Surface runoff pollution by cattle slurry and inorganic fertilizer spreading: chemical oxygen demand, ortho-phosphates, and electrical conductivity levels for different buffer strip lengths

Water Science and Technology: **Vol 44 No1 pp 173–180** © IWA Publishing 2001

A. Núñez-Delgado[†*], E. López-Periago[*], F. Quiroga-Lago[+] and F. Díaz-Fierros Viqueira[*]

[+]Departmento de Edafoloxía e Q. A. (Soil Science and Agricultural Chemistry), E.P.S., Campus Univ. s/n, 27002 Lugo, Spain

[*]Departmento de Edafoloxía e Q. A., Fac. Farmacia, Campus Univ. s/n, 15706 Santiago de Compostela, Spain (E-mail: *edavelin@usc.es*)

Abstract As a way of dealing with the removal of pollutants from farming practices generated wastewater in the EU, we investigate the effect of spreading cattle slurry and inorganic fertiliser on 8×5 m^2 and 8×3 m^2 areas, referred to surface runoff chemical oxygen demand (COD), ortho-phosphates (o-P) and electrical conductivity (EC) levels, and the efficiency of grass buffer strips of various lengths in removing pollutants from runoff.

The experimental plot was a 15% sloped *Lolium perenne* pasture. Surface runoff was generated by means of a rainfall simulator working at 47 mm h^{-1} rainfall intensity. Runoff was sampled by using Gerlach-type troughs situated 2, 4, 6 and 8 m downslope from the amended areas.

During the first rainfall simulation, COD, o-P and EC levels were consistently higher in the slurry zone, more evidently in the larger amended area. During the second and third rainfall simulations, concentration and mass levels show a downslope drift into the buffer zones, with no clear buffer strip length attenuation. Correlation between runoff and mass drift is clearly higher in the slurry zone.

Percentage attenuation in COD and o-P levels, referred to initial slurry concentrations – including rainfall dilution – were higher than 98%, and higher than 90% for EC.

Keywords Buffer strips; cattle slurry; mass drift; nutrient removal; simulated rainfall; surface runoff

Introduction

Wastewater and water pollution management in agriculture is a continuous challenge (Bahri, 1999), and COD, o-P and soluble salts are classical parameters to be aware of in wastes from agroindustries (Germirli *et al*., 1999). To help solving the problem, vegetated buffer strips have been proposed as a means of ameliorating the effects of diffuse source pollution, with relatively good efficiency (Núñez-Delgado *et al*., 1995; Haycock, 1997; Blackwell *et al*., 1999).

Cattle slurry is an organic fertiliser that may cause water pollution episodes, namely non point source pollution from pastures and croplands (Ackerman and Taylor, 1985; Amberger, 1987; Novotny and Olen, 1994). Galicia (NW Spain) is a region where cattle slurry is frequently spread on grasslands and crop fields, with growing risks of reaching problematic European areas farming-derived pollution values (Carballas *et al*., 1990; Díaz-Fierros *et al*., 1990; Díaz-Fierros *et al*., 1993; Núñez-Delgado *et al*., 1998). Our research group has previously performed several studies about cattle slurry characteristics (Díaz-Fierros *et al*., 1987, 1988), however in view of the enhanced risks related to unsuitable management of the organic manure, more recently we have focused on strategies aimed to diminishing diffuse source water pollution values (Núñez-Delgado *et al*., 1995, 1996, 1997a, 1997b).

Here we analyse COD, o-P and EC values in runoff generated in cattle slurry and inorganic fertiliser amended pastures, with buffer strips of different lengths, focusing on slurry/inorganic-fertiliser areas differences and attenuation results.

Methods

An experimental plot was established on a 15% sloped *Lolium perenne* pasture, in Boqueixón (A Coruña, Spain). Different configurations, layouts, fertiliser and pesticide application rates have been previously used in the same plot area (Díaz-Fierros *et al.*, 1990; Basanta *et al.*, 1995; Núñez-Delgado *et al.*, 1997b). The physico-chemical characteristics of the soil are shown in Basanta *et al.* (1995) and Núñez-Delgado *et al.*, (1997b).

In the experimental zone two subplots were marked out. One of them was destined for cattle slurry spreading. The other one received an inorganic N-fertiliser (NH_4NO_3 in solid form), without organic matter and without P. Each subplot consisted of two adjacent areas of 8×8 m^2 and 8×3 m^2. A 5.6 m wide corridor separated the subplots.

To ensure equal N-doses on slurry and fertiliser areas, cattle slurry was spread out at a rate of 341 $m^3\ ha^{-1}$ (a high but frequent value in Galicia) and inorganic fertiliser at 881 kg ha^{-1}. Adjusting the duration of homogeneous applications controlled the slurry dose. N-related results were previously published (Núñez-Delgado *et al.*, 1997b). Cattle slurry and ammonium nitrate were analysed following the protocols of *Standard Methods* (1989, 1998) and Tan (1996). The total N content of the inorganic fertiliser was 21.4% w/w, with 50% nitrate-N and 50% ammonium-N. The cattle slurry was pumped from a settling basin at a local supplier facility. Its basic physico-chemical characteristics were as follows: pH 7.1; EC ($\mu S\ cm^{-1}$) 5300; Cl^- ($mg\ l^{-1}$) 2494; o-P ($mg\ P\ l^{-1}$) 156.5; COD ($mg\ O_2\ l^{-1}$) 17700; Na^+ ($mg\ l^{-1}$) 620; K^+ ($mg\ l^{-1}$) 1695; NH_4^+ ($mg\ l^{-1}$) 606.04; NO_3^- ($mg\ l^{-1}$) 47.99.

Runoff was generated by means of a rainfall simulator according to Núñez-Delgado (1993) and Núñez-Delgado *et al.* (1997b), working at 47 mm h^{-1} rainfall intensity (simulating episodes of rather high rainfall intensity in Galicia), and fed with non-polluted water from a watercourse in the nearby area.

Rainfall events were simulated 1, 7 and 21 days after slurry/fertiliser spreading, affecting both the manured and buffer zones. During each day of rain simulation, moving the rainulator from each subarea to another (subareas A, B, C, and D) covered the whole plot. Runoff samples were collected using Gerlach-type troughs situated 2, 4, 6, and 8 m downslope from the end of the amended subplots.

Runoff samples were analysed for COD, o-P, and EC levels, according to Olsen and Sommers (1982), and *Standard Methods* (1989, 1998).

Results and discussion

Simulated rainfall depths (mm) in the three rainfall events were as follows: a) subarea-A: 23.5, 43.1, and 45.4 respectively; b) subarea-B: 39.2, 45.4, and 40.0; c) subarea-C: 53.3, 62.7, and 92.4; and d) subarea-D: 65.0, 78.3, and 69.7 respectively. For each subarea, simulated rainfall was maintained to allow sampling of runoff volumes enough to be analysed, giving different amounts of rainfall. There were no natural rainfall events during the study period.

Table 1 shows runoff percentages on the 4 different subareas, for the 4 different buffer lengths, and for the 3 rainfall events. Also shown are average runoff percentages for the slurry area and the inorganic fertiliser area, at different filter lengths and for the 3 rainfall events. During the first rainfall event, percentage runoff was consistently higher in the slurry area, probably resulting of partial soil pore blockage caused by the organic fertiliser (as described by Barrington and Madramootoo, 1989; Núñez-Delgado, 1993; Núñez-Delgado *et al.*, 1997b), and facilitated by partial soil pore saturation due to the liquid fraction of the slurry (tensiometer readings indicated that pre-rain soil humidity was higher in the slurry zone than in the inorganic fertiliser area). During the second and third rainfall events, runoff percentages show more similar values between slurry and inorganic fertiliser areas, except those referred to 8 m buffer strip length. Microtopographic irregularities increased

Table 1 Percentage runoff (average and individual values for the various slurry and inorganic fertiliser subareas) during the three rainfall simulations

	Slurry area			Fertiliser area		
	Subarea-A	Subarea-B	Average	Subarea-C	Subarea-D	Average
First rainfall event: buffer strip length						
2 m	3.28	1.38	2.33	0.77	0.18	0.48
4 m	2.06	0.49	1.27	0.06	0.03	0.04
6 m	0.33	4.23	2.28	0.07	0.09	0.08
8 m	13.83	0.28	7.06	0.13	0.07	0.10
Second rainfall event: buffer strip length						
2 m	0.46	0.26	0.36	0.19	0.33	0.26
4 m	0.37	2.11	1.24	0.29	0.01	0.15
6 m	0.09	0.90	0.49	0.05	0.13	0.09
8 m	28.51	0.55	14.53	0.06	0.19	0.13
Third rainfall event: buffer strip length						
2 m	0.45	0.90	0.68	0.26	0.10	0.18
4 m	0.11	1.73	0.92	0.08	0.21	0.15
6 m	0.08	0.18	0.13	0.01	0.19	0.10
8 m	10.99	0.04	5.52	0.08	0.09	0.09

runoff flow at this sampling point. Average runoff values also show the slurry influence during the first rainfall event, and the high runoff percentage maintained during the second and third rainfall event 8 m below the amended slurry area. Tensiometer readings indicated that pre-rain soil humidity was once again higher in the slurry zone during the second rainfall simulation, but lower during the third. Furthermore, the amounts of simulated rain falling on each subarea were always higher in the inorganic fertiliser zone (due to the need for all sampling points reaching runoff volumes high enough to be analysed) nevertheless the runoff percentages were always higher in the slurry zone, even when its soil pre-rain humidity was lower than that in the inorganic fertiliser area (during the third simulation). These events suggest that – as indicated – soil pore blockage and microtopographic irregularities are the major key factors to explain the runoff percentage differences between the slurry and inorganic fertiliser areas, rather than soil pre-rain humidity and rainfall amounts variability.

Table 2 shows timecourse of COD levels in runoff for both slurry and inorganic fertiliser zones, and average COD concentration values and mass in runoff for the various filter strip lengths during the three rainfall simulations. As expected, during the first rainfall event the subarea-A (slurry zone) shows the highest COD concentration levels, probably due to its amended area being higher than that of the also slurried subarea-B. Also showed are decreasing concentration values as a function of buffer strip length. COD levels in runoff from the slurry-amended subarea-B are only slightly higher than those in the fertiliser area, indicating that the organic matter transport is not so pronounced in this slurry subarea. During the second rainfall event, subarea-A and subarea-B concentration levels in runoff show the downslope drift of organic matter into the buffer zones, showing distance-related increasing values. This drift was previously detected in other experiments carried out in the same plot (Diaz-Fierros *et al.*, 1990; Núñez-Delgado *et al.*, 1997b) and by other authors (Magette *et al.*, 1986). The fertiliser area shows a high COD value 2 m downslope from the amended zone, probably due to vegetation-derived organic matter. During the third rainfall event, the slurry area continues to show the progressive downslope drift of organic matter. The fertiliser area maintains high COD concentrations in runoff. Concerning the mass, during the first rainfall simulation the slurry area shows a downslope drift, clearly increased in

Table 2 COD concentrations in runoff (mg O_2 l^{-1}) during the three rainfall simulations, and average concentration values and mass (mg)

	Slurry area				Fertiliser area			
	Subarea-A	**Subarea-B**	**Average**	**mg**	**Subarea-C**	**Subarea-D**	**Average**	**mg**
First rainfall event:								
buffer strip length								
2 m	177.01	38.48	108	354	30.78	7.70	19	25
4 m	177.01	7.70	92	186	15.39	7.70	12	2
6 m	146.22	69.26	108	656	23.09	0.00	12	4
8 m	115.44	23.09	69	927	38.48	34.48	38	17
Second rainfall event:								
buffer strip length								
2 m	23.09	46.18	35	28	69.26	0.00	35	32
4 m	30.78	61.57	46	154	7.70	0.00	4	2
6 m	53.87	76.96	65	101	7.70	0.00	4	2
8 m	153.92	46.18	100	5013	0.00	0.00	0	0
Third rainfall event:								
buffer strip length								
2 m	0.00	0.00	0	0	22.38	67.14	45	35
4 m	0.00	0.00	0	0	67.14	29.84	48	32
6 m	29.31	14.66	22	8	22.38	22.38	22	11
8 m	43.97	16.66	29	59	44.76	22.38	34	17

the second event and maintained during the third (but with minor mass values). Except for the third rainfall simulation, mass values in the fertiliser area are clearly lower than those in the slurry zone and for the former which do not confirm the downslope drift.

Table 3 shows timecourse of o-P concentration values in runoff for the three rainfall simulations, and average o-P concentration levels and mass. During the first rainfall event, o-P concentrations show the highest values in the slurry subarea-A, and also decreasing values as a function of buffer strip length. Subarea-B shows lower values (probably due to its smaller amended area), but clearly higher than those in the fertiliser zone (in fact, this inorganic fertiliser did not contain P). Whereas for COD, during the second and third rainfall events the slurry-area concentration values show a downslope drift into the buffer zone. The fertiliser zone generally shows lower o-P concentrations in runoff. A similar behaviour was been found for the slurry area mass levels which also show a downslope drift into the buffer zone. Fertiliser area mass levels are generally low.

Table 4 shows the timecourse of EC levels in runoff for the three rainfall simulations, and also average EC levels and the result of multiplying EC levels with runoff volume (litres). During the first rainfall simulation, slurry area shows runoff EC values clearly higher than those found in the fertiliser-amended zone. As with COD and o-P, it is especially consistent for the subarea-A, due to its bigger amended area. Buffer strip length attenuation effect is not very clear. During the second and third rainfall simulations, EC values in the slurry area show the same reported downslope drift into the buffer zone. In the fertiliser area, EC values become more similar to that in the slurry area. Similarly to mass behaviour for COD and o-P, the slurry area [EC-values * Runoff-volumes] shows a soluble salts downslope drift into the buffer zone. In the fertiliser-amended area, the obtained values are clearly lower.

Table 5 shows Pearson's correlation coefficients between percentage runoff and mass (or "EC-levels * runoff-volumes" products) transported to each sampling point for the 3 rainfall simulations. R-values are always higher in the slurry area, showing a deeper relation between runoff volumes and mass transport in this zone. During the second and third rainfall simulations correlations are clearly poorer in the fertiliser area. These results indicate that slurry spreading is more liable of causing runoff pollution than inorganic fertilisers like the one evaluated here.

Table 3 Concentration values in runoff for o-P (mg P l^{-1}) in the slurry and fertiliser areas during the three rainfall simulations, and average concentration values and mass (mg)

	Slurry area				Fertiliser area			
	Subarea-A	**Subarea-B**	**Average**	**mg**	**Subarea-C**	**Subarea-D**	**Average**	**mg**
First rainfall event:								
buffer strip length								
2 m	3.17	0.75	1.96	6.42	0.07	0.08	0.08	0.10
4 m	3.00	0.24	1.62	3.28	0.02	0.19	0.11	0.02
6 m	2.50	0.73	1.61	9.78	0.08	0.05	0.07	0.02
8 m	2.44	0.12	1.28	17.20	0.06	0.18	0.12	0.05
Second rainfall event:								
buffer strip length								
2 m	0.11	0.10	0.11	0.08	0.19	0.14	0.17	0.15
4 m	0.21	0.15	0.18	0.60	0.04	0.21	0.13	0.07
6 m	0.32	0.15	0.24	0.37	0.06	0.02	0.04	0.02
8 m	0.65	0.04	0.34	17.04	0.07	0.01	0.04	0.03
Third rainfall event:								
buffer strip length								
2 m	0.08	0.08	0.08	0.11	0.15	0.70	0.42	0.32
4 m	0.30	0.63	0.46	1.03	0.01	0.07	0.04	0.03
6 m	0.36	0.23	0.29	0.11	0.05	0.03	0.04	0.02
8 m	0.25	0.02	0.14	0.28	0.12	0.13	0.13	0.07

Table 4 EC levels in runoff (µS cm^{-1}) in the slurry and fertiliser areas during the three rainfall simulations, and average EC values and "EC-values * Runoff-volumes" obtained (µS cm^{-1} * L)

	Slurry area				Fertiliser area			
	Subarea-A	**Subarea-B**	**Average**	**EC*L**	**Subarea-C**	**Subarea-D**	**Average**	**EC*L**
First rainfall event:								
buffer strip length								
2 m	690	259	474	1552	99	105	102	135
4 m	694	117	405	820	100	127	113	17
6 m	579	392	485	2946	106	114	110	37
8 m	527	132	329	4422	106	138	122	56
Second rainfall event:								
buffer strip length								
2 m	109	102	105	83	112	111	111	103
4 m	111	98	104	348	110	175	142	81
6 m	172	165	168	261	97	114	105	49
8 m	172	95	133	6667	120	94	107	82
Third rainfall event:								
buffer strip length								
2 m	119	113	116	164	137	245	191	147
4 m	184	336	260	580	265	110	187	125
6 m	307	208	257	98	156	151	153	77
8 m	136	116	126	257	170	111	140	77

Table 5 Pearson's correlation coefficients (*r*) between percentage runoff and mass transported to the various distances below amended zones (*Significant for p=0.01)

	Rainfall event		
	1st	**2nd**	**3rd**
Slurry area			
COD	0.997*	0.999*	0.988*
o-P	0.986*	0.999*	0.990*
EC	0.997	0.999*	0.993*
Fertiliser area			
COD	0.941*	0.190	0.546
o-P	0.922*	0.701	0.343
EC	0.986*	0.952*	0.796

Table 6 Attenuation levels (% and concentration ratios) for COD, o-P, and EC below the slurry area during the three rainfall events

	Attenuation (%)			Concentration ratio		
	COD	o-P	EC	COD	o-P	EC
First rainfall event: buffer strip length						
2 m	99.39	98.74	91.06	164	80	11
4 m	99.48	98.96	92.36	192	96	13
6 m	99.39	98.97	90.85	164	97	11
8 m	99.61	99.18	93.79	257	122	16
Second rainfall event: buffer strip length						
2 m	99.80	99.93	98.02	506	1486	50
4 m	99.74	99.88	98.04	385	867	51
6 m	99.63	99.85	96.83	272	664	32
8 m	99.44	99.78	97.49	177	459	40
Third rainfall event: buffer strip length						
2 m	100	99.95	97.81		1950	46
4 m	100	99.71	95.09		339	20
6 m	99.88	99.81	95.15	805	537	21
8 m	99.84	99.91	97.62	610	1156	42

Table 6 above shows: a) average percent attenuation in parameter concentrations (or EC levels) for each sampling distance below the slurry area, referred to initial slurry levels; b) slurry concentration (or EC levels) to runoff samples concentration (or EC values) ratios for each sampling distance below the slurry area. Attenuation values are always higher than 98% for COD and o-P, and higher than 90% for EC. The ratios between slurry concentration and runoff samples concentration show more easily the differences in attenuation for the various strip lengths: the highest the ratio value, the greater the attenuation value. Note that these attenuation results take into account the dilution effect due to the rain falling which generate the surface runoff where those parameters were analysed.

Conclusions

In the experimental plot, where this study was carried out, percentage runoff was consistently higher in the slurry area, but only during the first rainfall simulation, thus suggesting a temporary soil pore blockage caused by the spreading of the organic fertiliser. The overall percentage runoff results, together with the amounts of simulated rainfall, and the pre-rain soil humidity data suggest that soil clogging and microtopographic irregularities are the key factors to explain differences in runoff percentages between the organic and inorganic fertiliser areas.

During the first rainfall event, subarea-A (slurry zone) shows the highest COD, o-P and EC values in runoff, due to its bigger amended area. Furthermore, parameter values in the whole slurry area are clearly higher than those in the inorganic fertiliser zone. During the second and third rainfall events, concentration values in runoff samples from the slurry zone show the downslope drift of organic matter, o-P and soluble salts into the buffer areas.

Since the first rainfall simulation, the slurry area shows a downslope mass drift of pollutants into the buffer zone (clearly increased in the second event) except for the third rainfall simulation, where mass values in the fertiliser area are clearly lower than those in the slurry zone.

In order to fulfil quality guidelines, mass drift into the buffer zones should be considered initially when designing vegetative filter strips to improve removal of pollutants from runoff and wastewater.

Pearson's correlation coefficients between percentage runoff and mass transported to each sampling point were always higher in the slurry zone. In the fertiliser area correlations were clearly lower, especially during the second and third rainfall simulations.

Referred to initial slurry concentration values, attenuation percentages were always higher than 98% for COD and o-P, and higher than 90% for EC, however, buffer strips length effect is not clearly stated. These attenuation results include the rainfall dilution effect.

Comparing the organic and inorganic fertilisers evaluated, the reported results suggest that additional care should be taken when spreading slurries on soils in sloped areas, due to its clogging properties and to its greater probability of runoff transporting pollutants

References

Ackerman, E.O. and Taylor, A.G. (1985). Ten reasons why livestock waste management systems fail. In: *Agricultural Waste Utilization and Management,* Converse J.C. (ed.), A.S.A.E., St. Joseph, pp. 705–711.

Amberger, A. (1987). Utilization of organic wastes and its environmental implications. In: *Agricultural Waste Management and Environmental Protection*, Welte E. and Szablocs I. (eds), vol. 1, C.I.E.C., F.A.R.C., Braunschweig-Voelkenrode, pp. 37–54.

Barrington, S.F. and Madramootoo, C.A. (1989). Investigating seal formation from manure infiltration into soils. *Trans. ASAE*, **32**(3), 851–856.

Basanta, R., Núñez-Delgado, A., López, E., Férnandez, M. and Díaz-Fierros, F. (1995). Measurement of cholinesterase activity inhibition for the detection of organophosphorus and carbamate pesticides in water. *Intern. J. Environ. Studies*, **48**, 211–219.

Bahri, A. (1999). Agricultural reuse of wastewater and global water management. *Wat. Sci. Tech*., **40**(4–5), 339–346.

Blackwell, M.S.A., Hogan, D.V. and Maltby, E. (1999). The use of conventionally and alternatively located buffer zones for the removal of nitrate from diffuse agricultural run-off. *Wat. Sci. Tech*., **39**(12), 157–164.

Carballas, T., Díaz-Fierros, F., Acea, M.J., Cabaneiro, A., Carballas, M., Gil, F., Leiros, M.C., López, E., Núñez-Delgado, A. and Villar, M.C. (1990). *El Purín de Vacuno en Galicia. Caracterización, Poder Fertilizante y Problemas Ambientales [Cattle slurry in Galicia. Characterisation, Fertilising Power and Environmental Problems]* COTOP-Xunta de Galicia, Santiago de Compostela, Spain.

Díaz-Fierros, F., Villar, M.C., Gil, F., Leiros, M.C., Carballas, M. and Carballas, T. (1987). Laboratory study of the availability of nutrients in physical fractions of cattle slurry. *J. Agric. Sci.*, **108**, 353–359.

Díaz-Fierros, F., Villar, M.C., Carballas, M., Leiros, M.C., Carballas, T. and Cabaneiro, A. (1988). Effects of cattle slurry fractions on nitrogen mineralization in soil. *J. Agric. Sci.*, **110**, 419–497.

Díaz-Fierros, F., Núñez-Delgado, A. and López, E. (1990). Risks of water contamination by superficial run-off resulting from the spreading of cattle slurry. In: *Nitrates, Agriculture, Eau*, Calvet R. (ed.), INRA Editions, Paris, pp. 481–486.

Díaz-Fierros, F., Núñez-Delgado, A. and López, E. (1993). *As concas fluviais de Galicia. Características e Riscos de Contaminación Difusa [Galician's Basins. Characteristics and Risks of Diffuse Source Pollution]*. Univ. Santiago, Santiago de Compostela, Spain.

Germirli, F., Çekyay, E., Eremektar, G. and Orhon, D. (1999). Pollution loads and inert COD in the laying chickens industry. *Wat. Sci. Tech*., **40**(1), 207–214.

Haycock, N., Burt, T., Goulding, K. and Pinay, G. (eds.) (1997). *Buffer Zones: their Processes and Potential in Water Protection*. Quest Environmental, Harpenden, UK.

Magette, W.L., Brinsfield, R.B., Palmer, R.E. and Wood, J.D. (1986). *Vegetated filter strips for nonpoint source pollution control*. ASAE Paper No. 86-2024, 16 pp.

Novotny, V. and Olen, H. (1994). *Water Quality. Prevention, Identification and Management of Diffuse Pollution*. VNR, New York, USA.

Núñez-Delgado, A. (1993). *Riesgos de Contaminación de las Aguas Continentales por Aplicación de Purines sobre Praderas en Pendiente [Risks of surface water pollution caused by cattle slurry spreading on sloped pastures*]. Unpublished Ph.D. dissertation. Univ. Santiago. Santiago de Compostela, Spain.

Núñez-Delgado A., López E. and Díaz-Fierros F. (1995). Vegetated filter strips for wastewater purification: a review. *Bioresource Technol.*, **51**, 13–22.

Núñez-Delgado, A., López, E. and Díaz-Fierros, F. (1996). Vertical leaching of contaminants present in cattle slurry: column trials with uncultivated and cultivated soils. *Int. J. Environ. Studies*, **50**, 27–39.

Núñez-Delgado, A., López, E. and Díaz-Fierros, F. (1997a). Breakthrough of inorganic ions present in cattle slurry: soil column trials. *Wat. Res.*, **31**, 2892–2898.

Núñez-Delgado, A., López, E. and Díaz-Fierros, F. (1997b). Effectiveness of buffer strips for attenuation of ammonium and nitrate levels in runoff from pasture amended with cattle slurry or inorganic fertiliser. In: *Buffer Zones: Their Processes and Potential in Water Protection*, Haycock, N.E., Burt, T.P., Goulding, K.W.T. and Pinay, G. (eds.), Quest Environmental, Harpenden, pp. 134–139.

Núñez-Delgado, A., López, E. and Díaz-Fierros, F. (1998). La contaminación difusa y las actividades agropecuarias [Diffuse source pollution and farming activities]. *Rev. Real Acad. Galega Cienc.*, **XVII**, 89–120.

Olsen, S.R. and Sommers, L.E. (1982). Phosphorus. In: *Methods of Soil Analysis. Part 2,* Page A.L., Miller R.H. and Keeney D.R. (eds.), A.S.A. & S.S.S.A. Publisher, Madison, pp. 403–430.

Standard Methods for the Examination of Water and Wastewater. (1989). American Public Health Association/American Water Works Association/Water Environment Federation, Washington D.C., USA.

Standard Methods for the Examination of Water and Wastewater. (1998). American Public Health Association/American Water Works Association/Water Environment Federation, Washington D.C., USA.

Tan, H.K. (1996). *Soil Sampling, Preparation, and Analysis*. Marcel Dekker, Madison, USA.