Final report

A. Project information:

Project title: Remediation of tile drain water using denitrification bioreactors

Project leaders:

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B. Objectives:

A. Evaluate the environmental and economic feasibility of denitrification bioreactors for the removal of nitrate from tile drain effluent and surface runoff.
B. Extend the results of this research to coastal vegetable growers to stimulate action toward compliance with water quality regulation.

C. Abstract:

Two pilot-scale denitrification bioreactors were constructed in 2011 on tile-drained commercial vegetable farms in the Salinas Valley. Pits were dug, lined with polyethylene sheeting, and filled with chipped wood waste obtained from the Monterey Regional Waste Management District. Pumps were installed in the collection sumps of the farms' tile drain systems. Tile drain effluent was continuously pumped into the bioreactors at a rate to provide approximately 2 days of residence time in the reactors (based on total porosity) before the water was released into the drainage ditch that normally received the tile drain effluent. A third bioreactor was constructed in 2012 to treat surface runoff. Because runoff contains a substantial sediment load, a pretreatment system using polyacrylamide (PAM) was necessary to remove sediment and prevent fouling of the bioreactor.

Sampling over the 2011, 2012 and 2013 irrigation seasons showed that the denitrification rate averaged 8-11 PPM NO_3-N denitrified per day of residence time in the bioreactors; higher rates were observed with surface runoff treatment, probably due to higher water temperature. These denitrification rates were similar to those reported from bioreactor studies in other areas of the country, and substantially higher than that typically achieved in constructed wetlands (another approach to biological

denitrification). However, the high initial NO_3-N concentrations observed, particularly in tile drain water (often > 100 PPM), would require extended treatment time, and therefore would require very large bioreactors.

The injection of methanol (an easily metabolized carbon source to support the anaerobic bacteria responsible for denitrification) into the tile drainage bioreactors in 2013 increased denitrification rates, confirming that the wood chips were unable to supply sufficient labile carbon to maximize denitrification. In laboratory-scale bioreactors carbon enrichment using either methanol or glycerin (a byproduct of biodiesel fuel refining) increased denitrification in proportion to the amount of C injected. In 2014 methanol injection into one of the tile drainage bioreactors demonstrated that near-complete denitrification was possible in 2 days of residence time, provided sufficient C was injected to accommodate the inlet NO_3-N load.

Economic analysis suggested that operating wood chip bioreactors in a passive mode (no carbon enrichment) would cost approximately $1.50-1.80 per lb NO_3-N denitrified. The chemical cost of carbon enrichment would be in that same range, but C enrichment controlled by real-time inlet NO_3-N monitoring could maximize system efficiency, minimize the bioreactor size requirement, and achieve consistent outlet water quality.

D. Introduction:

Vegetable production on the Central Coast faces an unprecedented challenge from environmental water quality regulation. Maintaining surface runoff from vegetable fields below the Federal drinking water standard of 10 PPM NO_3-N presents a challenge, particularly if the irrigation water used is above this nitrate level (as are about 40% of irrigation wells in Monterey County). Extensive monitoring in recent years has shown that runoff NO_3-N is closely related to the concentration of the irrigation well, and that common conservation practices (vegetated ditches, buffer strips or tailwater ponds) have minimal effect on runoff NO_3-N concentration. Limiting the NO_3-N concentration of tile drain effluent to 10 PPM is even more problematic. NO_3-N concentration in the soil solution typically runs 3-5 times higher than soil NO_3-N expressed on a dry soil basis; this is because the solution phase weighs no more than 20-35% of the dry soil, depending on texture. With vegetable crop root zones commonly containing 20+ PPM NO_3-N on a dry soil basis, soil solution leaching from the root zone is typically several-fold higher.

While fertilizer management practices can reduce NO_3-N concentration somewhat, it is clear that some remediation technique for both surface water and tile drainage will be needed to meet regulatory standards. There are three plausible approaches to removing NO_3-N from surface runoff or tile drain effluent: reverse osmosis (RO), ion exchange (IE), and biological denitrification (BD). RO reduces the concentration of all ions, including NO_3-N, by filtration through a semi-permeable membrane. Unfortunately, this technique requires considerable expense to set up, and it generates a brine, the disposal of which is environmentally problematic. In IE NO_3-N is captured on an anionic resin, and a different anion replaces it in solution. This approach is widely used in municipal wastewater treatment, and a prototype IE system to treat agricultural wastewater is currently under evaluation on a farm in northern

Monterey County. This approach is both capital and technology intensive, and long-term performance and economic feasibility have yet to be demonstrated.

BD has been widely recognized as a promising technology for agricultural runoff and tile drain effluent remediation (Schipper et al., 2010b). BD is a passive process in which bacteria reduce NO_3^- to gaseous N compounds (mostly N_2). The requirements for BD to occur are an anaerobic environment, the presence of facultative anaerobic bacteria capable of this transformation, and labile carbon to power bacterial growth and act as a terminal electron acceptor. BD occurs naturally in wetlands, but the rate of denitrification is often severely limited by carbon availability; given the high NO_3-N concentration and relatively high volume of tile drain effluent and surface runoff from vegetable farms, the use of constructed wetlands would likely be space-prohibitive. Additionally, constructed wetlands provide wildlife habitat, potentially creating microbial food safety issues.

The use of denitrification bioreactors has been widely studied (Blowes et al., 1994; Moorman et al., 2010; Robertson and Merkley, 2009; Schipper et al., 2010a, b; Warneke et al., 2011). One common approach has been to cycle drainage water through an impoundment filled with a carbon source, typically wood chips or other agricultural waste products. While most research to date has evaluated relatively small installations, Schipper et al. (2010a) has operated a 20 x 600 ft bioreactor in New Zealand since 2006, treating high NO_3-N nutrient solution discharged by a hydroponic greenhouse operation. They documented long-term denitrification rates up to about 10 g N per m^3 per day, roughly an order of magnitude above typical rates achieved in constructed wetlands. In addition to greater denitrification potential, bioreactors do not create wildlife habitat because there is no exposed water surface (the buoyancy of the organic media creates a floating layer).

This project was conducted to evaluate the performance of wood chip denitrification bioreactors in removing NO_3-N from tile drain effluent and surface runoff from vegetable fields in the Salinas Valley.

E. Work description:

Two pilot-scale bioreactors were constructed in spring, 2011, on tile-drained commercial vegetable farms in the Salinas Valley. Pits of approximately 930 ft^3 (site 1) and 450 ft^3 (site 2) were dug, lined with polyethylene sheeting, and filled with chipped wood waste obtained from the Monterey Regional Waste Management District. The wood chips are unfinished construction wood waste crushed in a tub grinder. Total porosity of the chips as packed into the bioreactors was approximately 80%, with free-draining porosity of about 55%. Pumps were installed in the collection sumps of the farms' tile drain systems. Tile drain water was continuously pumped into the bioreactors at a rate to provide approximately 2 days of hydraulic residence time (HRT, calculated based on *total porosity* of the bioreactors) before the water flowed by gravity into the surface ditch draining the farm. Inlet and outlet water from the reactors was sampled, on average, 2-3 times per week during the crop production season and once per week during the winter. Both bioreactors were operated continuously until fall, 2013, when the site 2 reactor was removed.

In May, 2012, a third pilot-scale bioreactor was constructed on a commercial farm (site 3) to evaluate the remediation of surface runoff from vegetable fields. This reactor was approximately 430 ft^3 in volume, and contained the same wood waste medium used for the 2011 bioreactors, although of a finer grind (most chips < 1" diameter, whereas the 2011 bioreactors were filled with 1-2" chips). Water was continuously pumped into the bioreactor from an existing tailwater collection pond. Because this water contained a sufficient sediment load to quickly foul the bioreactor, the water was routed through a trough containing tablets of polyacrylamide (PAM) to flocculate soil particles. After this pretreatment the water was routed to a holding tank for approximately an hour before entering the bioreactor; this delay provided time for soil particles to aggregate and settle out. The pretreatment system applied between 2-5 PPM PAM. Additionally, alum (aluminum sulfate) was periodically injected during pretreatment at approximately 20 PPM; surface runoff from vegetable fields can have undesirably high PO_4-P, and the use of alum has been successful in removing PO_4-P from municipal wastewater. The site 3 bioreactor was sampled 2-3 times per week during the 2012 and 2013 crop production seasons, and then removed in the fall of 2013. Additional wood chips were applied annually to all bioreactors to make up for the microbial degradation of the chips; annual application amounted to approximately 10% of the original chip volume.

All inlet and outlet samples from the bioreactors were analyzed for NO_3-N concentration. Nitrite-N (NO_2-N) was measured in selected samples; NO_2-N is an intermediate compound formed during denitrification, and was of interest because its measurement gave insight into denitrification dynamics. Dissolved organic carbon (DOC) was analyzed for most samples collected in the first summer of operation at each site, and periodically thereafter. Water temperature was continuously monitored by two thermistors placed mid-depth in each bioreactor. NO_3-N and NO_2-N concentrations were determined by the method of Doane and Horwath (2003), and PO_4-P by the method of Quinlan and DeSesa (1955). DOC was determined by UV-persulfate oxidation (Phoenix 8000; Teledyne-Telemar, Mason, OH).

In bioreactor research conducted throughout the world, wood chip bioreactors have been shown to be carbon-limited (the rate of denitrification is limited by the microbial availability of carbon). To test whether our bioreactors were carbon-limited, we injected methanol (a soluble, easily degradable carbon source widely used in municipal wastewater treatment to stimulate denitrification) at 20 PPM C into the site 1 and 2 bioreactors during alternate months of the 2013 irrigation season. Methanol injection did increase denitrification rate, confirming a carbon limitation.

In 2014, additional study of carbon enrichment was undertaken. Six laboratory-scale bioreactors were fabricated from 6" diameter PVC pipe, each of approximately 16 liter volume. These bioreactors were filled with aged wood chips from the field bioreactors. Peristaltic pumps were used to continuously apply NO_3-N solutions to the reactors; three of the reactors received just NO_3-N solution, the other 3 reactors received that same NO_3-N solution augmented by C at varying concentrations, and from two sources (methanol or glycerin). Our interest in glycerin stems from the fact that it is a byproduct of biodiesel fuel refining, and as such may become widely available in California at a competitive price; glycerin also has no safety concerns regarding flammability or toxicity, as is the case with methanol.

Flow rates were maintained to give approximately 2 days HRT, similar to the field bioreactors. The studies were conducted in a temperature-controlled facility maintained near 61 °F, the mean summer temperature of tile drain effluent at our field sites. The effect of C enrichment on denitrification rate was calculated on the basis of rates observed in the enriched reactors, minus the rates achieved in the unenriched reactors (which represented denitrification associated with the wood chips). Methanol enrichment was also evaluated at the site 1 field bioreactor. Industrial methanol used was obtained from a fuels vendor in Santa Cruz. Methanol was injected using peristaltic pumps from 15 May-22 July, and from 22 Aug.-30 Sept.

The use of denitrification bioreactors to remediate agricultural wastewater was subjected to detailed economic analysis. Costs associated with passive treatment in bioreactors were estimated, and were compared to costs associated with carbon enrichment using both industrial methanol and glycerin from biodiesel refining.

F. Results:

A high level of DOC was present initially in the outflow from all bioreactors, but declined to <20 PPM after several weeks of operation, stabilizing between 10-20 PPM, just a few PPM above the inlet C concentration (Fig. 1). High DOC may stimulate the biological oxygen demand of the receiving waters. Additionally, the reactor effluent in the initial weeks of operation had a brown color, suggesting that complex organic compounds were being leached from the wood chips. To minimize any adverse environmental effects arising from the operation of a bioreactor, water released during the initial weeks of operation might best be reapplied on-farm as pre-irrigation water. Tile drain effluent presents a potential problem in this regard, as it can be relatively high in salinity (the electrical conductivity of bioreactor effluent at sites 1 and 2 ranged between 2-4 dS/m). After the initial weeks of operation, bioreactor effluent did not appear to pose any environmental risk not present in the original wastewater.

The NO_3-N concentration of water entering the bioreactors varied substantially among sites, and over time at each site (Fig. 2). Tile drain effluent NO_3-N varied from approximately 100-160 PPM at site 1, and 80-120 PPM at site 2. The surface runoff at site 3 ranged from approximately 30-50 PPM NO_3-N. The much higher concentration of tile drain effluent was expected, as drainage from fertilized root zones typically carries more NO_3-N than surface runoff, which has limited contact with the soil volume. The variability in inlet NO_3-N concentration, and the 2 day time lag between inflow and discharge, meant that inlet and outlet NO_3-N samples collected on the same day were not directly comparable, and therefore inlet and outlet NO_3-N had to be averaged across many sampling dates to accurately estimate denitrification rates.

At all sites denitrification began within days of the initial filling of the bioreactors; denitrifying bacteria are ubiquitous, and ‘seeding’ of inoculum was not necessary. High initial denitrification rates over the first month of operation slowed as the reactors matured, undoubtedly related to reduced carbon availability. Once the site 1 and 2 bioreactors reached a ‘steady state’ condition, treatment reduced NO_3-N concentration by approximately 9 PPM NO_3-N per day of HRT during the rest of the 2011 summer season (Fig. 3). NO_2-N declined from approximately 2 PPM in the initial month of operation to < 1 PPM thereafter. Summer denitrification rates in 2012 and 2013 remained between 8-10 PPM per day of HRT, suggesting long-term stability of performance. During the winters of 2011-12 and 2012-13 denitrification rates averaged approximately 5 PPM NO_3-N per day of HRT at sites 1 and 2. Lower winter rates were undoubtedly due to lower water temperature, which averaged approximately 54 ^{o}F in winter compared to 61 ^{o}F in summer. Surface runoff temperature at site 3 averaged 69 ^{o}F over the summer irrigation season (June-September). The annual water temperature patterns were quite consistent across the years of this project.

After the initial month of operation in 2012, denitrification achieved at site 3 averaged 13 PPM NO_3-N reduction per day of HRT through the rest of that summer season. The bioreactor did not operate during the winter (no irrigation runoff), and was put back into service in April, 2013. Summer denitrification rates averaged approximately 10 PPM per day in 2013. The 2013 denitrification rate may have been adversely affected by sediment deposition in the bioreactor. Despite the PAM pretreatment (which removed > 90% of sediment), after two summers of operation the initial few feet of the bioreactor had accumulated a significant amount of sediment. The generally higher rates observed at site 3 compared to the other sites was assumed to be due to higher temperature of the surface runoff. At all sites equipment malfunction periodically affected HRT; all reported denitrification rates have been adjusted to the actual HRT, based on inlet water meter readings.

PO_4-P concentration in surface runoff was relatively high at site 3, ranging between 0.3-0.8 PPM. Alum pre-treatment reduced PO_4-P by > 50% (Fig. 4). With or without alum pre-treatment, PO_4-P was reduced during bioreactor treatment, presumably due to denitrifying bacteria assimilating PO_4-P into their biomass. Although the PO_4-P concentration in tile drain effluent was much lower than surface runoff it still averaged approximately 0.20 PPM at sites 1 and 2, above the environmental target level of 0.1 PPM. Bioreactor treatment of tile drain effluent (no alum pretreatment) reduced PO_4-P by > 50% on average at both sites, resulting in a mean discharge concentration of approximately 0.08 PPM PO_4-P.

Methanol injection at 20 PPM C in 2013 significantly increased denitrification rate at sites 1 and 2. Averaged across sites, the mean increase in denitrification was 5 PPM NO_3-N per day of HRT, or about 10 PPM NO_3-N in the typical 2-day residence time in the bioreactor. This 2:1 ratio of C injected to additional NO_3-N denitrified underestimated the potential of methanol enrichment. Enrichment was done in alternate months at sites 1 and 2. Since bacteria populations capable of efficiently metabolizing methanol require time to develop (Bilyk et al., 2011), relatively short-term methanol enrichment may not have given optimal results.

The efficiency of methanol in increasing denitrification rate was improved in the laboratory-scale bioreactors, in which several weeks of methanol injection was done to ‘condition’ the bioreactors before denitrification rates were measured (Fig. 5). Across a range of methanol C concentrations the ratio of C added to additional N denitrified was approximately 1.4 on a weight:weight basis. Glycerin was also effective in stimulating denitrification, but the C:N ratio was approximately 2.0, substantially higher than with methanol. This result was consistent with prior reports (Ledwell et al., 2011) that with glycerin a larger fraction of applied C goes into the development of additional bacterial biomass than is the case with methanol.

Methanol injection at field site 1 in 2014 confirmed that C enrichment has the potential to reduce NO_3-N concentration to environmentally acceptable levels (Fig. 6). Data in this figure do not include sampling in the 10 day ‘conditioning’ period following the start of methanol injection. At an injection rate of 105 PPM C the NO_3-N concentration in the outlet water was reduced on average by 107 PPM. Given the prior years' performance, without C enrichment NO_3-N would be expected to decline by approximately 18 PPM in the course of 2 days of HRT. Based on this assumption, enrichment at 105 PPM C increased denitrification by a C:N ratio of approximately 1.2. However, given the high inlet NO_3-N concentration, C injection at this rate was insufficient to achieve complete denitrification. NO_2-N concentration was also elevated during this enrichment period, indicating incomplete denitrification. When enrichment was increased to 230 PPM C, virtually all NO_3-N was removed (mean outlet concentration was 4 PPM). The C:N ratio achieved during this high level of C enrichment was approximately 1.4; however, DOC was elevated during this period, suggesting this injection rate to be more than was necessary to denitrify the inlet NO_3-N load. These field results, which agreed well with the laboratory data, confirmed that the amount of denitrification achieved by C enrichment is predictable. Therefore, enrichment could be scaled to the NO_3-N concentration of inlet water to achieve consistent outlet water quality.

Economic analysis:

Appendix 1 contains a detailed economic analysis of the construction, maintenance and operation of wood chip denitrification bioreactors. Two sizes of bioreactors for tile drainage treatment were analyzed, along with a bioreactor and supplemental sediment basin for surface runoff treatment. Assumptions about water volume to be treated, NO_3-N concentration, and portion of the year that the bioreactor would function all affect the analysis. All analyses presented assumed that the bioreactor would operate for 10 years before major renovation was required; the only major annual maintenance expense would be the addition of new wood chips (10% of the initial volume) to replace those chips degraded by microbial action.

Regarding treatment of tile drain effluent, costs were calculated based on a mean denitrification rate of 8 PPM N per day of HRT and operation over an 8 month irrigation season each year; these assumptions resulted in an estimated 2.6 lb NO_3-N denitrified annually per cubic yard of bioreactor volume. Using net present value (NPV) analysis, costs over a 10 year period would average approximately $1.50 per lb NO_3-N denitrified. The larger (2,444 yd^3) bioreactor would have slightly lower cost per lb NO_3-N denitrified ($1.45) than the smaller (1,344 yd^3) bioreactor ($1.54). Even though higher denitrification rates may be achieved due to higher water temperature, the cost of treating surface runoff would be at least twice as high per pound of NO_3-N denitrified due to the costs associated with removing sediment before bioreactor treatment.

Our analysis suggests that carbon enrichment using either methanol or glycerin is economically feasible. Industrial methanol bought in bulk would cost approximately $1.30 per lb C; at a C:N ratio of 1.4 (suggested both by our laboratory study and the 2014 field verification), chemical cost would run about $1.80 per lb NO_3-N denitrified. At an estimated market price of $0.75 per lb C for refined glycerin from biodiesel production, and a C:N ratio of 2.0, chemical cost would be about $1.50 per lb NO_3-N denitrified.

An important advantage of carbon enrichment is that it is scalable (i.e. it can be adjusted to the water volume and NO_3-N concentration entering the bioreactor). A bioreactor operating in a passive mode (no enrichment) has a steady N removal capacity. However, since both flow volume and NO_3-N concentration change over time, a passively-operated bioreactor is likely to be in turns too big or too small to efficiently remove the N load. A treatment system consisting of a small bioreactor and C enrichment controlled by real-time NO_3-N monitoring could provide consistent discharge water quality.

G. Discussion:

Wood chip denitrification bioreactors can clearly provide consistent, long-term removal of NO_3-N from agricultural wastewater. The denitrification rates documented in this study (approximately 8-11 PPM NO_3-N per day of HRT, depending on water temperature) are substantially higher than typically achieved in constructed wetlands, an alternative treatment approach that has been widely studied. However, given the relatively high NO_3-N concentration of wastewater encountered at these field sites, a bioreactor capable of consistently reducing NO_3-N below an environmental target value of 10 PPM would require a very large footprint. Even with the conservative assumption of a 60 PPM NO_3-N mean concentration made in our economic analysis of tile drainage treatment, a 200 acre ranch would require a bioreactor of approximately 2,400 cubic yards of volume (about 200’ x 50’ x 6’) with a construction cost of > $60,000. Based on our observations at the bioreactor sites, reaching a mean NO_3-N concentration of 60 PPM would require substantially tighter control of irrigation and N inputs than is currently practiced. Absent such control, a bioreactor would have to be even larger.

However, our carbon enrichment data suggests that nearly complete denitrification, even with an inlet NO_3-N concentration approaching 200 PPM, can be achieved within 2 days of HRT. This means that a 200’ x 20’ x 6’ bioreactor would be adequate for the 200 acre ranch scenario, *regardless of inlet NO_3-N concentration*. Additional research is underway to determine if even shorter residence time may be sufficient; if so, an even smaller bioreactor may be adequate.

Wood chip bioreactors have a potential environmental drawback, the release of nitrous oxide (N_2O), which is a potent greenhouse gas of significant interest to air quality regulators. N_2O is an intermediate compound formed during denitrification, and in systems in which incomplete denitrification is achieved N_2O release can be substantial (Schipper et al., 2010a). Again, using carbon enrichment to achieve near complete denitrification may substantially reduce N_2O emission (at least as a percentage of inlet N), but this would have to be documented by future research.

In summary, wood chip bioreactors provide a reliable method to remove NO_3-N from agricultural wastewater. However, given the variable but generally high N loads observed at these field sites, consistently achieving environmental water quality goals would require the use of carbon enrichment controlled by real-time NO_3-N monitoring. Although the substantial cost of using this remediation approach (approximately $1.50-1.80 per lb NO_3-N denitrified) is economically feasible when high value crops such as vegetables and berries are grown, it does provide an incentive for more careful management of N and irrigation inputs to limit the N load requiring remediation.

H. Project impacts:

We believe this project has provided a comprehensive evaluation of the performance of wood chip bioreactors for treatment of high NO_3-N agricultural wastewaters. Our work has been carefully followed, and several groups are planning to construct larger-scale bioreactors in the coastal district. Perhaps the most important finding of this project was that carbon enrichment appears to be an economically and technologically feasible practice, one that realistically offers the possibility that agricultural wastewater, in particular tile drain effluent, could be treated to produce a consistent, environmentally acceptable NO_3-N concentration. In this region the large majority of N loading to agricultural land results from the use of mineral fertilizers; documenting an effective technique for wastewater remediation advances the CDFA-FREP goal of improving the environmentally safe use of N fertilizers.

The degree to which this remediation technology may be embraced by the commercial industry will be driven largely by the direction the Central Coast Region Water Quality Control Board takes in regulating surface water quality. Given the Federal TMDL process for soluble nutrients currently underway in this region, the Board appears likely tighten rules for nutrient discharges to surface water.

I. Outreach summary:

The Project Leaders conducted a substantial number of outreach activities over the life of this project. Project results were presented at the following events:

- Leafy Greens Research Board mid-year meeting, Seaside, 11 Oct., 2011
- UC Irrigation and Nutrient Management meeting, Salinas, 21 Feb, 2012
- Leafy Greens Research Board annual meeting, Coalinga, 20 March, 2012
- USDA National Water Conference, Portland, OR, 23 May, 2012
- Ventura County Water Quality meeting, Oxnard, 11 Oct., 2012
- California Soil and Plant conference, Visalia, 7 Feb., 2013
- UC Irrigation and Nutrient Management meeting, Salinas, 26 Feb., 2013
- Leafy Greens Research Board annual meeting, Coalinga, 19 March, 2013
- UC Water Quality Co-management meeting, Watsonville, 21 Aug., 2013
- AgKnowledge Foundation seminar, Castroville, 23 Aug., 2013
- California Leafy Greens Board meeting, Salinas, 8 Oct., 2013
- AgKnowledge Foundation seminar, King City, 11 Oct., 2013
- CDFA-FREP annual meeting, Modesto, 29 Oct., 2013
- Vegetable grower seminar, Camarillo, 8 April, 2014
- Seed Central industry networking meeting, Salinas, 26 June, 2014
- Leafy Greens Research Board meeting, Salinas, 7 Oct., 2014

In addition to these formal presentations, field day events included:

- Site tour for UC-ANR and Grower-Shipper Association personnel, 10 Feb., 2012
- Site tour for the California Undersecretary of Agriculture, 6 June, 2012
- Site tour for the Leafy Greens Research Board, 16 Oct., 2012

Additionally, informal tours of the bioreactor sites were given to individual growers and small groups or individuals representing NRCS, Resource Conservation Districts, Region 3 Water Quality Control Board, The Nature Conservancy and CSU-Monterey Bay.

J. Factsheet:

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Grant Agreement Number: 11-0462-SA

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2011-2014

Locations: UC Davis, and commercial farms in Monterey County

Highlights:

- Wood chip denitrification bioreactors can consistently removed nitrate-nitrogen (NO_3-N) from tile drain effluent and surface runoff over years of operation.
- Given the relatively high NO_3-N concentrations typical of agricultural wastewater from coastal fields, carbon enrichment of bioreactors by injecting industrial methanol or glycerin is likely to be required to reduce NO_3-N to environmentally acceptable levels.
- Costs of NO_3-N removal using this technology will be approximately $1.50-1.80 per pound of N denitrified.

Introduction:

Surface water monitoring in the vegetable production areas along the Central Coast of California has shown nitrate-nitrogen (NO_3-N) concentrations often far above environmentally desirable levels. Although improved irrigation and N fertilizer management could reduce N loss, management changes alone are unlikely to meet environmental targets. A technology that has shown promise elsewhere in the country in removing NO_3-N from agricultural wastewater is managed biological denitrification using denitrification bioreactors. A bioreactor is simply a plastic-lined pit filled with an organic waste material (most often wood chips) in which nitrate-laden water is treated. The carbon in the wood chips sustains populations of anaerobic bacteria that chemically reduce nitrate to N_2 (a benign gas that makes up most of the atmosphere). In this project three pilot-scale wood chip bioreactors were constructed on commercial farms in the Salinas Valley to treat either tile drainage (two sites) or surface runoff (one site). The performance of the bioreactors was documented from 2011-2014.

Methods:

The bioreactors were filled with crushed construction wood waste obtained from the Monterey Regional Waste Management District. At sites 1 and 2 tile drain effluent was continuously pumped into the bioreactors from the farms' tile drain sumps at a rate to allow a 2 day residence time in the bioreactor before the water drained by gravity into a surface ditch. At site 3, water from a tailwater collection pond was pumped into the bioreactor after treatment with polyacrylamide (PAM) to remove sediment. Since prior research with bioreactors suggested that wood chips could not supply carbon fast enough to maximize denitrification, experiments were conducted at UC Davis to evaluate the effect of injecting additional carbon into lab-scale bioreactors. The soluble carbon sources used were methanol and glycerin, two relatively inexpensive sources of microbially-available carbon. Carbon enrichment did indeed increase denitrification rate, and in 2013 and 2014 C enrichment was evaluated in the field bioreactors.

Findings:

Sampling over the 2011, 2012 and 2013 irrigation seasons showed that the denitrification rate averaged 8-11 PPM NO_3-N denitrified per day of residence time in the bioreactors; higher rates were observed with surface water treatment, probably due to higher water temperature. However, the high initial NO_3-N concentrations observed, particularly in tile drain water (often > 100 PPM), meant that extended treatment time, and therefore very large bioreactors, would be needed to reduce NO_3-N to environmental target values (≤ 10 PPM).

Carbon enrichment using either methanol or glycerin substantially increased denitrification rate, reducing NO_3-N to ≤ 10 PPM in 2 days of treatment or less, regardless of initial NO_3-N concentration. Methanol C was somewhat more efficient in stimulating denitrification, but the higher cost of methanol offset this advantage. Economic analysis suggested that operating wood chip bioreactors in a passive mode (no carbon enrichment) would cost approximately $1.50 per lb NO_3-N denitrified; however, because NO_3-N concentration fluctuated substantially over time at all sites, a bioreactor would by turns be either too big or too small to efficiently treat wastewater. The chemical cost of carbon enrichment was estimated to be approximately $1.50-1.80 per lb NO_3-N denitrified. C enrichment has the advantage of being scalable in the sense that, if it was controlled by real-time inlet NO_3-N monitoring, bioreactor size could be minimized while a consistent outlet water quality could be achieved.

K. Products:

A refereed journal article summarizing this project is in preparation, and it will be forwarded to CDFA-FREP upon publication.

Literature cited:

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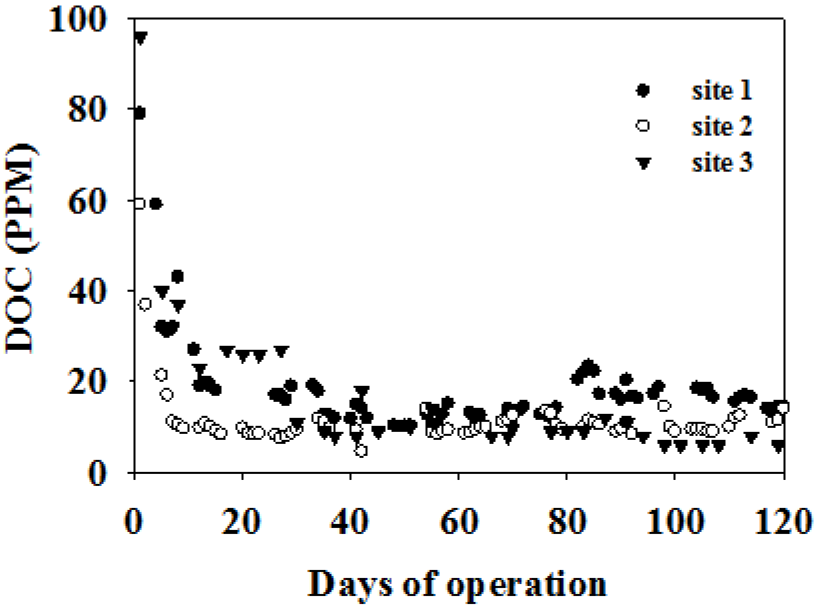


Fig. 1. Dissolved organic carbon (DOC) in outlet water of the bioreactors during the initial 120 days of operation.

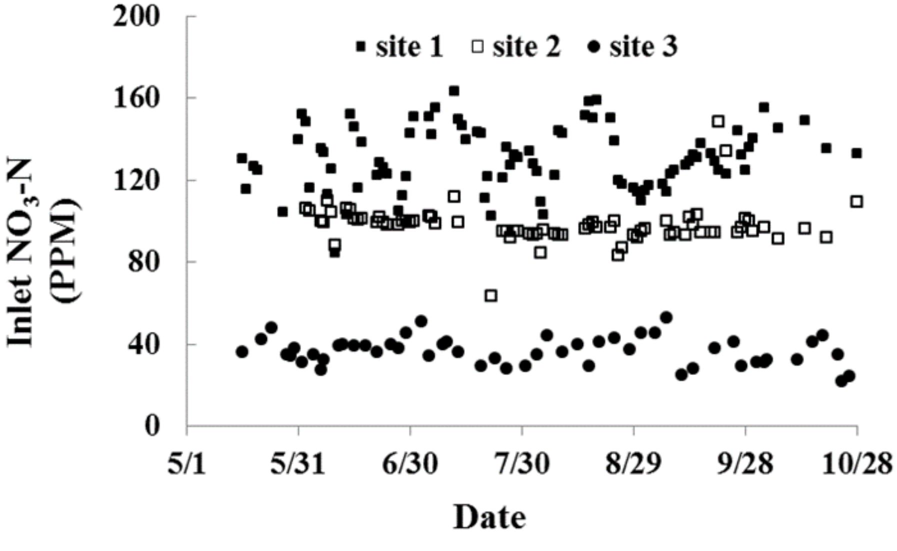


Fig. 2. Daily inlet NO3-N observed during the first summer season for the three bioreactors; data represents the 2011 season for sites 1 and 2 (tile drain effluent) and the 2012 season for site 3 (surface runoff).

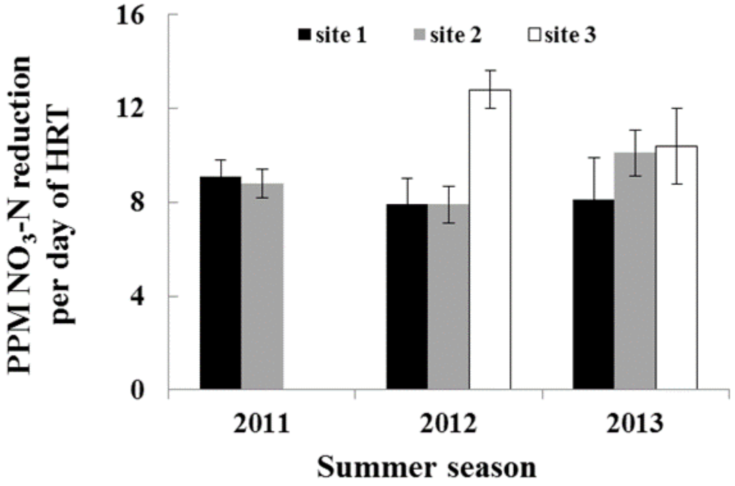


Fig. 3. Mean denitrification per day of hydraulic residence time (HRT) achieved over the summer seasons (June - September) in the bioreactors; bars represent the standard error of measurement. Means for 2013 at sites 1 and 2 do not reflect sampling during methanol injection.

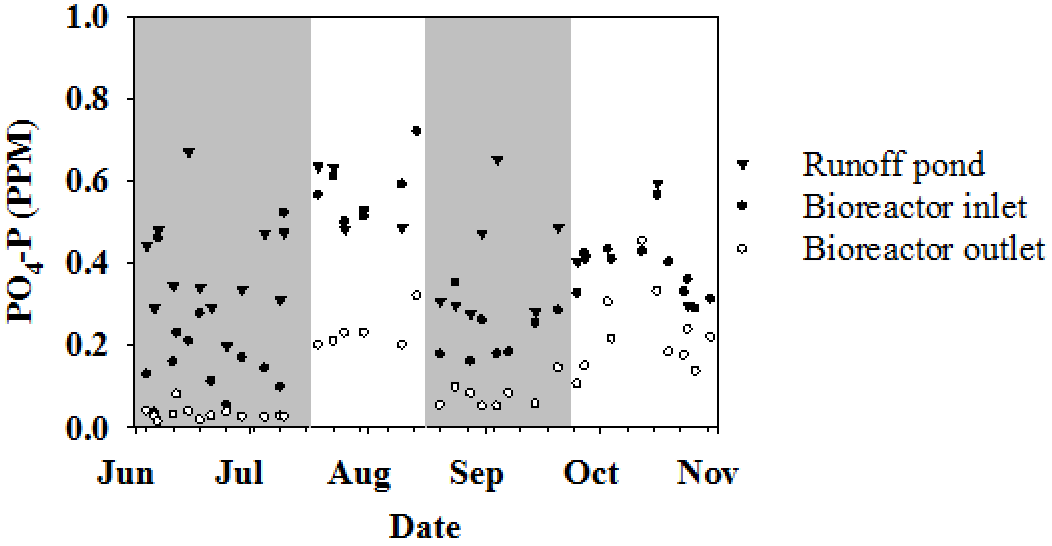


Fig. 4. Effect of bioreactor treatment and alum injection on PO_4-P concentration at site 3; shaded portions of the graph represent periods of alum injection.

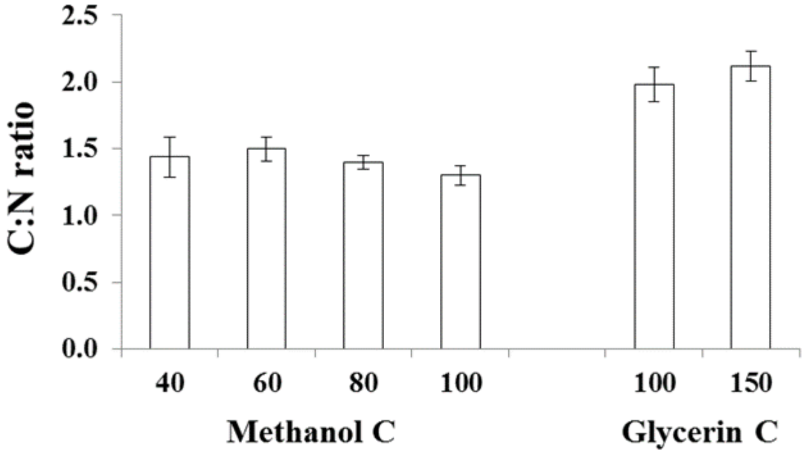


Fig. 5. Relative efficiency of methanol and glycerin (in PPM of carbon) in stimulating denitrification in laboratory bioreactors; bars represent the standard error of measurement. C:N ratio (w/w basis) reflected the amount of carbon needed to denitrify a given amount of NO_3-N.

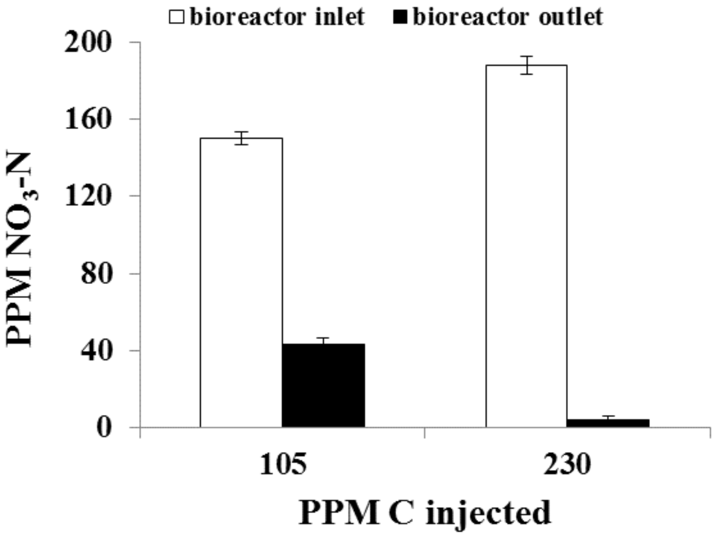


Fig. 6. Effects of methanol enrichment on denitrification in the site 1 bioreactor during the 2014 summer season; bars represent the standard error of measurement.

Appendix 1: Economic analysis

The costs for construction, operation and maintenance of a denitrification bioreactor to treat tile drainage or surface runoff from a hypothetical 200 acre coastal ranch producing vegetable crops have been estimated based on a set of assumptions regarding mean denitrification rates achievable, the wastewater volume to be treated, and the mean NO_3-N concentration of that wastewater. For the treatment of tile drainage, these assumptions include:

- mean of 8 PPM NO_3-N reduction per day of hydraulic residence time (HRT)
- mean of 60 PPM NO_3-N in tile drainage
- mean of 65,000 gallons per day of tile water volume
- bioreactor operation over an 8 month irrigation season

Assumptions regarding the treatment of surface runoff include:

- mean of 10 PPM NO_3-N reduction per day of hydraulic residence time (HRT)
- mean of 30 PPM NO_3-N in surface runoff
- mean of 43,000 gallons per day of surface runoff volume
- bioreactor operation over an 8 month irrigation season
- sediment removal would require a supplemental sediment basin

For each scenario, cost estimates for two sizes of bioreactors were estimated, the smaller based on the size required to denitrify half of the incoming N load, and the larger based on the size required to achieve a mean outlet concentration of 10 PPM NO_3-N (the Federal drinking water standard). The bioreactors would be dug by backhoe and lined with polyethylene pond liner rated for 10-15 yr life. The wood chips used would be chipped construction waste wood from the Monterey Regional Waste Management District in Seaside. Wood chip cost is estimated as $35/ton, plus hauling. Due to microbial degradation it was estimated that 10% of wood chip volume would need replacement each year of operation.

The detailed analysis is shown on tables 1 through 7. Tables 1 (A and B) through 4 (A and B) present cost estimates for the construction, operation, and maintenance of the different DBRs. Table 5 (A and B) presents a cost estimate for the supplemental sediment basin (SSB). Table 6 summarizes the DBR and SSB cost estimates, and also includes estimates of reduced returns from land that is assumed to be taken out of lettuce production to accommodate the DBRs and SSB. Table 7 shows the net present value and annual payment for the four DBR scenarios and the SSB when considering both estimated costs and reduced returns over time.

Assumptions for cost estimates (tables have additional detail):

1. DBR and SSB life: 10 years.
2. Custom equipment & labor rates:
   - Custom equipment rental: $150 per hour (plus 1X staging charge = $300).
   - Custom labor = $65 per hour.
   - Ranch machine operator = $19.10 per hour; ranch field labor = $12.39 per hour (both include a 34% benefits package).
3. Materials: All supplies and materials include 8 percent sales tax; shipping costs to the Salinas area.

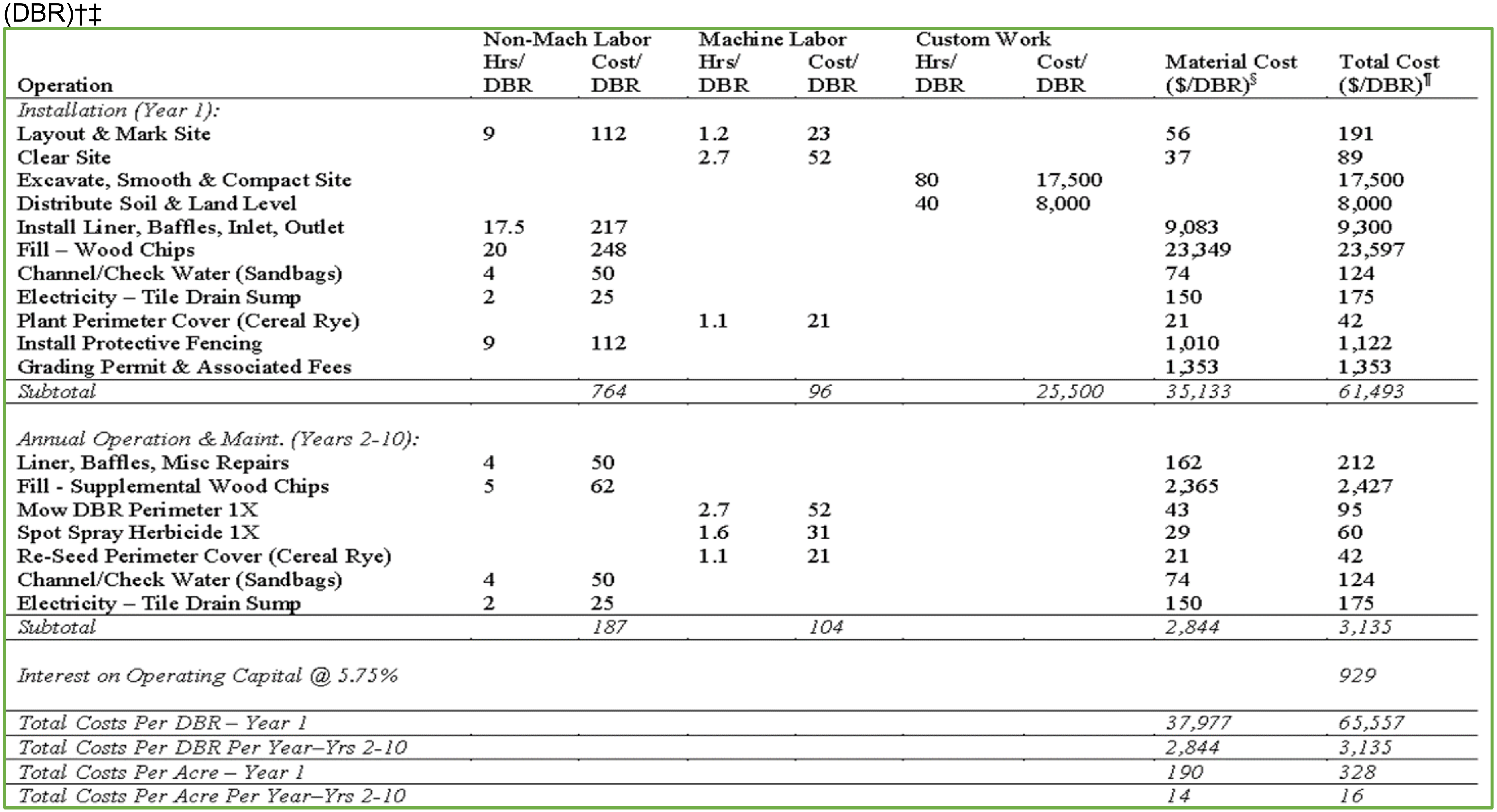
4. Grading permits: Grading permits are required for earthmoving projects over 100 cubic yards in Monterey County. Estimated costs are $1,353 per DBR, which includes cost for permit issuance, plan review, inspection, and recording.
5. Interest on operating capital: 5.75 percent;
6. Interest for net present value, annual payment: 4.75 percent.
7. Construction of each DBR and SSB is calculated using a custom operator (equipment and labor).
8. DBR liners are custom made and include 1 boot for inlet; assumes gravity fed outlet.
9. Wood chips: cost is $43/ton including hauling; 4.5 tons/cubic yard; 10% replenished each year.
10. SSB is lined with sodium bentonite using a custom operator.

Assumptions for reduced return estimates:
Each DBR and SSB is assumed to treat irrigation runoff from a 200 acre ranch that produces two head lettuce crops per year. Land is removed from production to accommodate the construction, operation, and maintenance of each DBR, resulting in reduced returns each year as follows.

1. Tile drain system 1 (TD1): 0.7 acre removed from production;
   reduced returns are estimated at $1,106 per year*.
2. Tile drain system 2 (TD2): 0.4 acre removed from production;
   reduced returns are estimated at $632 per year.
3. Surface water system 1 and 2 (SW1 and SW2): 0.25 acre (each) removed from production;
   reduced returns are estimated at $396 (each) per year.
4. Supplemental sediment basin (SSB): 0.1 acre removed from production;
   reduced returns estimated at $158 per year.

*Reduced returns are calculated using estimates from Tourte, L. and R. Smith. 2010. Sample Production Costs for Wrapped Iceberg Lettuce – Sprinkler Irrigated – 40” Beds. http://coststudies.ucdavis.edu/current.php.

Table 1A. Installation, Operation & Maintenance Costs for a Tile Drainage System (TD1) Denitrification Bioreactor (DBR)†‡



Operation	Non-Mach Labor Hrs/ DBR	Non-Mach Labor Cost/ DBR	Machine Labor Hrs/ DBR	Machine Labor Cost/ DBR	Custom Work Hrs/ DBR	Custom Work Cost/ DBR	Material Cost ($/DBR)§	Total Cost ($/DBR)¶
Installation (Year 1):								
Layout & Mark Site	9	112	1.2	23			56	191
Clear Site			2.7	52			37	89
Excavate, Smooth & Compact Site					80	17,500		17,500
Distribute Soil & Land Level					40	8,000		8,000
Install Liner, Baffles, Inlet, Outlet	17.5	217					9,083	9,300
Fill – Wood Chips	20	248					23,349	23,597
Channel/Check Water (Sandbags)	4	50					74	124
Electricity – Tile Drain Sump	2	25					150	175
Plant Perimeter Cover (Cereal Rye)			1.1	21			21	42
Install Protective Fencing	9	112					1,010	1,122
Grading Permit & Associated Fees							1,353	1,353
Subtotal		*764*		*96*		*25,500*	*35,133*	*61,493*
Annual Operation & Maint. (Years 2-10):								
Liner, Baffles, Misc Repairs	4	50					162	212
Fill - Supplemental Wood Chips	5	62					2,365	2,427
Mow DBR Perimeter 1X			2.7	52			43	95
Spot Spray Herbicide 1X			1.6	31			29	60
Re-Seed Perimeter Cover (Cereal Rye)			1.1	21			21	42
Channel/Check Water (Sandbags)	4	50					74	124
Electricity – Tile Drain Sump	2	25					150	175
Subtotal		*187*		*104*			*2,844*	*3,135*
Interest on Operating Capital @ 5.75%								*929*
Total Costs Per DBR – Year 1							*37,977*	*65,557*
Total Costs Per DBR Per Year–Yrs 2-10							*2,844*	*3,135*
Total Costs Per Acre – Year 1							*190*	*328*
Total Costs Per Acre Per Year–Yrs 2-10							*14*	*16*

† TD1 costs are for a 2,444 cubic yard or 11,000 square foot/6 foot depth DBR.

‡ DBR installed to treat irrigation runoff on a 200 acre ranch.

§ Includes materials; fuel, lube and repairs; services other than custom equipment use and labor.

¶ Column and row totals may differ slightly because of rounding.

Table 1B. Detail of Material and Input Costs for a Tile Drainage System (TD1) Denitrification Bioreactor (DBR)†‡

Material	Quantity/ DBR	Unit	Cost/ Unit	Material Cost ($/DBR)§
Installation (Year 1):				
Marker Flags	1	hundred	12.95	13
Tape Measure (100 Yd)	1	each	39.95	40
Custom DBR Liner	16,296	sq. ft	0.53	8,637
Custom DBR Boot (Inlet)	1	each	162.00	162
Baffles	4	roll	71.00	284
Wood Chips	543	ton	43.00	23,349
Sandbags (Channel/Check Water)	2	hundred	37.00	74
Electricity – Tile Drain Sump	50	ac ft	3.00	150
Cereal Rye (Seed Perimeter Cover)	18	pound	0.57	10
Protective Fencing	14	roll	47.00	658
Fencing Posts & Gate	1	DBR	352.00	352
Grading Permit & Associated Fees	1	DBR	1,353.00	1,353
Fuel, Lube, Repairs				51
Subtotal				*35,133*
Annual Operation & Maintenance (Years 2-10):				
Liner, Baffles, Misc Repair	2	roll	81.00	162
Supplemental Wood Chips	55	ton	43.00	2,365
Herbicide	4	pints	6.10	24
Cereal Rye (Re-Seed Perimeter Cover)	18	pound	0.57	10
Sandbags (Channel/Check Water)	2	hundred	37.00	74
Electricity – Tile Drain Sump	50	ac ft	3.00	150
Fuel, Lube, Repairs				59
Subtotal				*2,844*
Total Material Costs Per DBR – Year 1				*37,977*
Total Material Costs Per DBR Per Year–Yrs 2-10				*2,844*
Total Material Costs Per Acre – Year 1				*190*
Total Material Costs Per Acre Per Year–Yrs 2-10				*14*

† TD1 costs are for a 2,444 cubic yard or 11,000 square foot/6 foot depth DBR.

‡ DBR installed to treat irrigation runoff on a 200 acre ranch.

§ Includes 8 percent sales tax and shipping costs as appropriate.

Table 2A. Installation, Operation & Maintenance Costs for a Tile Drainage System (TD2) Denitrification Bioreactor (DBR)[†‡]

	Non-Mach Labor		Machine Labor		Custom Work			
Operation	Hrs/ DBR	Cost/ DBR	Hrs/ DBR	Cost/ DBR	Hrs/ DBR	Cost/ DBR	Material Cost ($/DBR)[§]	Total Cost ($/DBR)[¶]
Installation (Year 1):								
Layout & Mark Site	5	62	1.0	23			56	141
Clear Site			1.5	29			21	49
Excavate, Smooth & Compact Site					48	10,620		10,620
Distribute Soil & Land Level					24	4,800		4,800
Install Liner, Baffles, Inlet, Outlet	9.5	118					5,516	5,634
Fill – Wood Chips	11	136					12,814	12,950
Channel/Check Water (Sandbags)	2	25					37	62
Electricity – Tile Drain Sump	2	25					150	175
Plant Perimeter Cover (Cereal Rye)			.6	11			12	23
Install Protective Fencing	5	62					777	839
Grading Permit & Associated Fees							1,353	1,353
Subtotal		*428*		*63*		*15,420*	*20,736*	*36,646*
Annual Operation & Maint. (Years 2-10):								
Liner, Baffles, Misc Repairs	2	25					81	106
Fill - Supplemental Wood Chips	3	37					1,290	1,326
Mow DBR Perimeter 1X			1.5	29			24	53
Spot Spray Herbicide 1X			.9	17			14	32
Re-Seed Perimeter Cover (Cereal Rye)			.6	11			12	23
Channel/Check Water (Sandbags)	2	25					37	62
Electricity – Tile Drain Sump	2	25					150	175
Subtotal		*112*		*57*			*1,608*	*1,777*
Interest on Operating Capital @ 5.75%								*368*
Total Costs Per DBR – Year 1							*22,344*	*38,791*
Total Costs Per DBR Per Year–Yrs 2-10							*1,608*	*1,777*
Total Costs Per Acre – Year 1							*112*	*194*
Total Costs Per Acre Per Year–Yrs 2-10							*8*	*9*

[†] TD2 costs are for a 1,334 cubic yard or 6,000 square foot/6 foot depth DBR.

[‡] DBR installed to treat irrigation runoff on a 200 acre ranch.

[§] Includes materials; fuel, lube and repairs; services other than custom equipment use and labor.

[¶] Column and row totals may differ slightly because of rounding.

Table 2B. Detail of Material and Input Costs for a Tile Drainage System (TD2) Denitrification Bioreactor (DBR)†‡

Material	Quantity/ DBR	Unit	Cost/ Unit	Material Cost ($/DBR) §
Installation (Year 1):				
Marker Flags	1	hundred	12.95	13
Tape Measure (100 Yd)	1	each	39.95	40
Custom DBR Liner	9,936	sq. ft	0.53	5,266
Custom DBR Boot (Inlet)	1	each	108.00	108
Baffles	2	roll	71.00	142
Wood Chips	298	ton	43.00	12,814
Sandbags (Channel/Check Water)	1	hundred	37.00	37
Electricity – Tile Drain Sump	50	ac ft	3.00	150
Cereal Rye (Seed Perimeter Cover)	10	pound	0.57	6
Protective Fencing	10	roll	47.00	470
Posts & Gate	1	DBR	307.00	307
Grading Permit & Associated Fees	1	DBR	1,353.00	1,353
Fuel, Lube, Repairs				30
Subtotal				*20,736*
Annual Operation & Maintenance (Years 2-10):				
Liner, Baffles, Misc Repair	1	roll	81.00	81
Supplemental Wood Chips	30	ton	43.00	1,290
Herbicide	2	pints	6.10	12
Cereal Rye (Re-Seed Perimeter Cover)	10	pound	0.57	6
Sandbags (Channel/Check Water)	1	hundred	37.00	37
Electricity – Tile Drain Sump	50	ac ft	3.00	150
Fuel, Lube, Repairs				32
Subtotal				*1,608*
Total Material Costs Per DBR – Year 1				*22,344*
Total Material Costs Per DBR Per Year–Yrs 2-10				*1,608*
Total Material Costs Per Acre – Year 1				*112*
Total Material Costs Per Acre Per Year–Yrs 2-10				*8*

† TD2 costs are for a 1,334 cubic yard or 6,000 square foot/6 foot depth DBR.

‡ DBR installed to treat irrigation runoff on a 200 acre ranch.

§ Includes 8 percent sales tax and shipping costs as appropriate.

Table 3A. Installation, Operation & Maintenance Costs for a Surface Water System (SW1) Denitrification Bioreactor (DBR)[†‡]

	Non-Mach Labor		Machine Labor		Custom Work			
Operation	Hrs/ DBR	Cost/ DBR	Hrs/ DBR	Cost/ DBR	Hrs/ DBR	Cost/ DBR	Material Cost ($/DBR)[§]	Total Cost ($/DBR)[¶]
Installation (Year 1):								
Layout & Mark Site	2	25	.5	10			55	90
Clear Site			1	19			14	33
Excavate, Smooth & Compact Site					32	7,180		7,180
Distribute Soil & Land Level					16	3,200		3,200
Install Liner, Inlet, Baffles, Outlet	7.5	93					3,020	3,113
Fill – Wood Chips	7	87					5,332	5,419
Channel/Check Water (Sandbags)	2	25					37	62
Plant Perimeter Cover (Cereal Rye)			.6	11			9	21
Install Protective Fencing	3	37					591	628
Grading Permit & Associated Fees							1,353	1,353
Subtotal		*267*		*40*		*10,380*	*10,411*	*21,098*
Annual Operation & Maint. (Years 2-10):								
Liner, Baffles, Misc Repairs	1	12					81	93
Fill - Supplemental Wood Chips	2	25					559	584
Mow DBR Perimeter 1X			.8	15			13	28
Spot Spray Perimeter 1X			.5	10			7	17
Re-Seed Perimeter Cover (Cereal Rye)			.6	11			9	21
Channel/Check Water (Sandbags)	2	25					37	62
Subtotal		*62*		*36*			*706*	*805*
Interest on Operating Capital @ 5.75%								*210*
Total Costs Per DBR – Year 1							*11,117*	*21,113*
Total Costs Per DBR Per Year–Yrs 2-10							*706*	*805*
Total Costs Per Acre – Year 1							*56*	*111*
Total Costs Per Acre Per Year –Yrs 2-10							*4*	*4*

[†] SW1 costs are for a 556 cubic yard or 3,000 square foot/5 foot depth DBR.

[‡] DBR installed in association with a Supplemental Sediment Basin (SSB) to treat irrigation runoff on a 200 acre ranch (Tables 5A and 5B).

[§] Includes materials; fuel, lube and repairs; services other than custom equipment use and labor.

[¶] Column and row totals may differ slightly because of rounding.

Table 3B. Detail of Material and Input Costs for a Surface Water System (SW1) Denitrification Bioreactor (DBR)†‡

Material	Quantity/ DBR	Unit	Cost/ Unit	Material Cost ($/DBR)§
Installation (Year 1):				
Marker Flags	1	hundred	12.95	13
Tape Measure (100 Yd)	1	each	39.95	40
Custom DBR Liner	5,226	sq. feet	0.53	2,770
Custom DBR Boot (Inlet)	1	each	108.00	108
Baffles	2	roll	71.00	142
Wood Chips	124	ton	43.00	5,332
Sandbags (Channel/Check Water)	1	hundred	37.00	37
Cereal Rye (Seed Perimeter Cover)	6	pound	0.57	3
Protective Fencing	7	roll	47.00	329
Posts & Gate	1	DBR	262.00	262
Grading Permit & Associated Fees	1	DBR	1,353.00	1,353
Fuel, Lube, Repairs				22
Subtotal				*10,411*
Annual Operation & Maintenance (Years 2-10):				
Liner, Baffles, Misc Repair	1	roll	81.00	81
Supplemental Wood Chips	13	ton	43.00	559
Herbicide	1	pint	6.10	6
Cereal Rye (Re-Seed Perimeter Cover)	6	pound	0.57	3
Sandbags (Channel/Check Water)	1	hundred	37.00	37
Fuel, Lube, Repairs				20
Subtotal				*706*
Total Material Costs Per DBR – Year 1				*11,117*
Total Material Costs Per DBR Per Year–Yrs 2-10				*706*
Total Material Costs Per Acre – Year 1				*56*
Total Material Costs Per Acre Per Year–Yrs 2-10				*4*

† SW1 costs are for a 556 cubic yard or 3,000 square foot/5 foot depth DBR.

‡ DBR installed in association with a Supplemental Sediment Basin (SSB) to treat irrigation runoff on a 200 acre ranch (Tables 5A and 5B).

§ Includes 8 percent sales tax and shipping costs as appropriate.

Table 4A. Installation, Operation & Maintenance Costs for a Surface Water System (SW2) Denitrification Bioreactor (DBR)[†,‡]

	Non-Mach Labor		Machine Labor		Custom Work			
Operation	Hrs/ DBR	Cost/ DBR	Hrs/ DBR	Cost/ DBR	Hrs/ DBR	Cost/ DBR	Material Cost ($/DBR)[§]	Total Cost ($/DBR)[¶]
Installation (Year 1):								
Layout & Mark Site	1.3	16	.5	10			54	80
Clear Site			.7	13			9	23
Excavate, Smooth & Compact Site					24	5,460		5,460
Distribute Soil & Land Level					12	2,400		2,400
Install Liner, Inlet, Baffles, Outlet	4.7	58					2,413	2,472
Fill – Wood Chips	4.5	56					3,870	3,926
Channel/Check Water (Sandbags)	1.3	16					37	53
Plant Perimeter Cover (Cereal Rye)			.5	10			7	17
Install Protective Fencing	3	37					535	572
Grading Permit & Associated Fees							1,353	1,353
Subtotal		*183*		*33*		*7,860*	*8,278*	*16,356*
Annual Operation & Maint. (Years 2-10):								
Liner, Baffles, Misc Repairs	1	12					81	93
Fill - Supplemental Wood Chips	1.5	19					387	405
Mow DBR Perimeter 1X			.5	10			8	18
Spot Spray Perimeter 1X			.5	10			9	19
Re-Seed Perimeter Cover (Cereal Rye)			.5	10			9	19
Channel/Check Water (Sandbags)	1.2	16					37	53
Subtotal		*47*		*30*			*531*	*607*
Interest on Operating Capital @ 5.75%								*163*
Total Costs Per DBR – Year 1							*8,809*	*17,126*
Total Costs Per DBR Per Year–Yrs 2-10							*531*	*607*
Total Costs Per Acre – Year 1							*44*	*86*
Total Costs Per Acre Per Year –Yrs 2-10							*3*	*3*

[†] SW2 costs are for a 407 cubic yard or 2,200 square foot/5 foot depth DBR.

[‡] DBR installed in association with a Supplemental Sediment Basin (SSB) to treat irrigation runoff on a 200 acre ranch (Tables 5A and 5B).

[§] Includes materials; fuel, lube and repairs; services other than custom equipment use and labor.

[¶] Column and row totals may differ slightly because of rounding.

Table 4B. Detail of Material and Input Costs for a Surface Water System (SW2) Denitrification Bioreactor (DBR)[†‡]

Material	Quantity/ DBR	Unit	Cost/ Unit	Material Cost ($/DBR)[§]
Installation (Year 1):				
Marker Flags	1	hundred	12.95	13
Tape Measure (100 Yd)	1	each	39.95	40
Custom DBR Liner	4,216	sq. feet	0.53	2,234
Custom DBR Boot (Inlet)	1	each	108.00	108
Baffles	1	roll	71.00	71
Wood Chips	90	ton	43.00	3,870
Sandbags (Channel/Check Water)	1	hundred	37.00	37
Cereal Rye (Seed Perimeter Cover)	5	pound	0.57	3
Protective Fencing	6	roll	47.00	282
Posts & Gate	1	DBR	253	253
Grading Permit & Associated Fees	1	DBR	1,353.00	1,353
Fuel, Lube, Repairs				14
Subtotal				*8,278*
Annual Operation & Maintenance (Years 2-10):				
Liner, Baffles, Misc Repair	1	roll	81.00	81
Supplemental Wood Chips	9	ton	43.00	387
Herbicide	1	pint	6.10	6
Cereal Rye (Re-Seed Perimeter Cover)	5	pound	0.57	3
Sandbags (Channel/Check Water)	1	hundred	37.00	37
Fuel, Lube, Repairs				17
Subtotal				*531*
Total Material Costs Per DBR – Year 1				*8,809*
Total Material Costs Per DBR Per Year–Yrs 2-10				*531*
Total Material Costs Per Acre – Year 1				*44*
Total Material Costs Per Acre Per Year–Yrs 2-10				*3*

[†] SW2 costs are for a 407 cubic yard or 2,200 square foot/5 foot depth DBR.

[‡] DBR installed to treat irrigation runoff on a 200 acre ranch.

[§] Includes 8 percent sales tax and shipping costs as appropriate.

Table 5A. Installation, Operation & Maintenance Costs for a Supplemental Sediment Basin (SSB)[†‡]

	Non-Mach Labor		Machine Labor		Custom Work			
Operation	Hrs/ Basin	Cost/ Basin	Hrs/ Basin	Cost/ Basin	Hrs/ Basin	Cost/ Basin	Material Cost ($/Basin)[§]	Total Cost ($/Basin)[¶]
Installation (Year 1):								
Layout & Mark Site	1	12	.5	10			2	24
Clear Site			.8	16			11	27
Excavate, Smooth & Compact Site					8	2,020		2,020
Distribute Soil & Land Level					4	800		800
Install Sealant, Inlet, Outlet					8	1,720	1,374	3,094
Install Runoff/PAM Distribution System					15	975	4,232	5,207
Channel/Check Water (Sandbags)	.5	6					19	25
Monitor System & Basin Turbidity	3	37					1,350	1,387
Plant Perimeter Cover (Cereal Rye)			.6	10			7	17
Install Protective Fencing	2	25					139	164
Subtotal		*80*		*36*		*5,515*	*7,134*	*12,766*
Annual Operation & Maint. (Years 2-10):								
Remove & Redistribute Sediment 2X					8	2,600		2,600
Sealant, Misc Repairs	1	12					11	23
Monitor Turbidity/PAM System	2	25					209	234
Channel/Check Water (Sandbags)	.5	6					19	25
Mow Basin Perimeter 1X			.5	10			8	18
Spot Spray Herbicide 1X			.3	6			4	11
Re-Seed Perimeter Cover			.5	10			7	17
Subtotal		*43*		*26*		*2,600*	*258*	*2,928*
Interest on Operating Capital @ 5.75%								*150*
Total Costs Per SSB – Year 1							*7,392*	*15,844*
Total Costs Per SSB Per Year–Yrs 2-10							*258*	*2,928*
Total Costs Per Acre – Year 1							*37*	*79*
Total Costs Per Acre Per Year–Yrs 2-10							*1*	*15*

[†] SSB costs are for a 30 cubic yard or 200 square foot/4 foot depth SSB.

[‡] SSB installed in association with a Surface Water System Denitrification Bioreactor (DBR) to treat irrigation runoff on a 200 acre ranch (Tables 3A and 3B and Tables 4A and 4B).

[§] Includes purchase of materials; pump; tanks; fuel, lube and repairs.

[¶] Column and row totals may differ slightly because of rounding.

Table 5B. Detail of Material & Input Costs for a Supplemental Sediment Basin (SSB)†‡

Material	Quantity/ Basin	Unit	Cost/ Unit	Material Cost ($/Basin)§
Installation (Year 1):				
Sodium Bentonite (DBR Sealant)	3+	superbag	458.00	1,374
Electric Pump (5HP), Flow Meter, Float	1	each	1,652.00	1,652
Water Tank (3,000 Gallon)	1	each	2,053.00	2,053
PAM Mix Tank (100 Gallon)	1	each	400.00	400
PAM	1	5 gal. pail	127.00	127
Sandbags (Channel/Check Water)	.5	hundred	37.00	19
Turbidity Monitor	1	each	1,350.00	1,350
Cereal Rye (Seed Perimeter Cover)	5	pound	0.57	3
Protective Fencing	2	roll	47.00	94
Posts	1	DBR	45.00	45
Fuel, Lube, Repairs				17
Subtotal				*7,134*
Annual Operation & Maintenance (Years 2-10):				
Sealant, Misc Repairs	1	bag	11.00	11
PAM & Turbidity System Maintenance	2	percent	82.00	82
PAM	1	5 gal. pail	127.00	127
Herbicide	.5	pint	6.10	3
Cereal Rye (Re-Seed Perimeter Cover)	5	pound	0.57	3
Sandbags (Channel/Check Water)	.5	hundred	37.00	19
Fuel, Lube, Repairs				13
Subtotal				*258*
Total Material Costs Per SSB – Year 1				*7,392*
Total Material Costs Per SSB Per Year–Yrs 2-10				*258*
Total Material Costs Per Acre – Year 1				*37*
Total Material Costs Per Acre Per Year–Yrs 2-10				*1*

† SSB costs are for a 30 cubic yard or 200 square foot/4 foot depth SSB.

‡ SSB installed in association with a Surface Water System Denitrification Bioreactor (DBR) to treat irrigation runoff on a 200 acre ranch (Tables 3A and 3B and Tables 4A and 4B).

§ Includes 8 percent sales tax and shipping costs as appropriate.

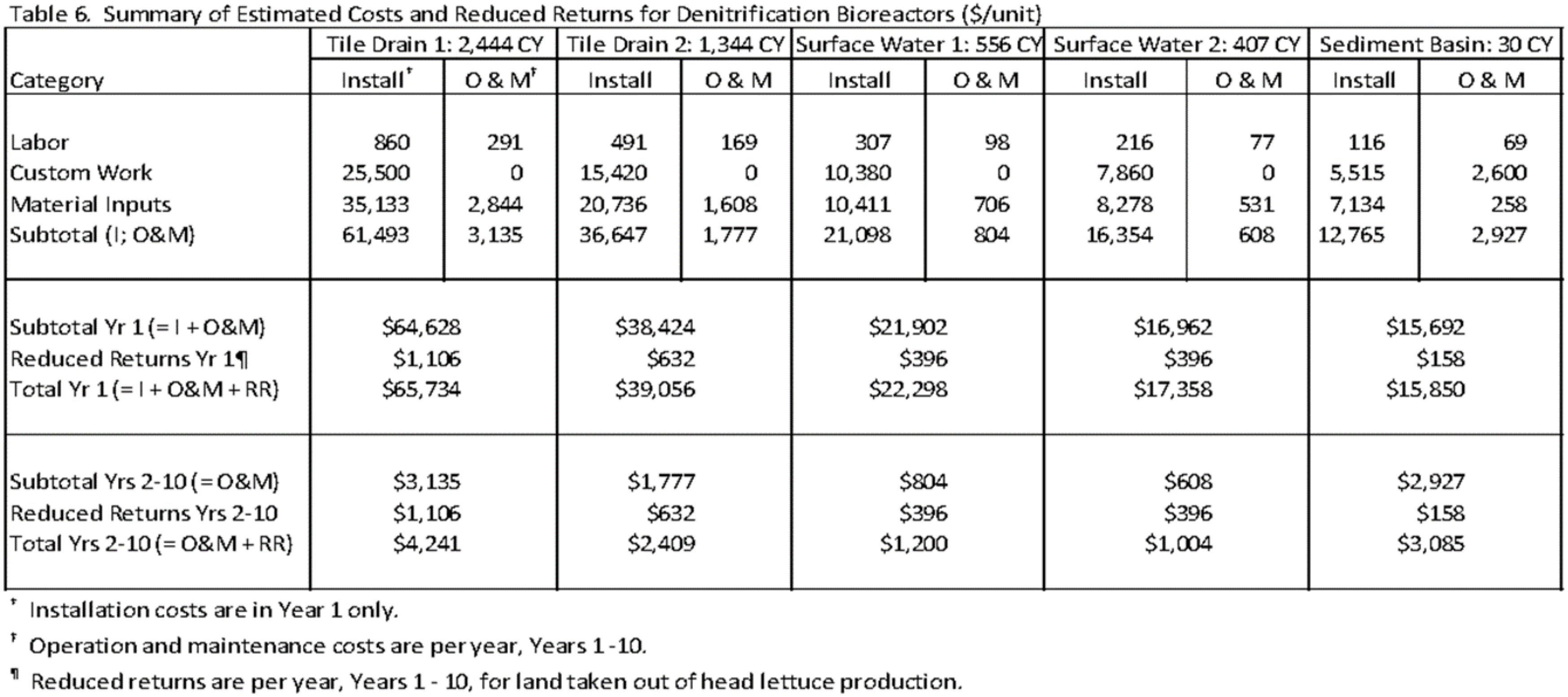


Table 6. Summary of Estimated Costs and Reduced Returns for Denitrification Bioreactors ($/unit)

	Tile Drain 1: 2,444 CY		Tile Drain 2: 1,344 CY		Surface Water 1: 556 CY		Surface Water 2: 407 CY		Sediment Basin: 30 CY	
Category	Install[†]	O & M[‡]	Install	O & M	Install	O & M	Install	O & M	Install	O & M
Labor	860	291	491	169	307	98	216	77	116	69
Custom Work	25,500	0	15,420	0	10,380	0	7,860	0	5,515	2,600
Material Inputs	35,133	2,844	20,736	1,608	10,411	706	8,278	531	7,134	258
Subtotal (I; O&M)	61,493	3,135	36,647	1,777	21,098	804	16,354	608	12,765	2,927
Subtotal Yr 1 (= I + O&M)	$64,628		$38,424		$21,902		$16,962		$15,692	
Reduced Returns Yr 1¶	$1,106		$632		$396		$396		$158	
Total Yr 1 (= I + O&M + RR)	$65,734		$39,056		$22,298		$17,358		$15,850	
Subtotal Yrs 2-10 (= O&M)	$3,135		$1,777		$804		$608		$2,927	
Reduced Returns Yrs 2-10	$1,106		$632		$396		$396		$158	
Total Yrs 2-10 (= O&M + RR)	$4,241		$2,409		$1,200		$1,004		$3,085	

[†] Installation costs are in Year 1 only.

[‡] Operation and maintenance costs are per year, Years 1 - 10.

[¶] Reduced returns are per year, Years 1 - 10, for land taken out of head lettuce production.

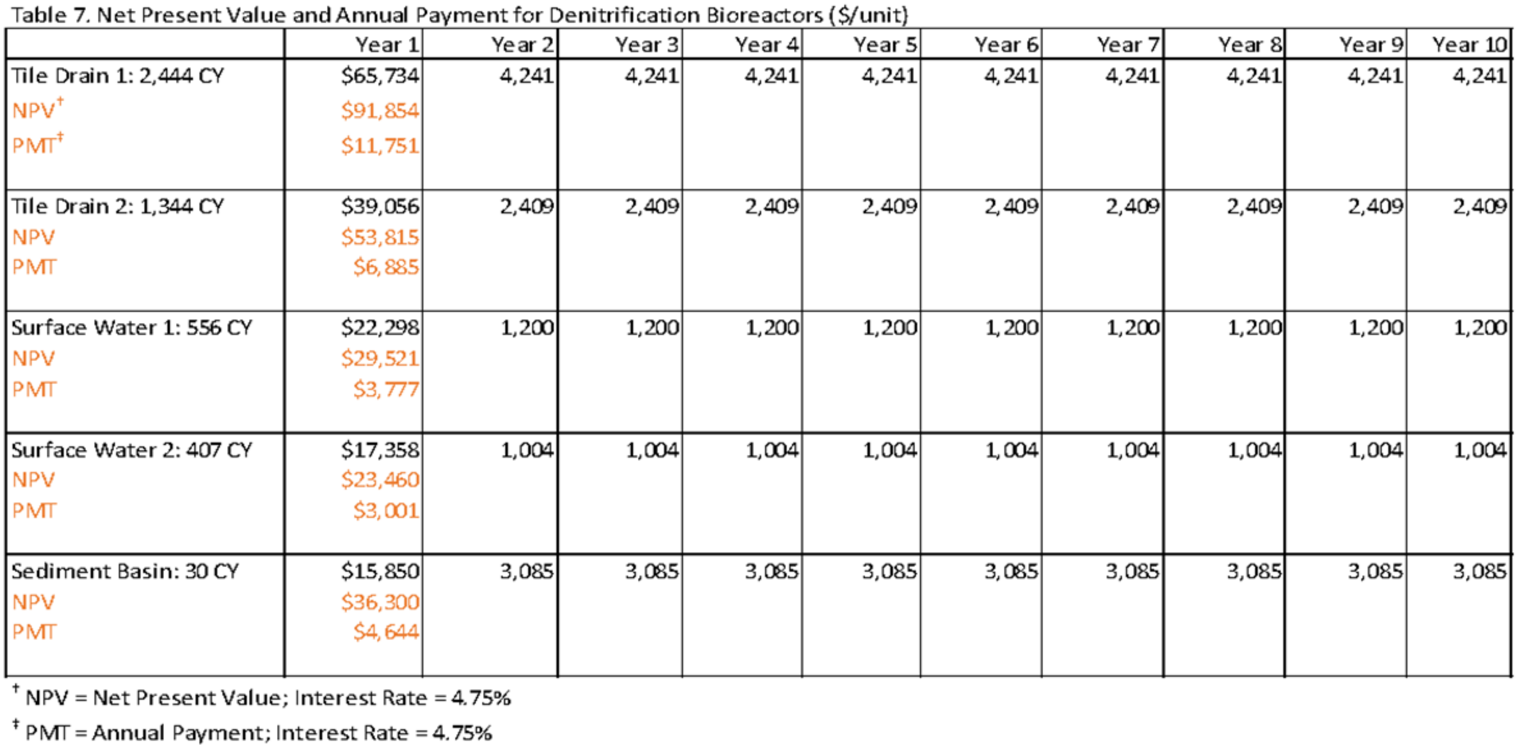


Table 7. Net Present Value and Annual Payment for Denitrification Bioreactors ($/unit)

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Tile Drain 1: 2,444 CY	$65,734	4,241	4,241	4,241	4,241	4,241	4,241	4,241	4,241	4,241
NPV[†]	$91,854									
PMT[‡]	$11,751									
Tile Drain 2: 1,344 CY	$39,056	2,409	2,409	2,409	2,409	2,409	2,409	2,409	2,409	2,409
NPV	$53,815									
PMT	$6,885									
Surface Water 1: 556 CY	$22,298	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200
NPV	$29,521									
PMT	$3,777									
Surface Water 2: 407 CY	$17,358	1,004	1,004	1,004	1,004	1,004	1,004	1,004	1,004	1,004
NPV	$23,460									
PMT	$3,001									
Sediment Basin: 30 CY	$15,850	3,085	3,085	3,085	3,085	3,085	3,085	3,085	3,085	3,085
NPV	$36,300									
PMT	$4,644									

[†] NPV = Net Present Value; Interest Rate = 4.75%

[‡] PMT = Annual Payment; Interest Rate = 4.75%