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THE NATURAL HISTORY OF SLAPTON LEY NATURE RESERVE XIX: A PRELIMINARY STUDY ON THE CONTROL OF NITRATE AND PHOSPHATE POLLUTION IN WETLANDS

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ABSTRACT

Within a context of lake eutrophication control, tracing of water flow through wetlands has been undertaken in (I) a marsh receiving a point-source sewage effluent, (II) an adjacent stream with no vegetation and (III) a reed bed system receiving river flow from an agricultural area with non-point sources. Methods used involved injection of ^{15}N, Lissamine FF dye, chloride, nitrate and phosphate fertiliser. Tracing labelled bodies of water showed that, below the sewage works point source, there was a considerable decrease in nitrate concentrations across the marsh, but an increase in phosphate. In the reed bed, there were decreases in both nitrate and phosphate concentrations. The results of this preliminary survey indicate that, if the marsh is effective in reducing nitrate concentrations from point-source sewage effluent, then wetlands can be used for nitrate control; but source control is necessary for phosphate.

INTRODUCTION

THERE IS considerable interest in the use of wetlands in water quality control, especially where the control of nutrient inputs in effluents or runoff is expensive or unlikely (e.g. Ritter, 1988). However, input- throughput-output studies of wetlands can be difficult unless the quantitative relationship between the input water and the output water is known. Input water bodies may be labelled (e.g. with fluorescent dye) so that their passage through a wetland can be monitored, together with any changes in water quality. The arrival of the labelled water at the output can be identified and any nutrient losses to the wetland estimated.

In management terms, one of the defences for inaction on both the improvement of sewage effluent quality and the reduced use of fertiliser is that wetlands, lying between source areas and any fresh water body beyond, act to retain nutrients, minimising their impact (Watts & Moore, 1987; Reddy & Reddy, 1987; Lowrance, *et al.*, 1984; Peverly, 1982; Howard-Williams, 1981; Leah, *et al.*, 1978). Support for this argument comes from Gilliam, *et al.*, (1979) who demonstrated losses of nitrate by denitrification in agricultural runoff stored in holding ponds before release to streams. These observations support the use of storage ponds but do not, necessarily, indicate nutrient behaviour during the passage of water through wetland. There is also the argument that wetlands have a limited nutrient retention capacity and that there is a finite recycling capability in the system, with any excess nutrients appearing in outflow from the wetland unless the green vegetation is harvested. Recently, Gehrels & Mulamoottil (1989) have suggested that phosphate exports from wetlands may be greater than imports.

If nutrients are retained in wetlands, source control is unnecessary for eutrophication control of lakes with marginal wetlands. If they are not, source control *is* necessary. In order to contribute to this discussion, we used fluorescent dyes to label water bodies and then studied the fate of nitrate, ^{15}N, and phosphate in (I) sewage effluent discharging through a marsh towards a lake, (II) a small stream and (III) agricultural runoff flowing, via a river, into reed beds towards a lake.

Parallel work has been undertaken by Bowmer (1987) and Dunbabin, *et al.* (1988) using bromide and tracer dyes in wetlands. They concluded that nitrogen removal could be susbstantial, though limited by oxygen supply in the rhizosphere. Their work was undertaken in specially constructed 50m trenches. Our work used natural ecosystems and there is thus an additional interest in comparing the results.

FIELD AREA

In Slapton Ley Nature Reserve (South Devon), point sources of nitrate and phosphate from a sewage works, and from agricultural runoff, are causing a freshwater lake, Slapton Ley, to become hypertrophic (Heathwaite & O'Sullivan, 1989; Johnes & O'Sullivan, 1989). The associated ecological changes, including algal blooms, profuse macrophyte growth and decline in fish and bird populations, are generally seen as undesirable.

The research was conducted at three sites (Figs 1 and 2). The first trace was below the Slapton village, where effluent from a sewage works reaches the Lower Ley through the marshland area of Ireland Bay. The sewage works has been calculated to contribute 20% of the dissolved phosphate-phosphorus load to Slapton Ley (Heathwaite *et al.*, 1989). The second area of interest was the Higher Ley, a wetland consisting largely of reedbed (*Phragmites australis*) through which the River Gara drains to the Lower Ley, which is still an area of open water. The River Gara is the largest feeder river to the Ley, draining about 55% (23 km^2) of the total 46 km^2 basin. This water drains from the input point (Fig. 1) through the Higher Ley which, although mostly covered with reed, has small islands of terrestrial carr vegetation and there is a clearly discernible channel during high discharges. This, then, forms the main input (71% of total annual inflow) to the large (77 ha) fresh water lake of the Lower Ley (Van Vlymen, 1979).

The Gara catchment is intensively farmed, with mixed grass and arable. Freely draining soils (Trudgill, 1983) and steep slopes facilitate high levels of nitrate leaching (Burt *et al.*, 1983). Monitoring of the nitrate-nitrogen levels in streams has shown increases in recent years. In Slapton Wood catchment, the mean annual nitrate-nitrogen concentration has risen from 5.14 mg l^{-1} in 1971 to 8.32 mg l^{-1} in 1985 (Burt *et al.*, 1988).

RESEARCH STRATEGY

Our aim was to establish the extent to which the current vegetation and flow patterns were effective in decreasing the nitrate and phosphate concentrations within identifiable bodies of water. Significant decreases in concentration might indicate that vegetation barriers, or buffer zones, would be a preferable management strategy to attempting control of input concentrations.

The three sites for tracer experiments are shown on Figs 1 and 2: (I) from the sewage works input to the marsh above Ireland Bay. (II) A small stream flowing from Slapton

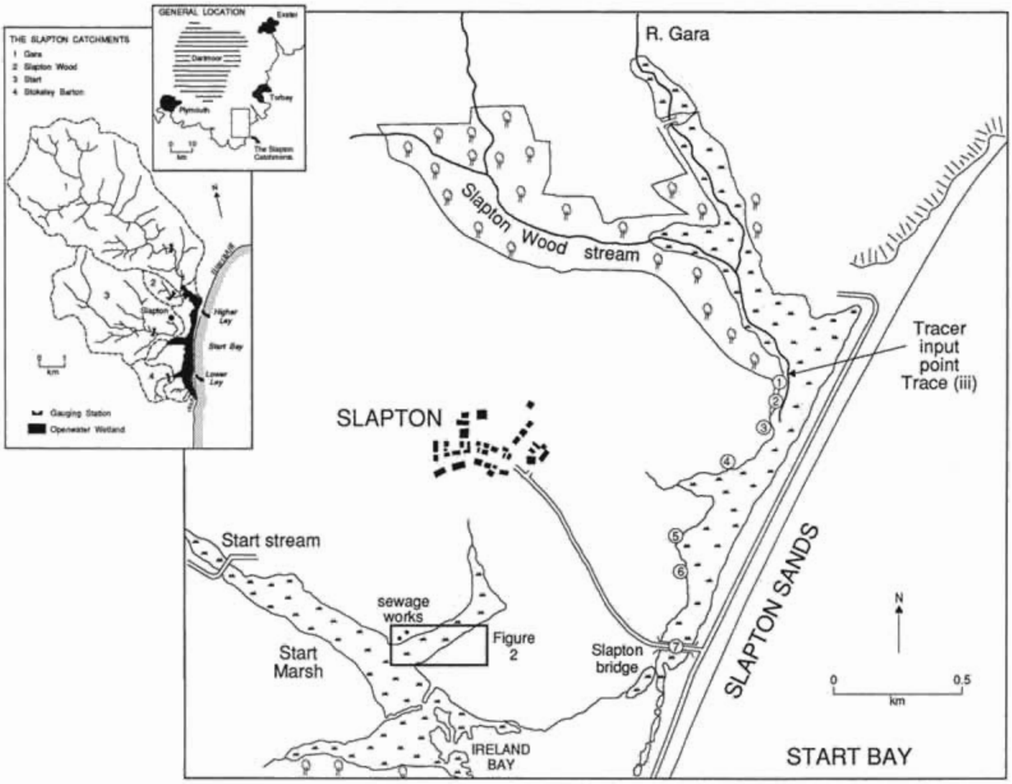

FIG. 1.

Location of the field study area. 1–7 are sampling points in the Higher Ley used during trace (III). Inset for Fig. 2 is location of traces (I) and (II).

village into the same marsh; and (III) from where the River Gara enters the Higher Ley, through the reed beds down to Slapton Bridge. Sampling points were as numbered on the maps.

(I) The marsh receiving sewage

The first trace was taken where the sewage works outfall debouches onto marshland, some 150 m wide, draining to a stream which then enters the Ley. Dye and ^{15}N tracers were injected into the outfall and samples were subsequently taken from standing pools and running water across the marsh.

(II) The marsh receiving stream flow

As a control, a second trace was taken in an adjacent small stream, with approximately the same discharge. This stream forms an open conduit with little vegetation to reduce flow or allow nutrient loss until it reaches the lower part of the same marsh.

(III) The wetland receiving runoff from an agricultural catchment

A third trace involved injections of fertiliser and tracers (Table 1) into the River Gara. Sampling points were in the stream channel (points 1–3 on Fig. 1) and then from the flow at the side of the Ley (4–6) and finally from the Higher Ley outflow at Slapton Bridge (point 7).

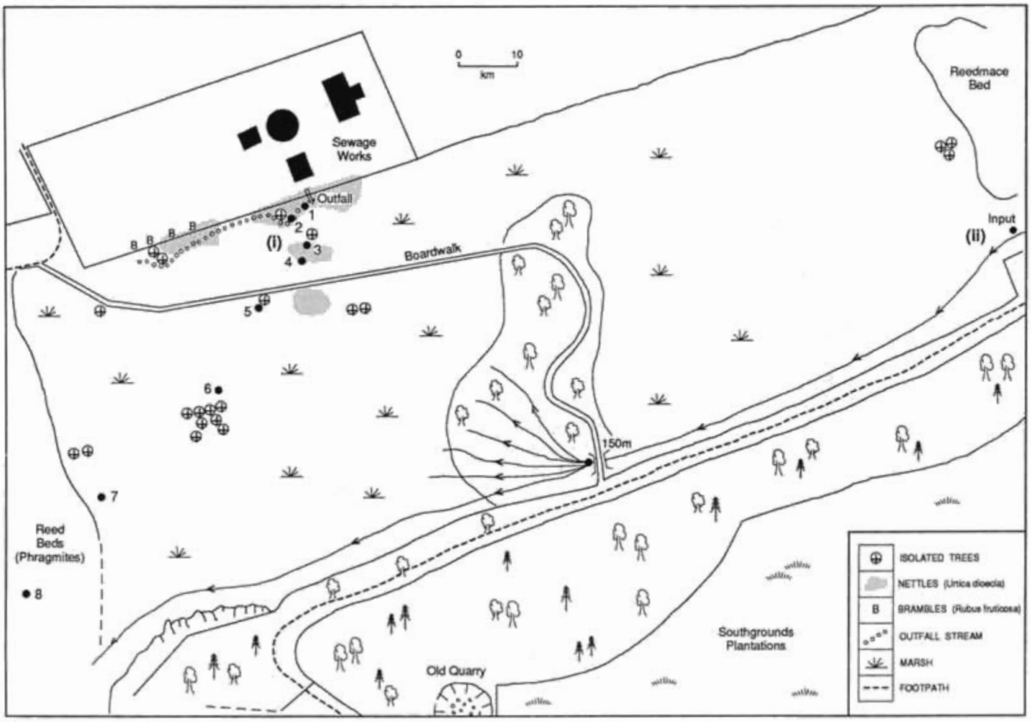

FIG. 2.
Location of traces (I) from sewage works and (II) Slapton Village stream. 1–8 are sampling points for sewage works outfall–marsh trace (I). For trace (II) samples were taken down the reach to the bridge at 150 m.

TABLE 1.
Trace input specifications

(I) SEWAGE WORKS TRACE (Fig. 2). Input time 1308 on 26 April 1988 in sewage outflow.
Lissamine FF – 800 ml of 10 g l^{-1} = 8 g total dye.
chloride – 1,500 g in 4.93 litres = 184,572.11 mg l^{-1}
^{15}N – 0.5 g in 100 ml @ 99% enrichment (of the nitrate-nitrogen in ammonium nitrate)
= 5 g in 1 litre = 5,000 mg l^{-1}

(II) SLAPTON VILLAGE STREAM (Southgrounds Farm to Boardwalk)
Input time 1412 on 26 April 1988. Discharge = 6 l s^{-1}
Total length of trace = 150 m from small bridge to marsh.
Lissamine FF – 800 ml of 10 g l^{-1} = 8 g total dye.
chloride – 1,500 g in 5.1 litres = 178,419.71 mg l^{-1}
^{15}N – 0.5 g in 100 ml @ 99% enrichment (of the nitrate-nitrogen in ammonium nitrate)
= 5 g in 1 litre = 5,000 mg l^{-1}

(III) GARA—HIGHER LEY TRACE, Input time 1230 on 27 April 1988
2 litres of 50 g l^{-1} Lissamine FF = 100 g.
2 × 1.5 kg common salt (sodium chloride) = 187,616.6 mg l^{-1}
1 bag NPK fertiliser mixed as slurry: UKF No.4, 50 kg (110 lb) 15–15–20
Total nitrogen 15%; nitric-nitrogen: 5.57, ammonia-nitrogen: 9.57
Phosphorus pentoxide in ammonium citrate 15%; 6.5% phosphorus
Potassium oxide = 20%: 16.6% potassium

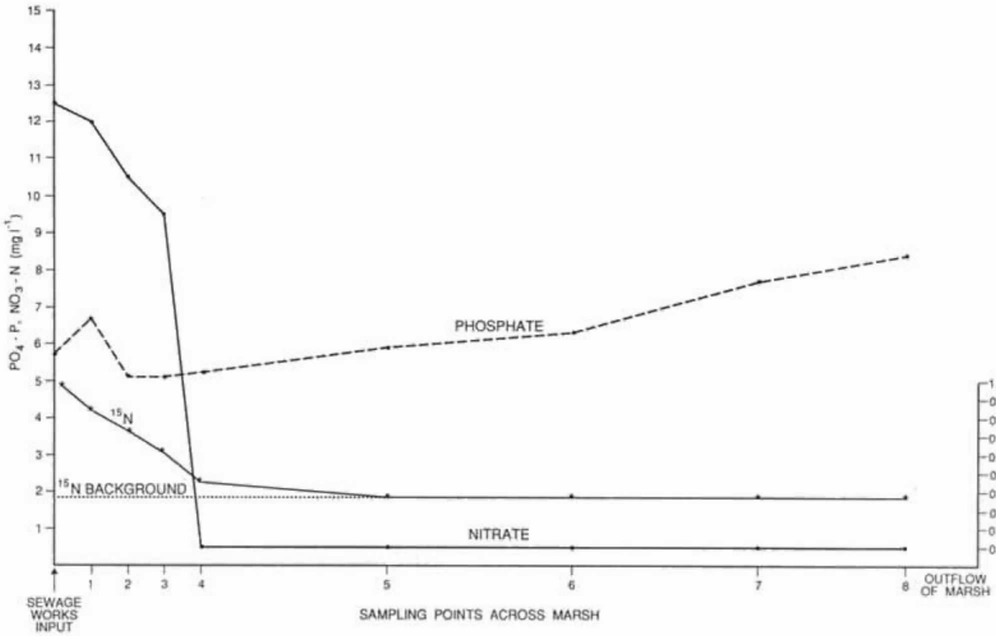

FIG. 3.

Composite diagram of nutrient concentrations across the marsh in trace (I). Data points are for samples with first recorded positive dye detections.

ANALYTICAL METHODS

Tracer inputs are specified in Table 1. Lissamine FF (LFF) dye (Merantine Brilliant Flavine FF) was used for dye tracing, as specified in Trudgill (1987). Dye concentrations were measured using a Spex fluorometer.

Samples were analysed within 10 hours, and mostly within 6 hours, of collection. All were filtered under suction prior to analysis using Whatman GF/C filter paper.

^{15}N analysis was undertaken by Long Ashton Research Station, Bristol, using a mass spectrometer. Nitrate-nitrogen and phosphate-phosphorus concentrations were measured using automated colorimetric versions of the techniques described by Hendriksen & Selmer-Olsen (1970) and Murphy & Riley (1962) on a Chemlab autoanalyser (hydrazine-copper reduction with azo dye and molybdate reaction and with ascorbic acid respectively). Ammonia-nitrogen analysis followed the method of Crooks & Simpson, 1971). Chloride analyses were also undertaken using a Chemlab autoanalyser using a ferric nitrate-mercuric thiocyanate method.

RESULTS

DATA

The data are shown in Figs 3–5 and in Table 2. Locations are numbered on Figs 1 and 2. Figs 3–5 show nitrate nitrogen and phosphate-phosphorus concentrations in the first arrival of positively dyed water.

Trace (I): Sewage works outflow

Lissamine dye proved to be a better tracer than chloride. It was far more detectable, despite inputs of 1,500 g chloride and only 8 g dye. Maximum dye backgrounds were

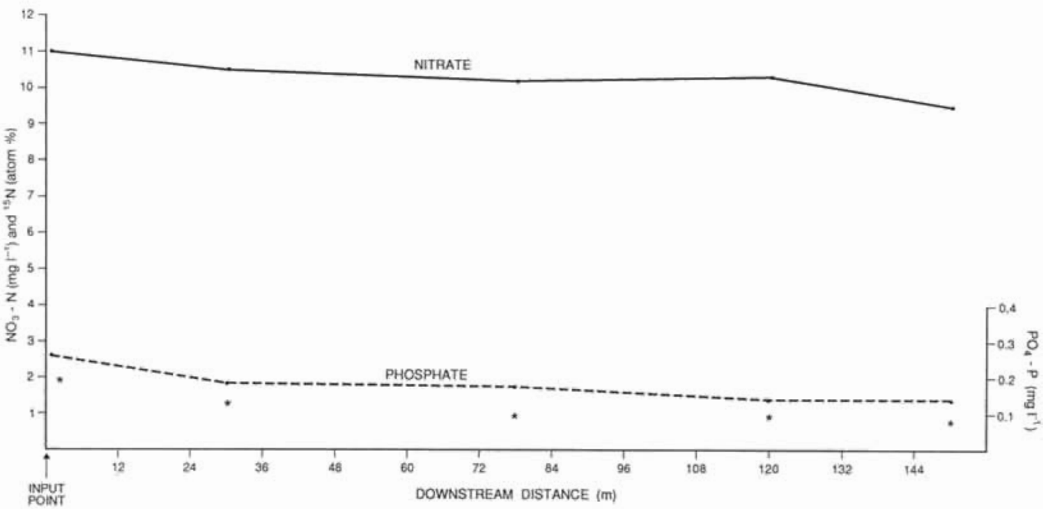

FIG. 4.

Composite diagram of nutrient concentrations downstream during trace (II). Data points are for samples with first recorded positive dye detections. * = ^{15}N (Background 0.38)

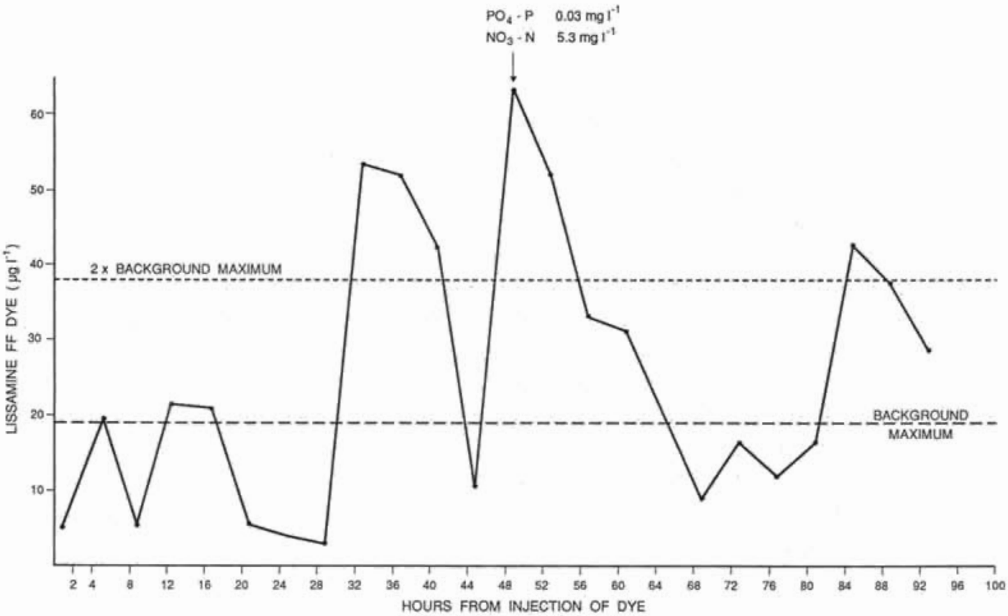

FIG. 5.

Concentrations of Lissamine FF dye at Slapton Bridge (point 7 on Figure 1) during trace (III). Maximum detection peak occurred at 49 hours after input.

6.1 $\mu g\,l^{-1}$ and chloride at 55 $mg\,l^{-1}$. When chloride concentrations were approaching background levels, dye concentrations were still well above them. The use of chloride was thus regarded as unsuccessful. A positive dye trace was taken as twice the background level, to allow for variation in the latter (cf. Trudgill, 1987). The presence of traced input was, therefore, taken to be those samples where dye concentrations were over 12 $\mu g\,l^{-1}$. Dye was detectable above this background level for the whole trace period over much of the marsh. Background data for ^{15}N were consistent at 0.38 atom%.

After two days, the input tracer was found to be present in samples across the marsh. Its presence at the marsh outflow, some 150 m away, shows that the actual input water body had moved to the marsh outflow. The input concentration of nitrate-nitrogen was 12.5 $mg\,l^{-1}$ from the sewage effluent pipe. There was a rapid decline in these concentrations across the marsh, with a drop to 0.5 $mg\,l^{-1}$ within 10 m. Fig. 3 shows the composite set of nitrate data for those samples where the first dye levels were recorded above background.

The ^{15}N data confirm that nitrate decreases rapidly across the marsh; values were down to background levels within 10 m (input 0.92 atom% to 0.38 background). There was also a significant decrease in ammonium-nitrogen, from 1.3 at the sewage works outflow to 0.3 $mg\,l^{-1}$ at the marsh outflow.

Phosphate, however, showed no such drop; indeed input levels of 5.5 $mg\,l^{-1}$ phosphate phosphorus increased across the marsh. Values around 5 and 6 across the marsh, rose to 7 or 8 $mg\,l^{-1}$ towards the outer edge (Fig. 3).

Trace (II): Slapton Stream

Dye concentrations decreased over a 150 m reach from 4,352 $\mu g\,l^{-1}$ Lissamine FF at input, to a downstream maximum of 113 $\mu g\,l^{-1}$. In this water with the maximum dye concentrations, ^{15}N data showed a loss of 68%, with an input of 2.0 atom% and a maximum concentration downstream of 0.64 atom%. Chloride rapidly declined to background before the end of the reach. Nitrate-nitrogen data showed a decrease from 11 $mg\,l^{-1}$ at the start of the reach to 9.5 $mg\,l^{-1}$, a loss of 13.6%. Phosphate had an initial concentration of 0.26, decreasing to 0.138 $mg\,l^{-1}$, a loss of 46.9% (Fig. 4). Ammonia-nitrogen concentrations decreased by 83% from 0.30 to 0.05 $mg\,l^{-1}$.

Trace (III): River Gara—Higher Ley

Input concentrations of dye (peak 5,880 $\mu g\,l^{-1}$) rapidly declined within a few metres but the dye was still detectable at Slapton Bridge, about 1 km from input (Fig. 5). Backgrounds at the start of the trace ranged from 5.4–19.3 $\mu g\,l^{-1}$ at Slapton Bridge. Again, taking the evidence for a positive trace as concentrations exceeding twice the maximum recorded background (38.6), a positive dye recovery was first evident in a sample taken at Slapton Bridge (2200 hrs, 28.4.88, concentration = 53.9 $\mu g\,l^{-1}$), 33 hours after input. This represents a travel time of 30 $m\,hr^{-1}$. Peak detection was 49 hours after input (20 $m\,hr^{-1}$ travel time) with decreasing concentrations evident to 53 hours after input and a minor peak at 85 hours.

For the water samples in which dye was detected, the input pulse of nitrate was undetectable after about 500 m (Fig. 6). Prior to injection, nitrate-nitrogen decreased by 18.5% from 6.5 $mg\,l^{-1}$, at the input point, to 5.3 at Slapton Bridge. It should be noted that diffuse inputs, from adjoining agricultural land, drain directly into the Higher Ley between the injection point and Slapton Bridge; these complicate any interpretation of nitrate loss through the Higher Ley. After injection, 50 m downstream, the nitrate value was near background again (5.8) but dye was clearly detectable (1,560 $\mu g\,l^{-1}$).

Phosphate-phosphorus concentrations were 0.185 $mg\,l^{-1}$ at the input point and 0.03 at the output prior to the trace. During the trace, the levels fell from 5.49 at input, with a drop off similar to that of nitrate-nitrogen, to background at 0.03.

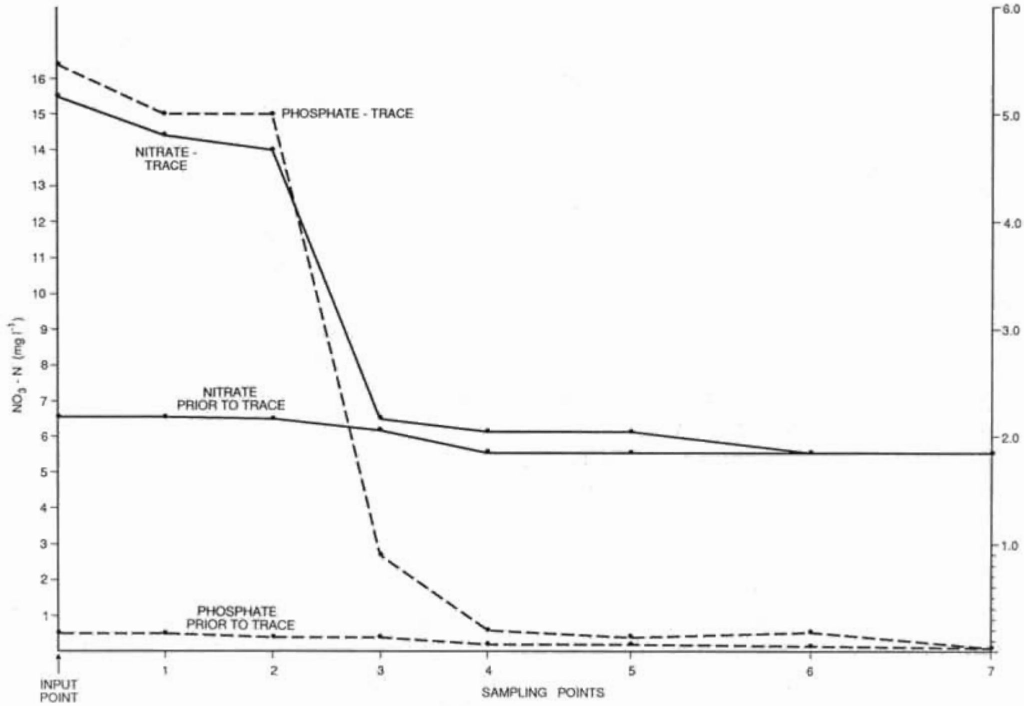

FIG. 6.

Composite diagram of nutrient concentrations in the Higher Ley in trace (III). Data points are for samples with first recorded positive dye detections. See Fig. 1 for the exact locations shown on the horizontal axis.

INTERPRETATION

(I) Sewage works marsh

Dye tracing successfully followed a body of water dispersing over the marsh. Since both the nitrate and ^{15}N showed rapid decreases to background levels within 10 m in the dye-traced waters, the conclusions are that nitrate-nitrogen concentrations were substantially decreased by passage of water over the marsh; and that the wetland was effective in causing nitrate losses. Since inputs from the sewage effluent are continuous, is concluded that nitrate is actually lost (e.g. by biological by uptake, denitrification and volatilisation), rather than just diluted in the water body.

The marsh is, however, not at all efficient in reducing phosphate concentrations. These were high across the marsh and, as levels increased in the dye-marked water, it is concluded that retention was not occurring but, rather, that there is phosphate input from the marsh.

(II) Slapton stream

The decrease in nitrate concentration was much lower than in the marsh below the sewage works. This indicates that the marsh was more effective in decreasing nitrate concentrations than an open conduit. ^{15}N in dyed water merely showed a decrease, rather than a total loss. In contrast to the marsh, there were some downstream losses of phosphate in the same dyed water. This confirms that, compared to a stream, wetlands can be a source of phosphate (rather than a sink), most probably through the release of phosphate from sediments.

TABLE 2.
Summary of Input–Output Relationships
a) Changes in Concentrations ($mg\ l^{-1}$)*

	MARSH				STREAM				REED BED†			
	IN	OUT	LOSS	%Loss	IN	OUT	LOSS	%Loss	IN	OUT	LOSS	%Loss
N	12.50	0.50	12.00	96.0	11.00	9.50	1.50	13.60	6.50	5.30	1.20	22
P	5.80	8.40	+2.6	+44.8	0.26	0.14	0.12	46.90	0.19	0.30	0.16	83

* + indicates an increase or "negative loss", implying a release of nutrients into the flow.
†Without fertiliser addition

b) Changes per length of traces

	MARSH	STREAM	REED BED†
length of trace (m)	150	150	1,000
% loss of Nitrogen m^{-1} (% loss per 100 m)	0.64 (64.0) [9.6 over actual 10 m of loss]	0.091 (9.1)	0.0226 (2.26)
% loss of Phosphorus m^{-1} (% loss per 100 m)	+0.2987 (+29.8)	0.313 (31.3)	0.0837 (8.3)
loss of Nitrogen in $mg\ l^{-1}\ m^{-1}$ (100 m)	0.08 (8.0) [1.2 over actual 10 m of loss]	0.01 (1.0)	0.0012 (0.12)
loss of Phosphorus in $mg\ l^{-1}$ 100 m^{-1} (100 m)	+0.017 (+1.7)	0.00081 (0.081)	0.000155 (0.0155)

% loss per 10 m^{-1}
Nitrogen: Marsh (9.6) > Stream (0.91) > Reed Bed (0.226)
Phosphorus: Stream (3.13) > Reed Bed (0.837) > Marsh (+2.987)

$mg\ l^{-1}$ loss 10 m^{-1}

Nitrogen: Marsh (actual loss) 1.2 > Stream (0.10) > Reed Bed (0.012)
Stream (0.10) > Marsh (calculated 0.8) > Reed Bed (0.012)

Phosphorus: Stream (0.0081) > Reed Bed (0.00155) > Marsh (+0.17)

c) Reed bed trace with fertiliser input

	IN	OUT	LOSS	%LOSS	%10 m^{-1}	$mg\ l^{-1}$ 10 m^{-1}
$mg\ l^{-1}$						
Nitrogen	15.50	5.30	10.20	65.80	0.66	0.10
Phosphorus	5.49	0.03	5.46	99.40	0.99	0.05

Percentage Nitrogen	Marsh > Reed Bed > Stream
Percentage Phosphorus	Stream > Reed Bed > Marsh
Nitrogen $mg\ l^{-1}$	Marsh > Stream > Reed Bed
Phosphorus $mg\ l^{-1}$	Reed Bed > Stream > Marsh

(III) River Gara—Higher Ley

Tracing the same body of water using dye and injected fertiliser suggested that nitrate and phosphate decrease can be rapid. Table 2 shows a comparison of the relative changes in the three situations. Table 2(a) shows actual $mg\ l^{-1}$ losses and the percentage changes.

Using the data prior to injection, the percentage losses are in the order marsh > reed bed > stream for nitrogen and reed bed > stream > marsh for phosphorus.

Since these calculations are for unequal distances, Table 2(b) compares the the actual mg l^{-1} and percentage losses. For the latter, the order of efficiency of removal per 10 m is marsh > stream > reed bed for nitrogen and stream > reed bed > marsh for phosphorus. For absolute losses the order is marsh > stream > reed bed for nitrogen, using the more realistic 10 m loss distance, and stream > marsh > reed bed using the total trace length. For phosphorus, the order is stream > reed bed > marsh.

Table 2(c) shows the data for injection of fertilisers into the input of the reed bed. The relative effectiveness per distance then becomes marsh > reed bed > stream for percentage nitrogen loss and stream > reed bed > marsh for percentage loss of phosphorus. For absolute losses, the nitrogen order is marsh > stream > reed bed and that for phosphorus, reed bed > stream > marsh.

The conclusion is that the overall order for nitrogen removal is marsh > stream > reed bed but, if fertiliser is injected into the reed bed as a point source, the large body of water changes the order to marsh > reed bed > stream. For phosphorus removal, the order is stream > reed bed, with the marsh being ineffective. With fertiliser injection into the reed bed, the order is reed bed > stream.

IMPLICATIONS FOR MANAGEMENT

These preliminary tracer experiments confirm the work of Gilliam, *et al.*, (1979). Wetlands can be used to decrease concentrations of nitrate. They also confirm the work of Gehrels and Mulamoottil (1989) that, not only can wetlands be poor at phosphate retention, they can also act as a source of phosphate. The implications are that, where nitrate levels give cause for concern, wetlands intervening between a source and a lake can be useful in the eutrophication control of that lake. The same would appear to apply for non-point phosphate sources. However, wetlands may not decrease phosphate concentrations from point sources and indeed may actually add to the problem.

CRITIQUE

We have made no attempt to study the mechanism of nutrient decrease/increase and the relative roles of dilution, biological uptake, denitrification, volatilisation and adsorption are unknown (Swank, 1986). Neither are the mechanisms of phosphate adsorption and release from sediments indicated (Fox, 1989). The method of analysis gives results for soluble reactive phosphate in filtered samples and the transport of sediment-associated phosphate is not covered (Gray & Kirkland, 1986). In addition, this preliminary trace refers only to April. Further work should include other seasons, and a range of flows. Any nutrient removal process may be less efficient at higher flows. Sediment loads may also be higher at times of high flow and the transport of phosphate attached to sediments and of organic particulate nitrogen may well be more significant.

The dye tracing was used merely to label a body of water so that we knew that the samples for nutrient anlysis came from the same one. This work could be extended, for dye tracing with and without injection of labelled and unlabelled nutrients, in order to separate sensitivity in detection and the relationships between input tracer amounts and dilution from actual losses. The cumulative effects of sustained nutrient inputs to and build-up in the ecosystem (Peverly, 1982) and the role of nutrient removal by vegetation harvesting also needs further investigation. However, the utility of the work lies in highlighting the efficiency of nitrate loss and the inefficiency of phosphate retention by a wetland, especially from point sources.

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REFERENCES

BOWMER, K. H. (1987). Nutrient removal from effluents by an artificial wetland: influence of rhizosphere aeration and preferential flow studies using bromide and dye traces. *Water Research*, **21** (5), 591–599.

BURT, T. P., ARKELL, B. P., TRUDGILL, S. T. and WALLING, D. E. (1988). Stream nitrate levels in a small catchment in South West England over a period of 15 years (1970–1985). *Hydrological Processes*, **2**, 267–284.

BURT, T. P., BUTCHER, D. P., COLES, N. and THOMAS, A. D. (1983). The Natural History of Slapton Ley Nature Reserve XV. Hydrological processes in the Slapton Wood catchment. *Field Studies*, **5**, 731–752.

CROOKE, W. M. and SIMPSON, W. E. (1972). Determination of ammonium in Kieldahl digests of crops by an automated procedure. *Journal of the Science of Food and Agriculture*, **22**, 9–10.

DUNBABIN, J. S., PORORNY, J. and BOWMER, K. H. (1988). Rhizosphere oxygenation by *Typha domeingensis* Pers. in miniature artificial wetland filters used for metal removal from wastewaters. *Aquatic Botany*, **29**, 303–317.

FOX, L. E., (1989). A model for inorganic control of phosphate concentrations in river water. *Geochimica et Cosmochimica Acta*, **53** (2), 417–428.

GEHRELS, J. and MULAMOOTTIL, G. (1989). The transformation and export of phosphorus from wetlands. *Hydrological Processes*, **3**, 365–370.

GILLIAM, J. W., SKAGGS, R. W. and WEED, S. B. (1979). Drainage control to diminish nitrate loss from agricultural fields. *Journal of Environmental Quality*, **8**, 137–142.

GRAY, C. B. and KIRKLAND, R. A. (1986). Suspended sediment phosphorus composition in tributaries of the Okanagan Lakes, BC. *Water Research*, **20**, 1193–1196.

HEATHWAITE, A. L., BURT, T. P., TRUDGILL, S. T. and O'SULLIVAN, P. E. (1989). *The impact of changing agricultural practices on adjacent terrestrial and aquatic ecosystems*. Final Report to NERC on Research Grant, GST/02/198. Unpublished; Natural Environment Research Council.

HEATHWAITE, A. L., and O'SULLIVAN, P. E. (1991). Sequential inorganic chemical analysis of a core from Slapton Ley. *Hydrobiologia*, **214**, 125–135.

HENRIKSEN, A. and SELMER-OLSEN, A. R. (1970). Automated methods for determining nitrate and nitrite in water and soil extracts. *Analyst*, **95**, 514–518.

HOWARD-WILLIAMS, C., 1981. Studies of the ability of a *Potamogeton pectinatus* community to remove dissolved nitrogen and phosphorus compounds from lake water. *Journal of Applied Ecology*, **18**, 619–637.

JOHNES, P. J. and O'SULLIVAN, P. E. (1989). The Natural History of Slapton Ley Nature Reserve XVIII. Nitrogen and phosphorus losses from the catchment–an export coefficient approach. *Field Studies*, **7**, 285–309.

LEAH, R. T., MOSS, B. and FORREST, D. E. (1978). Experiments with large enclosures in a fertile, shallow, brackish lake, Hickling Broad, Norfolk, United Kingdom. *International Revue der Gesamten Hydrobiologie*, **63** (3), 291–310.

LOWRANCE, R., TODD, R. L. and ASMUSSEN, L. E. (1984). Nutrient cycling in an agricultural watershed: I. Phreatic movement. *Journal of Environmental Quality*, **13** (1) 22–27.

MURPHY, J. and RILES, J. P. (1962). A modified single solution method for the determination of phosphate in natural water. *Analytica Chimica Acta*, **27**, 31–36.

PEVERLY, J. H. (1982). Stream transport of nutrients through a wetland. *Journal of Environmental Quality*, **11** (1), 38–43.

REDDY, G. B. and REDDY, K. R. (1987). Nitrogen transformations in ponds receiving polluted water from nonpoint sources. *Journal of Environmental Quality*, **16** (1), 1–5.

RITTER, W. F. (1988). Reducing inputs of nonpoint source pollution from agriculture: a review. *Journal of Environmental Science and Health*, A23, **7**, 645–667.

SWANK, W. T. (1986). *Biological control of solute losses from forest ecosystems.* Chapter 3 in: Trudgill, S.T., (Ed.) *Solute Processes.* Wiley. pp. 85–139.

TRUDGILL, S. T. (1983). The Natural History of Slapton Ley Nature Reserve XVI: The soils of Slapton Wood. *Field Studies*, **5**, 883–840.

TRUDGILL, S. T. (1987). Soil water dye tracing with special reference to the use of Rhodamine WT, Lissamine FF and Amino-G Acid. *Hydrological Processes*, **1**, 149–170.

Van VLYMEN, C. D. (1979). The Natural History of Slapton Ley Nature Reserve XIII: The water balance of Slapton Ley. *Field Studies*, **5**, 59–84.

WATTS, C. D. and MOORE, K. (1987). *The transport and fate of organic pollutants in rivers* –a progress report on project 4233. Water Reseach Centre, UK, PRU 1592–M.