NITRATE-N DISTRIBUTIONS AND DENITRIFICATION POTENTIAL ESTIMATES FOR AN AGROFORESTRY SITE IN THE OZARK HIGHLANDS, USA

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ABSTRACT

Transport and biogeochemical processing of nitrate-N in upland watersheds is rather poorly known, and denitrification potential estimates for the thin soil veneers of the Ozark Highlands have yet to be documented. Since March 2001, nitrate-N distributions have been monitored from an array of 53 shallow wells (0.5-5.6 m deep) emplaced in a 4.3 ha experimental agroforestry site (receiving split-field treatment of poultry litter to the eastern half in spring, and a comparable annual N-load from commercial fertilizer applied on the western half in spring and fall). The field integrates subsurface flows from a small upland catchment and, in March 2001, contained several "hot spots" with ground water nitrate-N varying from 25.0-64.5 mg/L. Late winter peaks in nitrate-N from this 6 year-old alley cropping system have steadied over the last 2 years (13.2 mg/L for mid-March 2003; 12.0 mg/L for late-February 2004). Saturated hydraulic conductivity means for 3 down-gradient wells (2.0-3.6 m) ranged from 0.83±0.17 to 1.12±0.20 m/day during baseflow conditions. High aquifer-stand hydraulic conductivity estimates were significantly lower for two out of three wells, expanding the range to 0.41±0.05 to 1.39±0.02 m/day, with the well in the lowest landscape position stemming the flow through this hillslope soil assemblage. Mean denitrification potentials, based solely on declines in nitrate-N throughout the growing season for this key ground water integration area, were 8.15±6.20 kg/ha (2002), 20.80±10.23 kg/ha (2003), and 7.11±3.65 kg/ha (2004). Cross-validation of these estimates, using dissolved organic carbon (DOC), resulted in mean denitrification potentials of 22.45±4.41 kg/ha and 16.78±3.63 kg/ha for the 2003 and 2004 growing seasons, respectively.

Keywords: Denitrification, ground water, hydrodynamics, nitrate-N, soil water, vadose zone

INTRODUCTION

Water available for plant growth can be highly variable in karst terrain; thus, the establishment of a sustainable silvopastoral agroecosystem is heavily dependent on site hydrology. Catchment hydrodynamics also heavily influences nutrient transport and transformation. The dynamics of nutrient infiltration and subsurface transport and transformation in karst terrains characterized by high soil heterogeneity, multi-level permeability contrasts (e.g., plowpans, fragipans, and relict chert layers), rapidly fluctuating unconfined aquifers, and preferential flow paths (i.e., interflow) is very poorly understood.

Agroforestry systems, with their potential for enhanced water and nutrient uptake, need to be evaluated in the Ozark Highlands region for their ability to serve as nutrient sinks for reducing off-site impacts of land-applied animal wastes, sites for enhancing C sequestration, and as viable strategies for diversifying farm operations and elevating incomes from nut crop, forage, and/or forestry production. Close scrutiny of hydrological as well as biogeochemical alterations associated with land use modifications at the field-to-catchment scale is warranted if we are to remedy adverse off-site impacts of key nutrients (Walter et al. 2000; Brye et al. 2001). The principal objectives of this GIS-based study of an experimental agroforestry tract were to: (1) produce a field-scale model of hydrodynamics, based on fluctuations in the unconfined aquifer; (2) map changes in nitrate-N concentrations from ground water for the past three growing seasons (2002-2004); (3) characterize the saturated hydraulic conductivity distributions for subsoils proximate to the karst interface intercepted by three down-gradient wells; and (4) estimate deep soil denitrification potentials for a key hillslope hydrologic zone based on nitrate-N and DOC concentrations in shallow ground water.

MATERIALS AND METHODS

Site Description

The Agroforestry Experimental Field (AEF) located on the University of Arkansas Farm (Washington County, AR) encompasses 4.3 ha, and was planted in fall 1999–fall 2000 (Figure 1). Prior to conversion, the site had been fallowed for about a decade; earlier (ca. 1950s-1980s), it was a tall fescue pasture, grazed by dairy cattle. The AEF consists of three tree zones (*Quercus rubra*, *Juglans nigra*, and *Carya illinoensis*), each approximately 1.2 ha in aerial extent. The Northern red oaks (which occupy the northernmost portion of the field, encompassing rows 1-5) were transplanted as 1 year-old seedlings with 2.4 m intra-row spacing; the Eastern black walnuts (residing in the "middle" of the field from row 6-10) and pecans (residing in the southern third of the field from row 11-15) were 2 year-old rootstocks and 1 year-old scions at 9.1 m intra-row spacing. Orchard grass, *Dactylis glomerata* (var. Benchmark), was seeded in the alleys between tree rows (15 m row spacing) during the fall of 2000.

Fifty-three piezometers were installed from 2000-2001. These shallow wells were designed to sample throughout the vadose zone to the karst interface (with depths varying from 0.5 to 5.6 m). Seventy-five percent of the shallow wells (N=40) intercept the unconfined aquifer in the aforementioned tree zones.

Five soil series comprise this hillslope assemblage, with the mapped extents of Typic, Ochreptic, and Aquic Fragiudults dominating the field (namely, Captina, Nixa, and Johnsburg series soils). Surface infiltrability was parameterized for topographic patches (high and low) of the three prevalent soil series. Variability of mean ponded infiltration rates from 18 sites was quite high, with the overall range from 4.0±1.7 cm/h for Captina soils at high topographic positions to 18.0±6.0 cm/h for Nixa soils at high topographic positions. Johnsburg soils, at the lowest landscape positions, exhibited infiltration rates of 12.0±6.0 cm/h. These ultisols developed under mesic conditions, and are underlain by the Boone Formation (a cherty limestone of Mississippian age).

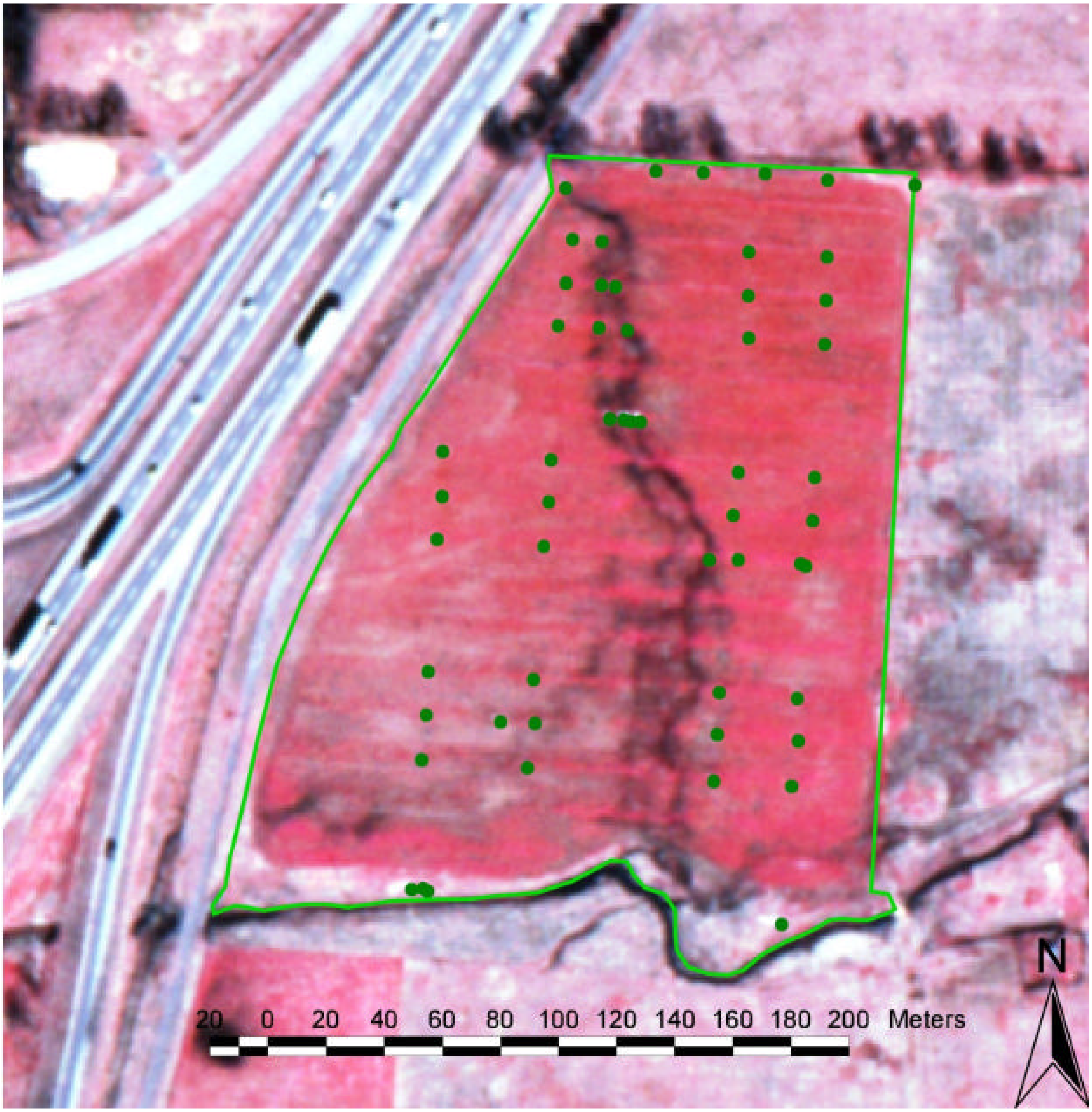

Figure 1. A color infrared image of the 4.3 ha Agroforestry Experimental Field (AEF) highlighting the distributed array of 53 shallow wells (shown by green dots) used for environmental monitoring. CIR image date 21 February 2001.

The 30-year average annual rainfall is 1119 mm, with a low of 47 mm in January and a high of 128 mm in May (recorded at a station 8 km from the AEF [Owenby and Ezell 1992]). Mean temperatures for January and July are 1.1 and 25.9 degrees Celsius, respectively. Precipitation totals for the years 2002-2004 were 1094 mm**,** 962 mm, and 1210 mm. Estimates of inorganic N

(NH_4 and NO_3) inputs contributed by annual rainfall (1999-2003) varied from 10.36-15.31 kg/ha/y (National Atmospheric Deposition Program/National Trends Network for the AR27 station).

The AEF resides in a small catchment (approximately 18 ha in aerial extent) in the uppermost reaches of the Illinois Watershed (HUC 11110103). This small catchment is part of a subbasin (2.8 km^2) comprised of a network of ephemeral channels that contribute to Hamestring Creek which, in turn, flows into Clear Creek and finally the Illinois River. The Illinois Watershed has been designated as a "nutrient surplus area;" recent state legislation regulates the use and management of poultry litter and other nutrients (Goodwin et al. 2003).

Field Treatments

Beginning in 2001, half of the AEF received a single 4.5 Mg/ha application of poultry litter each Spring (approximately 110 kg N and 40 kg P per hectare); the other half was treated with a split application of commercial fertilizer (amounting to 56 kg N per hectare) during spring and fall.

Soil Water and Ground Water Monitoring and Analysis

Concentrations of nitrate-N and total P in the soil and ground waters have been regularly monitored over the past three growing seasons (March 2002–October 2004), and include a few storm events. Water samples from porous cups and shallow wells were colorimetrically analyzed for nitrate-N using a Lachat continuous-flow ion analyzer. Ground water DOC (collected over two growing seasons, from May 2003–October 2004) was determined using a Shimadzu TOC-V_{CSH} Analyzer.

Subsoil Hydraulic Conductivities

Saturated hydraulic conductivities for select wells were derived from bail-down data. Well recoveries were plotted in Excel. The Bouwer and Rice method (incorporating modifications from Bouwer 1989) was used to estimate subsoil saturated hydraulic conductivities. This methodology was designed to account for the geometry of partially penetrating or fully penetrating wells in unconfined aquifers.

GIS Database

A DGPS unit was used to produce a high-resolution topographic map of the AEF. The GIS database (ArcView 3.3) incorporates topography, soils, unconfined aquifer fluctuations (including basic water quality parameters), electromagnetic induction (EMI) geophysical surveys, tree growth patterns, nitrate-N profiles, and the spatiotemporal delineation of N pools developed at the soil-karst interface of this agroecosystem. The ArcView Hydro extension was used to produce a simple model of the AEF's surface hydrology. Field-scale nitrate-N distributions for porous cup and well datasets were mapped using grid interpolation techniques (i.e., Spline method with a 1 meter cell size, weight varied 100-700 for the purpose of optimization, number of points varied from 2-4, type Tension). Change detection operations were performed on optimized grid maps using Map Calculator.

RESULTS AND DISCUSSION

Nitrate-Nitrogen

Ground water nitrate-N concentrations did not differ significantly between field treatments over the last three growing seasons (Table 1). However, elevated levels of nitrate-N (i.e., >10 mg/L) typically persisted from March through July on the portion of the field receiving commercial fertilizer (Table 2; Figures 2 and 3). Concentrations were usually highest in February to March, then showed steady decline through the late Spring and Summer months. As the small catchment approached baseflow conditions (usually sustained from late July through October) or after a strong summer storm event, a few of the integrating wells recorded slight ($\leq$ 1.5 mg/L) to moderate (around 3.0-5.0 mg/L) increases in nitrate-N levels. Variability was high for the 18 well sites that permitted cross-comparison with DOC concentrations; percentage coefficients of variation (%CV) for nitrate-N exceeded 50% for 11 out of 18 wells (Table 1).

DOC

Dissolved organic carbon (DOC) concentrations from ground water samples did not differ significantly between field treatments over the last two growing seasons (Table 1). DOC contents for the east half of the paddock (which received poultry litter) ranged from 0.51-13.31 mg/L; DOC concentrations from the west half (which received comparable, annual N applications of ammonium nitrate) ranged from 0.62-12.58 mg/L. Variability in DOC content was quite high for most wells yielding samples on three or more collection dates (N=18), with percentage coefficients of variation (%CV) greater than 50% for 10 out of 18 well sites. Typically, the highest ground water DOC concentrations for any given well were observed during July or August (Table 2). Exceptions to this general trend were observed on a few occasions in three of the wells active during baseflow conditions; samples from all three wells exhibited peak DOC values in October 2004. An interesting pattern (usually noted for some zone 3 and zone 4 wells) consisted of the co-occurrence of ground water nitrate-N samples assigned to the “not detectable” (ND) category and elevated DOC concentrations—suggesting that under nitrate-N limiting conditions DOC was accumulating at these loci; thus, “priming” certain areas to serve as denitrification “hot spots” when water levels surged back up, a new supply of nitrate-N was received, and anaerobic conditions were restored.

Table 1. Summary of nitrate-N and DOC concentrations from the unconfined aquifer. EAF wells occur on the eastern half of the field receiving poultry litter; WAF wells reside in the western half of the field receiving ammonium nitrate. Nitrate-N samples were collected from March 2002-October 2004; DOC samples were collected from May 2003-October 2004.

Well ID	Hydro Zone	NO_3-N samples	Min mg/L	Max ----	Mean ----	SD ----	%CV	DOC samples	Min mg/L	Max ----	Mean ----	SD ----	%CV
EAF8-6.5	3	15	2.6	6.9	4.1	1.0	25.5	8	1.55	3.64	2.45	0.78	31.93
EAF9-6.25	4	16	0.9	8.8	5.0	2.8	55.0	9	0.66	5.28	2.14	1.37	64.09
EAF9-7.5	4	9	1.1	5.7	2.0	1.5	73.1	6	1.96	3.50	2.70	0.60	22.24
EAF12-3.5	4	14	0.5	6.8	2.2	1.6	73.1	10	1.35	4.93	2.36	1.44	60.99
EAF12-6.5	4	14	0.3	7.0	1.9	1.8	92.7	8	1.16	5.06	2.41	1.46	60.63
EAF13-3.5	4	18	2.0	7.2	3.5	1.4	40.8	11	0.51	6.91	1.92	1.98	103.23
EAF13-6.5	4	11	0.4	4.7	1.3	1.3	98.3	6	1.07	1.85	1.44	0.29	20.41
EAF14-3.5	3	11	0.5	10.1	4.6	2.9	62.7	6	1.63	6.67	2.92	1.90	65.00
EAF14-6.5	4	11	1.0	5.3	2.2	1.3	61.7	6	1.23	2.89	2.05	0.60	29.48
WAF3-12	3	5	0.4	2.3	1.2	0.8	71.8	3	1.85	2.43	2.23	0.33	14.83
WAF4-11.1	4	5	0.8	2.6	1.7	0.8	46.4	4	2.30	12.48	5.49	4.70	85.54
WAF4-12	3	6	0.3	11.0	4.2	4.2	100.9	3	1.31	1.76	1.61	0.26	16.17
WAF9-13.5	3	7	2.4	16.5	9.6	5.4	55.8	3	1.71	6.94	3.70	2.83	76.51
WAF12-17.5	2	18	5.1	11.3	7.5	1.9	24.7	11	0.62	4.64	2.01	1.51	75.39
WAF13-13.5	3	10	4.5	10.1	6.5	1.8	27.3	6	0.69	1.79	1.03	0.41	40.09
WAF13-14.75	3	11	1.9	21.1	11.2	5.3	47.7	7	0.92	4.70	2.57	1.35	52.56
WAF14-13.5	2	9	3.7	10.4	6.3	2.1	34.3	6	2.65	6.32	4.49	1.47	32.84
WAF14-17.5	2	6	3.8	16.5	8.9	5.2	57.7	4	0.90	2.99	1.85	1.10	59.46

Table 2. Comparison of dissolved organic carbon (DOC) and nitrate-N (NO_3) concentrations (mg/L) from select wells (N=20), for the 2004 field season. EAF wells occur on the eastern half of the field receiving poultry litter; WAF wells reside in the western half of the field receiving ammonium nitrate.

	Hydro	18-Oct		31-Aug		3-Aug		19-Jul		17-May		1-Apr		27-Feb	
Well ID	Zone	DOC	NO_3	DOC	NO_3	DOC	NO_3	DOC	NO_3	DOC	NO_3	DOC	NO_3	DOC	NO_3
EAF8-6.5	3	n/a	n/a	1.55	2.9	1.83	3.2	2.55	2.6	2.05	3.5	1.94	3.9	2.49	4.6
EAF9-3.75	2	n/a	n/a	n/a	n/a	13.31	0.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	N/a
EAF9-6.25	4	n/a	n/a	2.07	2.0	2.69	2.4	1.88	1.9	1.04	0.9	1.18	2.1	1.73	1.5
EAF9-7.5	4	n/a	n/a	n/a	n/a	3.24	1.2	2.33	1.1	2.84	1.1	2.31	1.5	1.96	1.5
EAF12-3.5	4	4.61	ND	1.72	1.1	1.55	1.3	1.50	1.4	1.35	1.4	1.35	2.6	1.64	1.7
EAF12-6.5	4	n/a	n/a	1.52	0.7	1.57	1.1	4.33	1.1	1.67	0.8	2.28	1.5	1.16	0.7
EAF13-3.5	4	1.58	2.5	1.46	2.7	0.95	3.4	0.90	3.1	0.60	3.9	0.94	5.2	1.00	4.8
EAF13-6.5	4	n/a	n/a	n/a	n/a	1.51	0.8	1.85	1.0	1.45	0.4	1.61	0.7	1.07	0.8
EAF14-3.5	3	n/a	n/a	n/a	n/a	1.90	2.4	3.02	3.4	1.97	4.2	1.63	4.9	2.32	5.6
EAF14-6.5	5	n/a	n/a	n/a	n/a	1.50	1.0	2.16	1.3	2.89	1.2	2.10	1.6	1.23	1.0
WAF3-11.5	3	n/a	n/a	n/a	n/a	6.10	ND	n/a	n/a	3.63	0.4	n/a	n/a	n/a	N/a
WAF3-13.5	2	n/a	n/a	n/a	n/a	1.06	2.1	n/a	n/a	1.17	6.1	n/a	n/a	n/a	N/a
WAF4-11.1	4	n/a	n/a	n/a	n/a	3.47	ND	n/a	n/a	2.30	ND	n/a	n/a	n/a	N/a
WAF4-12	3	n/a	n/a	n/a	n/a	1.76	0.8	n/a	n/a	1.31	0.3	n/a	n/a	n/a	N/a
WAF9-13.5	3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.45	9.0	1.71	10.4	n/a	N/a
WAF12-17.5	2	1.89	6.3	1.19	6.4	1.35	7.2	1.21	7.7	0.62	8.1	0.73	6.4	1.16	7.4
WAF13-13.5	3	n/a	n/a	n/a	n/a	0.90	4.5	1.79	4.8	0.81	5.0	0.69	5.7	1.23	7.1
WAF13-14.75	3	n/a	n/a	n/a	n/a	2.68	2.4	3.19	1.9	0.92	12.7	1.25	11.0	1.76	12.0
WAF14-13.5	2	n/a	n/a	n/a	n/a	4.38	4.9	6.32	3.7	4.55	4.7	3.10	6.7	2.65	6.8
WAF14-17.5	2	n/a	n/a	n/a	n/a	0.92	4.7	2.59	3.8	0.90	6.5	n/a	n/a	n/a	N/a

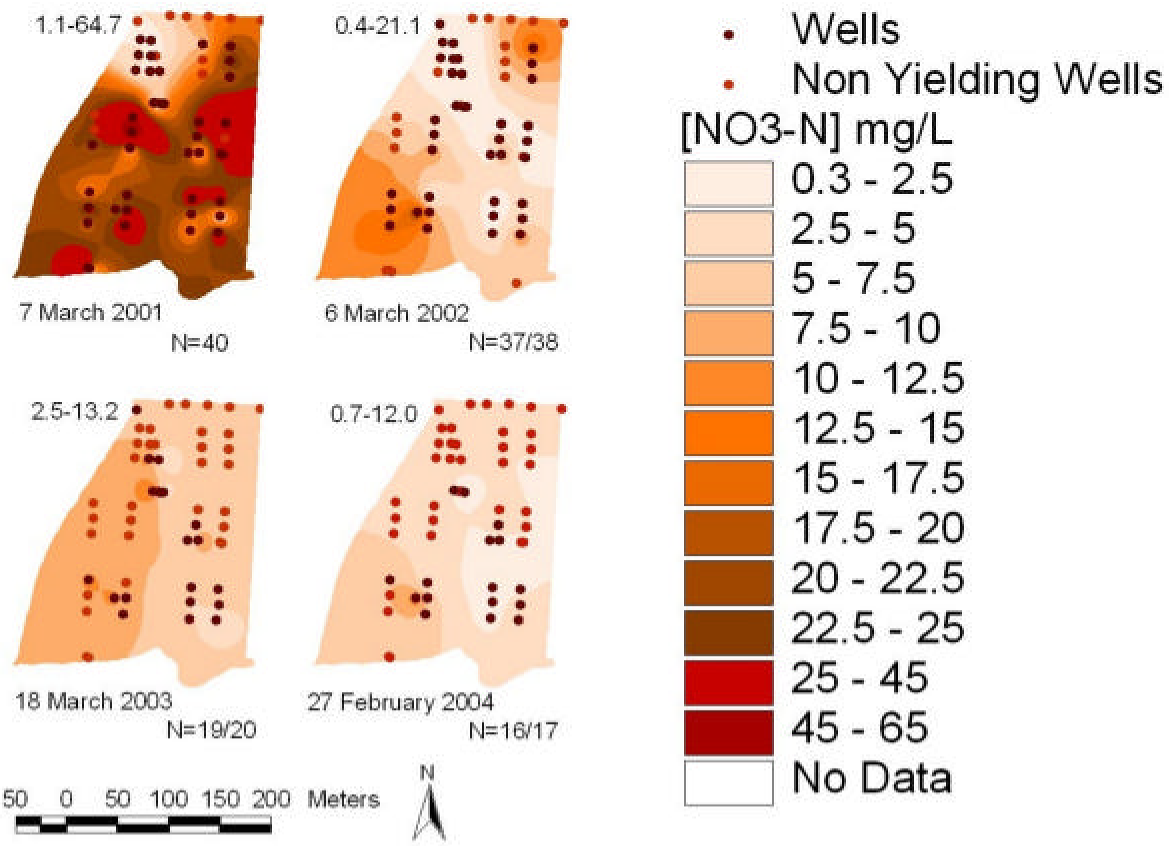

Figure 2. A "near anniversary date" assemblage of ground water nitrate-N distributions from the Agroforestry Experimental Field. The upper left hand corner of each map frame indicates the range of nitrate-N concentrations (mg/L) for that collection date. "N" values provide the number of wells with nitrate-N concentrations above MDL.

Spatial Hydrology

Nitrate-N Distributions. Some of the topographic sinks recognized in the surface hydrology model (not shown) coincided with hot spots of nitrate-N recorded during the first ground water collection event (March 2001). At that time, the field contained several hot spots with nitrate-N concentrations in excess of 25 mg/L (Figure 2). These patches most likely represented residual accumulations of nitrate-N shed in response to changes in subsoil pH (the delayed result of liming the field in 1999) which, in turn, gradually altered the anion exchange capacity (AEC) proximate to the deep soil-karst interface and released nitrate-N stored in these highly acidic subsoil pockets (DeFauw 2005). The leaching index in NLEAP (i.e., the nitrate leaching economic analysis package) indicates that ground water concentrations of 21-30 mg/L correspond to a leaching potential of 301-450 kg/ha, and >40 mg/L is correlated with nitrate-N release in excess of 600 kg/ha (Shaffer et al. 2001). By spring 2002, nitrate-N levels were significantly reduced (via leaching, immobilization, as well as denitrification), and a new nutrient assimilation "pattern" based on the commercial fertilizer vs. poultry litter treatments for this agroecosystem was emerging.

Zones of accumulation as well denitrification/leaching/immobilization loss were tentatively identified based on the spatial resolution of the waxing and waning of nitrate-N pools developed in this alley cropping system over the past few years of ground water quality monitoring (Figure 3 displays a series of change detection grids summarizing nitrate-N distributions for 2002). These preliminary results provided insights on hydrologically active areas as well as possible stagnation zones, and led to the development of a hydrologic zone model for this field.

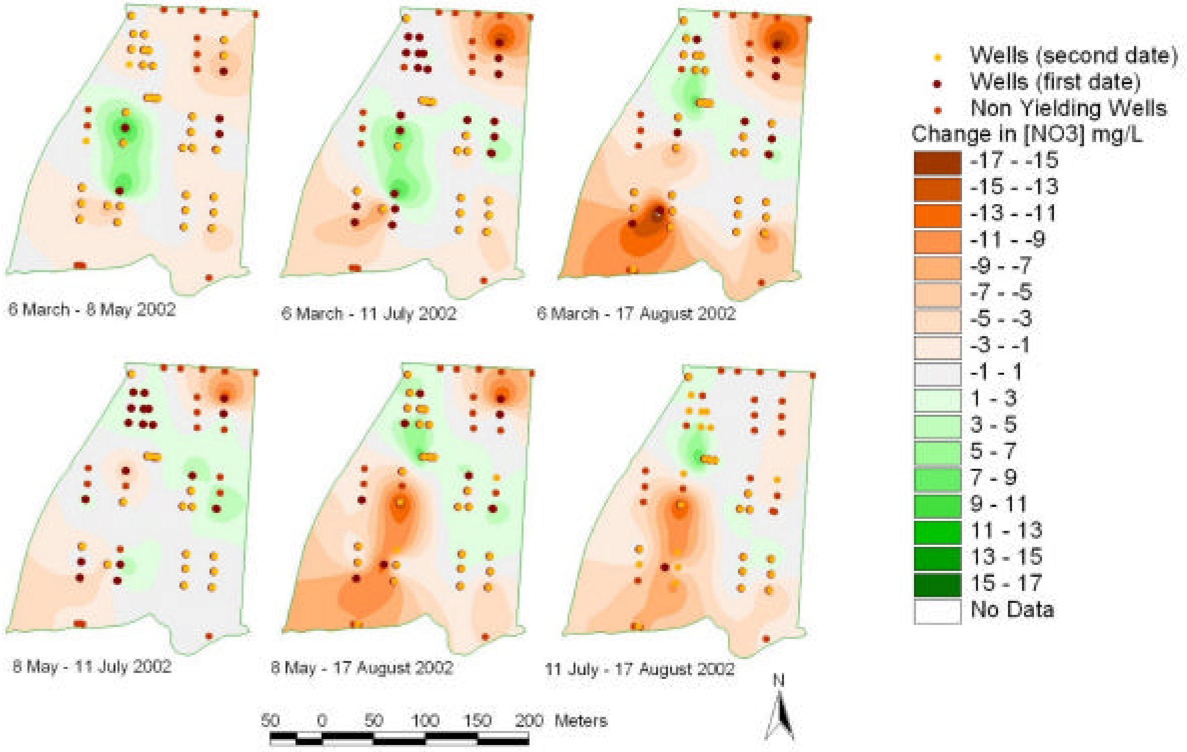

Figure 3. A change detection series of ground water nitrate-N concentrations highlights the spatiotemporal variability of potential zones of accumulation (in shades of green) as well as denitrification/leaching/immobilization loss (shown in shades of orange).

Hydrologic Zones. A time-series assemblage of 66 water table maps (constructed from over 3200 depth to water records for the shallow well array over a 17-month interval—late May 2003 to late October 2004, including 6 maps from 2002) was used to create a simple, field-scale model of hydrodynamics (Figure 4). Based on the percentage coefficient of variation (%CV), five hydrologic zones were resolved; these zones were classified by standard deviation departures from a mean of 30.9%. The green areas approximate most of the spatial extent of the hydrologically sensitive areas (these HSAs were typically present from early February through March), although several small patches (<25 m^2) prone to saturation excess runoff were detected in three EMI surveys of this field (not shown). A series of storm events in April 2004, prolonged the persistence of HSAs until mid-May. The quantification of HSAs in watersheds where variable source area hydrology is a dominant process provides a starting point for water quality risk assessment and the development of management practices for non-point source (NPS) pollution (Walter et al., 2000).

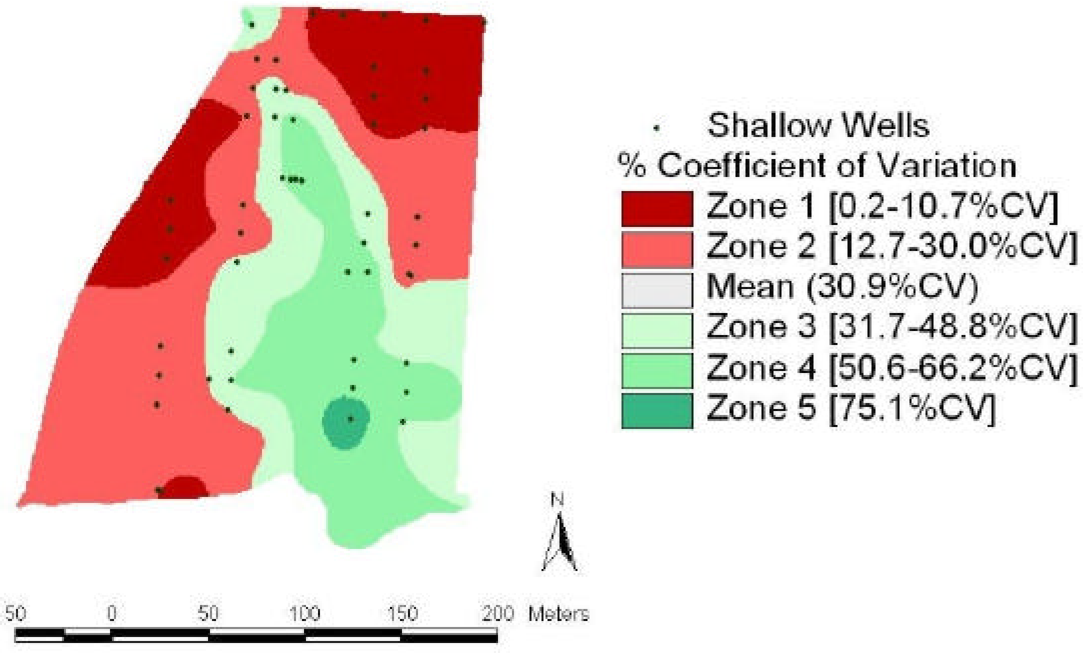

Figure 4. A composite map produced using 66 depth to water table datasets (March 2002-October 2004) yields a simple model of hydrologic activity (distinguishing 5 zones). "Zone" determination for each shallow well is based on a set range of standard deviations derived from the percentage coefficient of variation (%CV).

Denitrification Potential Estimates

Deep subsoil denitrification potentials for a key integration area (in the southeast quadrant) of the agroforestry field were estimated in two ways. Initial estimates were calculated based on an averaged decline in nitrate-N concentrations sampled by three down-gradient wells, situated in Johnsburg series soils (at depths of 2.0-3.6 m), over each growing season (2002-2004). During baseflow conditions (i.e., early September 2004), mean saturated subsoil hydraulic conductivities ranged from 0.83±0.17 to 1.12±0.20 m/day. These flow rates combined with diminishing nitrate-N levels detected for the 2002, 2003, and 2004 growing seasons resulted in mean denitrification estimates of 8.15±6.20 kg/ha, 20.80±10.23 kg/ha and 7.11±3.65 kg/ha, respectively. High aquifer-stand (late February-early March 2005) hydraulic conductivity estimates were significantly lower for two out of the three wells, thus expanding the range to 0.41±0.05 to 1.39±0.02 m/day, with the well in the lowest landscape position stemming the flow through this hillslope soil assemblage. Therefore, during high aquifer conditions (which includes some storm event responses), the denitrification potential of this portion of the catchment appears to be enhanced (if the appropriate combination of availability of nitrate-N, labile DOC, pH, temperature and anaerobic microsites prevail).

Brye et al. (2001) examined the likelihood of deep soil denitrification based on year-round collection of nitrate-N and organic C (OC), from Plano silt loam soils, using equilibrium-tension lysimeters (at 1.4 m below the surface). Denitrification potential was estimated by coupling the dissimilatory half-reactions (i.e., OC substrate oxidized to CO_2, and the reduction of NO_3^- to $1/2N_2O$), and by assuming that all of the OC was available to support microbial denitrifying activity under suitable anaerobic conditions. Using these criteria, mean denitrification potentials for a key ground water integration area on the agroforestry site (flowing through Johnsburg series subsoils) were 16.78 ± 3.63 kg/ha and 22.45 ± 4.41 kg/ha for the 2003 and 2004 growing seasons, respectively. It is understood that the DOC-derived values are overestimates due to the multiplicity of fates for this soluble nutrient mélange (e.g., refractory DOC is not bioavailable).

Denitrification is a pulsed process controlled primarily by soil water contents in excess of 60% water-filled pore space (Linn and Doran 1984), which restricts oxygen availability (as denitrifying microbes require a very low dissolved oxygen concentration <0.4mg/L). Coupled with this key requirement are the interactive effects of nitrate-N concentration, organic carbon availability, pH, temperature, and the timing and abundance of rainfall. Investigators have recognized that the interplay of these regulative factors create hot spots of denitrification activity; thus, this process has the largest spatial and temporal variability of any of the N cycle processes (Tiedje et al. 1989). Since there is no consensus on the best quantification method for assessing denitrification in the field (Mosier et al. 2002), estimates derived from two ground water quality parameters are presented in this paper.

CONCLUSIONS

Traditional hydrologic monitoring efforts reveal an exceedingly small fraction of a field's (or small catchment's) hydrodynamic character. The spatiotemporal integration of water table fluctuations, subsoil hydraulic conductivities, and key ground water quality parameters (i.e., nitrate-N and DOC) offers valuable insights on process-response relationships for a small headwater catchment in the Ozark Highlands. Substantial epikarst accumulations of one form of reactive nitrogen (nitrate-N) were recorded in year two (2001) of this pasture conversion project (Figure 2); by the Spring of 2002, close to two-thirds of this N-load had dissipated from the field (via leaching, immobilization, and denitrification).

Nutrient assimilation, which occurs by some combination of plant and microbial uptake as well as a site's inherently patchy biogeochemistries, is strongly influenced by catchment hydrodynamics. Late winter peaks in nitrate-N from this 6 year-old alley cropping system have steadied over the last two years (2003-2004); perhaps indicating that a quasi-stable, biogeochemical processing "state" has been achieved in response to annual nutrient inputs of poultry litter and commercial fertilizer. Hydraulic conductivity distributions estimated for a key ground water integration area (in the southeast quadrant of the field) suggest enhanced opportunities for deep soil denitrification may occur when subsurface flows diminish during the transition from baseflow to aquifer high-stand conditions.

As the trees mature and a canopy is established to shade the orchard grass, N and C cycling efficiencies will improve. This GIS-based investigation on field-scale nitrate-N distributions and denitrification potential provides benchmark data on process-response relationships that have developed in a young agroforestry ecosystem (converted from fallowed land in 1999). These results will facilitate the discernment of longer-term trends in the biogeochemical processing of subsequent N inputs from poultry litter, commercial fertilizer, and cattle on this site, as well as be of use in the refinement of nutrient management strategies for the Ozark Highlands region.

Future work (to be accomplished during the 2005 field season) includes: (1) stable isotope analyses of water (^{2}H and ^{18}O) to determine transit times of precipitation inputs to the shallow aquifer; (2) use of the denitrifier method (using stable isotopes ^{15}N and ^{18}O) to examine the denitrification potentials of three down-gradient wells situated in Johnsburg series and Johnsburg-Captina-Cleora transition soils proximate to an ephemeral channel; and (3) field-scale mapping of the saturated subsoil hydraulic conductivities for high aquifer conditions to further refine the delineation of areas prone to saturation excess runoff (HSAs), leaching, and denitrification in this small upland catchment.

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REFERENCES

Bouwer, H. 1989. The Bouwer and Rice slug test–an update. *Ground Water* 27(3):304-309.

Brye, K. R., J. M. Norman, L. G. Bundy, and S. T. Gower. 2001. Nitrogen and carbon leaching in agroecosystems and their role in denitrification potential. *J Environ Qual* 30:58-70.

DeFauw, S. L. 2005. Hydrodynamics of a Hillslope Soil Assemblage in the Ozark Highlands, USA. Unpublished data from a Ph.D. dissertation manuscript in preparation, University of Arkansas.

Goodwin, H. L., F. T. Jones, S. E. Watkins, and J. S. Hipp. 2003. New Arkansas laws regulate use and management of poultry litter and other nutrients. UACES-FSA 29, 4 pp.

Linn, D. M., and J. W. Doran. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Sci Soc Am J* 48:1267-1272.

Mosier, A. R., J. W. Doran, and J. R. Freney. 2002. Managing soil denitrification. *J Soil and Water Conserv* 57(6):505-513.

Owenby, J. R., and D. S. Ezell. 1992. Monthly station normals of temperature, precipitation, and heating and cooling degree days, 1961-90, Arkansas. Climatography of the United States, no. 81. Asheville, NC: US Department of Commerce, National Climatic Data Center.

Shaffer, M. J., K. Lasnik, X. Ou, and R. Flynn. 2001. NLEAP internet tools for estimating NO_3-N leaching and N_2O emissions. In *Modeling Carbon and Nitrogen Dynamics for Soil Management*, eds., Shaffer, M. J., L. Ma, and S. Hansen, 401-426. Boca Raton, FL: Lewis Publishers.

Tiedje, J. M., S. Simkins, and P. M. Groffman. 1989. Perspectives on measurement of denitrification in the field including recommended protocols for acetylene based methods. In *Ecology of Arable Land,* eds., Clarholm, M., and L. Bergstrom, 217-240. Dordrecht, Holland: Kluwer Academic Publications.

Walter, M. T., M. F. Walter, E. S. Brooks, T. S. Steenhuis, J. Boll, and K. Weiler. 2000. Hydrologically sensitive areas: Variable source area hydrology implications for water quality risk assessment. *J Soil and Water Conserv* 55(3):277-284.