of nutrient spiraling and *in situ* denitrification in these systems.

Denitrification: Denitrification rates were measured in 29% of the studies. Denitrification was measured using denitrification enzyme assays, ^{15}N denitrification capacity assays, ^{15}N laboratory mesocosms, and ^{15}N *in situ* push-pulls. Denitrification enzyme assays are laboratory methods that use acetylene to block the microbial conversion of N_2O to N_2, allowing more easily measured N_2O to accumulate in assay bottles. Denitrification enzyme assays were used in 75% of the denitrification studies evaluating stream and floodplain restoration. The denitrification enzyme assay methods are useful for conducting simultaneous measurement of numerous replicates over both space and time. Some of the denitrification enzyme assay studies used ambient levels of nitrogen and carbon [20,51,80]. Other denitrification enzyme assay studies added sufficient levels of nitrogen and carbon so that denitrification was not limited and rates measured were considered potential denitrification rates [16,18,24,28,30,51,81]. Additionally, other studies using denitrification enzyme assays added nitrate but not carbon in order to examine the influence of carbon sources [21,23,32].

The ^{15}N *in situ* push-pulls were used by 15% of the denitrification studies [1,29,31]. The ^{15}N *in situ* push-pull method involved drawing groundwater or hyporheic water from a shallow well, amending the sample water with ^{15}N enriched nitrate and a conservative tracer (SF_6), injecting the solution back into the well for an incubation, and then drawing the water back up and analyzing dissolved gas concentrations in the water samples. The push-pull method allows measurement of denitrification in restored streams under ambient conditions, but is labor intensive.

The ^{15}N denitrification capacity assay is a method that incubated anoxic samples of soil with $^{15}NO_3^-$ in the laboratory without any addition of organic carbon [27]; this method avoids the complications of acetylene block [82]. The ^{15}N laboratory mesocosm experiments manipulated undisturbed floodplain sediment under controlled conditions to separate the effects of the riverine nitrate input and changes in dissolved organic matter composition on the rate of denitrification, DNRA, and anammox [25].

2. Evaluating Potential Controlling Factors of Nutrient Uptake

Watershed Scale Variables: We examined four watershed scale variables: watershed area, % impervious surface coverage, % disturbance intensity, and % developed. Watershed drainage area, the most common variable, ranged from 80 to 1620 ha with a median value of 407 ha, and was recorded by 47% of studies. Impervious surface coverage varied from 17 to 38% in restored streams and was recorded in 27% of studies. Percent watershed disturbance intensity was defined as the % of watershed area covered by unpaved roads or bare ground on slopes >5% [7]. Percent development in both the watershed and the riparian area (defined as a 30 m stream buffer) was calculated by reclassifying 2001 National Land Cover Dataset (NLCD) into four categories: developed, agriculture, undeveloped, and water [13].

Reach Scale Variables: We examined 11 reach scale variables: study reach length, average reach width, average reach depth, discharge (Q), velocity, flashiness (estimated from changes in mean hourly discharge [13]), longitudinal slope, % canopy cover, % coarse woody debris, above-water photosynthetically active radiation (PAR) in mol quanta photons $m^{-2}\cdot day^{-1}$, and % substrate. Average stream width ranged from 0.06 to 7 m with a median value of 2 m. Discharge was recorded for all of the studies and varied from 3 to 344 L/s with a median value of 11.5 L/s. Stream velocity ranged from 0.042 to 5 m/s with a median value of 0.24 L/s.

Water Chemistry Variables: We examined 6 water chemistry factors: concentration, temperature, dissolved O_2 (mg/L), dissolved O_2 (%), specific conductance (μS/cm), and pH. There were over 15 different concentration variables measured that could influence nutrient spiraling rates; the most commonly listed ones were NH_4^+ (80%), NO_3^- (67%), and SRP (27%).

Transient Storage Variables: We examined 7 transient storage factors: F_{med}^{200}, stream area (A), storage area (As), the ratio of storage to stream area (As/A), dispersion coefficient (D), exchange coefficient (α), and Rh Factor (As/Q). F_{med}^{200} is the fraction of the median travel time attributable to transient storage calculated over a standardized length of 200 m [83]. Area-based measurements included the main channel cross-sectional area (A; m^2), transient storage zone cross-sectional area (A_S; m^2), and the relative size of the transient storage zone (A_S/A). Transient storage coefficients include the dispersion coefficient (D; m^2/s) and the exchange coefficient between the main channel and the transient storage zone (α; s^{-1}). The hydraulic retention factor (Rh) represents the time water spends in the transient storage zone for each meter advected downstream and is calculated as A_S/Q [84].

Metabolism Variables: We examined 6 stream metabolism factors: production (GPP), respiration (ER), net daily metabolism (NDM), P:R, Chl-*a*, and U/Chl-*a*. Stream gross primary production (GPP; g/m^2/day) is the total production of energy within a stream and is primarily driven by nutrient, light, and stable habitat availability. Ecosystem respiration (ER; g/m^2/day) is a stream's total consumption of energy including both autotrophic and heterotrophic respiration. Net daily metabolism (NDM; g/m^2/day) is the net production or consumption of energy, which is calculated as the difference between production and respiration (GPP minus ER). Some studies also report the photosynthesis to respiration ratio (P:R). Benthic algal abundance was measured as chlorophyll-*a* (Chl-*a*). Nutrient uptake per unit Chl-*a* was determined by dividing areal uptake by biomass, measured as U/Chl-*a.*

Table S2. The 15 nutrient spiraling studies measured 45 diverse potential controlling variables. We divided these variables into 5 categories: watershed, reach, water chemistry, transient storage, and metabolism characteristics. Shaded boxes indicate that a variable was measured in the specific study. The two columns on the right show the total number and percent of studies that recorded each variable.

Categories	Citation #	15	7	8	10	3	14	5	46	16	1	13	4	12	6	9	N	% of Studies
Watershed Characteristics	Watershed Area																7	47
	% Impervious																4	27
	% Disturbance																1	7
	% Developed																1	7
Reach Characteristics	Study Reach Length																15	100
	Width																10	67
	Depth																5	33
	Discharge (Q)																15	100
	Velocity																6	40
	Flashiness																1	7
	Slope																1	7
	% Canopy Cover																4	27
	% Woody Debris																1	7
	Radiation (PAR)																1	7
	% Substrate																2	13
Water Chemistry Characteristics	Ammonium (NH_4^+)																11	65
	Nitrate (NO_3^-)																11	65
	Nitrite (NO_2^-)																2	12
	Total N (TN)																2	12
	Dissolved Organic N																2	12
	SRP																4	24
	Dissolved Organic C																4	24
	Phosphate (PO_4^-)																1	6
	Total P																1	6
	Total Dissolved P																1	6
	Benthic Organic Matter (BOM)																1	6

Table S2. *Cont.*

Categories	Citation #	15	7	8	10	3	14	5	46	16	1	13	4	12	6	9	N	% of Studies
Water Chemistry Characteristics (Continued)	Total Dissolved Solids (TDS)																1	6
	Temperature																5	33
	Dissolved O_2																3	20
	% Dissolved O_2																2	13
	Specific Conductance																2	13
	pH																1	7
Transient Storage Characteristics	F_{med}^{200}																5	33
	Stream Area (A)																1	7
	Storage Area (A_s)																2	13
	Storage Ratio (A_s/A)																4	27
	Dispersion Coefficient																3	20
	α Exchange Coefficient																2	13
	Rh Factor (As/Q)																1	7
Metabolism Characteristics	Production (GPP)																5	33
	Respiration (ER)																5	33
	Net Metabolism																3	20
	P:R																1	7
	Chl-*a*																4	27
	U/Chl-*a*																1	7

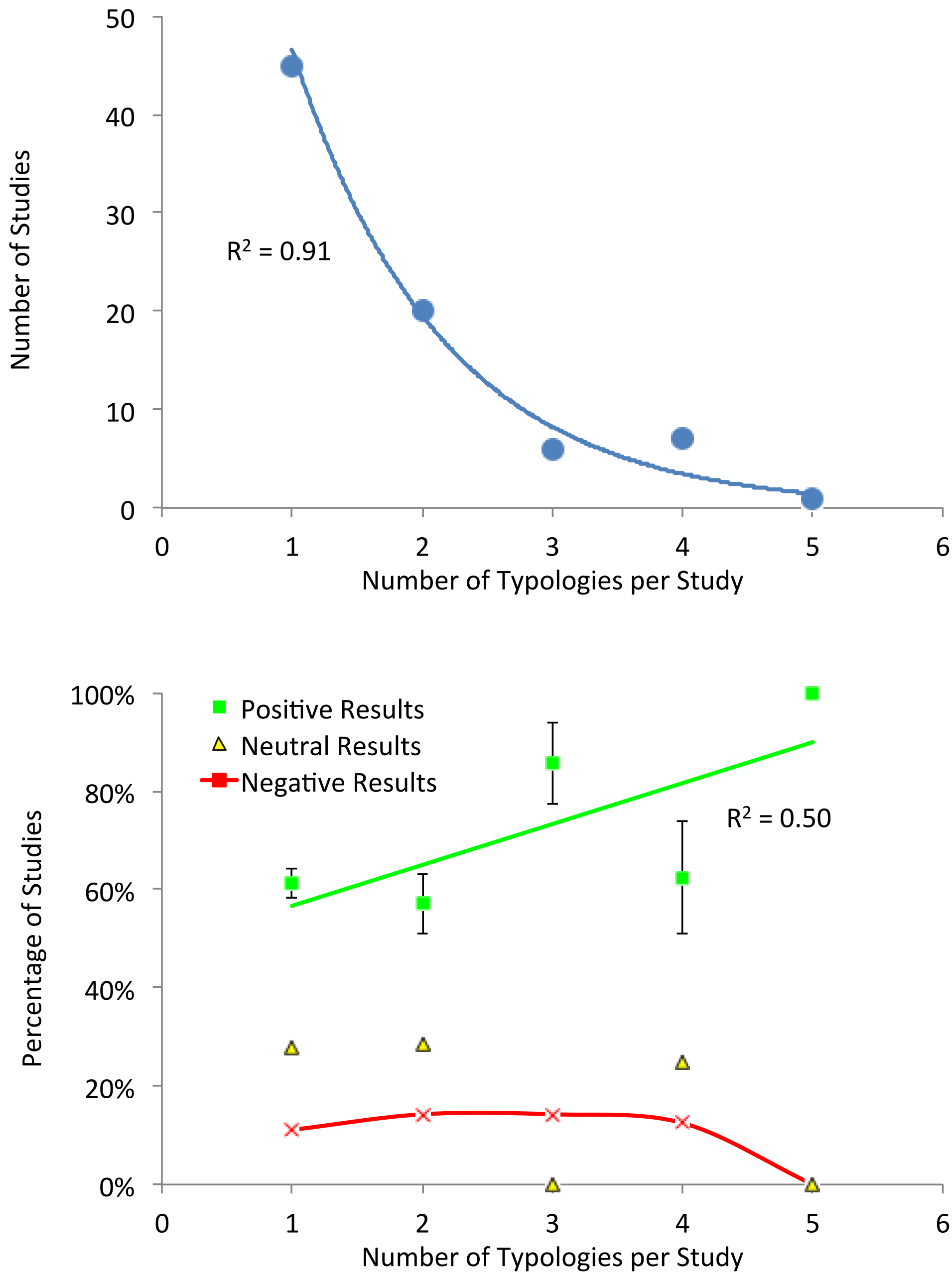

Figure S2. Top panel: As the number of typologies per study increased from 1 to 5, the number of studies declined exponentially from 45 to 1. Bottom panel: In contrast, as the number of typologies per study increased from 1 to 5, the % of positive results increased from 59% to 100%.

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