# Modelling of change in total phosphorus and ecological status of Loch Tay with increase in fish cage biomass.

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# 1. Modelling

This study used the InVEST NDR catchment model (Redhead et al, 2018) combined with three different lake models, LakeMab (Hakanson & Bryhn, 2008), and the Dillon and Rigler (1974) and OECD (1982) models, to predict P levels in Loch Tay under differing production scenarios.

For the loch catchment, the InVEST NDR model provided values of phosphorus export to waterways under differing land use and land cover between 2020 and 2025. These values were then used as inputs to the lake models.

As Loch Tay has been used for aquaculture production and the total phosphorus (TP) levels within the loch have been measured for a number of years, the model was tested by comparing modelled TP inputs from catchment and fish farm with the measured data. For the OECD and Dillon & Rigler models this used the annual geometric means. For the dynamic LakeMab model this used the geometric mean contentions from each sampling occasion. Measured and modelled data was tested between 2020 and 2025.

Once the likely error of the model was known the models were re-run under a number of scenarios: 50% (**284 t)**, 70% (**322 t)**, 100% (**379 t)**, 200% (**568 t)**, and 300% (**757 t)** increase in existing biomass, in order to predict TP levels under new production levels.

Predicted TP concentrations under baseline conditions (no change in biomass) and under 100%, 200%, and 300% increases in production were converted to total lake phosphorus mass. Using the Dillon & Rigler model outputs, each predicted concentration was multiplied by the loch's volume ($1.6 \times 10^{12}$ L), assuming the loch is well mixed, and phosphorus is evenly distributed throughout the water column.

The modelled outputs for each scenario were assessed against a change in ecological status for TP of the loch according to SEPA WFD criteria of 12 $\mu g\ L^{-1}$ (Good-Moderate status; Scotland River Basin District (Standards) Directions, 2014), and the more conservative TP threshold of 8.81 $\mu g\ L^{-1}$ (High-Good status)

# 2. Study area

Loch Tay is a body of freshwater situated in mainland Scotland which runs between Aberfeldy and Killin. It is a long narrow loch of approximately 23 km long, following the line of the valley in a southwest to northeast orientation (see Figure 1). It is the sixth largest loch in Scotland by area and up to 150m at its deepest. With an average depth of 60 m and surface area of 26.4 $km^2$, the loch has an approximate water volume of $1600 \times 10^6$ $m^3$ (Murray and Pullar, 1910).

The catchment is in the Grampians (rising up to >1200m) and is steeply sloping except for the valley bottom. Mountainous, often snowy in winter. Bedrock almost all metamorphic; half overlain by superficial deposits. Land use rough grazing with forest. Catchment contains Loch Tay and some smaller lochs upstream. Hydro-electric power schemes have developed in the catchment.

A map of Loch Tay and its catchment is given in Figure 1. This shows the land-use characteristics and percentage areas (NFRA, 2026 - https://nrfa.ceh.ac.uk/data/station/spatial/15016*)*. This is used in InVEST NDR to calculate TP export over time.

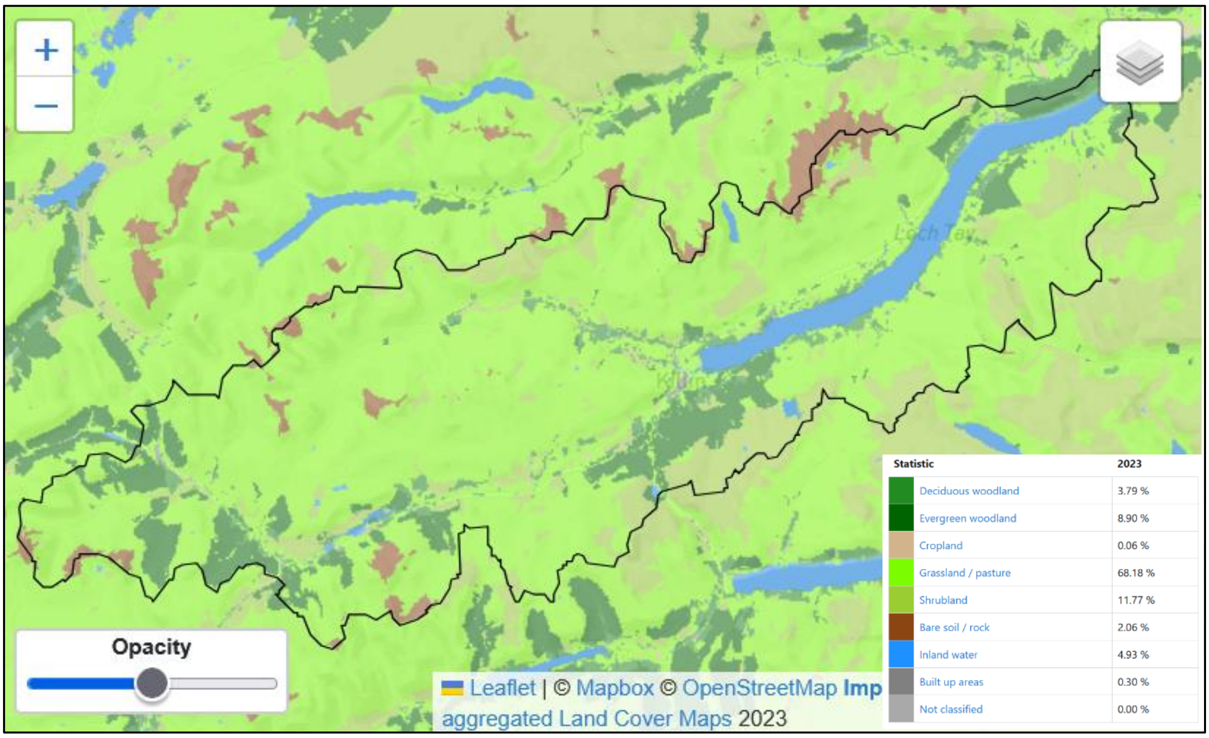


***Figure 1. Loch Tay catchment and land-use (NFRA, 2026).***

## 3. Measured data – collection and analysis

Water samples were collected by the University of Stirling (UOS) staff using a 5-litre capacity Van Dorn water sampler lowered through the water column using a rope marked at 1m intervals. The Van Dorn was lowered in the open position to the correct depth, and the closure mechanism was triggered by a messenger weight dropped down the rope from the surface, which closed the sampler.

After retrieval to the surface, water was decanted into acid-washed 500 ml polyethylene bottles and retained for analysis of Chlorophyll-a concentration. A 100 ml aliquot was decanted from the sampler into acid washed glass flasks with cleaned foil beneath screw caps, which was then used for analysis of total phosphorus. In all cases the bottles were washed through with collected water, which was then discarded, before the sample itself was taken. All samples were transported to the laboratory at Stirling for analysis.

Total phosphorus was determination using a standard perchlorate extraction and molybdenum-blue analysis method (HMSO, 1981). After extraction in methanol, chlorophyll *a* was measured spectrophotometrically (Golterman *et al*,1978).

Total Phosphorus levels measured throughout the year by the UOS (black symbols), are given in Figure 2 between 2017 and 2025. In addition, SEPA measured results are given for comparison (grey symbols). Both results show seasonal variability and overall fluctuations but show similar ranges. A linear line of best fit for each dataset over the sampling period show similar characteristic values and trends. There is a gap in the data between 2020 and later 2021 for Stirling and 2023 for SEPA due to Covid 19 restrictions and technical issues.

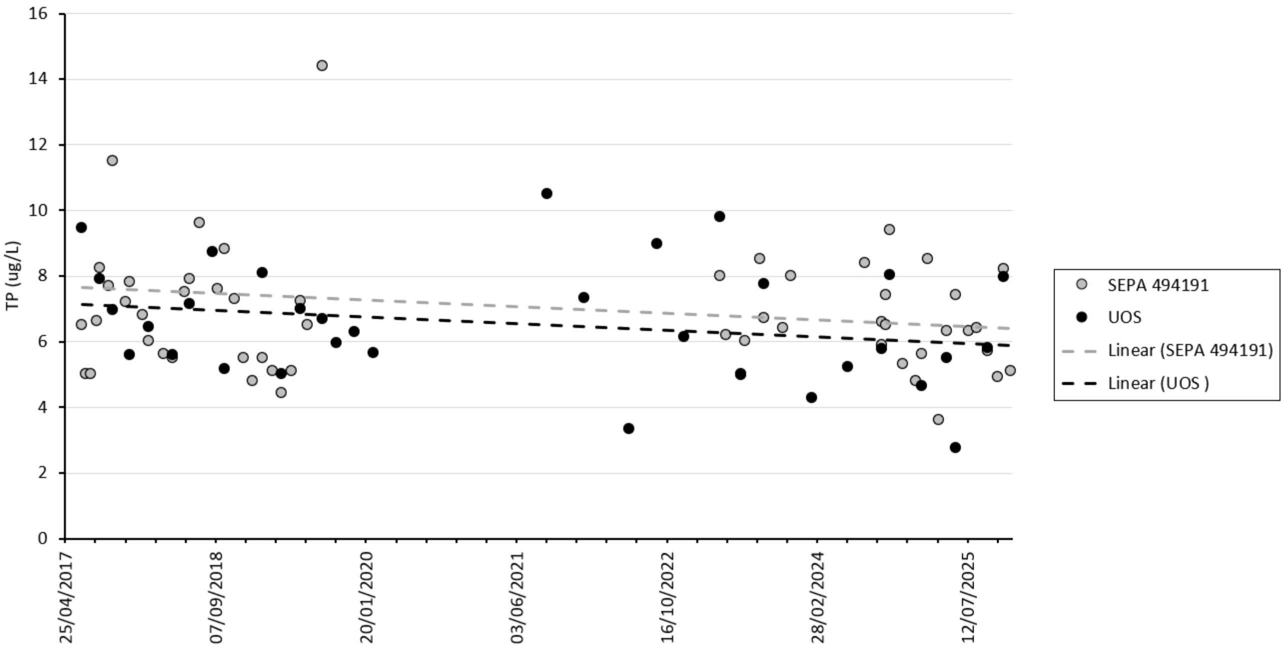


***Figure 2. Measured concentrations of total phosphorus (μgl$^{-1}$) for each sampling occasion with linear trendline from June 2017 to June 2025. Data is given from a geometric mean of Stirling results over the loch and for SEPA results taken from the outflow into the River Tay (Station 494191). These allow a comparison.***

# 4. Results

## 4.1 Model testing with measured data

The models were tested in Loch Tay by comparing predicted values against measured data. Using the existing 2025 aquaculture biomass, the models produced similar results which were within a standard deviation of the mean of the measured values for SEPA (6.74 ± 0.64 μg L$^{-1}$) and UOS (6.32 ± 0.82 μg L$^{-1}$) – see Figure 3. The Dillon & Rigler and OECD models were in line with the measured values for TP (6.13 ± 0.62 μg L$^{-1}$ and 6.53 ± 0.44 μg L$^{-1}$, respectively). The RMSE values varied slightly with SEPA comparison being 0.96 and 0.22 μg L$^{-1}$ for Dillon & Rigler and OECD respectively. The RMSE values for UOS measured data comparison was 0.81 and 0.88 μg L$^{-1}$ for Dillon & Rigler and OECD respectively. The annual mean measured levels of TP and modelled TP are plotted together to allow comparison in Figure 4.

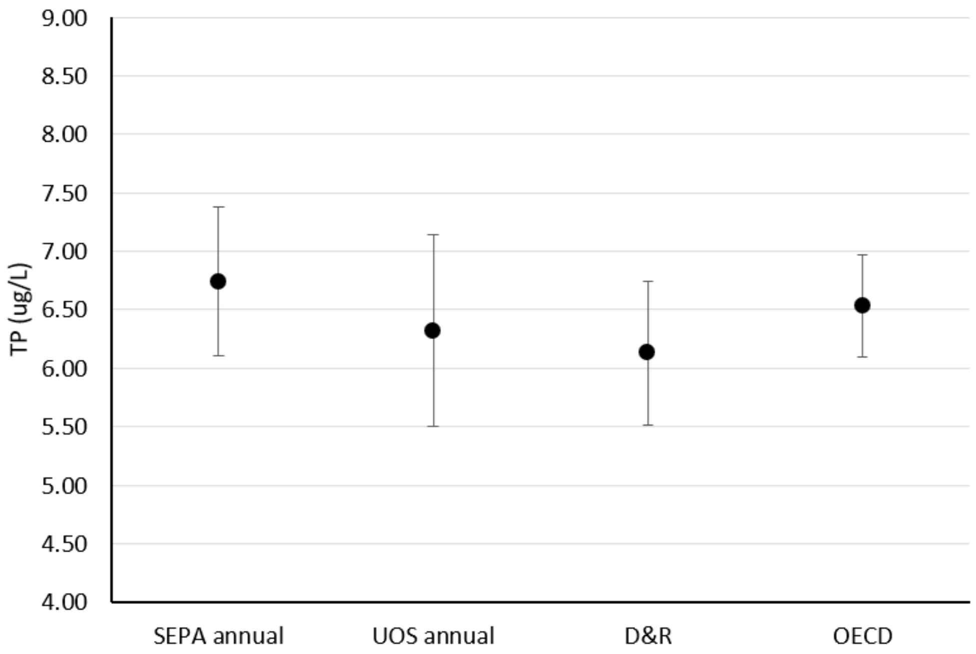


***Figure 3  Overall mean and standard deviation of the measured and modelled for annual TP in Loch Tay from 2020 to 2025.***

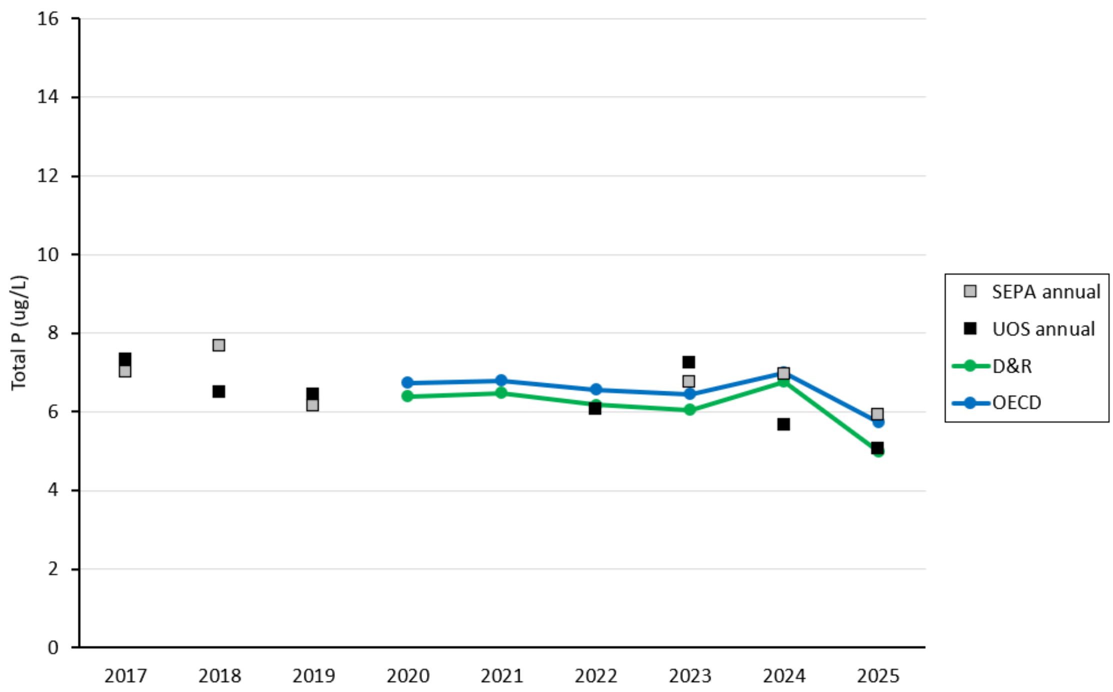


***Figure 4 The total phosphorus modelled by the OECD and Dillon & Rigler models for 2020 - 2025 with no change to the aquaculture biomass in Loch Tay. For comparison annual geometric mean values calculated for UOS and SEPA's results are plotted for 2017 – 2025.***

The LakeMab model overpredicted the TP (7.25 ± 0.69 μg $L^{-1}$), producing an RMSE value of 2.76 μg $L^{-1}$, though, notably, this model allows for seasonal variability. The modelled values for the original production biomass are compared with the measured levels in Table 1 and Figures 4 and 5.

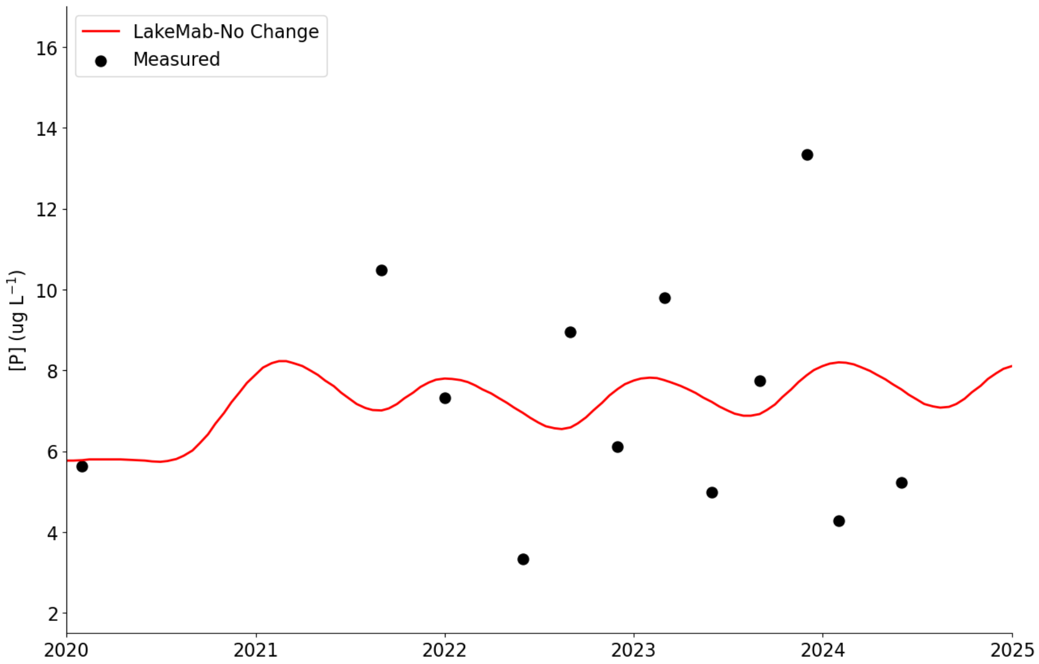


***Figure 5. The total phosphorus concentration measured (UOS) and modelled by the LakeMab model for 2020-2025 with no change to the aquaculture biomass in Loch Tay.***

## 4.2 Additional fish cage biomass

To understand the capacity for increased production, we modelled TP concentrations under scenarios representing a 50% (**284 t)**, 70% (**322 t)**, 100% (**379 t)**, 200% (**568 t)**, and 300% (**757 t)** increase in farming activity. The results can be found in Table 1 with figure representations in Figures 6-11.

***Table 1 Mean modelled concentrations for TP (ug/L) under baseline production (189 t) and increased farming production scenarios (50% [284 t], 70% [322 t], 100% [379 t], 200% [568 t], 300% [757 t]) between 2020 and 2025***

| Model | Original ($\mu g\ L^{-1}$) | Production level increase<br>50% ($\mu g\ L^{-1}$) | 70% ($\mu g\ L^{-1}$) | 100% ($\mu g\ L^{-1}$) | 200% ($\mu g\ L^{-1}$) | 300% ($\mu g\ L^{-1}$) |
|---|---|---|---|---|---|---|
| OECD | 6.83 ± 0.47 | 7.76 ± 0.55 | 8.12 ± 0.58 | 8.66 ± 0.63 | 10.36 ± 0.78 | 11.97 ± 0.92 |
| Dillon & Rigler | 6.40 ± 0.64 | 7.27 ± 0.73 | 7.62 ± 0.76 | 8.14 ± 0.82 | 9.89 ± 0.99 | 11.64 ± 1.17 |
| LakeMab | 7.25 ± 0.69 | 7.79 ± 0.74 | 8.00 ± 0.77 | 8.33 ± 0.80 | 9.41 ± 0.93 | 10.48 ± 1.05 |
| Measured annual mean (SEPA) | 6.74 ± 0.64 | | | | | |
| Measured annual mean (UOS) | 6.32 ± 0.82 | | | | | |

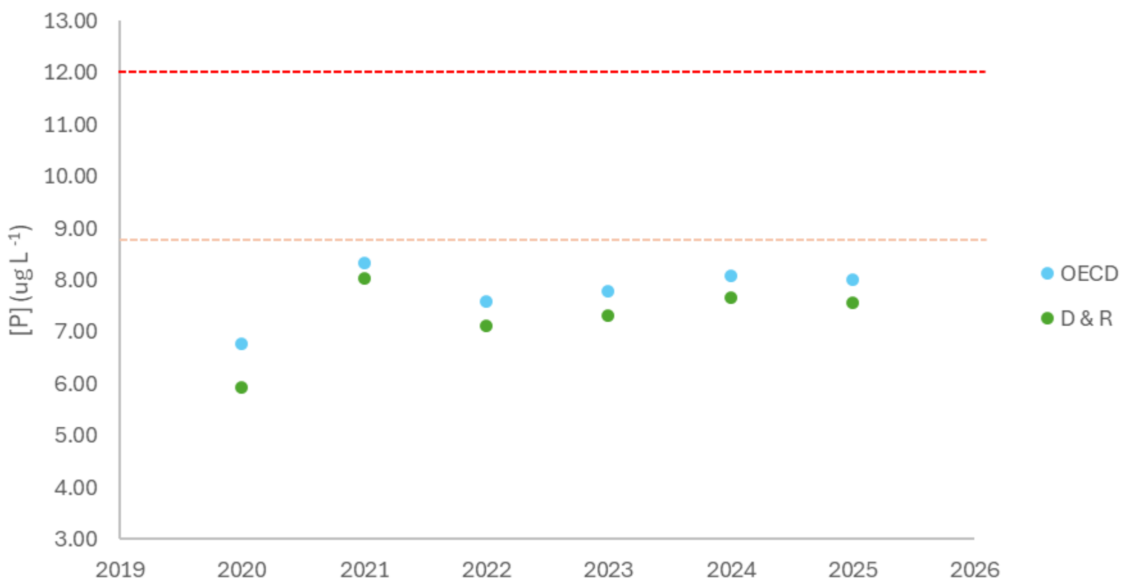


***Figure 6. The total phosphorus concentration modelled by the OECD and Dillon & Rigler models for 2020-2025 with a 50% increase to the aquaculture biomass in Loch Tay. Horizontal lines mark the conservative 8.81 $\mu g\ L^{-1}$ TP threshold and the 12 $\mu g\ L^{-1}$ boundary for a change in ecological status under SEPA WFD criteria.***

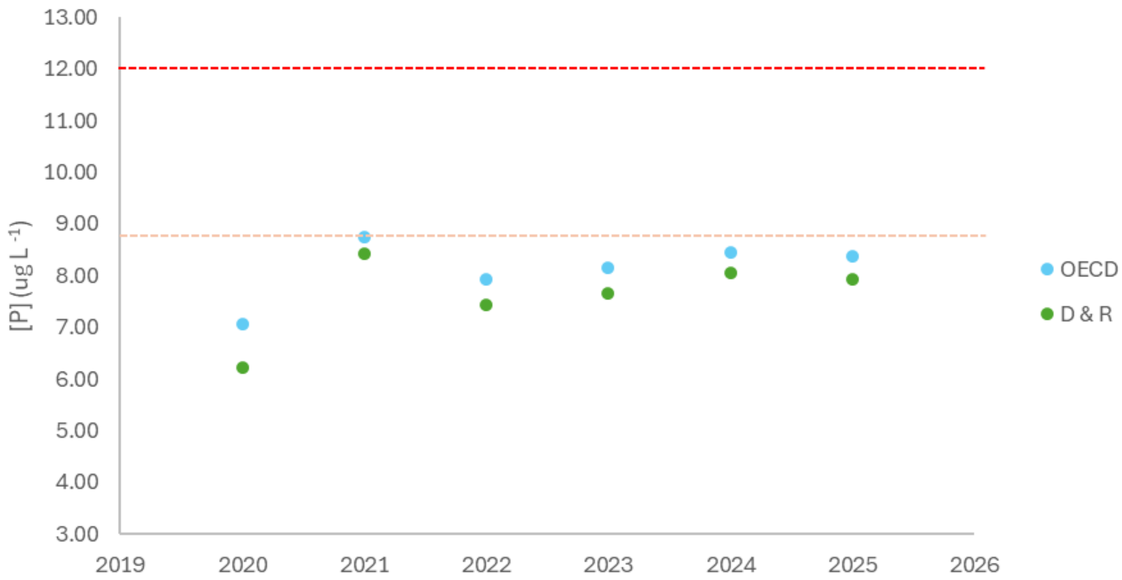


***Figure 7. The total phosphorus concentration modelled by the OECD and Dillon & Rigler models for 2020-2025 with a 70% increase to the aquaculture biomass in Loch Tay. Horizontal lines mark the conservative 8.81 μg L $^{-1}$ TP threshold and the 12 μg L $^{-1}$ boundary for a change in ecological status under SEPA WFD criteria.***

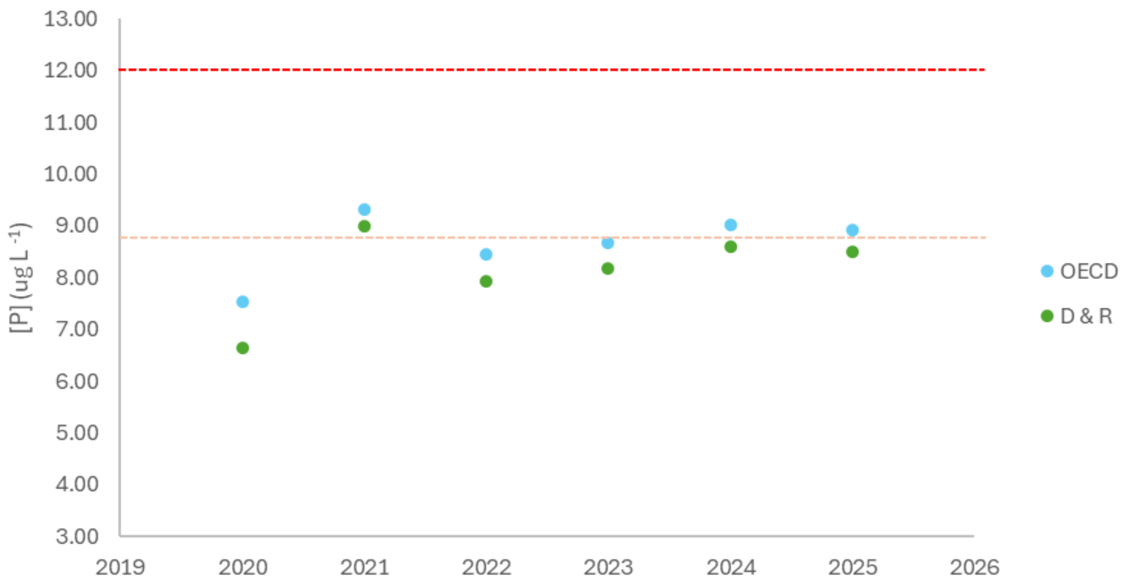


***Figure 8. The total phosphorus concentration modelled by the OECD and Dillon & Rigler models for 2020-2025 with a 100% increase to the aquaculture biomass in Loch Tay. Horizontal lines mark the conservative 8.81 μg L $^{-1}$ TP threshold and the 12 μg L $^{-1}$ boundary for a change in ecological status under SEPA WFD criteria.***

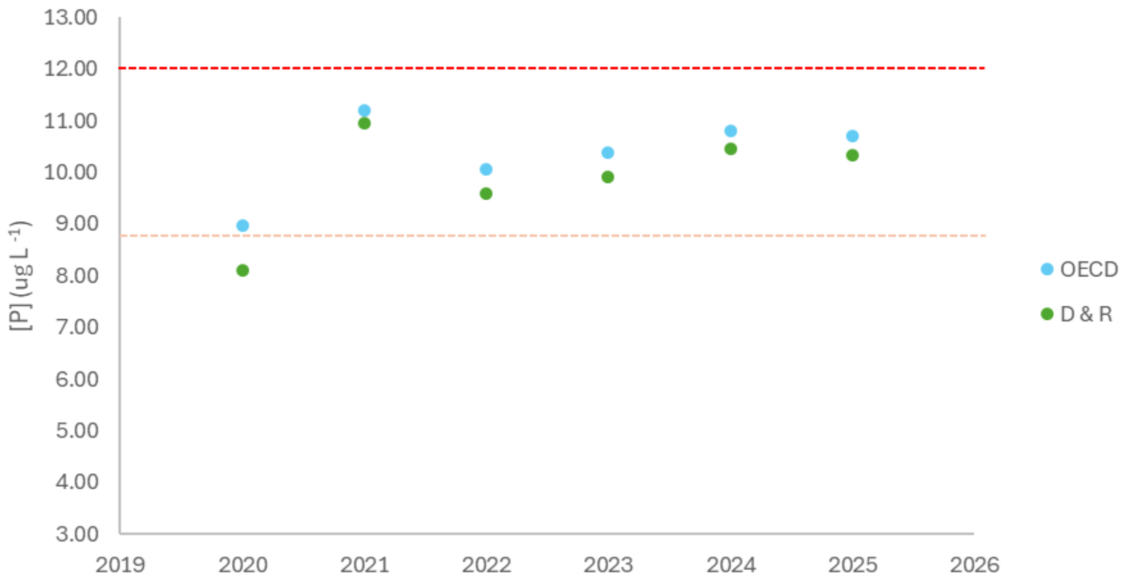


***Figure 9. The total phosphorus concentration modelled by the OECD and Dillon & Rigler models for 2020-2025 with a 200% increase to the aquaculture biomass in Loch Tay. Horizontal lines mark the conservative 8.81 µg L $^{-1}$ TP threshold and the 12 µg L $^{-1}$ boundary for a change in ecological status under SEPA WFD criteria.***

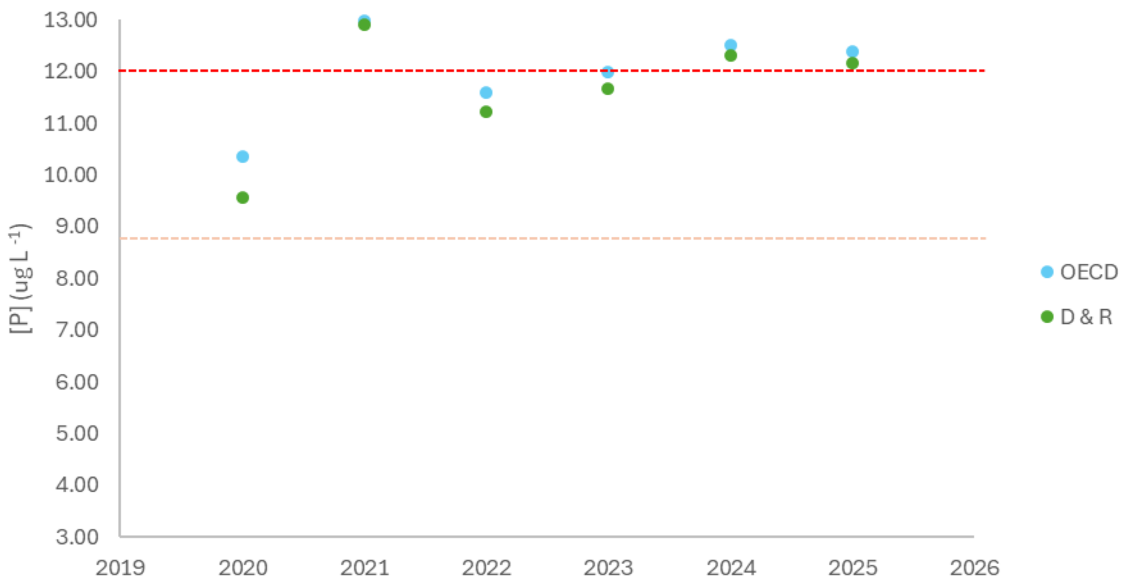


***Figure 10. The total phosphorus concentration modelled by the OECD and Dillon & Rigler models for 2020-2025 with a 300% increase to the aquaculture biomass in Loch Tay. Horizontal lines mark the conservative 8.81 µg L $^{-1}$ TP threshold and the 12 µg L $^{-1}$ boundary for a change in ecological status under SEPA WFD criteria.***

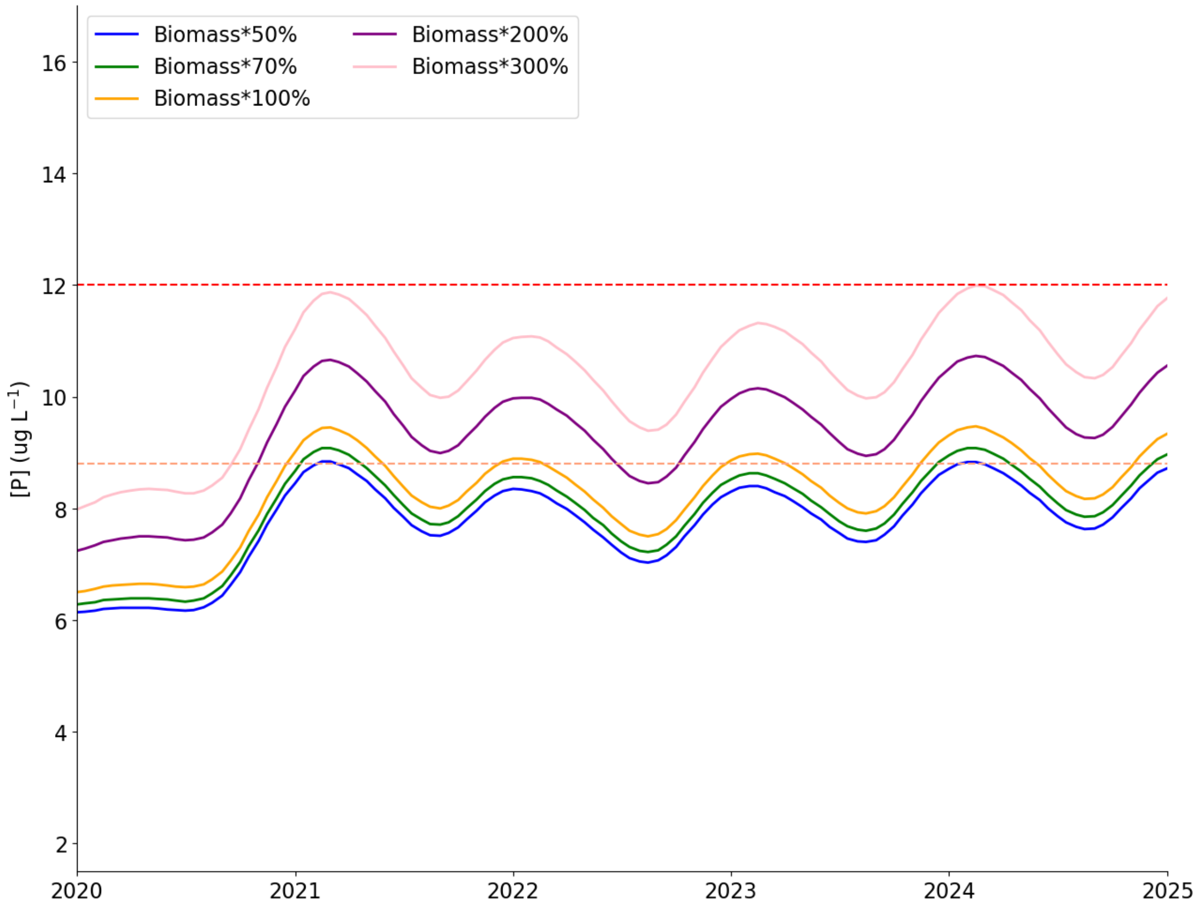


***Figure 11. The total phosphorus concentration modelled by the dynamic LakeMab model for 2020-2025 with 50% (blue), 70% (green), 100% (orange), 200% (purple), and 300% (pink) increase to the aquaculture biomass in Loch Tay. Horizontal lines mark the conservative 8.81 µg L $^{-1}$ TP threshold and the 12 µg L $^{-1}$ boundary for a change in ecological status under SEPA WFD criteria.***

Modelled phosphorus concentrations corresponded to a TP load of 9524 ± 231 kg y$^{-1}$ to the loch, under baseline conditions with no change to production biomass. With 100%, 200% and 300% increase to production the predicted TP mass increased to 12124 ± 234 kg y$^{-1}$, 14725 ± 238 kg y$^{-1}$, and 17325 ± 243 kg y$^{-1}$, respectively. These values were compared with the two management thresholds outlined previously which equate to a conservative threshold of 13239 ± 1501 kg y$^{-1}$ and 17854 ± 2044 kg y$^{-1}$ for the upper limit prior to a change in the ecological status of the loch. The conversion from concentration to mass discharge per year did not alter the relative pattern of model outputs but provided a clearer basis for evaluating the loch's status against the regulatory limit. These results are outlined in Table 2 and Figure 12 below.

*Table 2. The total phosphorus (kg $y^{1}$) discharge in the loch including the catchment and farm production under the baseline [189 t] conditions and increases in production of 100% [to 379 t], 200% [to 568 t], 300% [to757 t], compared to the 8.81 μg $L^{-1}$ thresholds.*

| Model | Thresholds 8.81 μg $L^{-1}$ (kg $y^{-1}$) | 12 μg $L^{-1}$ (kg $y^{-1}$) | Production level increase Original (kg) | 100% (kg) | 200% (kg) | 300% (kg) |
|---|---|---|---|---|---|---|
| Dillon & Rigler | **13239±1501** | **17854±2044** | 9524±231 | 12124±234 | 14725±238 | 17325±243 |

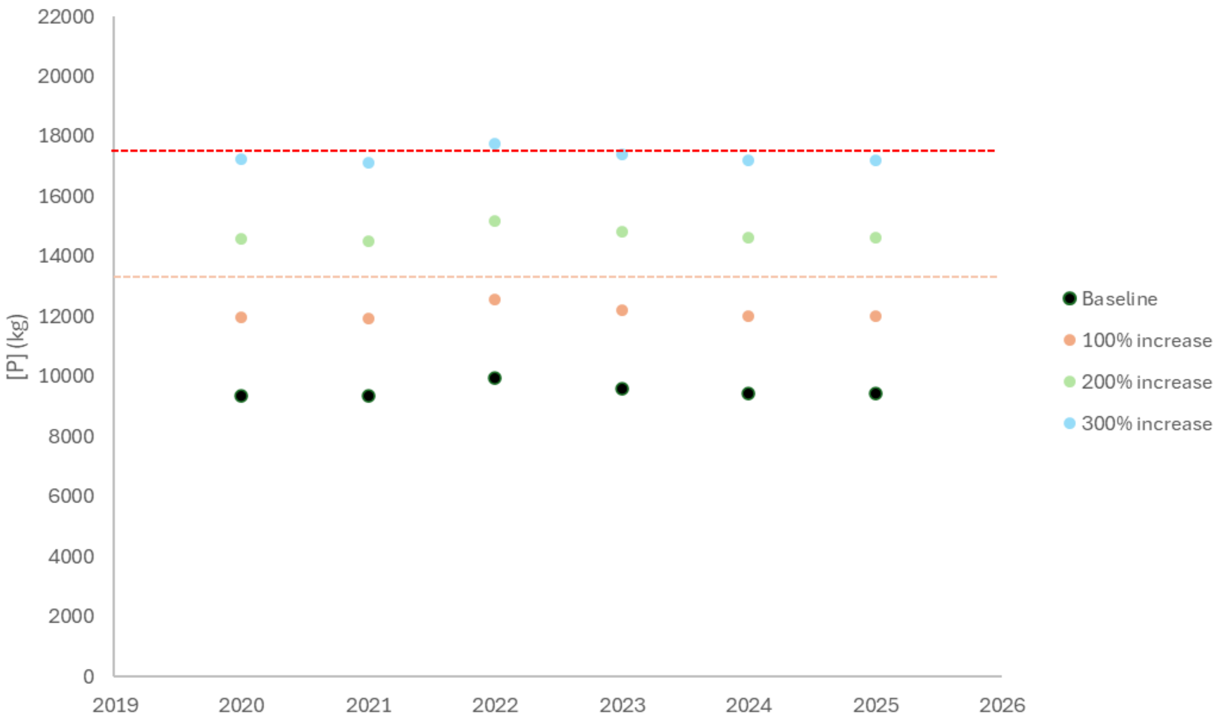


*Figure 12. The total phosphorus discharge (kg $y^{1}$) modelled by the Dillon & Rigler model for 2020-2025 with no change in biomass (baseline; black), 100% (orange), 200% (green), and 300% (blue) increase to the aquaculture biomass in Loch Tay. Horizontal lines mark the conservative 8.81 μg $L^{-1}$ (mean 13 239 kg $y^{1}$) TP threshold and the 12 μg $L^{-1}$ (17 854 kg $y^{1}$) boundary for a change in ecological status under SEPA WFD criteria.*

## 5. Conclusions

All three models showed similar performance for the baseline conditions, with RMSE values consistent with those observed in the model testing study (2.68, 2.69, 2.76 μg $L^{-1}$ for OECD, Dillon & Rigler, and LakeMab, respectively; Burke et al., *under review*). Given their similar and relatively low error magnitudes, all three models appear suitably accurate for subsequent scenario analyses.

Across all models and production scenarios, mean predicted TP concentrations between 2020 and 2025 remain below the Water Framework Directive threshold of 12 μg $L^{-1}$, as defined in the *Scotland River Basin District (Standards) Directions 2014*. SEPA sets a conservative TP threshold of 8.81 μg $L^{-1}$, and under these conditions the models suggest a 100% increase in biomass or less remains within this boundary.

From Table 2, existing production and loading from other sources, gives a modelled input on 9,524 kg $y^{-1}$ TP into the loch. A conservative increase in production by 100% over existing would be the equivalent total load of 12,124 kg $y^{-1}$ TP of which 2,600 kg $y^{-1}$ TP would enter Loch Tay from the aquaculture site.

However, the total modelled loading within the loch to reach the annual geometric mean TP concentration of 13,239 kg $y^{-1}$of which 3,715 kg $y^{-1}$ would be from aquaculture. However, as this is at the limit of capacity and to give a more conservative figure by allowing a 5% buffer (662 kg $y^{-1}$) this would give an additional modelled TP loading capacity of 3,053 kg $y^{-1}$ from aquaculture in Loch Tay.

This conclusion is supported by the consistency of results across three independent loch modelling approaches, each of which incorporates different assumptions and levels of complexity for nutrient behaviour within the loch. The similarities in model outputs indicates that, under the production scenarios, the loch's ecological status defined by TP would remain unchanged. While the models carry inherent uncertainties, the agreement across multiple methods provides confidence in the overall direction and robustness of the findings.

There are, however, several limitations to acknowledge. The static models rely on simplifying assumptions that may not fully capture the dynamic behaviour of the system, particularly under changing environmental conditions. For the LakeMab model, fixed loch-specific parameterisation (e.g. sedimentation rate, stratification, sediment thickness) introduces additional uncertainty, especially where empirical data were limited. Despite these caveats, the models provide a valuable framework for understanding potential system responses and for comparing the relative effects of different production scenarios to aid in decision-making.

## 6. References

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