Supporting Information for

Field and laboratory studies linking hydrologic, geochemical, and microbiological processes and enhanced denitrification during infiltration for managed recharge

Galen Gorski, Andrew T. Fisher, Sarah Beganskas, Walker Weir, Kaitlyn Redford, Calla Schmidt, and Chad Saltikov

24 Pages
11 Figures
3 Tables
**S1 Detailed materials and methods**

**S1.1 Field site and setting**

The Pajaro Valley is bounded by the Pacific Ocean to the west and the San Andreas Fault to the east (Figure S1). Soils in the valley range from very sandy near the ocean and in the higher elevations, to soils with a higher clay and silt content in lowland areas near the Pajaro River which drains much of the valley. Soils at the site are representative of soils in the southeastern portion of the valley, which include fluvial sediments and flood deposits from the Pajaro River. The field site where the tests took place was planted with strawberries and lettuce in previous years but was not in rotation in summer 2016 when the tests took place, nor when the soil cores were collected in winter 2016.

Water used for the field tests was drawn from a nearby agricultural well, screened at depths of 27-38 and 48-52 m below ground surface. Given the screened depths and regional geology, well water is likely a mixture of water drawn from two sources: 1) the shallow alluvial aquifer; quaternary deposits of unconsolidated sand and gravel units and 2) the Upper Aromas red sands unit, a well-sorted, unconsolidated Pleistocene shoreline deposit that forms the primary aquifer unit for much of the Pajaro Valley.

**S1.2 Experimental design and scale – Field studies**

The infiltration capacity of soil is a key parameter in controlling the residence time of infiltrating water within the PRB layer and the saturated zone, where dominant geochemical cycling takes place. Soil infiltration capacity can be measured using a variety of tools and methods, many of which use analytical corrections or assumptions to account for the well-known issue of lateral flow. This study is unique in presenting results from linked field and laboratory
studies, using materials from the same site. In this section, we explain the basis for field infiltration testing and compared methods applied in this study to others. In Section S1.10 we explain the basis for column testing in the lab using soil samples collected adjacent to field test plots.

Generally, the contribution of lateral flow to overall infiltration has an inverse relationship with the scale of the infiltration measurement due to the ratio of circumference to surface area of the test\textsuperscript{2,5}. Additionally, as the scale of infiltration tests increases, more soil heterogeneity is incorporated, and the overall infiltration rate generally increases as more fast paths are exploited\textsuperscript{6,7}. While larger scale studies may limit lateral flow and give more spatially representative infiltration rates by incorporating soil heterogeneity, they present practical challenges such as increased construction costs, water needs, and land use, particularly when considering replicates and controls and running long-term tests lasting weeks.

Due to water availability, consideration for farm activities, the need for side-by-side tests and the design of previous successful experiments, we elected to construct 1m\textsuperscript{2} plots to measure total infiltration by mass balance and vertical infiltration using heat as a tracer. The scale of the experiments is larger than what is commonly applied during infiltration testing using disk or ring infiltrometers\textsuperscript{2,3} and is consistent with plot sizes used in other studies\textsuperscript{6,8}.

We observed different infiltration rates in tests conducted side by side, which is consistent with other studies in agricultural soils that demonstrate comparable heterogeneity at similar scales\textsuperscript{9–11}. Local soil heterogeneity is likely responsible for these differences, as plots were constructed within a few meters of each other with identical configurations and materials. Soil samples collected for grainsize analysis from the BC-Perc showed a 1-meter depth weighted median of 37.7% sand compared to 49.8% and 49.9% for WC-Perc and NS-Perc respectively,
with a higher percentage of silt and clay in the BC plot (Figure S5); subtle differences in grain
size distribution can lead to large variations in hydraulic properties. Vertical rates are especially
useful for comparison to full-scale MAR settings, as edge effects become proportionately less
important as the infiltration area increases\textsuperscript{5,12}.

\textit{S1.3 Construction and operation – Field studies}

The experimental design for the percolation tests was developed for an earlier study\textsuperscript{12} and
deployed in the current study with some modifications that are highlighted herein. Three plots
were hand dug with dimensions 1m x 1m x 1m. The plots were installed approximately 5 meters
apart to ensure that there was no communication between the plots but also in an attempt to
produce similar soil conditions. In each plot, 1-meter tall fiberglass walls were installed on four
sides to force vertical flow through the bottom of the plot. The corner joints of the fiberglass
walls were caulked to prevent leakage, and the annulus around the outside of the fiberglass walls
was filled with bentonite chips (approx. 10 cm), which were activated with water to create a seal.
The remaining depth of the annulus was backfilled with native soil.

One plot was left unamended with native soil as a control (\textit{NS-Perc}), and two plots were
installed with 40 cm of PRB material; woodchips (\textit{WC-Perc}) or biochar (\textit{BC-Perc}). Tests were
run in series, for 14-15 continuous infiltration days to establish saturated conditions below the
plot. During each test, water was applied to the plot through an inlet hose connected to a nearby
well. An automated inflow management system consisting of a float switch connected to a
solenoid valve controlled the water level in the plot so as to maintain saturated conditions, while
avoiding overtopping of the plot walls. When the valve was open, water would pour into the plot
until the water reached a level that activated the float switch and closed the valve. Water then

\textit{S3}
infiltrated into the soil until the float switch was activated at the bottom of the cycle, opening the valve to refill the plot for another fill cycle.

S1.4 PRB materials

Wood chips are common garden amendments and are thought to stimulate denitrification through the release of organic carbon. Biochar is organic material that has undergone pyrolysis (heating in the absence of oxygen), which results in a soil amendment with numerous documented benefits including increases in soil pH, water, nutrient and metal retention, improved soil structure and adsorption of anthropogenic chemicals, as well as decreases in greenhouse gas emissions. Additionally, both wood chips and biochar have been shown to fundamentally shift soil microbial populations and increase the relative abundance of genera responsible for key steps in nutrient cycling including hydrocarbon degradation, nitrification, and denitrification.

Woodchips were made from local redwood, purchased from TriCounty Landscape Supply (Watsonville, CA), and had an average size of 3-5 cm in length. Biochar was purchased from Biochar Now (Loveland, CO) and had an average size of 1-3 cm in length. Biochar was derived from Colorado pine beetle die off and was pyrolyzed for up to 8 hours between 550-650°C. PRB materials with particle sizes much larger than soil grain size were selected to avoid impacting the effective infiltration capacity (saturated hydraulic conductivity) during percolation tests.

The amount, rate and depth of denitrification that the woodchip layer is able to enhance is likely dependent on a host of factors including the source and age of woodchips, infiltration rate, soil properties, underlying microbial communities, and water chemistry. Similarly, the effect that
biochar has on soil properties has been shown to be dependent on the source material used, the
time and temperature of pyrolysis, soil properties and many other factors\textsuperscript{20,21}. In this comparison
study, we sought to demonstrate the potential application of biochar as a carbon amendment
during infiltration, rather than conduct an exhaustive examination of biochar as a soil
amendment, which has been done elsewhere\textsuperscript{22–24}. To this end, we chose biochar that was
available from an established national supplier at a moderate cost as a representative material.
The observed effects are likely to vary with different sources and types of biochar.

\textit{S1.5 Physical hydrology – Field studies}

For field percolation tests, total infiltration was measured using mass balance, by placing
a pressure piezometer on the surface of the plots, correcting for barometric pressure and dividing
by the density of water (1000 kg/m\textsuperscript{3}) and g (9.81 m/s\textsuperscript{2}) to calculate water height. Each fill cycle
was then used as an infiltration test resulting in a high-resolution record of total infiltration.

The vertical component of infiltration was measured using heat as a tracer\textsuperscript{25}. Two kinds
of probes were deployed: one that allowed real-time monitoring as each test was run, and one
that recorded data internally. The real-time probe was built within a piece of polyvinyl chloride
(PVC) tubing, \(\frac{3}{4}\)” ID. Temperature sensors were mounted on a fiberglass rod and placed inside
the tubing, which was backfilled with silica slurry (to assure a good thermal contact) and capped.
Sensor cables were connected to a central data logger, which recorded additional hydrologic
information, with near real-time telemetry of data during tests. Autonomous thermal probes were
self-recording temperature sensor/loggers, suspended on a weighted cable inside a PVC tube (1
\(\frac{1}{4}\)” ID), which is filled with water and capped. The water in the tube assures a good thermal
contact between the thermal sensors and the wall of the tube.
In the field, both kinds of PVC probes were installed in dry plots in a hand-augured hole in the bottom of the plot at a depth such that the sensors were positioned at 5 and 20 cm below the base of the plot. The annulus between the hole wall and the PVC probe was backfilled with silica slurry to ensure a good thermal contact with the soil, and prevent the flow of water down and around the probe. This slurry is poured in when it has the consistency of pancake batter. Because tests are run with a steady flow of water from above, the silica seal around the probe does not desiccate; we verify this when recovering the probes after the tests. The thermal probes were installed within the central 0.16 m$^2$ of each plot in an effort to make measurements at a location where the vertical component of infiltration was greatest.

Time-series thermal records from the probes were processed using a bandpass filter centered on the dominant signal frequency (generally a period of 24 or 12 hrs), with the bandpass selected for each probe and test based on a frequency spectrum of the data. The amplitude reduction of the signal between shallow and deep sensors was then used to calculate vertical infiltration rates using a transient equation for conductive-advective-dispersive heat transport during steady-state fluid flow$^{25}$. The data reported were collected using the real-time probes, as those temperature sensors produced the most consistent responses (being smaller diameter than the autonomous probes). When both sets of probes (real-time and autonomous) reported usable data, calculated vertical infiltration rates were consistent between the two.

**S1.6 Microbiological data analysis**

Illumina sequencing data were filtered and corrected using the Divisive Amplicon Denoising Algorithm version 1.7.7 (DADA2)$^{26}$. Sample sequences were assigned to Operational Taxonomic Units (OTUs) with the Silva reference database version 132$^{27}$ using an RDP naïve
Bayes classifier\textsuperscript{28}. This resulted in a total of 1376 individual OTUs. The total number of reads per sample ranged from 60,143 to 271,135 with a median value of 89,537. The taxa were then normalized to the total number of reads for each sample and pruned such that each remaining OTU was \( \geq 1\% \) within at least one sample, resulting in 351 remaining OTUs that accounted for \( \geq 90\% \) of reads for each sample.

Across all sample groups, Proteobacteria was the most abundant phylum with an average of 24.5\% relative abundance followed by some order of Acidobacteria, Chloroflexi, Actinobacteria and Gemmatimonadetes which averaged 16.3\%, 10.4\%, 8.9\% and 8.0\% across all sample groups. All sample groups contained Archea within the phylum Thaumarchaeota at \( >3.0\% \) with an average across samples of 4.3\%.

The phyloseq package (v. 1.22.3)\textsuperscript{29} in R (v. 3.4.3) was used to calculate and visualize beta (between sample) diversity for samples. A beta-diversity matrix was obtained using Bray-Curtis dissimilarity coefficients which was then reduced to two dimensions for visualization using non-metric multidimensional scaling (NMDS) with 20 runs and a stress factor \( \sim 0.1 \)\textsuperscript{30,31}.

Laboratory and field samples clustered separately in terms of beta diversity (Figure 4B), which may be due to fine-scale soil heterogeneity, the difference in time of year that the samples were collected (summer for the field and winter for the laboratory), and/or differences in the depth of sampling.

\textit{S1.7 Fluid chemistry sample collection and analysis}

For field percolation tests, two nests of fluid sampling piezometers were installed in each plot to sample the surface and subsurface fluid during infiltration tests. Fluid samplers were constructed from polycarbonate tubing with drilled holes which were wrapped in mesh to
prevent clogging. Each fluid sampler had a 10-cm screened interval and was attached to a length
of 6-mm ID nylon tubing for sampling. For each nest, three samplers were lashed to a fiberglass
rod and installed in an augured hole with a horizontal layer of activated bentonite as a seal
between the samplers to prevent cross flow. The fluid sampling nests were installed such that the
middle of the screened intervals for the fluid samplers were 30, 55 and 80 cm below the surface
of the plot. An additional fluid sampler was installed at the plot surface to sample water before
infiltration. In the WC-Perc and BC-Perc plots, a fluid sampler was placed within the PRB layer.

Daily fluid samples were collected by connecting a peristaltic pump to the nylon tubing
attached to the fluid samplers and wasting the appropriate amount to clear stagnant water within
the lines and fluid samplers. Samples were then collected for nitrogen species (NO$_3$-N, NO$_2$-N
and NH$_4$-N), dissolved organic carbon (DOC) and $\delta^{15}$N and $\delta^{18}$O of NO$_3$. Nutrient samples were
filtered with 0.45 µm nylon filters and isotope samples were additionally filtered at 0.2 µm, both
were collected in acid washed HDPE bottles and placed on ice. DOC samples were filtered at
0.45 µm and collected in glass vials, then placed on ice. Once returned to the lab, all samples
were stored at -4°C and analyzed within 2 weeks of collection.

Although fluid chemistry and sediment samples from field and laboratory studies were
collected separately, they were analyzed in the same manner to facilitate comparison, unless
otherwise noted, the following is a description of analytical techniques that were carried out to
analyze samples from both field and laboratory studies.

Nutrient samples were analyzed using a Lachat QuickChem (Loveland, CO). 3 channels
simultaneously measure NO$_3$-N, NO$_2$-N and NH$_4$-N using colorimetry, resulting in +/- 4%, +/-
2% and +/- 7% variability respectively (st.dev./average value for check standards). DOC samples
were analyzed by a Shimadzu TOC Analyzer (Kyoto, Japan) resulting in +/-2\% variability (stdev/average value for check standards).

For field tests, net changes in nutrients were calculated as the difference between the surface water and the fluid sampler at 80 cm depth, the deepest fluid samplers that reliably produced water. Sample values from the two fluid sampling nests were averaged at each depth. For the laboratory column studies, net changes were calculated as the difference between the influent water and the effluent water. For the analysis of net nitrogen removal in the system, we refer to nitrogen as the suite of inorganic species (NO$_3$-N +NO$_2$-N+NH$_4$-N), which accounts for the inter-conversion of N into different reactive species. Soil nitrogen constituents are not included in this formulation as measurement of bulk soil nitrogen before and after each test show no significant or systematic changes (Figure S7).

A subset of samples collected during the percolation studies were selected for NO$_3$ stable isotope analysis. NO$_3$ isotope samples were sent to UC Davis Stable Isotope Facility (Davis, CA), where samples were prepared using the bacterial method$^{32}$ and $\delta^{15}$N and $\delta^{18}$O were measured using a Thermo Scientific Delta V Plus IRMS (http://stableisotopefacility.ucdavis.edu/no3.html), with an accepted precision of 0.4\%o for $\delta^{15}$N and 0.5\%o for $\delta^{18}$O. Stable isotopes are reported in per mil notation:

$$\delta = (1 - \frac{R_{\text{sample}}}{R_{\text{standard}}}) \times 1000$$ \hspace{1cm} [S1]

where R = the ratio of heavy/light isotope in the system. The apparent enrichment factor for both oxygen and nitrogen isotopes can be calculated using a simplification of the Rayleigh distillation model for a closed system$^{33}$:
$$\delta \equiv \delta_o + \varepsilon \ln(f)$$  

Where \(\delta\) = isotopic ratio of sample in delta notation [‰]

\(\delta_o\) = initial isotopic ratio [‰]

\(\varepsilon\) = apparent enrichment factor

\(f\) = fraction of the initial reactant remaining

S1.8 Sediment sample collection

Sediment samples were collected before and after each experiment to characterize ambient soil conditions as well as to measure changes due to infiltration. Samples before each test were collected adjacent to the plots so as to avoid disturbance in the bottom of the plot. Samples were collected at 10 cm resolution below plot surface (bps) for 1) soil texture 2) total organic carbon (TOC) and total nitrogen (TN) and 3) phylogenetic sequencing of microbial DNA.

TOC, TN and DNA samples were collected with a hand auger, placed in labeled sterile whirlpacks and placed in a liquid N\(_2\) field dewar for transport. Samples were then stored in a -80°C freezer until analysis. After each test TOC, TN and DNA samples were collected at 10 cm resolution from directly below the plot soon after the tests had ended so the soil was still saturated, and conditions were similar to those during the test. Results are shown in Figures S6-7.

S1.9 Sediment analysis

Sediment samples were analyzed for TOC and TN using a Thermo Fisher Flash 2000. Samples were homogenized, oven-dried, vapor acidified for 24-hours, oven-dried again, packed
into tin capsules, and crushed into cubes for analysis. A reference material was analyzed every 10 samples, resulting in a standard deviation of <3%.

Samples collected for textural analysis were digested in 30% hydrogen peroxide to remove organic carbon, deflocculated using a hexametaphosphate solution (4 mg/L) and analyzed on a Beckman Coulter LS 13320 Particle Size Analyzer. Volume fraction of sample is binned by grainsize, and commercial standards and sample replicates showed a 3-5% precision (relative) for each grain size bin.

S1.10 Experimental design – Lab studies

Column studies were designed as direct analogs to the field percolation tests where fluid flow rates through the soil could be more tightly controlled in a laboratory setting. From the same site where percolation testing took place, soil cores were collected in-situ using a custom-built, attachable coring shoe affixed to a 10-cm ID 100-cm length of schedule 40 PVC. The top of the PVC was fit with a custom-built coring cap, and shaft which was used to drive the device into the ground using a slide hammer. The core was then recovered using truck jacks, resulting in a sediment core with preserved soil structure and layering. Three cores were collected from the site and transported back to the lab (Figures S2-3).

Woodchips, biochar, or inert sand was added to the top of the cores as a PRB layer, they were then sealed and inverted to match the layering and flow direction from the percolation tests, so that each column consisted of 30 cm of PRB material (or inert sand in the case of the NS column) and 60 cm of soil. This construction also preserved the ratio of PRB material to saturated soil for the WC-Perc and BC-Perc tests. In the case of the native soil column, the saturated zone was thicker in the column than in the field due to the addition of inert sand.
Using a peristaltic pump, local tap water with added NO$_3$ (30 mg/L NO$_3$-N), was pumped through the column in an upward flow direction to facilitate even saturation of the material as well as better control of flow rates through the adjustment of the pumping rate, as has been done in previous column studies$^{34-36}$. Water was pumped in an upward direction for two primary reasons: 1) by pumping water in an upward flow direction, the flow rate (and thus fluid residence time) can be manipulated without changing soil saturation, and 2) by initially saturating the columns very slowly from the bottom, the development of preferential flow paths is minimized and saturation is more homogeneous. Water was introduced slowly with driving pressures up to 140 kPa, to saturate the cores and allow trapped air to dissolve and be removed. Tap water was used due to the large volume of water required for the tests (>1000 L).

The rate of water flow through the columns was calculated by measuring the amount of water discharged in a known amount of time. Flow rate was initially kept low (~1 ml/min or ~0.17 m/day) in an effort to stabilize the flow and overlap with vertical infiltration rates observed in the percolation tests. After multiple days of fluid sampling at the lower flow rate showed stable nutrient concentrations and patterns, the pump was turned up to a higher flow rate (~4.5 ml/min or ~0.7 m/day), (Figure S4).

Once columns had been saturated and flow and pressure had stabilized, column influent and effluent were sampled daily for NO$_3$-N, NO$_2$-N, NH$_4$-N, and DOC. Influent samples were collected from the artificial groundwater reservoir and effluent samples were collected directly from the column through a sampling port installed with a microporous ceramic rhizon sampler. All fluid samples collected were filtered through 0.22 um nylon filtered before storage at -4°C. Samples collected for nitrogen species were stored in acid washed HDPE bottles and DOC samples were stored in glass vials for analysis.
In a similar manner to the percolation tests, sediment samples were collected before and after the column studies using the same sterile methods of collection and storage. Pre-experiment samples were collected adjacent to the location of core collection, and sample splits were collected for soil texture, TOC, TN and DNA analysis. Post-experiment samples were collected from the columns after the experiments had finished and splits were collected for TOC, TN and DNA analysis (Figures S6-7).

S2 Results and discussion

S2.1 Comparison to bioreactor studies

We observed active cycling during infiltration both within the PRB and in the soil below the PRB. The latter represents a fundamental difference from traditional bioreactor applications that generally emphasize nitrogen removal within a carbon source region (e.g. a woodchip bioreactor). However, comparing nitrogen removal rates measured in this study to rates obtained from traditional woodchip bioreactors is useful for placing the current results in context.

For the sake of comparison, we treat the entire PRB/soil system as if it were a bioreactor with 0.4 m$^3$ and 2.3x10$^{-3}$ m$^3$ reactive material (woodchips or biochar) for the field and laboratory studies respectively, resulting in an average N-removal rate of $\Delta N_L = -4.8$ g-N day$^{-1}$•m$^{-3}$ (reactive material) for WC-Perc, and $\Delta N_L = -5.3$ and -3.3 g-N day$^{-1}$•m$^{-3}$ for WC-Col AP1 and AP2, respectively. Similarly, during BC-Perc N-removal rates were $\Delta N_L = -4.5$ g-N day$^{-1}$•m$^{-3}$, and $\Delta N_L = -3.0$ and -1.3 g-N day$^{-1}$•m$^{-3}$ for BC-Col AP1 and AP2, respectively.

These values are similar to values reported for a within-stream woodchip bioreactor installed to receive and process agricultural runoff (average -3.2 g-N/day•m$^{-3}$) and higher than values reported for a woodchip denitrification wall installed to intercept nitrate contaminated...
groundwater from nearby dairy operations (average -1.4 g-N/day•m$^{-3}$)$^{38}$. In general, our values fall towards the higher end of values reported for denitrification walls, -0.014 to -3.6 g-N day$^{-1}$•m$^{-3}$, and at the lower end of values reported for denitrification beds, -2 to -22 g-N day$^{-1}$•m$^{-3}$.$^{39}$ The majority of the studies cited use woodchips as a reactive material to enhance denitrification.

**S2.2 Depth of saturated zone in field studies**

The conceptual model of denitrification during infiltration, developed in section 4.4, utilizes observations of the thickness of the saturated zone beneath the surface of the soil during infiltration testing in the current study, and similar tests carried out in coarse-grained soils (>90% sand). The thickness of the saturated zone is dictated by the driving head of the surface water as well as the physical properties of the soil that control drainage from below (e.g. pore size, pore network connectivity). While the depth of the saturated zone was not explicitly measured in either study, we infer that the deepest depth bps that successfully produces a fluid sample can be used to indicate the minimum depth of saturation. Due to the design and construction of the subsurface fluid sampling piezometers, samples can only be collected if the screened area of the piezometer and the surrounding gravel pack is completely saturated with fluid, and thus is above the inverted water table. Unsaturated or partially saturated conditions resulted in no sample collection.

During the field studies, we collected subsurface samples from duplicate nests of fluid samplers on 33 sampling days (during both initialization and analysis periods) for a total of 66 individual observations of the minimum depth of saturation. 82% of observations showed a minimum depth of saturation of 80 cm, with the remaining observations showing 55 cm depth (Figure S11).
During field tests similar to the current study done in coarser soil (> 90% sand)\textsuperscript{12}, the deepest samples collected came from a range of shallower depths, suggesting a shallower depth of saturation. During 64 total subsurface sampling campaigns, the deepest sample collected came from 80 cm bps in 31% of samples collected, from 55 cm bps in 53% of samples collected, and from 30 cm bps in 16% of samples collected (Figure S11). The inability to draw water with a peristaltic pump may result from partial or fully unsaturated conditions, or from other circumstances, such as clogging, or pinched/broken tubing. However, the consistent inability to collect samples at depth from duplicate fluid sampling nests in replicate experiments suggests unsaturated conditions. A similar pattern was seen in an earlier study shallow infiltration in an active MAR system having a range of soil textures\textsuperscript{40,41}. In the earlier study, fluid samples were routinely collected from greater depths in areas of the MAR infiltration basin where soils were finer, and no samples were collected from comparable depths where soils were coarser.

Given similar experimental designs with similar driving head between the current study and tests done in sandy soil, we infer that physical soil characteristics play an important role in determining the saturated zone thickness, with larger soils with larger grain sizes promoting a thinner saturated zone in general.
Figure S1 Map of the Pajaro Valley Drainage Basin in central coastal California, USA\textsuperscript{42}. Solid black star indicates the location of the current study site. Open star labeled “HS” indicates location of the Harkins Slough managed recharge system, location of an earlier PRB study completed in coarser soil\textsuperscript{12}. Red box shows a regional soil map near the current study site. Soils in the region are generally loam to sandy loam, being flood plain, alluvial, and fluvial deposits, and vary considerably in texture and composition over short distances.
Figure S2 Soil cores used for laboratory column studies were collected using a custom-built coring apparatus consisting of A a stainless-steel drive shaft mountable on a schedule 40, PVC tube for hammering to depth with a slide hammer, and B a coring shoe with a core catcher, which secures the core during extraction. C shows the core catcher after extraction and D shows the core extraction method; using truck jacks and a “pipe dog” to pull the core upward using the drive shaft. The intact core is extracted from the ground, then brought back to the laboratory for testing.
Figure S3 Laboratory column experimental configuration. A All three columns running simultaneously driven by the same peristaltic pump. Installation of biochar B and woodchips C as PRB materials at the bottom of the columns before they were sealed and inverted. D Single column showing valves, water flow direction (blue arrows), and sampling ports. E Detail showing column manifold. Release valve and pressure gauge were used to maintain and monitor stable flow throughout the tests.
Figure S4 Laboratory column studies experimental conditions and analysis periods. Two analysis periods were chosen for comparison to field studies, AP1 and AP2, based on relatively stable flow and pressure conditions. A Infiltration rate (m/day) controlled by a peristaltic pump and measured daily for each treatment. B $\Delta[N]$ for each treatment, with the [N] of influent water shown in open circles. C $\Delta N_L$ for each treatment.
Figure S5  **Left panel** Grain size analyses from field and laboratory studies showing samples from 10-100 cm at 10 cm intervals binned into clay (<4µm), silt (4-63µm) and sand (>63µm) and **Right panel** Box and whisker diagrams showing the percentage distribution of clay, silt and sand size particles for field and laboratory experiments, and for similar experiments done at the Harkins Slough MAR site in very coarse sandy soil. Grainsize samples for laboratory studies were collected adjacent from within 10 cm of the location of all three columns.
Figure S6 Soil total organic carbon content for field studies (A) and laboratory studies (B) collected before (open circles, dotted lines) and after (closed circles, solid lines) each experiment.
Figure S7 Soil total nitrogen content for field studies (A) and laboratory studies (B) collected before (open circles, dotted lines) and after (closed circles, solid lines) each experiment.
Double isotope plot of residual pore water NO$_3$ during field percolation tests for different treatments. Surface samples are shown with open circles and subsurface samples are shown with closed circles. For each treatment, the average of multiple samples is shown (NS, n = 2; WC, n = 6; BC, n = 3). Dotted lines show linear regression for WC-Perc and BC-Perc treatments, WC-Perc had a slope of 0.72 and BC-Perc had a slope of 0.71, similar to slopes from other studies of denitrification (0.53 and 0.67$^{43,44}$).
Figure S9 Comparison of $\Delta N_L$ for field percolation tests to laboratory column studies across a range of infiltration rates measured for all soil treatments with percolation tests shown with closed circles and column experiments shown with open circles. Bars show standard deviation of values measured for each test during each analysis period. In general, $\Delta N_L$ shows a stronger dependence on infiltration rate for the PRB treatments than for the native soil treatment (Table S2). Dashed lines show hypothesized relationships between infiltration rate and $\Delta N_L$. 
Figure S10 Relative abundance of the 10 most frequently found phyla for all study groups for each experiment. The 10 most abundant phyla represented ≥80% of total reads for all samples.
Figure S11 The deepest depths at which samples could be collected from three infiltration tests in coarse-grained soil (Beganskas et al. 2018) (A-C) and in finer-grained soil (this study) (D-F). Plot construction in both studies consisted of two replicate nests with fluid samplers at multiple depths, and paired bars show the deepest depth of sample collected for each replicate. Coarse-grained sites showed more variability in depth within the range sampled, while the finer-grained soils consistently produced from 80 cm depth.
Table S1 Effect of soil treatments: T-tests to compare ∆[N] and ∆N_L values for each soil treatment within each experiment

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<td>1</td>
<td>2.0E-08</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>WC vs NS</td>
<td>3</td>
<td>1</td>
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<td>9.6E-02</td>
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<tr>
<td>AP2</td>
<td>BC vs NS</td>
<td>3</td>
<td>1</td>
<td>4.5E-01</td>
<td>0</td>
<td>4.5E-01</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>WC vs BC</td>
<td>3</td>
<td>1</td>
<td>4.8E-02</td>
<td>1</td>
<td>5.4E-02</td>
<td>0</td>
</tr>
</tbody>
</table>

a where 1 indicates a statistically significant difference and 0 indicates that none was detected.

Table S2 Effect of infiltration rates: T-tests to compare ∆[N] and ∆N_L values for each soil treatment between experiments

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Signif. Compar.</th>
<th>Type</th>
<th>Tails</th>
<th>∆[N] p.value</th>
<th>sig @0.05 ?</th>
<th>∆N_L p.value</th>
<th>sig @0.05 ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
<td>Perc vs AP1</td>
<td>3</td>
<td>1</td>
<td>9.4E-03</td>
<td>1</td>
<td>3.7E-02</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Perc vs AP2</td>
<td>3</td>
<td>1</td>
<td>2.4E-01</td>
<td>0</td>
<td>4.2E-01</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>AP1 vs AP2</td>
<td>3</td>
<td>1</td>
<td>9.4E-03</td>
<td>1</td>
<td>4.2E-01</td>
<td>0</td>
</tr>
<tr>
<td>WC</td>
<td>Perc vs AP1</td>
<td>3</td>
<td>1</td>
<td>4.8E-01</td>
<td>0</td>
<td>2.3E-02</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Perc vs AP2</td>
<td>3</td>
<td>1</td>
<td>1.2E-06</td>
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<td>1.8E-03</td>
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<tr>
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<td>AP1 vs AP2</td>
<td>3</td>
<td>1</td>
<td>2.8E-12</td>
<td>1</td>
<td>1.7E-02</td>
<td>1</td>
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<tr>
<td></td>
<td>Perc vs AP1</td>
<td>3</td>
<td>1</td>
<td>2.2E-02</td>
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<td>7.8E-03</td>
<td>1</td>
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<tr>
<td>BC</td>
<td>Perc vs AP2</td>
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<td>1</td>
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<td>6.4E-04</td>
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<tr>
<td></td>
<td>AP1 vs AP2</td>
<td>3</td>
<td>1</td>
<td>4.5E-08</td>
<td>1</td>
<td>5.0E-02</td>
<td>1</td>
</tr>
</tbody>
</table>

a where 1 indicates a statistically significant difference and 0 indicates that none was detected.

Table S3 Effect of depth during field experiments: Single factor ANOVA, Factor: depth

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Signif. Compar.</th>
<th>[N] p.value</th>
<th>sig @0.05 ?</th>
<th>[DOC] p.value</th>
<th>sig @0.05 ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
<td>All depths</td>
<td>3.9E-01</td>
<td>0</td>
<td>2.3E-01</td>
<td>0</td>
</tr>
<tr>
<td>WC</td>
<td>All depths</td>
<td>7.3E-11</td>
<td>1</td>
<td>1.8E-09</td>
<td>1</td>
</tr>
<tr>
<td>BC</td>
<td>All depths</td>
<td>5.6E-10</td>
<td>1</td>
<td>3.2E-10</td>
<td>1</td>
</tr>
</tbody>
</table>

a where 1 indicates a statistically significant difference and 0 indicates that none was detected.
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(18) Xu, H.; Wang, X.; Yao, H.; Su, J.; Li, H.; Zhu, Y.-G. Biochar Impacts Soil Microbial


