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Evidence for a delayed response of riverine phosphorus exports from increasing agricultural catchment pressures in the Lough Neagh catchment

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Abstract

Total phosphorus (TP) exports from the rivers draining into Lough Neagh increased between 1974 and 2000 despite lower TP inputs to the rivers from point sources. Over this period annual diffuse exports of dissolved reactive P (DRP) increased by 238%, from 17 to 57 kg P km^{-2} with an annual rate increase of 1.6 ± 0.3 kg P km^{-2} yr^{-1}. Dissolved unreactive P exports increased by 0.4 ± 0.2 kg P km^{-2} yr^{-1}, but particulate P exports did not increase. Annual exports of these three P fractions were positively correlated with annual runoff. The catchment of Lough Neagh has experienced an intensification of agriculture, with phosphorus inputs of manures and fertilizers to agricultural land increasing from 1,176 kg P km^{-2} yr^{-1} in 1925 to 3,823 kg P km^{-2} yr^{-1} in 2000. However 85% of this increase predated 1975. Increasing DRP exports after 1974 were better correlated with increasing soil P, and 70% of the increase in P accumulation by soils since 1925 occurred after 1974. Land use remained stable after 1974 with a historically low component of arable (<5%) and a dominance of grassland (>63%). The principal decade of intensification was in the 1940s, but this coincided with a greater arable component of land use. This period predated the increase in diffuse DRP exports. Intensively managed grasslands appear to be vulnerable to high DRP exports, reflecting surface application of manures, accumulation of soil P at the surface, and the creation of bypass flow pathways that facilitate the loss of P from soil to water.

Lough Neagh, located in northeast Ireland, experienced algal blooms in the late 1960s. Regular monitoring of the lake and inflowing rivers began in 1970, and these data were used in the OECD study on eutrophication (OECD 1982). Waste water treatment works were found to be the largest source of phosphorus (P) in the 1970s, but the emphasis was on dissolved reactive P (DRP) because of its high bioavailability (Table 1). Based on rates of diatom frustule accumulation in the lake sediments, Battarbee (1977) also interpreted the enrichment history of the lake within a framework of increasing inputs of P from urban areas. Since 1981, point source discharges of P have been declining, but, despite this, total P (TP) concentrations in Lough Neagh increased from 110 μg P L^{-1} in 1980 to 145 μg P L^{-1} in 2000 (Foy et al. 2003). In reviewing the effects of point source discharges, Foy et al. (2003) concluded they provided a good explanation of the enrichment of Lough Neagh only up to 1960 since, after this, concentrations of TP in the lake were progressively greater than could be attributed to point source inputs. This divergence is partly due to the onset of a large summer internal loading of P, but this has not increased to account for the recent increase in lake TP (Gibson et al. 2001).

The recent increase of TP in the lake is catchment related because it parallels an increase in the flow-weighted TP concentrations in the inflowing rivers to Lough Neagh and increased diffuse exports of DRP (Foy et al. 1995, 2003). Previously, the increase of DRP exports has been considered in terms of how P has accumulated in the soils of the catchment (Heaney et al. 2001). The present paper examines for the first time to what degree quantitative changes in land use and farming intensity within the catchment can be linked to diffuse exports of P. It extends to 2000 the previously published time series of DRP exports and, for the first time, analyzes time series of TP, dissolved unreactive P, and particulate P exports. Since diatom inferred concentrations of lake TP show that diffuse effects on P exports were low and stable up to the 1950s, it is of interest to determine how current agricultural variables have altered over a longer time frame than is covered by the river monitoring (Anderson 1997; Jordan et al. 2001). Catchment changes are therefore analyzed from 1847, when an annual farm census began.

Methods

Catchment characteristics—The catchment area of Lough Neagh is 4,450 km^2, and the six major rivers shown in Fig. 1 drain 88% of the area (Smith 1977). Woodland accounts

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Table 1. Summary of estimates of point sources to published phosphorus budgets to Lough Neagh in the 1970s. TP, total phosphorus; DRP, dissolved reactive phosphorus; BAP, biologically available phosphorus. Runoff values marked with an asterisk were not presented in original paper.

Period	P fraction	Lough input ($10^3 \times$ kg P yr^{-1})	Point sources ($10^3 \times$ kg P yr^{-1})	Point sources (%)	Annual runoff (m yr^{-1})	Reference	Comment on estimation of point sources
1970	TP	325	256	79	0.61*	Wood and Gibson (1973)	Literature derived urban per capita of 1.46 kg P yr^{-1}
1971–1974	DRP	254	131	51	0.60*	Smith (1977)	Regression derived urban DRP per capita of 0.69 kg P yr^{-1}
1971–1974	BAP	322	200	62	0.60*	Smith (1977)	Assumed TP from point sources was BAP
1979	DRP	256	153	60	0.58	Foy et al. (1982)	Urban DRP per captia of 0.57 kg P yr^{-1} plus DRP input from creameries

for 2% of the area, leaving agriculture, and in particular grassland that sustains cattle and sheep rearing, the predominant land use. In declining order of importance, agricultural P exports can be ranked as milk, beef, poultry, pigs, and sheep (Foy et al. 2002). Agriculture uses imported animal feeds, and grass receives P inputs from chemical fertilizers. Cattle are housed during the winter, as are poultry and pigs throughout the year so that approximately 50% of animal excreta is collected, with manure spreading occurring throughout the year and commonplace in winter (Tunney et al. 1998). The clay mineral soils have impeded drainage, and most have experienced some form of subsurface drainage since 1945 (Wilcock 1997). Extended periods of snow or frozen ground are rare, and precipitation of 1,060 mm yr^{-1} is predominately low-intensity rainfall ($<$4 mm h^{-1}). River flow responds rapidly to rainfall, especially in the winter when soils are at or near field capacity. Average runoff from 1974 to 2000 was 0.65 m yr^{-1}, and runoff is on average three times higher from October to March in comparison with April to September (Wilcock 1997)

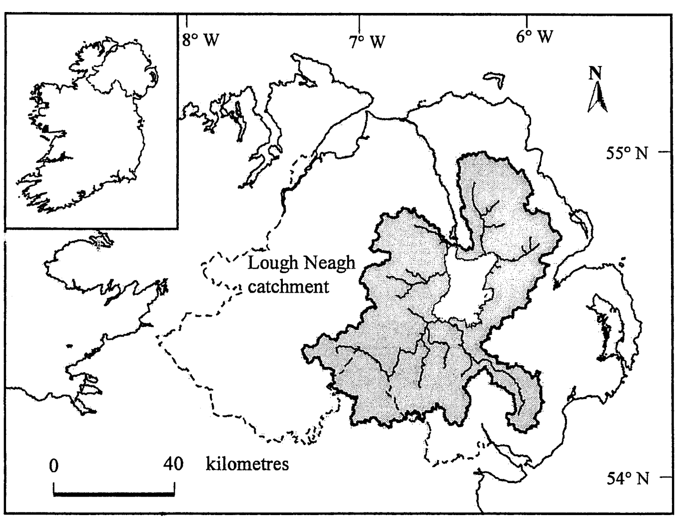

Fig. 1. Lough Neagh catchment (shaded area) showing the six inflowing major rivers. Dashed line shows border between Northern Ireland and Republic of Ireland.

River exports of phosphorus—Weekly grab samples have been taken from the six inflowing rivers at points close to where they enter Lough Neagh (Smith 1977). Samples were analyzed for TP and, after filtration with 0.45-μm membranes, for total dissolved P (TDP) and DRP using the standard methods given by Lennox et al. (1997). For the hydrological year October to September, daily P exports from each river were calculated from log P concentration versus log flow regressions. Separate regression equations were calculated for the months October to March and April to September, and predicted concentrations were corrected for the negative bias introduced by the log transformation the data (Lennox et al. 1997). Particulate P (PP) exports were calculated by difference (TP $-$ TDP) and dissolved unreactive P (DUP) as TDP $-$ DRP. Although exports to Lough Neagh have been published from 1970, analytical data, particularly for TP and TDP, are now regarded as less reliable for the earliest years, and so the data set presented here covers only the period October 1974 to September 2000. Exports from the six rivers have been combined to give a single catchment export (Table 2). Diffuse exports within this single catchment were calculated by difference from point source inputs as described by Foy et al. (1995, 2003). Since these inputs are only to the monitored river catchments, they are lower than those given by Foy et al. (2003) for the whole lake catchment area.

Catchment statistics—An annual agricultural census in Northern Ireland (NI) collects statistics on land use and animal numbers, the latter being categorized according to their type, age, and sex. Data are available by administrative district, and, from 1974 onward, annual catchment totals for Lough Neagh are based on returns from farms in administrative districts that are within the catchment of the Lough. A complete run of annual statistics was available for NI from the first census in 1847, but accessing data by administrative district before 1974 was less straightforward. Data from

Table 2. Annual exports from Lough Neagh rivers and point source inputs to these rivers of total phosphorus (TP), total dissolved phosphorus (TDP), and dissolved reactive phosphorus (DRP) plus annual catchment runoff. Note hydrological year begins in October, so 1975 = October 1974–September 1975.

	River annual loads ($10^3 \times$ kg P yr^{-1})			Point source inputs ($10^3 \times$ kg P yr^{-1})			Annual runoff
Year	TP	TDP	DRP	TP	TDP	DRP	(m yr^{-1})
1975	280	176	157	178	166	149	0.48
1976	323	228	163	177	165	149	0.41
1977	431	277	219	178	166	150	0.65
1978	359	255	203	173	162	145	0.60
1979	496	327	271	179	167	150	0.69
1980	494	341	276	179	167	150	0.73
1981	655	353	286	183	151	134	0.74
1982	465	282	223	151	124	108	0.64
1983	425	273	216	145	122	106	0.67
1984	376	244	201	148	124	109	0.58
1985	542	320	252	151	127	110	0.71
1986	457	274	211	144	123	108	0.63
1987	485	313	247	145	125	110	0.61
1988	506	356	286	145	121	105	0.77
1989	358	247	210	130	109	95	0.58
1990	359	256	211	135	111	96	0.58
1991	351	274	216	113	93	80	0.60
1992	425	327	237	110	88	73	0.65
1993	526	396	305	113	88	73	0.73
1994	565	405	332	110	90	76	0.75
1995	461	331	266	112	94	82	0.56
1996	486	342	265	116	97	85	0.67
1997	449	327	258	110	93	82	0.56
1998	636	468	355	104	88	78	0.71
1999	753	474	368	103	86	76	0.83
2000	495	356	283	103	85	74	0.69

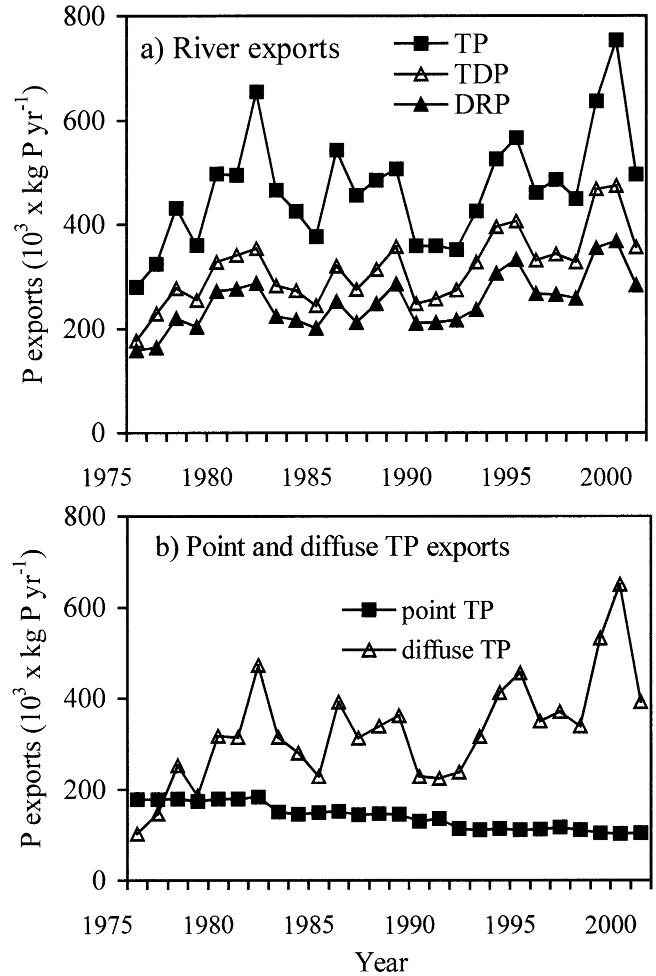

Fig. 2. River exports of (a) total phosphorus (TP), total dissolved phosphorus (TDP), and dissolved reactive phosphorus (DRP) and (b) point source inputs of TP and, calculated by difference, TP exports from diffuse sources.

1925 to 1974 were in hand written ledgers, which were subsampled at approximately decadal intervals. Since catchment totals tended not to vary independently of the NI total, for the intervening years catchment totals were interpolated from the NI data set. Only incomplete census data were available from 1919 to 1922. Data prior to 1921 are held on database at Queen's University Belfast and were also sampled at decadal intervals with values for intervening years interpolated relative to the annual NI totals. The partition of Ireland in 1921 divided the catchment of Lough Neagh between NI (91%) and the Republic of Ireland (9%). While data from before the 1921 census are available for the portion now in the Republic of Ireland, it has not been possible to access later census data. Therefore, for consistency, the agricultural data used are for the 91% of the catchment within NI. Agricultural land use has been reduced to three categories: arable crops, grassland, and rough grazing, which is typically moorland above 150–200 m. Animal numbers have been combined with manure P per capita values for livestock in Irish agriculture to calculate an index of manure P loading (Foy and Lennox 2000). Time series of the annual inputs and outputs of P in agriculture within NI since 1925 are those calculated by Foy et al. (2002). Inputs consist of chemical fertilizers and imported animal foodstuffs, while outputs are P in agricultural product. Inputs, outputs, and surpluses are expressed per unit of agricultural land of NI and are taken to be representative of the Lough Neagh catchment, which occupies 30% of the NI land area.

Statistical analyses—Two sets of data were subjected to multiple regression analyses with catchment variables: annual river exports based on the hydrological year from October to September and, for the same period, the annual flow-weighted mean concentrations of P calculated as the river export divided by river flow. Only those equations in which an independent variable was correlated with the river P variable at the $p < 0.05$ level are presented. A $\pm$ sign in the text denotes confidence limits (95%) of the regression coefficients.

Results

Catchment P exports—Before allowance is made of the effects of lower point source contributions to river P exports, there were significant upward trends between 1974 and 2000 in the river export of TP ($p < 0.05$), TDP ($p < 0.001$), and

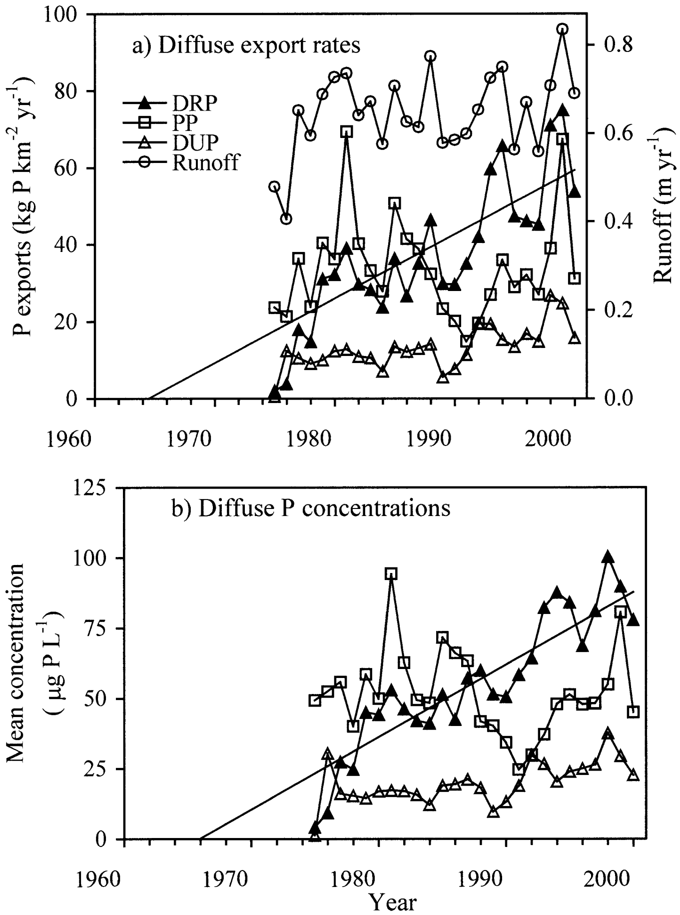

Fig. 3. Time series of diffuse source phosphorus fractions (a) export rates and catchment runoff and (b) annual flow-weighted mean concentrations. Trend lines are for export rate and mean concentration of DRP under conditions of average runoff and calculated from regression equations in Table 3.

Table 3. Multiple regression analyses of annual diffuse export rates (kg P km^{-2}) and annual flow weighted mean concentrations (μg P L^{-1}) versus year (1975 = 1) and runoff (m yr^{-1}). Values in parentheses denote the 95% confidence limits of the regression coefficients, and *, **, and *** denote regression coefficients that are significant at $p<0.05$, <0.01, and <0.001 respectively.

	Regression equation	R^2
Export rate		
Eq. 1:	TP = 220(69)runoff*** + 1.56(0.84)year*** − 79(42)	0.80
Eq. 2:	DRP = 94(25)runoff*** + 1.62(0.31)year*** − 45(15)	0.93
Eq. 3:	DUP = 23(18)runoff* + 0.38(0.21)year** − 6.9(10.7)	0.59
Eq. 4:	PP = 89(46)runoff*** − 24(20)	0.40
Mean concentration		
Eq. 5:	TP = 147(98)runoff** + 2.5(1.2)year*** − 0.8(60)	0.66
Eq. 6:	DRP = 71(37)runoff*** + 2.6(0.5)year*** − 25(23)	0.91
Eq. 7:	DUP = 0.59(0.33)year** + 12.0(5.2)	0.33

DRP ($p < 0.001$) (Fig. 2a). The rates of increase for TP and TDP were similar at 6.4 and 6.1 $\times 10^3 \times$ kg P yr^{-1}, respectively, showing that the increase in TP reflected increasing dissolved P exports rather than PP exports. Point source input of TP from October 1997 to September 2000 was 103 $\times 10^3 \times$ kg P yr^{-1} and equivalent to only 16% of the river TP export over the same period, but for the 3 yr from October 1974 the 178 $\times 10^3 \times$ kg P yr^{-1} from point sources represented 52% of river TP export. Since point source TP was a comparatively minor proportion of river export by 2000, calculating diffuse exports as river exports less point inputs accentuated the trend increase with time (Fig. 2b).

The primary cause of increasing diffuse TP and TDP exports was progressively higher DRP export rates (Fig. 3a). The influence of flow and time as catchment variables on diffuse export rates of TP and the three constituent P fractions was quantified by multiple regression analyses (Table 3). Time, as a variable, was significantly correlated with export rates of DRP and DUP, but the rate of increase for DRP of 1.6 kg P km^{-2} yr^{-1} was four times the increase for DUP of 0.4 kg P km^{-2} yr^{-1}. Export rates of all P fractions were positively correlated with flow, and the highest regression coefficient for flow was obtained for DRP. Effects of flow on diffuse P exports can be compared from their predicted responses with an increase of 0.1 m yr^{-1} in runoff, which is equivalent to 15% of average runoff and interannual variations in excess of this occurred in 42% of years. The export rate of DRP increased by 9.4 kg P km^{-2} yr^{-1} compared with an increase of 2.3 kg P km^{-2} yr^{-1} for DUP export rate. These predicted responses to flow are equivalent to almost 6 yr of the respective trend increases in export rate with time. Exports of PP showed no trend with time but were positively correlated with flow. The 15% increase in runoff of 0.1 m yr^{-1} increased PP export by 8.9 kg P km^{-2} yr^{-1}, which represents 26% of the PP export of 34 kg P km^{-2} yr^{-1} in an average runoff year.

The annual mean (flow weighted) concentration of DRP also shows an upward trend with time that is more pronounced than for DUP (Fig. 3b). Multiple regression analysis of annual concentrations with time and flow show that runoff remained significantly correlated with DRP, indicating that the mean concentration of DRP from diffuse sources increased with annual flow (Table 3). From the flow regression coefficient, a 0.1 m variation in annual runoff would be expected to change DRP by 7.1 μg P L^{-1}. There were no significant correlations between runoff and mean concentration of PP or DUP, indicating that annual flows did not result in a change in the average annual concentration of these P fractions.

When compounded over the 26 yr of the study, the annual rate of increase of DRP of 2.58 μg P L^{-1} yr^{-1} equates to a cumulative increase in the DRP concentration from diffuse sources of 67 μg P L^{-1}. The trend lines for annual exports and concentrations of DRP in Fig. 3 are those of the respective regression equations in Table 3 and employ the average runoff of 0.65 m yr^{-1}. Their intercepts are in 1963 and 1965, respectively, implying zero or very low DRP export rates from diffuse sources before those dates. Using average

Table 4. Diffuse export rates under average runoff of 0.65 m yr^{-1} in 1975 and 2000 for TP, total phosphorus; DRP, dissolved reaction phosphorus; DUP, dissolved unreactive phosphorus; and PP, particulate phophorus. Rates calculated using regression equations listed in Table 3.

	P fraction	Diffuse exports (kg P km^{-2} yr^{-1}) 1975	2000	Change (%)
Eq. 1	TP	64.6	103.7	+61
Eq. 2	DRP	17.0	57.4	+238
Eq. 3	DUP	8.3	17.9	+116
Eq. 4	PP	33.9	33.9	0

runoff, diffuse DRP export rates increased by 238%, from 17 to 57 kg P km^{-2} yr^{-1} between 1975 and 2000 (Table 4). The increase in predicted exports of TP was almost the same quantity, but, since the TP exports included an unchanging PP input, the percentage increase was smaller at 61%.

The diffuse exports, calculated here by difference, also include scattered point inputs, the most obvious of which are rural septic tanks. Between 1974 and 2000, Foy et al. (2003) calculated that TP contributed by septic tanks remained quite constant within the catchment of Lough Neagh at close to 13.5 kg P km^{-2} yr^{-1}, while modest population growth was counterbalanced by declines in detergent P. The septic tank contribution was based on a 60% connectivity of septic tank discharges to surface waters. Inflating connectivity to 100% therefore equates to a further septic tank loading of only 9 kg P km^{-2} yr^{-1} and is considerably less than the increase in diffuse exports. A further portion of the diffuse inputs can be considered to be the background export rate of TP required to maintain Lough Neagh in its reference state. From sediment accumulation rates of diatom frustules, Lough Neagh was naturally mesotrophic, with TP concentrations close to 20 μg P L^{-1}, which, using a TP loading model for lakes in Northern Ireland, would require an input concentration for TP of 38 μg P L^{-1} (Foy 1992; Foy et al. 2003). Hence, using average runoff, the reference TP export rate from the catchment is calculated as $0.65 \times 38 = 24.8$ kg P km^{-2} yr^{-1} or only 24% of the trend diffuse export rate of TP for 2000 but 41% of the rate in 1975 (Table 4).

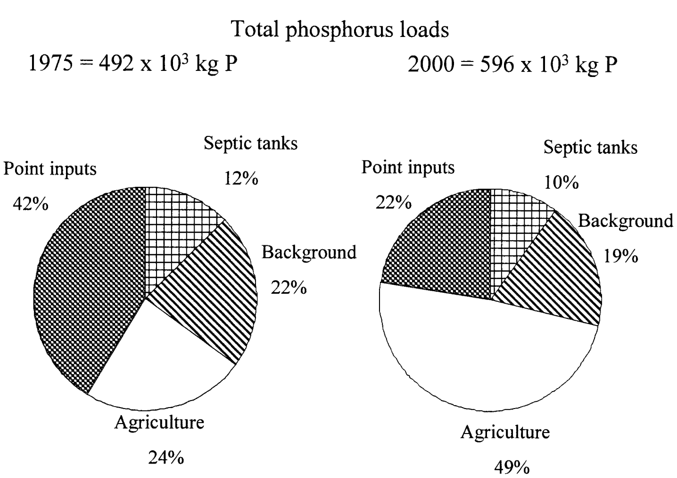

Fig. 4. Predicted breakdown of total phosphorus export to Lough Neagh in 1975 and 2000 under conditions of average flow.

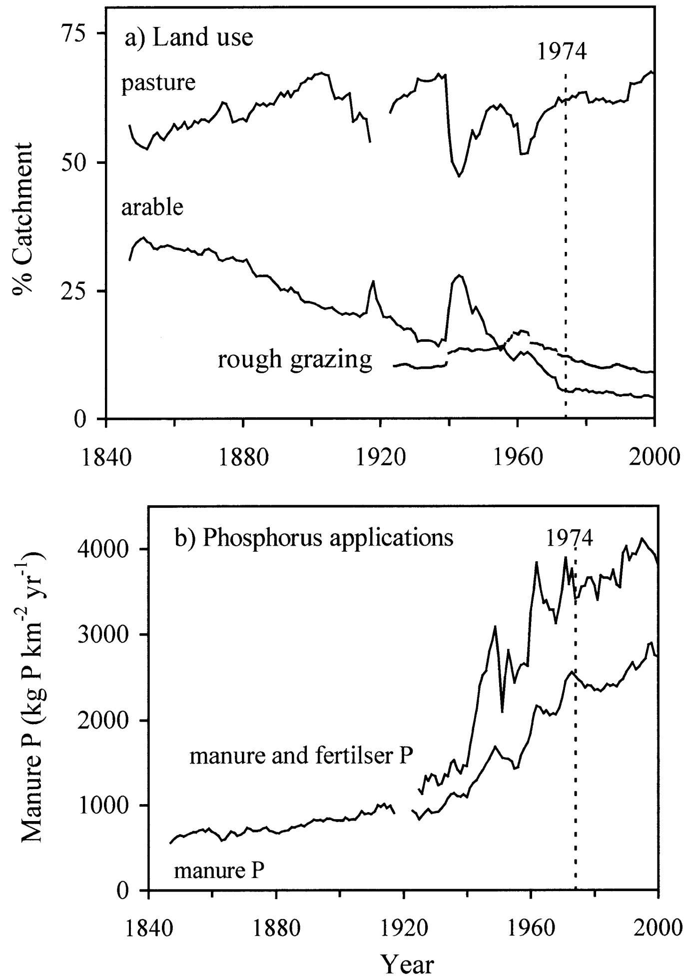

Fig. 5. Lough Neagh catchment statistics for (a) land use and (b) inputs of phosphorus to land as manures and as manures plus chemical fertilizers. Phosphorus input rates calculated per unit area of grass and crops.

These considerations can be used to partition TP inputs from the whole lake catchment for 1975 and 2000, with diffuse exports scaled up to take into account the direct drainage area (Fig. 4). Data for point source and septic inputs are those given by Foy et al. (2003). Despite lower point source inputs, the catchment export of TP increased from $492 \times 10^3 \times$ kg P yr^{-1} in 1975 to $596 \times 10^3 \times$ kg P yr^{-1} in 2000. Point sources were the largest contributor in 1975, but by 2000 agriculture was the largest source, accounting for 49% of the TP export. It is against the scale of the increased agricultural contribution and the large percentage increase found for diffuse DRP river export that changes in catchment land use and agricultural intensification should be assessed.

Catchment changes—Only minor changes in catchment land use and P inputs to land occurred during the period of river monitoring after 1974 (Fig. 5a,b). Land use was dom-

Table 5. Diffuse exports of total phosphorus (TP) and total dissolved phosphorus (TDP) from Table 4 expressed as percentage of agricultural inputs and soil P statistics for 1975 and 2000. (TDP is sum of dissolved reactive and unreactive phosphorus exports).

Inputs/soil P statistic*	Input P or soil P (kg P km^{-2} yr^{-1}) 1975	2000	TP (loss as % input or soil P) 1975	2000	TDP (loss as % input or soil P) 1975	2000
Manure P	1,960	2,186	3.3	4.7	1.3	3.4
Manure P + fertilizer P	2,727	3,054	2.4	3.4	0.9	2.5
Soil P accumulation from 1925	47,627	81,002	0.14	0.13	0.05	0.09
Soil P accumulation from 1975		33,375		0.31		0.23

* Input and soil P rates are calculated per total catchment area and are lower than comparable rates shown in Figs. 5 and 6 since the latter are calculated per the areas of arable plus grassland only, which were 79.4% and 79.9% of total catchment areas in 1975 and 2000, respectively.

inated by grassland with only a very small arable component that declined from 5.4% of the area in 1974 to 4.0% in 2000. The combined percentages of arable, grass, and rough grazing returned by census remained quite constant at 89% in 1974 and 88% in 2000, although the step increase from 66% to 69% in the percentage of grass in 1997 reflects a change in methodology of sampling the smallest holdings. Rough grazing declined steadily, reflecting transfers to grass. Manure production is estimated to have increased by only 8% between 1974 and 2000, while the combined input of P in fertilizers and manures to land increased by 12% (Table 5).

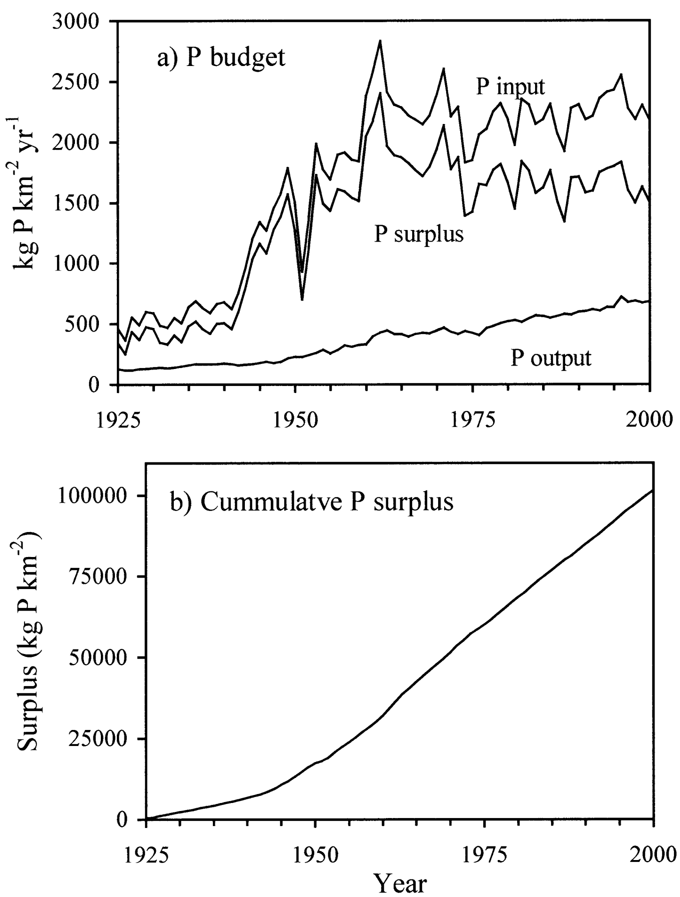

Fig. 6. Agricultural phosphorus (P) budget for Northern Ireland. (a) Inputs are sum of imported P in fertilizers and animal feeds, outputs are P in agricultural products, and surplus = inputs less outputs. (b) Accumulated P surplus since 1925. Values expressed per unit area of grass and crops.

In contrast to this relative stability, a loss of arable land was a feature of land use change prior to 1974, since in 1850 arable agriculture represented 34% of the catchment area but only 5% of the area in 1970. This decline was interrupted by two short periods of increase when, to meet the exigencies of wartime food production in 1914–1918 and 1939–1945, arable cropping became compulsory on farms. Animal production in the 20th century intensified from the mid-1930s with increasing inputs of P in fertilizers and manure to land, but 85% of the increase in their combined input from 1925 to 2000 took place before 1974. External inputs of P to agriculture in fertilizers and imported feedstuffs doubled in the decade 1940 to 1949, but after 1950 these inputs have remained quite constant (Fig. 6). While output of P in agricultural products has increased since 1950, the output in 2000 of 690 kg P km^{-2} remained much lower than the input of 2,170 kg P km^{-2}, leaving a surplus of 1,480 kg P km^{-2}. The constancy of this surplus since 1950 is reflected in the linear increase in soil P since then (Fig. 6). With 1925 as a base line, 70% of the soil P increase has occurred after 1974, while the linear nature of this increase parallels the increase in diffuse DRP export rates (Fig. 3).

While diffuse loss increases are in a limnological sense very large, they remained small when compared with agricultural input and tiny in comparison with the P that has accumulated in soils (Table 5). The annual loss of DRP in 1975 represented only 0.05% of accumulated soil P up to that year, while by 2000 the DRP loss rate represented only 0.09%.

Discussion

Controlling point sources of P has successfully reversed the eutrophication process, but in many lakes residual diffuse inputs are sufficient to maintain eutrophic conditions (Carpenter et al. 1998). Animal production based on grassland systems has particular eutrophication-related problems associated with manure applications and a buildup of soil P reflecting imbalances between inputs and outputs of P (Hooda et al. 2001). While losses of P from agricultural land are more often associated with PP, dissolved exports of P are important for fertile grassland soils, where DRP can be the dominant fraction (Hooda et al. 2001). Following surface applications of manures to grassland there is striking evidence for rapid contamination of drain flow with P, as shallow lateral flow pathways and macropores connect P mobilized at the soil surface to drain flow and so bypass the soil's capacity to sorb P (Jordan and Smith 1985; Preedy et al. 2001; Stamm et al. 2002). These ''edge of field'' losses are comparable in magnitude with the river P exports entering Lough Neagh (Lennox et al. 1997).

Such observations indicate that agriculture should be a significant contributor of P to Lough Neagh, but, since the scale of the increase in DRP export is much greater than the increase in manure and fertilizer application, soil P appears to be the primary source of increased DRP exports. There is of course a missing link or links between field losses and river exports of P, which is the fate of P within the river system. When comparing TP transport from the Taw River catchment in southwest England at scales ranging from grass plots of 30^2 m^2 with a river export from 914 km^2, Wood et al. (2002) concluded the evidence was ''strong but not conclusive'' that diffuse transfers of P from grassland determined river exports of P. The Taw catchment is largely grassland, with poorly drained soils and low base flows, and so is similar to the Lough Neagh catchment, for which a similar conclusion can been made.

Increasing river DRP exports within the Neagh catchment have occurred over extended periods when point source inputs remained unchanged, showing that increases in diffuse exports are not an artifact of calculating them by difference (Foy et al. 1995; Foy and Lennox 2000). Depending on the kinetics of P absorption–desorption equilibrium reactions, P exchange reactions with river sediments can modify river exports, but rivers in the Neagh catchment have bed sediments that consist largely of stones, gravels, and sand since frequent floods removes fine sediment. Limited equilibrium P measurements show bed sediment to be a sink rather than source of P throughout the year (Foy et al. 1995). The magnitude of this sink appears small since, in the short term (<5 yr), DRP exports declined by quantitatively similar amounts to the reductions from point source inputs (Foy et al. 1995). Over the long term, higher winter DRP concentrations have been the driver of the annual export increase, with DRP concentrations remaining lower during the summer long after a point source decline (Foy et al. 1995). The potential for a change in biotic uptake of P within rivers during the winter is unlikely since they are fast flowing with no extensive macrophyte beds.

An association of soil P with dissolved P exports can be considered in terms of plausible processes and likely scale of effect. At a laboratory scale, increasing soil P in noncalcareous soils increases water soluble P but only markedly when the degree of P saturation of soils exceeds 25% (Maguire et al. 2001). This nonlinear response therefore can explain why catchment P exports did not increase until after 1960, whereas soil P had been increasing since at least 1925 and probably since 1870 (Foy et al. 2002). At plot and field scales, concentrations of P in surface runoff and drain flow increase with soil P, but the data are inconsistent as to whether these increases are linear with soil P or exhibit lag or break point (McDowell et al. 2002).

Within Northern Ireland, P deficient soils are now rare, and over 50% of fields have soil P in excess of that required for intensive grass production (Heaney et al. 2001). This is a common experience in areas devoted to animal rearing, but, despite this, there are few parallels, apart from the neighboring catchment of Lough Erne, linking soil P to a measured increase in P export from a catchment (Zhou et al. 2000). Such a causal link has been proposed to account for the continued eutrophic state of Lake Mendota, and in the Netherlands saturation of soils with P is a recognized cause of elevated concentrations of DRP in groundwater (Van der Molen et al. 1998; Bennett et al. 1999). The absence of parallels within Great Britain may be a reflection of the absence of large lowland lakes as well as the uniquely long and detailed data set of TP exports to Lough Neagh. Interannual variability of river flows obscures trend increases of export rates that can only be evident with extended runs of data. The analysis of river exports of P measured from 1971 to 1979 reported by Foy et al. (1982) failed to identify a trend increase with time, but, in that study, flow increased after 1975 and hence covaried with time.

Single manure applications, when followed by drain flow, can result in a short-term export of P that is a large proportion of the annual total (Jordan and Smith 1985; Hooda et al. 2001). These short-term exports overwhelm relationships between soil P and P in runoff from grassland (McDowell et al. 2002). When combined with the current prevalence of winter applications of manure in the catchment, these observations suggest that manure plays a greater role in determining P exports to Lough Neagh than predicted by the poor relationship between annual manure P production and catchment export. Around 3% of P in manures was lost to drain flow after winter applications to grassland in southwest Scotland, and this scale of loss applied to the average winter manure applications of 1,000 kg P km^{-2} in the Neagh catchment represents approximately 30% of diffuse TP exports in 2000 (McGechan et al. 2002). Higher loss rates in excess of 10% of manure P have been reported in Ireland (Kiely 1981).

Increasing diffuse exports of P from the late 1970s to 2000 could plausibly reflect a switch from solid farmyard systems to liquid manures and the associated use of ''all weather'' winter manure spreading techniques. Additionally, the mobility of P in cattle manures may have increased because of an increase in the P content of winter feed of cattle caused by a switch from hay to silage and the inclusion of high P concentrate feeds. Enhanced dietary P increases the proportion of TP in manure that is soluble or colloidal, and these P fractions have a greater vulnerability to runoff loss in comparison with PP (Ebeling et al. 2002). Quantitative information on these changes is limited, leaving the mobility of manure P and vulnerability to loss an unresolved issue to be addressed in interpreting eutrophication history and the identifying control and remedial measures.

Since significant amounts of P are exported via drain flow, field drainage in the catchment from 1945 to 1975 may have altered P transport potentials (Wilcock 1997). Phosphorus exports from drained and undrained grassland in southwest England with matched P inputs were found to be 30% lower from the drained plots, a result that is consistent with the hypothesis that lowering water table by field drainage reduces the potential for surface runoff, which is the flow pathway associated with the highest P exports (Haygarth et al. 1998). Field drainage within the Neagh catchment would have therefore ameliorated the effects of increased agricultural P inputs before 1970, but separating drainage from intensification effects is difficult, especially since drainage was undertaken to facilitate agricultural intensification (Sims et al. 1998).

The almost complete predominance of grassland in the catchment of Lough Neagh is a recent phenomenon that coincides with the period of increasing P exports. Arable agriculture and ploughing are associated with high losses of PP through erosion, but the evidence from diatom enrichment proxies and lake sediment accumulation rates within Northern Ireland is that such losses of sediment have been small and did not affect eutrophication, probably reflecting the low rainfall intensities and soils that are resistant to erosion (Anderson 1997; Jordan et al. 2001). Enrichment proxies also show that increasing agricultural P inputs in the 1940s, in combination with increased ploughing, did not result in eutrophication. Compared with grassland, ploughing has ameliorative effects on P transport potentials, particularly for dissolved P, since it disrupts the macropore flow paths through which P mobilized at the surface can reach drain flow. Additionally it incorporates P in manures and chemical fertilizers into the soil, effectively diluting and immobilizing these inputs within the soil, as well as diminishing the build-up of P at the soil surface, which is a feature of grassland (Sharpley 2003).

Within a period of less than 30 years, diffuse exports of DRP to Lough Neagh have increased by an amount that, in limnological terms, is highly significant. Debates as to whether this enrichment is due to soil P or manure P are to a degree sterile, given that the Water Framework Directive of the European Union (EU) requires that Lough Neagh and all lakes within the EU be restored to a status that allows only slight deviation from reference conditions by 2015. Depending on how the word ‘‘slight’’ is interpreted, this will require a reduction of up to 75% in TP exports to Lough Neagh and can only be feasible with further reductions in point sources and a complete reversal of current trends in diffuse exports. This scale of change implies that no P source within the catchment can be ignored. At the time of writing in 2004, farm income support within the EU is changing from payments based on agricultural output, which favors high output and hence high input systems of production, to a single payment based on compliance with a series of EU environmental directives with no requirement by the farm to produce any product. One of these directives is the Nitrates Directive, compliance of which conceivably requires destocking on 50% of dairy farms and all pig and poultry units in Northern Ireland as well as the enforcement of a 4 month closed period for winter applications of manures (DOE 2004). While the Nitrate Directive aims to lower losses of nitrate to water, the proposed measures should be of benefit in lowering P losses by prohibiting manure application during the months with highest flow as well as reducing manure loadings. Combined with additional restrictions on the use of P fertilizers and a lowering of the P content of animal feeds to comply with a limit set on the maximum P surplus for farms, these measures provide an opportunity to reverse the current upward trend in P exports in the Lough Neagh catchment.

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