

**Research Article**

## Effects of recent zebra mussel invasion on water chemistry and phytoplankton production in a small Irish lake\*

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### Abstract

Lough Doon is a dual basin lake in the west of Ireland, split into an upper and lower basin that are morphometrically and physiochemically similar. Zebra mussels [*Dreissena polymorpha* (Pallas, 1771)] were introduced in the lower basin in 1998 and are now well established there. A survey in July 2007 involving scuba dive transects and dredging revealed a population of  $5.5 \times 10^8$  zebra mussels ( $4.9 \times 10^5$  kg) in the lower basin, while just 3 zebra mussels were recorded in the upper basin. To assess the effects of *Dreissena* infestation on suspended solids, algal production and nutrient concentrations, near-surface water samples from Lough Doon were analysed from January–July 2007 ( $n = 12$ ) for selected chemical and biological parameters. Sampling revealed marked differences in seston load between the two basins, with the infested lower basin exhibiting significantly reduced concentrations of suspended solids, chlorophyll-a and phytoplankton biovolumes and, conversely, greater Secchi transparency. Total phosphorus concentrations were lower in the lower basin but concentrations of ammonium and, particularly, nitrate were significantly higher. Inter-basin differences in Lough Doon mirror the post-invasion changes observed in other, larger European and North American lakes and reflect the effectiveness of coupled filter feeding-excretion by zebra mussels in reducing seston load and converting particulate nutrients into soluble forms. The data provide initial evidence that modest zebra mussel populations can significantly alter water chemistry in a small well-mixed lough, with implications for water quality management as the zebra mussel continues its rapid range extension in Ireland.

*Key words:* zebra mussel, *Dreissena polymorpha*, Ireland, invasive species, water quality, nutrients

### Introduction

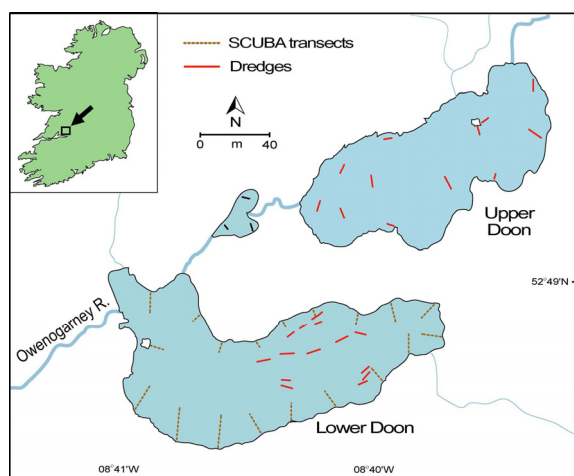
As in other countries, the rate of introduction and spread of exotic aquatic species is rapidly increasing in Ireland (Minchin 2007). Since its arrival in Ireland in c.1994 (McCarthy et al. 1997), the zebra mussel *Dreissena polymorpha* (Pallas, 1771) has quickly extended its range in Irish waters (Rosell et al. 1999; Minchin 2003). A native to the Black and Caspian Seas, the enormous ecological impacts of the zebra mussel

in lakes throughout Europe and North America are well documented. Vigorous filter feeding by zebra mussels directly reduces levels of plankton and suspended solids in lakes, increasing water clarity (Berg et al. 1996). Nutrient cycling is altered by the excretion and filter feeding activities of zebra mussels (James et al. 1997; Arnott and Vanni 1996), while the occurrence of nuisance or noxious cyanobacteria may increase due to *Dreissena* - induced changes in the N:P ratio (Raikow et al. 2004). Such changes

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**Figure 1.** An aerial view of the study lake, Lough Doon, in Co. Clare, Ireland (Google Earth™ 2007).



**Figure 2.** Map of the Upper and Lower basins of Lough Doon, illustrating the location of the SCUBA transects and dredges conducted during the zebra mussel population survey in July 2007.

**Table 1.** Principal morphometric and chemical characteristics of the Upper and Lower basins of Lough Doon. Values are mean for January–July 2007 (n=12) ± standard errors.

	Doon Upper	Doon Lower
Surface area (ha)	48.4	64.9
Volume (m <sup>3</sup> )	2.44 × 10 <sup>6</sup>	3.25 × 10 <sup>6</sup>
Mean depth (m)	5.04	5.0
Max. depth (m)	15.2	12.1
Residence time (mth)	1.88	1.67
pH	7.69 ± 0.08	7.83 ± 0.06
Conductivity (mS cm <sup>-1</sup> )	167 ± 4.8	200 ± 6.1
Temperature (°C)	12.4 ± 1.3	13.0 ± 1.3
DO (mg L <sup>-1</sup> )	10.5 ± 0.3	10.5 ± 0.3
Alkalinity (mg CaCO <sub>3</sub> L <sup>-1</sup> )	72.4 ± 4.4	89.7 ± 4.5

indirectly impact a wide variety of ecological processes, affecting the composition and distribution of native populations of macrophytes, macroinvertebrates, unionid mussels and fishes. Together with their nuisance biofouling of pipes and boats, these characteristics have made the zebra mussel perhaps the most notorious of aquatic invasive species.

Research on zebra mussels in Ireland has to date focused on large lakes on the Shannon and the Erne river systems (Maguire et al. 2003; Pollux et al. 2003; Astanei et al. 2005; Lucy 2006; Burlakova et al. 2006; Conn et al. 2007) while North American models of zebra mussel-induced changes have focused on the Great Lakes. As part of the EPA-funded BioChange project examining key threats to biodiversity in Ireland, this study (2006–2009) aims to elucidate, for the first time, the effects of recent *Dreissena* invasion on water chemistry and phytoplankton production in a small, well-mixed western Irish lake. Data from this study will ultimately help forecast changes in ecological processes and ecosystem structure in Irish lakes arising from zebra mussel invasion.

## Study Site

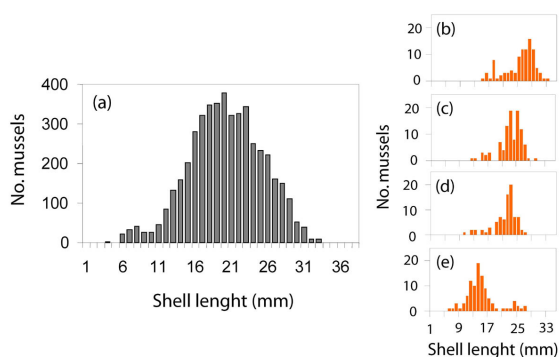
Lough Doon is a dual basin lake situated on the middle reaches of the Owenogarney river system in Co. Clare, Ireland, in a largely agricultural catchment (Figures 1 and 2). The main inflow into the Upper basin is the Killuran River and the Upper basin discharges into the Lower basin via a channel. The outflow from the Lower basin forms the Owenogarney River, discharging into the Shannon Estuary 20 km downstream. The Upper and Lower basins are physico-chemically similar, being circumneutral, generally well-mixed systems with low residence times (Table 1), and both basins meet the optimum ranges of pH, hardness temperature and dissolved oxygen required for zebra mussel colonisation (O'Neill 1996; Rosell et al 1999). Zebra mussels have been observed in Lower Lough Doon since c.1998 (Minchin 2003) and the basin is now heavily colonised in the littoral zone. Zebra mussels were undetected in Upper Lough Doon until dredging in July 2007 revealed a very low population (0.05 mussels m<sup>-2</sup>). Due to its unusual split basin characteristics, Lough Doon is an ideal case study in which to monitor the effects of zebra mussel infestation on water chemistry and ecological processes in a small Irish lough.

**Table 2.** Total number, biomass and filtration capacity of zebra mussels in the Upper and Lower basins of Lough Doon, and theoretical lake water recycling rates.

	Doon Upper	Doon Lower
Mean shell length (mm)	18.18	19.71
Total population	$2.2 \times 10^4$	$5.5 \times 10^8$
Total biomass (kg)	17	$4.9 \times 10^5$
Filtration capacity <sup>1</sup> ( $\text{m}^3 \text{d}^{-1}$ )	18.1	$5.22 \times 10^5$
Recycling rate <sup>2</sup> (d)	134,807	6

<sup>1</sup>Filtration rate calculated as  $44.4 \text{ mL g}^{-1} \text{ WTW h}^{-1}$  (wet tissue mass, shell plus tissue)

<sup>2</sup>Theoretical recycling rate = lake volume  $\div$  filtration capacity



**Figure 3.** (a) Length-frequency distribution of zebra mussels in Lower Lough Doon (mean shell length  $19.7 \pm 0.07 \text{ mm}$ ). Data are from 17 transects at depths of 1 m, 2 m, 3 m, and 4 m ( $n = 4,685$ ). Also shown are length-frequency distributions along a single transect at depths of (b) 1 m, (c) 2 m, (d) 3 m and (e) 4 m ( $n = 382$ ).

## Materials and methods

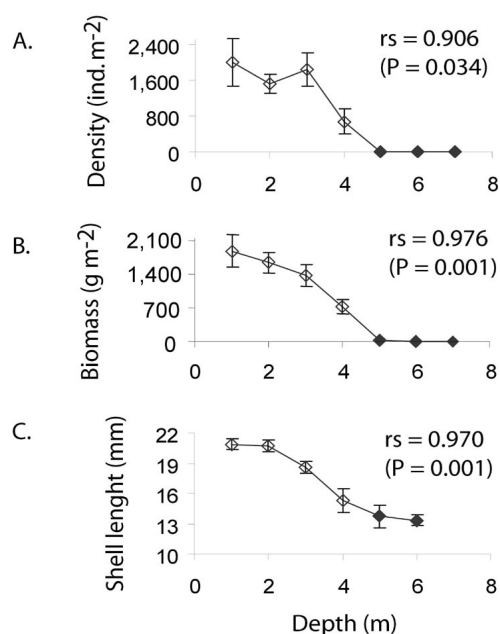
To estimate zebra mussel population density in the Lower basin of Lough Doon, mussels were collected by a SCUBA diver from  $25 \text{ cm}^2$  quadrats at depths of 1 m, 2 m, 3 m and 4 m along a transect. Sampling along 19 transects ( $n=76$ ) was conducted in the Lower Lough Doon in July 2007 (Figure 2). To investigate the presence of zebra mussels in the Upper basin, 25–70 m long dredges were carried out using a 50 cm wide dredge ( $n=12$ ). Dredge lengths were measured using a Trimble GeoXT differential GPS. Dredges were also carried out at depths of greater than 4 m in the Lower basin ( $n=16$ ) where zebra mussel densities were very low and patchy (Figure 2). Zebra mussels  $>1 \text{ mm}$  were counted and measured for shell length, then the entire sample was weighed for total wet weight

(soft tissue plus shell) after opening mussels, removing excess water from the mantle and blotting them dry with absorbent paper. Data on mussel densities, biomass and lengths at different depths were combined with information obtained from digital bathymetric maps on the percentage areas of the basins at different depths to provide estimates of the total zebra mussel populations in the Upper and Lower basins of Lough Doon. Relationships between depth and the density, biomass and shell length of zebra mussels were tested using the Spearman correlation coefficient ( $r_s$ ) and significance levels determined using a two-tailed t-test.

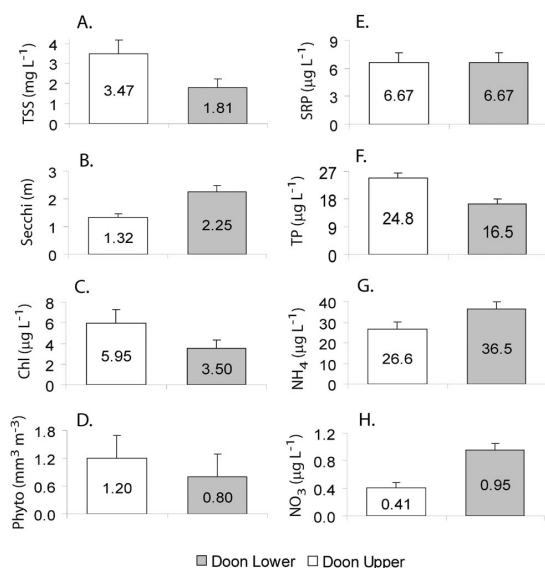
Near surface (0.2 m) samples for water chemistry analysis were collected from mid-lake stations on the Upper and Lower basins of Lough Doon monthly between January and March 2007 and biweekly from April to July 2007 ( $n=12$ ). Measurements of pH, dissolved oxygen (DO), conductivity, temperature and Secchi depth were made in the field with a multiparameter YSI meter and standard Secchi disk. Alkalinity was determined by standard HCl titration and total suspended solids (TSS) were determined gravimetrically (APHA 1998). Colorimetric methods were used for the determination of total phosphorus (TP) and soluble reactive phosphorus (SRP) (Murphy and Riley 1962), nitrate (Nelson, et al. 1954) and ammonium (Grashoff 1976). Chlorophyll was measured spectrophotometrically after extraction in 10% acetone/DMSO mixture (1:1 v/v) (Burnison 1980). Phytoplankton cell biovolumes were calculated on Lugols-preserved samples using the equations of Rott (1981). The statistical significance of differences in water chemistry/phytoplankton biomass between the two basins was determined using the Wilcoxon Signed Ranks test.

## Results

Results of the zebra mussel population survey (Table 2) emphasise the different levels of *Dreissena* infestation in the Upper and Lower basins of Lough Doon. The Lower basin had an estimated population of  $5.5 \times 10^8$  zebra mussels ( $4.9 \times 10^5 \text{ kg}$ ), equating to a filtration capacity of  $5.22 \times 10^5 \text{ m}^3 \text{d}^{-1}$ . By comparison, the Upper basin of Lough Doon was very mildly infested. Zebra mussels were recorded in only 3 of the 12 dredges ( $n=5$  zebra mussels) in the Upper basin, equating to a population of  $2.2 \times 10^4$  (17 kg) and a filtration capacity of  $18.1 \text{ m}^3 \text{d}^{-1}$ .



**Figure 4.** Variation in (a) density, (b) biomass, and (c) shell length, of zebra mussels with depth in Lower Lough Doon. Values plotted are mean for each depth; error bars showing the standard error (SE), Spearman Correlation Coefficients ( $r_s$ ) and levels of significance are also given. Data were collected by SCUBA transects (open-symbols) and dredging (closed symbols).



**Figure 5.** Comparison of water quality characteristics of the Upper and Lower basins of Lough Doon: (a) total suspended solids, (b) Secchi transparency, (c) chlorophyll, (d) phytoplankton biovolume, (e) soluble reactive phosphorus, (f) total phosphorus, (g) ammonium, (h) nitrate. Values shown are mean from January–July 2007 ( $n=12$ ); error bars show standard errors.

The mean shell size of zebra mussels in the Lower basin was 19.71 mm ( $n=4,685$ ) (Table 2) and the large majority of mussels were in the 2+ age cohort (16–23 mm) (Figure 3a). The length frequency distribution at different depths along a single transect (Figure 3b) reveals a second smaller peak at 6–9 mm, the 1+ cohort, likely representing settlement from the previous summer and autumn. The highest density of zebra mussels (1,999  $\text{ind. m}^{-2}$ ) was recorded in the Lower basin at 1 m depth (Figure 4a), while the mean density of zebra mussels lakewide was 860  $\text{ind. m}^{-2}$ . Shell size, population density and biomass were all decreased significantly with depth (Figure 4a–c). At 18.18 mm, the mean shell size of zebra mussels in the Upper basin was smaller than in the Lower basin (Table 2); however, the small sample size ( $n=5$ ) precludes a detailed characterisation of the zebra mussel population in the Upper basin.

Figure 4 compares the mean water chemistry of the two basins from January to July 2007 ( $n=12$ ). The Lower basin had 48% lower concentrations of total suspended solids ( $P=0.008$ ), 41% lower chlorophyll concentrations ( $P=0.004$ ) and 33% lower phytoplankton biomass ( $P=0.124$ ), with conversely 70% higher Secchi transparency ( $P=0.002$ ) (Figures 5a–d). Concentrations of TP were also lower in Lower Lough Doon but not significantly so (34%,  $P=0.150$ ), while mean SRP concentrations were identical in the two basins (Figures 5e–f). Both nitrate and ammonium concentrations were significantly higher in the Lower basin (134%,  $P=0.008$  and 37%,  $P=0.033$ , respectively) (Figures 5g–h).

## Discussion

The Upper and Lower basins of Lough Doon are physico-chemically and morphometrically similar, being circumneutral and generally well-mixed systems with high flushing rates. Both basins meet the optimum ranges of pH, hardness, temperature and dissolved oxygen required for zebra mussel colonisation. At present, however, only the Lower basin contains a sizeable, well established zebra mussel population ( $5.5 \times 10^8$ ) while the Upper basin is only mildly infested ( $2.2 \times 10^4$ ) to date. The mean (860  $\text{ind. m}^{-2}$ ) and maximum (1,999  $\text{ind. m}^{-2}$ ) density of zebra mussels in the Lower basin of Lough Doon is relatively low compared to mean (3,900  $\text{ind. m}^{-2}$ ) and maximum (6,800  $\text{ind. m}^{-2}$ ) densities in

Lough Key, Ireland (Lucy et al. 1995) or mean densities reported from the Great Lakes e.g. 10,000 ind. m<sup>-2</sup> in the western basin of Lake Erie (Arnott and Vanni 1996) and 33,200 ind. m<sup>-2</sup> in 1992 and 4,200 ind. m<sup>-2</sup> in 1993 in Saginaw Bay, Lake Huron (Nalepa et al. 1995). Thus, the zebra mussel population in Lower Lough Doon during July 2007 can be considered a modest infestation. The movement of boats into Lough Doon via a public slipway at the Lower basin is the most likely route of initial infestation in the mid or late-1990s. Zebra mussels now heavily colonise rocks and stones, macrophytes, dead *Anodonta* shells and aggregations of dead *Dreissena* shells in the littoral zone of the Lower basin at depths of 1–3 m. Zebra mussel density, biomass and shell size all declined significantly in the Lower basin below 3 m depth. Whether this trend reflects a higher proportion of young mussels or slower growth rates at greater depths is not yet known. The large difference in zebra mussel densities in the Upper and Lower basins of Lough Doon provided a unique experimental design to investigate whether the well-documented trends from large lakes in Europe and North America following *Dreissena*-infestation are replicated in a small, well-mixed Irish lough.

A comparison of water chemistry data from the Upper and Lower basins from January–July 2007 provides the first indication of the impact of zebra mussel infestation on water quality in Lough Doon. The reduced concentrations of TSS, chlorophyll and phytoplankton biovolumes and increased Secchi transparency in the Lower basin are likely to reflect the filter-feeding action of the zebra mussel population. *Dreissena polymorpha*'s efficacy in clearing large quantities of phytoplankton, small zooplankton and other suspended solids, thereby reducing water column turbidity and seston load, is well known (Berg et al. 1996, Lucy et al. 2005). Increases in the depth of the photic zone can enhance the growth of submerged macrophytes and periphyton in infested lakes (Zhu et al. 2006). Ongoing research will ascertain whether these indirect effects of zebra mussel filtration become manifest in Lower Lough Doon.

As well as differences in turbidity, the two basins also differed significantly in terms of nutrient concentrations. Concentrations of TP were lower in the Lower basin, SRP concentrations showed no change while concentrations of ammonium and, in particular, nitrate were

notably higher in the Lower basin. Observations of reductions in TP, a proportionately greater fraction of phosphorus as SRP and increases in nitrate and ammonium in the Lower basin of Lough Doon mirror findings from other infested lakes (Gardner et al. 1995; Holland et al. 1995; Arnott and Vanni 1996; Effler et al. 1996, James et al. 2000; Conroy et al. 2005), possibly indicating accelerated recycling of nutrients by the coupled consumption-excretion activities of zebra mussel populations in the Lower basin. As zebra mussels filter large amounts of water, they also process large amounts of suspended nutrients. Ingested nutrients can be utilised for growth and reproduction, excreted in particulate organic form as faeces or pseudofaeces or excreted in dissolved inorganic forms which are readily bioavailable. Excretion rates are biomass-dependent, with larger zebra mussels having higher nutrient excretion rates (Conroy et al. 2005). With a mean shell length of 19.71mm, zebra mussels in Lower Lough Doon can be categorised as large (Arnott and Vanni 1996) or moderately large (Conroy et al. 2005) relative to zebra mussels in other lakes. Some studies have shown that zebra mussels excrete N:P at below the Redfield ratio of 16:1, which can decrease P limitation but increase N limitation in lakes, offering an explanation for promoted growth of cyanobacteria in infested waterbodies (Arnott and Vanni 1992). Other studies have found that nutrients are excreted at mass ratios of greater than 40, suggesting that zebra mussels are a phosphorus sink and nitrogen source (Gardner et al. 1995). There was no difference in concentrations of SRP between the Upper and Lower basins during the current study. The likely explanation is that any remineralised phosphate would be rapidly taken up in Lough Doon due to the prevailing phosphorus-limiting conditions, as indicated by high ambient N/P ratios (TP:TN 44) in the lake.

By contrast, concentrations of ammonium and especially nitrate were significantly higher in the Lower basin of Lough Doon. The direct excretion of ammonium by zebra mussels has been found to elevate ambient ammonium concentrations in other infested lakes, profoundly affecting community nitrogen dynamics (Gardner et al. 1995). Increases in nitrate may arise indirectly from the oxidation of excreted ammonium to nitrate by nitrifying bacteria in environments where nitrogen concentrations exceed the needs of the biota (Gardner et al.

1995; James et al 1997). If, as these preliminary results suggest, excretion by zebra mussels is a major flux of dissolved inorganic nutrients, relative to other external and internal nutrient sources, it would be highly significant for the nutrient budget of Lower Lough Doon and potentially that of other similarly infested lakes. It is clear that continued monitoring and experimental manipulations are needed to conclusively demonstrate a causal link between *Dreissena* invasion and water quality differences between the infested and uninfested basins of Lough Doon, and to determine if these patterns persist in the long term as zebra mussel populations in the Lower basin stabilise and those in the Upper basin, likely, increase in time. Nevertheless, the coupled declines in phytoplankton biomass/turbidity and changes in nutrient concentrations recorded in the Lower basin strongly suggest that Lough Doon is experiencing similar changes following zebra mussel infestation as other larger lakes.

In conclusion, our data for Lough Doon provide early evidence that modest zebra mussel populations can markedly affect water quality in small lakes, reducing turbidity, phytoplankton biomass and particulate nutrient concentrations and increasing concentrations of dissolved inorganic nutrients, particularly nitrate. This new evidence of altered nutrient dynamics and energy flows in *Dreissena*-infested lakes holds important implications for both the ecology of Irish loughs and water quality management practices as the zebra mussel continues to spread.

## Acknowledgement

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