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Research Article

High Nitrogen Fertilization of Tobacco Crop in Headwater Watershed Contaminates Subsurface and Well Waters with Nitrate

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Our hypothesis was that subsurface and well waters in watershed with shallow, stony soils, steep landscapes, and cropped to tobacco are contaminated by nitrate. Nitrate in soil solution was monitored in (0.20 m) and below (0.5 m) root zone with tension lysimeters, in five transects. Water from two wells (beneath tobacco field and in native forest) used for human consumption was also analyzed for nitrate. Soil bulk density, porosity, and saturated hydraulic conductivity were evaluated. Soil physical and hydrological properties showed great variation at different landscape positions and soil depths. Soil coarse grain size, high porosity, and saturated hydraulic conductivity favored leaching nitrate. Nitrate in soil solution from tobacco fields was greater than in natural environment. Nitrate reached depths bellow rooting zone with values as high as 80 mg L^{-1} in tobacco plantation. Water well located below tobacco plantation had high nitrate concentration, sometimes above the critical limit of 10 mg L^{-1}. Tobacco cropping causes significant water pollution by nitrate, posing risk to human health. A large amount of nitrogen fertilizers applied to tobacco and nitrate in subsurface waters demonstrate the unsustainability of tobacco production in small farming units on steeps slopes, with stony and shallow soils.

1. Introduction

Studies in headwater watersheds are of noteworthy importance, since soil and water contamination at this scale, that is, zero-order watershed, affects water quality of higher-order watersheds and river basins. In small agricultural watersheds in Southern Brazil, pesticides [1, 2] and phosphorus are present in surface and well waters and sediments [3–7] in surface water in creeks. Although there exist management practices for soil and water protection [8], nitrate contamination in watersheds cropped to tobacco is a major concern.

Tobacco crops require large amounts of nitrogen until flowering, since deficiency during this period diminishes leaf yield and quality. Conversely, excess nitrogen in soil solution after tobacco flowering results in high leaf protein content, diminishing tobacco burning quality [9]. Nitrate regulates tobacco root system branching and allocation and distribution of carbohydrates between root system and aboveground biomass (leaves and stems) [10]. Thus, when there is low nitrate concentration in the rhizosphere, root growth and branching are stimulated rather than leaves and stems growth, which is an undesirable since tobacco leaves are the commercial component.

Tobacco companies strongly recommend that farmers apply high fertilizer doses, due to low nitrogen use efficiency by tobacco crop, especially in well-drained soils [11]. Nitrogen recovery rate diminishes as applied dose increases and rainfall increases (high precipitation) to compensate for nitrogen leaching and erosion loss [12].

Official recommendation foresees the use of complementary fertilization after frequent, intense rainfall [13]. This

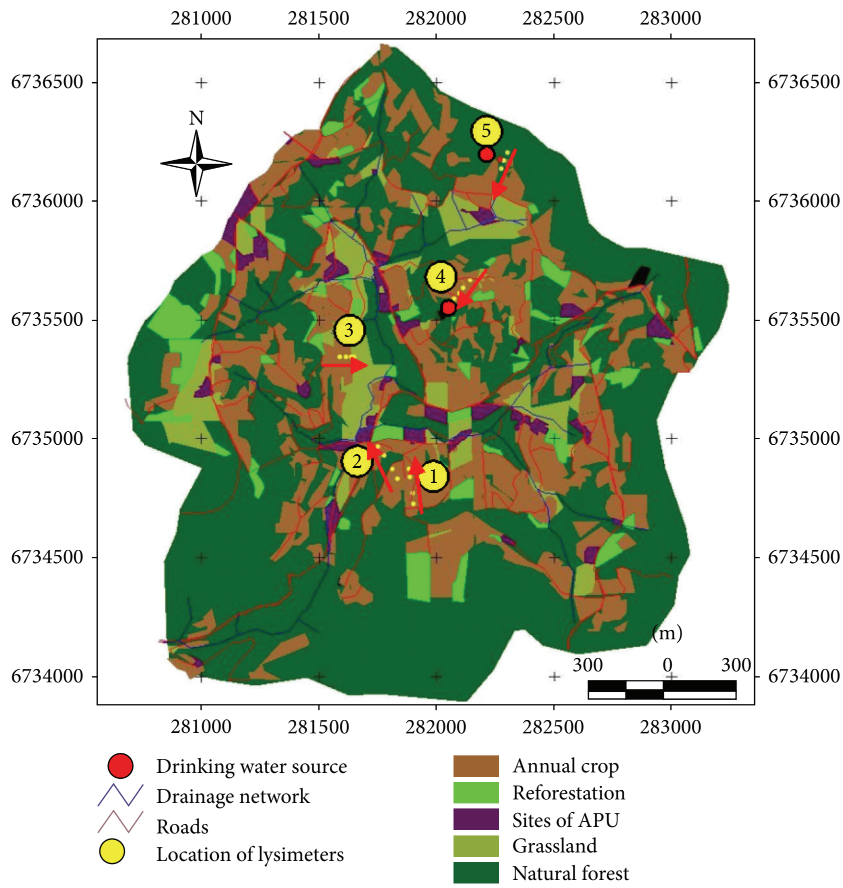

Figure 1: Collection sites on transects in the watershed. Points indicate transects in landscape and arrows indicate slope direction. APU: agricultural production units.

recommendation and especially the one adapted by tobacco companies require nitrogen to be applied in nitrate form. Although nitrate guarantees leaf quality [9], its high mobility in soil poses higher pollution potential.

Nitrate concentration in water (groundwater and surface water bodies) in natural environments is rarely more than $1\,mg\,L^{-1}$ [14]. However, anthropic activities strongly change the nitrogen cycle, particularly by increasing nitrate in soil and in water. When nitrate concentration in water reaches values above $10\,mg\,L^{-1}$, water is not recommended for human consumption [15], but values above $2\,mg\,L^{-1}$ may already cause ecological imbalance in aquatic environments [14]. In Europe, nutrient doses are defined not only by crop requirements but also by contamination possibility, with a legal framework that farmers must follow to attain good long-term water quality [16].

Runoff and subsurface water flow enriches water with sediments and nutrients [17]. Soil texture, permeability, and water-storage capacity are main factors involved in water movement and determine groundwater contamination susceptibility [18, 19]. On sloppy land and in shallow soils, infiltrated water may percolate among fissures of decomposing rocky material until it reaches groundwater. In low land regions, saturated zones and areas with source outcroppings are generally formed, and these constitute headwaters of many rivers and sites where water wells for human consumption are built. Thus, water quality is closely linked to land use and management, and it is an indicator of production systems impacts [20], especially in sites where soils have low water-storage capacity [21].

Our hypothesis was that subsurface and well waters in tobacco fields and in downhill forest are contaminated by nitrate in shallow, stony soils on steep landscapes. Our objective was to evaluate nitrate concentration in soil solution of tobacco fields compared with native forest and grasslands, in water wells for human consumption, with native forest between well and tobacco field, and in native forest.

2. Material and Methods

2.1. Study Site. The study was done in Arroio Lino watershed, a small agricultural watershed (480 ha) in Southern Brazil (Figure 1). Climate is humid subtropical (Cfa type) according to Köppen classification. Maximum mean temperature is above 22°C and minimum temperature of the coldest month is between −3 and 18°C. Rainfall is normally well distributed, ranging from 1300 to 1800 mm $year^{-1}$, where May and June have more rainfall [16].

Landscape has steep slopes, occupied by entisols on slopes and mollisols on terraces [22]. Lands in the watershed are farmed by 36 families, whose main cash crop is tobacco leaves. During 2005/2006 harvest, 80.4 ha of tobacco was grown: 53.5 ha (67%) under conventional tillage, 26 ha (32%) with minimum tillage, and 0.8 ha (1%) with no-till system. Soil is usually tilled with animal-drawn moldboard plough and disked with pin-harrow.

Fertilization practices are similar in all farming units, following tobacco-companies technological package, disconsidering soil analysis or agricultural history of the field. During 2005/2006 harvest cropping year, 36,900 kg of NPK (10-14-28) fertilizer was applied at transplanting tobacco seedlings and 6,850 kg of urea (45-00-00) plus 51,400 kg of Chile saltpeter (14-00-14) as topdressing fertilization on the 80.4 ha of tobacco crop.

During soil tillage, existing cover crop is plowed under with a moldboard plow and seedbed rows are prepared. Tobacco is planted in ridged rows spaced 1.2 m apart, plants are spaced 0.5 m apart in the row, and fertilizer is applied manually. Topdressing fertilization is usually divided into two applications: the first 20 days after transplanting is done by laterally distributing either urea or Chile saltpeter on the row and incorporating it into soil by moldboard plowing or applying it next to seedlings with a handheld fertilizer spreader and the second 40 days after transplantation is done with handheld fertilizer spreader for Chile saltpeter.

2.2. Experiment Design. Five transects were strategically chosen in the landscape, including tobacco fields, native forests, and grasslands (Figure 2). In a control transect, we chose three points situated on native forest in different landscape altitudes. For the other four transects with tobacco crops, four points were chosen: in transect 1, all points were in tobacco fields; in transect 2, two points were in tobacco fields (highland) and two in grassland (lowland); in transect 3, tobacco crops area is separated by a strip of native forest, where three points were chosen in tobacco fields (two above and one below native forest) and one point was chosen in native forest; and, in transect 4, the lowest point was in native forest and three other points were in tobacco fields. Landscape positions along the transects were 1, upper slope, 2, mid slope, 3, lower slope, and 4, plateau. Automatic tensiometers to measure the matric potential of soil water were installed, but they were inefficient because of the stony soil and, thus, it was not possible to estimate the water flow in the soil.

Water from two wells was sampled to determine quality of water used for human consumption. The first well was in the control transect and the second well on lowest part of transect 4. Although the well in transect 4 was positioned in lowlands, there was a strip of native forest between the well and tobacco crop field.

2.3. Sampling and Sample Analysis. Nitrate concentration in tobacco-fields soil solution was monitored in and below root growth zone. Water was collected by tension (suction) lysimeters with porous ceramic cups [23], installed at 0.2 and 0.5 m depth in tobacco rows. Porous cup lysimeters are considered an effective methodology to collect and evaluate soil solution [24–27]. In total, there were 40 monitoring points in the watershed: 24 tension lysimeters installed in tobacco fields, 10 in native forest, and 6 in pasture. The number of collection points was proportional to the land use in the watershed. The collection of soil solution occurred after 60 days of transplanting (DAT) tobacco seedlings, which is the period after the last topdressing with Chile saltpeter. The dates of the collections were period 1 = November 10, 2005 (60 DAT); period 2 = November 28, 2005 (78 DAT); period 3 = December 9, 2005 (89 DAT); period 4 = January 6, 2006 (117 DAT); period 5 = January 20, 2006 (131 DAT); period 6 = January 27, 2006 (138 DAT); and period 7 = February 10, 2006 (145 DAT).

Soil samples were collected at four depths (0.0-0.1, 0.1-0.2, 0.2-0.3, and 0.3-0.4 m) with metal rings (0.04 m high and 0.06 m diameter) to determine soil bulk density, porosity, saturated hydraulic conductivity, and particle-size distribution. In forested areas, soil samples were not collected because of excessive amount of roots and stony soil surface.

To extract soil solution, 50 kPa tension was applied to lysimeters with a manual vacuum pump immediately after rainfall events. Soil solution extracted by lysimeters was collected three days after tension application, and samples were stored in 50 mL glass vials previously washed with cleaning solution (0.0125 mol L^{-1} HCl) and dried in a laboratory oven at 105°C for 24 h. Between samplings, vacuum pump tubes were cleaned with cleaning solution and distilled water to avoid contamination of soil solution samples. Vials containing soil solution samples were stored in polystyrene boxes and maintained under refrigeration until laboratory analysis. Nitrate content was determined by the distillation method with a semi-micro-Kjeldahl procedure [28].

2.4. Data Analyses. Statistical analysis for physical properties and nitrate concentrations in soil solution, evaluated in different positions and soil uses, consisted of orthogonal contrasts using the SAS [29]. The contrasts were set up between different soil use conditions (tobacco × grassland; tobacco × forest), landscape positions (upper slope × mid slope; upper slope × lower slope; upper slope × plateau), and time of soil solution collection (60 DAT × 78 DAT, 60 DAT × 89 DAT, 60 DAT × 117 DAT, 60 DAT × 131 DAT, 60 DAT × 138 DAT, and 60 DAT × 145 DAT).

3. Results

3.1. Soil Physical and Hydraulic Characterization. Soils at collection sites are pedogenetically young and have large amount of coarse fractions (gravel and pebbles) (Table 1). Clay contents are higher in lower and flatter landscape positions, where soils are more developed and less eroded and are with sediment deposition.

Soils have low bulk density and high total soil porosity, macroporosity, and saturated hydraulic conductivity (Table 2). Because of conventional soil tillage, surface soil layer has significantly lower density and higher porosity when compared to native fields. Mean values of soil bulk density, total porosity, macroporosity, and microporosity

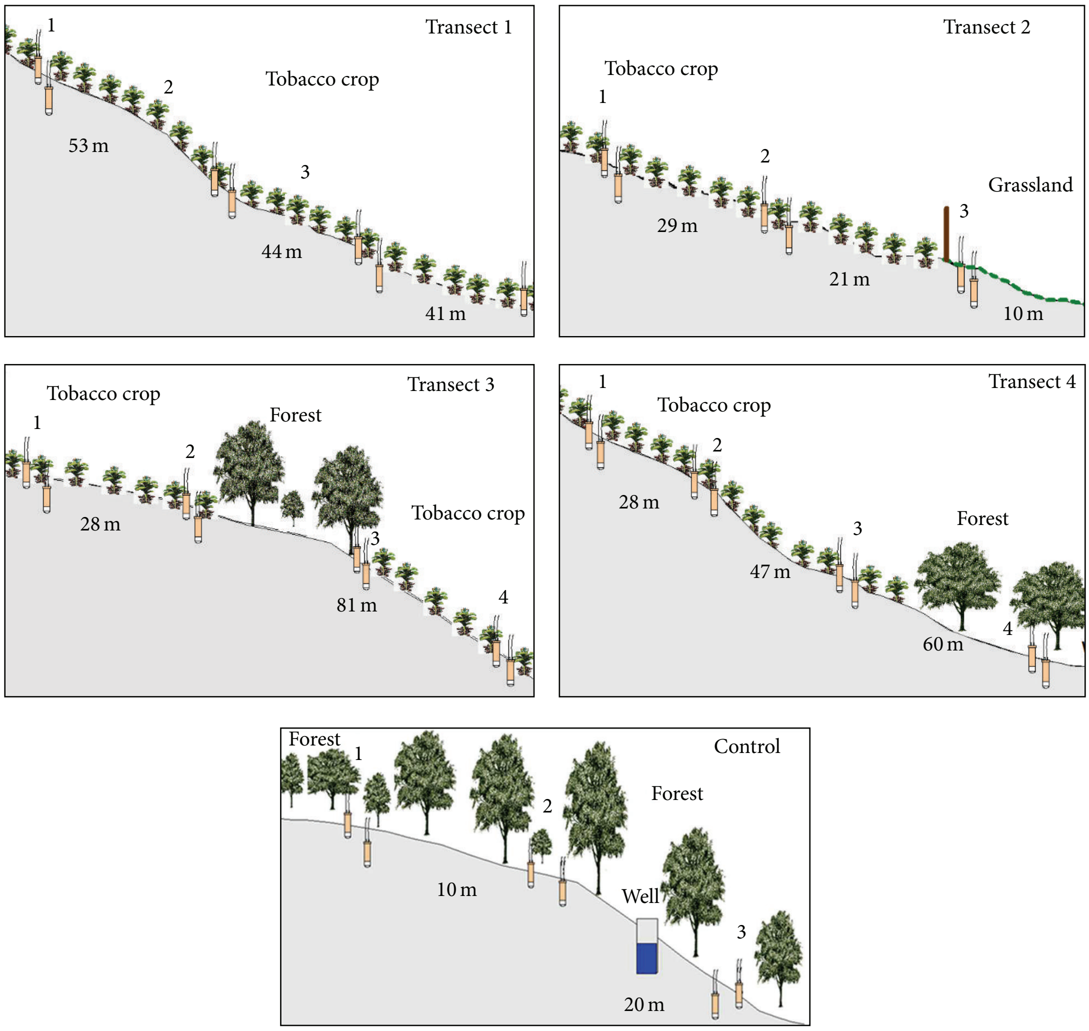

Figure 2: Distribution of collection points for transects with different soil uses. Points indicate lysimeters in transects along the landscape.

were, respectively, 1.18 Mg m^{-3}, 0.56 m^3 m^{-3}, 0.20 m^3 m^{-3}, and 0.36 m^3 m^{-3}. These conditions are favorable to soil water flow and may contribute to increased nitrate leaching. Saturated hydraulic conductivity (Ks) varied greatly among soil layers and collection sites from different landscape positions (from 47 to 609 mm h^{-1} and 298 mm h^{-1} the average value; Table 2). These values are considered high [30], mainly because of the coarse granulometry [31, 32], and indicate that under saturated soil conditions water flow is fast and favors groundwater contamination.

3.2. Rainfall. Rainfall was frequent and well distributed during the tobacco crop cycle (Figure 3). During the study period, total rainfall was 1079 mm, but in the first 380 mm of rain, nitrate losses were not monitored.

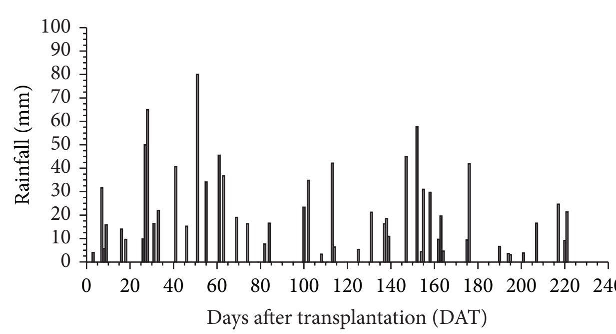

Figure 3: Rainfall during tobacco crop cycle.

3.3. Nitrate Contents in Soil Solution from Natural Environment. Nitrate concentration in soil solution from native environment (grassland and forest) was low when compared to values found within tobacco crops, even if organic matter contents are higher (Table 3).

3.4. Nitrate Contents in Soil Solution from Tobacco Crops. Nitrate concentration in tobacco crops soil solution varied with landscape position, depth, and period of collection.

Table 1: Particle-size distribution in soil surface layer at sampling points, for five transects and different points in the watershed.

Transect	Position/use*	Soil layer (m)	Pebbles	Gravel	Sand	Silt	Clay
					$g\,kg^{-1}$		
1	1, tobacco	0.0–0.2	470	87	177	196	70
		0.2–0.4	292	190	152	247	119
1	2, tobacco	0.0–0.2	272	91	259	292	85
		0.2–0.4	317	58	270	261	95
1	3, tobacco	0.0–0.2	299	20	313	259	109
		0.2–0.4	336	96	247	224	97
1	4, tobacco	0.0–0.2	241	86	260	309	103
		0.2–0.4	543	0	186	203	68
2	1, tobacco	0.0–0.2	152	0	308	314	226
		0.2–0.4	141	0	279	230	350
2	2, tobacco	0.0–0.2	119	0	415	292	175
		0.2–0.4	143	0	345	316	196
2	3, forest	0.0–0.2	383	251	164	149	55
3	1, tobacco	0.0–0.2	148	100	313	360	81
		0.2–0.4	437	90	238	169	65
3	2, tobacco	0.0–0.2	204	65	314	315	102
		0.2–0.4	51	0	358	434	156
3	3, grassland	0.0–0.2	122	86	404	297	90
		0.2–0.4	75	0	453	358	114
3	4, grassland	0.0–0.2	151	273	294	223	59
4	1, tobacco	0.0–0.2	294	0	397	187	122
		0.2–0.4	151	231	352	156	109
4	2, tobacco	0.0–0.2	249	101	362	183	104
		0.2–0.4	156	130	362	212	139
4	3, tobacco	0.0–0.2	253	395	121	146	83
		0.2–0.4	176	302	220	191	110

Pebbles (>20 mm), gravel (2–20 mm), sand (2–0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm). *Position: 1: upper slope, 2: mid slope, 3: lower slope, and 4: plateau.

The flatter areas in the landscape (Table 3, point 4) had higher nitrate concentration in soil solution (Table 4) when compared to higher and steeper positions in the landscape (Table 3, point 1).

Tobacco crops presented the largest nitrate contents predominantly from applied nitrogen fertilizers. When comparing different depths (0.20 and 0.50 m), nitrate concentrations were similar, although these concentrations tended to decrease over time, with the highest value immediately after fertilization.

3.5. Nitrate Contents from Sources Used for Human Consumption. Nitrate concentration in water from domestic wells varied over the monitored period (Figure 4). The water source located in native forest without neighboring tobacco crops (control well) presented the lowest nitrate concentration (Table 3; 2.6 $mg\,L^{-1}$ of N-NO_3^-), whereas in water well nearby a tobacco field in higher position nitrate concentration reached critical levels, varying from 8.5 to 12.8 $mg\,L^{-1}$, almost always considered improper for human consumption in four different collection dates.

4. Discussion

Soil heterogeneity [33] and coarse granulometry [30] induced great variability in soil saturated hydraulic conductivity (Ks) among different monitored landscape positions and soil layers (Table 2). High soil porosity and saturated hydraulic conductivity benefit water infiltration, creating an environment favorable to solute transport into groundwater. Furthermore, soil surface is very stony, contributing to runoff reduction and water infiltration increase [30, 34].

In natural environments, plant biomass and soil organic matter store large amounts of organic nitrogen. However, nitrate concentrations in soil solution from natural environments (grassland and forest) are low, below 2 $mg\,L^{-1}$ of N-NO_3^- [35], mainly due to synchronicity between nitrogen mineralization and plant absorption or immobilization by microorganisms.

Ecosystem dynamics for nitrogen is extremely complex. Slash-and-burn of native vegetation frequently used in tobacco crops leads to rapid decline in soil organic matter (low resistance). During fallow period, fast revegetation occurs because of high nutrient availability, including

Table 2: Bulk density (Bd), total porosity (Tp), macroporosity (Ma), microporosity (Mi), and saturated hydraulic conductivity (Ks) of soil for five transects and different points in the watershed.

Transect	Position/use**	Soil layer (m)	Bd $Mg\,m^{-3}$	Tp	Ma $m^3\,m^{-3}$	Mi	Ks $mm\,h^{-1}$
1	1, tobacco	0.0-0.1	1.01	0.65	0.33	0.32	482
		0.1-0.2	1.04	0.60	0.27	0.33	201
		0.2-0.3	0.92	0.59	0.30	0.29	209
		0.3-0.4	1.23	0.57	0.19	0.38	—*
1	2, tobacco	0.0-0.1	1.11	0.38	0.13	0.25	316
		0.1-0.2	1.23	0.56	0.19	0.36	461
		0.2-0.3	1.15	0.58	0.21	0.36	183
		0.3-0.4	1.19	0.56	0.20	0.36	148
1	3, tobacco	0.0-0.1	1.06	0.61	0.28	0.33	429
		0.1-0.2	1.19	0.58	0.22	0.36	449
		0.2-0.3	1.16	0.61	0.21	0.40	171
1	4, tobacco	0.0-0.1	1.22	0.57	0.14	0.43	151
		0.1-0.2	1.16	0.57	0.14	0.42	94
		0.2-0.3	1.07	0.57	0.15	0.42	315
2	1, tobacco	0.0-0.1	0.97	0.64	0.33	0.31	375
		0.1-0.2	1.33	0.58	0.25	0.34	138
		0.2-0.3	1.27	0.53	0.12	0.41	137
		0.3-0.4	1.14	0.65	0.09	0.56	554
2	2, tobacco	0.0-0.1	1.32	0.53	0.12	0.41	201
		0.1-0.2	1.26	0.53	0.15	0.38	215
		0.2-0.3	1.11	0.55	0.21	0.34	345
2	3, forest	0.0-0.1	1.02	0.53	0.29	0.24	609
		0.1-0.2	1.08	0.55	0.26	0.29	510
		0.2-0.3	1.11	0.54	0.26	0.29	564
		0.3-0.4	1.12	0.56	0.27	0.28	—*
3	1, forest	0.0-0.1	1.14	0.58	0.17	0.42	138
		0.1-0.2	1.10	0.59	0.20	0.39	130
		0.2-0.3	1.31	0.56	0.11	0.45	104
		0.3-0.4	1.15	0.59	0.17	0.41	362
3	2, forest	0.0-0.1	1.06	0.63	0.26	0.37	321
		0.1-0.2	1.16	0.61	0.19	0.42	103
		0.2-0.3	1.26	0.54	0.10	0.44	197
		0.3-0.4	1.10	0.63	0.17	0.46	378
3	3, grassland	0.0-0.1	1.31	0.54	0.11	0.42	113
		0.1-0.2	1.31	0.57	0.16	0.41	95
		0.2-0.3	1.26	0.55	0.14	0.41	54
		0.3-0.4	1.42	0.50	0.12	0.38	112
3	4, grassland	0.0-0.1	1.21	0.56	0.09	0.47	176
		0.1-0.2	1.35	0.53	0.16	0.37	336
		0.2-0.3	1.34	0.53	0.15	0.38	47
4	1, tobacco	0.0-0.1	1.19	0.55	0.25	0.30	585
		0.1-0.2	1.08	0.55	0.26	0.29	463
		0.2-0.3	1.11	0.54	0.26	0.29	452
		0.3-0.4	1.12	0.56	0.27	0.28	451
4	2, tobacco	0.0-0.1	1.11	0.52	0.27	0.26	374
		0.1-0.2	1.18	0.51	0.27	0.25	490
		0.2-0.3	1.24	0.52	0.24	0.28	389
4	3, tobacco	0.0-0.1	1.16	0.53	0.26	0.27	447
		0.1-0.2	1.30	0.50	0.19	0.31	142
		0.2-0.3	1.23	0.51	0.24	0.27	427
		0.3-0.4	1.45	0.43	0.14	0.28	435
Mean			1.18	0.56	0.20	0.36	298

*Not possible to measure due to very coarse texture. **Points: 1: upper slope, 2: mid slope, 3: lower slope, and 4: plateau.

Table 3: Nitrate concentration in soil solution under different conditions of land uses and landscape positions in the watershed.

Transect	Position/use	Depth (m)	November 10, 2005	November 28, 2005	December 9, 2005	January 6, 2006	January 20, 2006	January 27, 206	February 10, 2006	Mean
			Date of collection N-NO_3^- (mg L^{-1})							
1	1, tobacco	0.2	0*	0	4.3	0	10.3	9.8	14.2	5.5
		0.5	19.0	0	4.8	0	8.7	5.3	21.0	8.4
1	2, tobacco	0.2	11.9	0	0	9.8	11.8	11.8	28.1	10.5
		0.5	56.1	0	0	0	0	5.1	0	8.7
1	3, tobacco	0.2	31.8	0	1.5	3.6	16.0	19	32.8	15.0
		0.5	28.9	0	1.6	0	13.8	15.1	0	8.5
1	4, tobacco	0.2	0	0	0	0	36.4	40.1	15.9	13.2
		0.5	79.9	37.6	2.0	4.4	19	24.2	18.5	26.5
2	1, tobacco	0.2	33.7	0	5.6	13.0	7.2	9.2	0	9.8
		0.5	0	0	0	0	0	21.5	0	3.1
2	2, tobacco	0.2	43.7	0	0	0	0	0	0	6.2
		0.5	52.8	17.6	4.7	0	33.3	0	0	15.5
2	4, tobacco	0.2	158.4	4.8	4.1	0	0	0	23.8	27.3
		0.5	52.0	0	19.5	0	26.2	27	30.0	22.1
3	1, tobacco	0.2	0	0	0	0	14.5	17.6	0	4.6
		0.5	0	0	0	0	0	10.9	0	1.6
3	2, tobacco	0.2	71.2	0	3.2	0	5.1	14.3	16.4	15.7
		0.5	19.5	0	0	0	0	13.5	23.5	8.1
4	1, tobacco	0.2	17.1	6.4	2.3	2.9	8.3	1.2	1.0	5.6
		0.5	0	7.0	4.2	0	29.8	31.6	2.3	10.7
4	2, tobacco	0.2	29.5	11.3	3.7	0	3.8	4.9	2.6	8.0
		0.5	39.5	0	3.3	0	6.5	7.8	1.0	8.3
4	3, tobacco	0.2	0.0	11.7	10.8	13.1	10.2	11.2	13.2	10.0
		0.5	24.2	17.8	6.3	0	1.8	9.3	6.6	9.4
	Mean		32.1	4.8	3.4	2.0	10.9	12.9	10.5	**10.9**
3	3, grassland	0.2	7.3	0.9	0	0	0	0	0	1.2
		0.5	0.0	0	0	0	0	0	0	0.0
3	4, grassland	0.2	0.4	0	0.3	0	0	0.1	0	0.1
		0.5	0.0	1.6	1.1	4.8	4.9	3.1	3.5	2.7
	Mean		1.9	0.6	0.4	1.2	1.2	0.8	0.9	**1.0**
2	3, forest	0.2	0	0	0	0	0	0	0	0.0
		0.5	39.1	0	24.8	0	0	1.3	0	9.3
4	4, forest	0.2	7.5	7.6	6.7	8.5	10.8	11.5	9.7	8.9
		0.5	8.4	9.3	9.2	10.0	9.8	10.9	11.0	9.8
5	1, forest	0.2	9.3	21.1	16.5	0	1.7	0	0	6.9
		0.5	0	0	0	0	0	0	0	0.0
5	2, forest	0.2	4.3	27.6	14.1	0	2.5	0	1.0	7.1
		0.5	25.8	0	15.4	0	4.0	0.7	0	6.6
5	3, forest	0.2	8.1	2.8	0	0	2.0	0.7	1.0	2.1
		0.5	0	2.5	2.6	0	0	0.1	1.0	0.9
	Mean		10.3	7.1	8.9	1.9	3.1	2.5	2.4	**5.7**

*The periods without data represent dates when it was not possible to collect the soil solution due to low soil moisture at these points. Position: 1: upper slope, 2: mid slope, 3: lower slope, and 4: plateau.

Table 4: Orthogonal contrasts for nitrate concentrations in soil solutions between different positions in landscape, between collection times, and between land uses.

Contrast	Depth (m) 0.2	0.5
Positions in the landscape		
1 × 2	ns	ns
1 × 3	ns	ns
1 × 4	*	**
Land use		
Tobacco × grassland	ns	*
Tobacco × forest	ns	ns
Collection periods		
1 × 2	*	*
1 × 3	*	*
1 × 4	*	*
1 × 5	*	*
1 × 6	*	*
1 × 7	*	*

*5% significant; **1% significant; ns: nonsignificant. Collection periods: 1 = November 10, 2005 (60 days after transplanting (DAT)); 2 = November 28, 2005 (78 DAT); 3 = December 09, 2005 (89 DAT); 4 = January 06, 2006 (117 DAT); 5 = January 20, 2006 (131 DAT); 6 = January 27, 2006 (138 DAT); and 7 = February 10, 2006 (145 DAT). Position in the landscape: 1: upper slope, 2: mid slope, 3: lower slope, and 4: plateau.

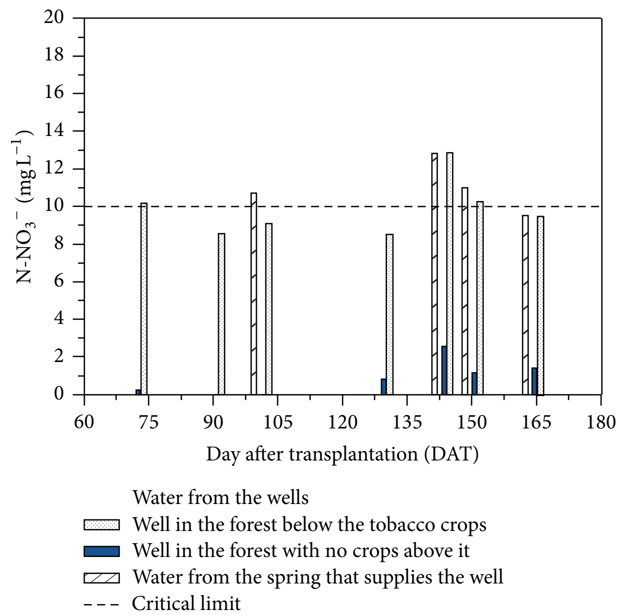

Figure 4: Nitrate concentration in water from the sources used for domestic supply.

nitrogen. This "new organic matter" has higher nitrogen content, which helps in explaining high $N\text{-}NO_3^-$ measured in revegetated forest and grassland (mean values of 7.2 mg L^{-1}).

Nitrate concentration in soil solution from tobacco fields was higher than in natural environment but lower than values found immediately after tobacco transplanting when nitrate concentration rises above 100 mg L^{-1} [27]. Soil solution collected with lysimeters represents the fraction retained by soil after rainfall, since tension application is only possible under high soil moisture conditions [36]. Preferential flow via soil fissures and pores that are common in soils with coarse fractions [37] is ignored. The lysimeters were installed in sites where soil had favorable conditions and, thus, nitrate concentration data in soil solution presented herein may be underestimated, since soil hydraulic conditions are favorable to fast water drainage, increasing leaching losses.

Nitrate contents found in our study are comparable to concentrations observed for different crops. Oliveira et al. [38] observed loss of 76 kg ha^{-1} due to leaching when 190 kg ha^{-1} of nitrogen was applied in sugarcane. When total nitrogen applied was 803, 1,607, and 2,388 kg ha^{-1} (sewage sludge), average $N\text{-}NO_3^-$ contents in soil solution reached 29 mg L^{-1}, 39 mg L^{-1}, and 85 mg L^{-1}, respectively. The highest concentrations and losses occurred during the first samplings after fertilizer application.

Nitrate leached below root system has limited upward capillarity movement because of the large amount of coarse particles and macropores. Hence, little nitrate at 0.5 m is absorbed by tobacco crops, since rooting system is mainly located in the first 0.2 m layer. Besides, nitrate applied at transplanting and at first topdressing is usually more susceptible to leaching due to plant's low nitrogen demand during this crop phase [9].

Conventional soil tillage maintains low cover during tobacco growth, exposes soil to erosion, and increases soil organic matter decomposition. Additionally, in tobacco crops, plant residues (stems and roots) are very low, inducing the use of greater quantities of mineral fertilizers [39].

Mean nitrogen dose applied in this watershed was 177 kg ha^{-1}. Considering that (i) mean leaf production was 2,114 kg ha^{-1}, (ii) mean root and stem dry mass was 2,358 kg ha^{-1} [40], and (iii) average nitrogen content was 2.6% in leaves [41] and 1.1% in roots and stems [42], it can be estimated that 56 kg ha^{-1} (32%) is exported with leaves and 26 kg ha^{-1} (14%) remains in stems and roots. Therefore, 95 kg ha^{-1} (54%) was not used by tobacco crop and is subject to migration into the aquatic systems, contaminating subsurface water resources [43], or is biotransformed.

Under optimal soil nutrient availability, tobacco crops absorb at most 70 kg ha^{-1} of nitrogen to produce approximately 4,000 kg ha^{-1} of dry leaf mass [9]. In Southern Brazil, 370,830 ha was cultivated to tobacco in 2010/2011 harvest [44], representing a loss of 3.52×10^7 kg of nitrogen. If all this nitrogen reached groundwater, it contaminated 3.52×10^{12} liters of water to 10 mg NO_3^- L^{-1} [15]. This shows the great invisible impact of tobacco farming on groundwater quality. It is worthy to mention that remaining soil nitrogen from previous crops and nitrogen supplied by soil organic matter mineralization were not considered in our estimations, since their contents are extremely low.

Landscape positions where groundwater is present in shallow soils and over solid rock are more prone to nitrate contamination, since leaching occurs by preferential flow in soil fissures. Besides, under these conditions denitrification is diminished by greater amount of oxygen present in drained water [14]. Nitrate contents in groundwater are major indicators of leaching and water contamination [21]. Preferential lateral flows may contaminate domestic water sources [45], as is the case in the Arroio Lino watershed.

Depth to water table is considered a major factor in water contamination [46]. In surface water table, infiltrated water reaches saturated zones faster, thus reducing the possibility of contaminants absorption or biodegradation [18]. To achieve efficient nitrate removal by denitrification, which is optimal in riparian zone, water flow must be slow [47]. Pionke and Lowrance [45] determined denitrification rate of 31 $kg\,ha^{-1}\,year^{-1}$ for a riparian zone, while Nelson et al. [48] quantified nitrate removal capacity value of 120 $kg\,ha^{-1}\,year^{-1}$. Under natural conditions, denitrification varies from 2 to 9% for well-drained soils with organic matter contents of less than 2% [43], as is the case in our watershed.

In our study, leached nitrate in soil profile had already reached surface water table as shown by the high nitrate level in water source below tobacco fields (Figure 4). According to the World Health Organization [14], methemoglobinemia may occur when nitrate ingestion varies from 0.09 to 45 $mg\,kg^{-1}$ of the body weight. Nitrate concentration above 10 $mg\,L^{-1}$ in water is considered critical by regulatory standards [15] and poses risk to human health, particularly to children under six months of age [49, 50].

Since nitrate is essentially originated from agriculture, as long as there are no nearby tobacco plantations, nitrate contents in water sources are usually below 3 $mg\,L^{-1}$, representing noncontaminated groundwater by anthropic activities [14]. Forest nitrate filtering effect was not sufficient to reduce nitrate concentration below acceptable limits, probably due to high water flow, which diminishes water permanence time in the biologically active soil layer [20]. In general, a limiting factor in denitrification in aquifers is the availability of oxidable organic carbon [35], provided population of denitrifiers naturally occurs in groundwater [51].

In tobacco farms in Southern Brazil, percolation due to a coarse soil granulometry along with conventional soil tillage and low crop residues input are the main causes of nitrogen loss. Thus, protecting wells with a brickwork structure is ineffective in reducing water contamination by nitrate, and other alternatives must be sought to reduce the input of mineral fertilizers and to further improve management systems for soil organic nitrogen buildup. It is also important to seek adequate planning of soil use and wells location, to reduce environmental impact in these fragile environments.

Splitting nitrogen dose in tobacco crop is a good alternative to reducing water contamination by nitrate, to avoid having high nitrate concentration in the soil during periods of heavy rainfall. However, timing between the crop nitrogen needs and periods of intense rainfall is hard to be balanced and this enhances the loss of nitrogen in the system and water contamination. Additional alternatives are the adoption of no-tillage systems, use of cover crops and crop rotation, and promoting changes in land use in the watershed, by avoiding tobacco cultivation in areas with shallow and stony soils and leaving these areas under native vegetation or with grasses for grazing in silvopastoral systems. The restoration of riparian forests and the preservation of water wells are also needed in the watershed. This set of associated practices could minimize soil loss and contamination of surface and groundwater with $N\text{-}NO_3^-$.

5. Conclusion

Soil physical and hydrological properties are highly variable at different landscape positions and soil depth. Coarse grain size, high porosity, and saturated hydraulic conductivity of the soil are conditions that favor nitrate losses by leaching. Concentration of nitrate in soil solution from tobacco fields is greater than in natural environment due to high amount and low efficiency of applied nitrogen fertilizers. Nitrogen leaching in tobacco fields contaminates water for human consumption. Large amounts of nitrogen fertilizers applied to tobacco and nitrate contamination of subsurface waters demonstrate the unsustainability of growing tobacco in small farming units on steeps slopes, with stony and shallow soils.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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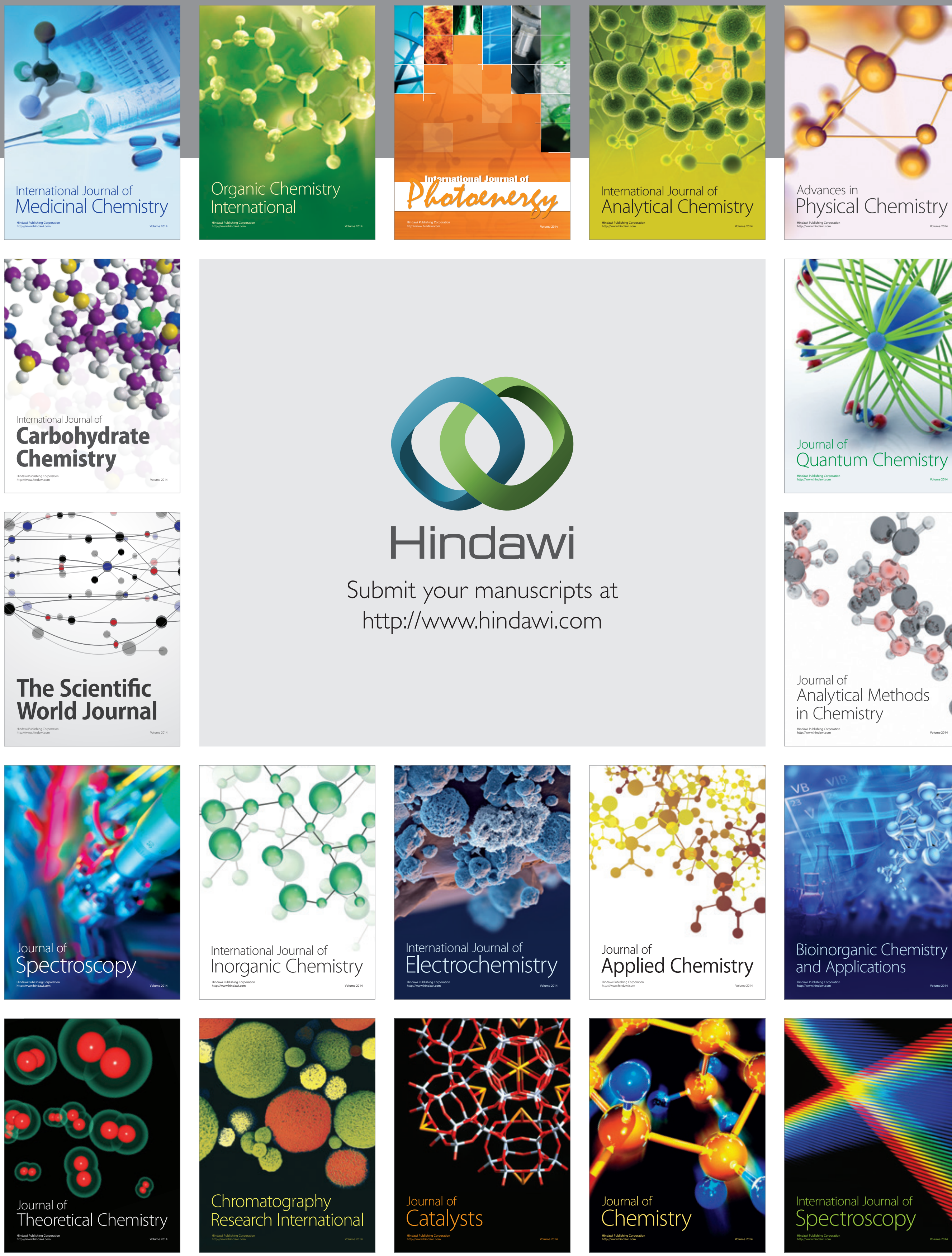
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