USING LINEAR MIXED MODELS IN LAKE MANAGEMENT AND DECISION MAKING

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INTRODUCTION

Lake management for reducing in-lake chlorophyll *a* concentrations focuses usually on the role of nutrients. Although there is a somewhat linear relationship between phosphorus/nitrogen levels and chlorophyll *a*, it is often impossible to examine it by using linear regression, without violating the assumptions about normality, homoscedasticity or independence. In addition, nutrients alone do not explain all the variation in chlorophyll *a*.

Proper analysis of data with a complex, hierarchical structure is possible with **linear mixed models (LMM)**, that take into account the variation that is not generalisable to the independent variables. Responses from a subject are thought to be the sum of fixed (affect on population mean) and random (contribution to the covariance structure of the data) effects. LMM allow interactions between any combination of discrete and continuous variables.

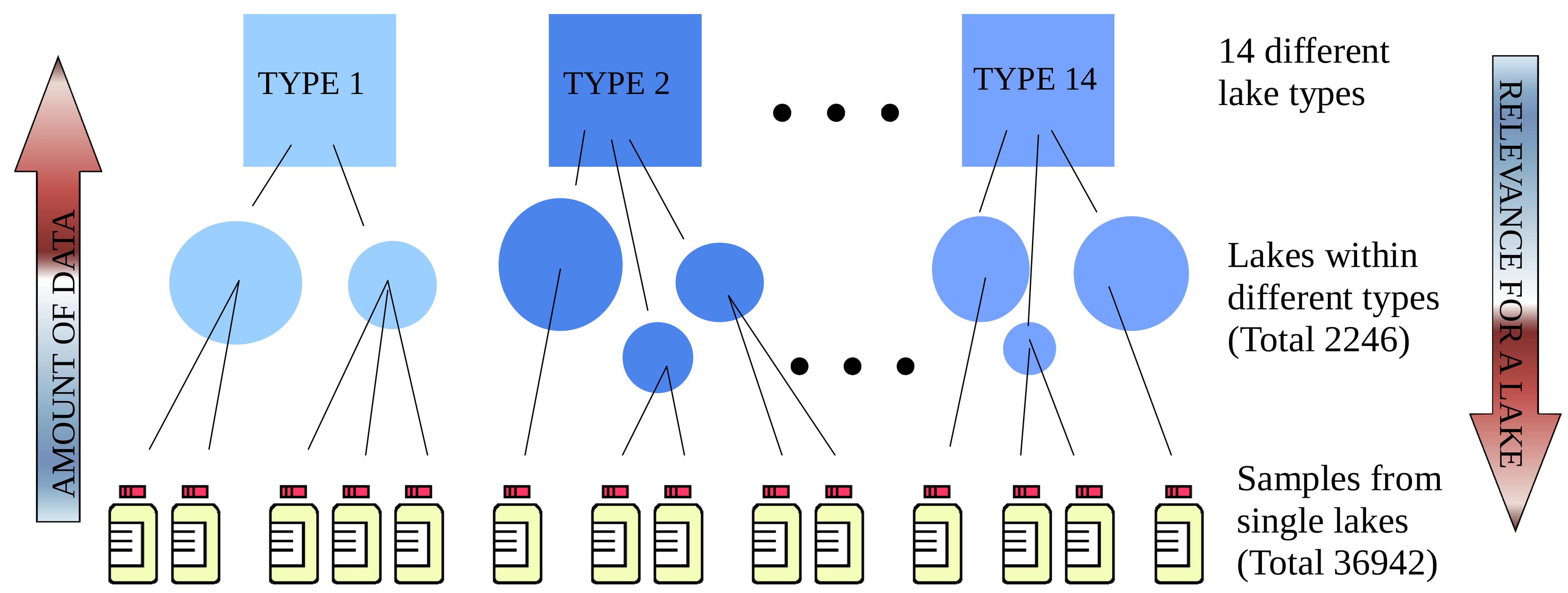


Fig 1. Hierarchical data structure of chlorophyll *a* in Finnish lakes that weights the observation data from the study lake when there is plenty, but enables predictions also for less studied lakes or beyond the range of observed values for invocation of data from more general levels. The number of lakes within different lake types varies from 10 to 400 and the samples taken from single lakes from few to several hundred.

METHODS

Our data included all the concurrent sampling results of total phosphorus, nitrogen and chlorophyll *a* concentrations of the Finnish Environment Administration. The data was given a hierarchical structure (Fig 1).

We set the main effects of phosphorus and nitrogen concentrations as fixed variables. Their effect on chlorophyll *a* concentration vary within lake types and lakes which where therefore treated as random variables.

Bayesian inference with Markov Chain Monte Carlo (MCMC) method was used to simulate the posterior distribution of the model parameters thus giving more realistic assessment of the model uncertainty.

The mixed effects chlorophyll *a* model was implemented in the easy to use and free LakeLoadResponse (LLR) tool, in which the dependency of in-lake concentrations on external nutrient loading is also estimated. This way our model can be directly applied for lake management planning aiming to loading reductions. LLR is accessible from

http://lakestate.vyh.fi and http://www.environment.fi/syke/gisbloom

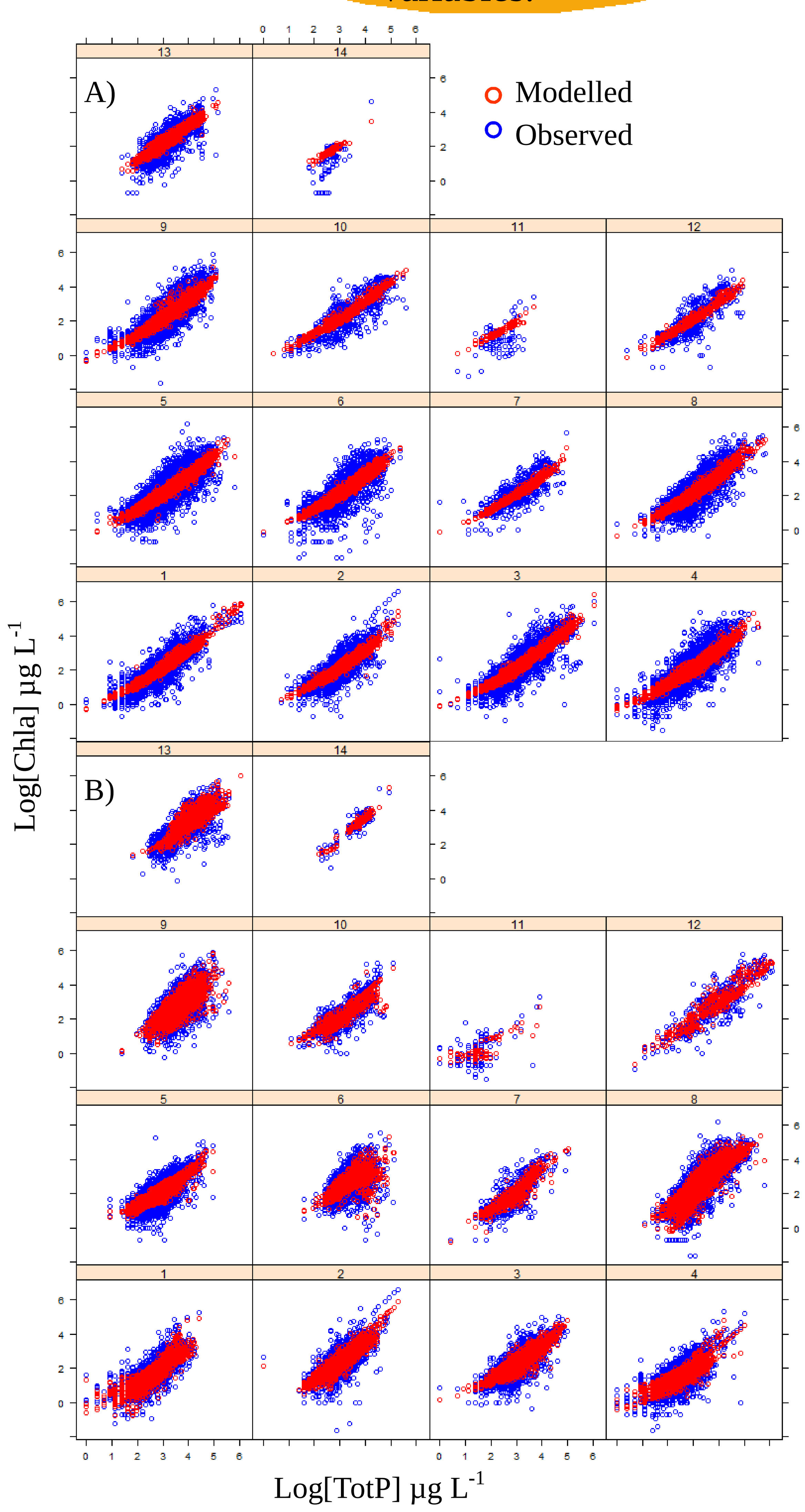
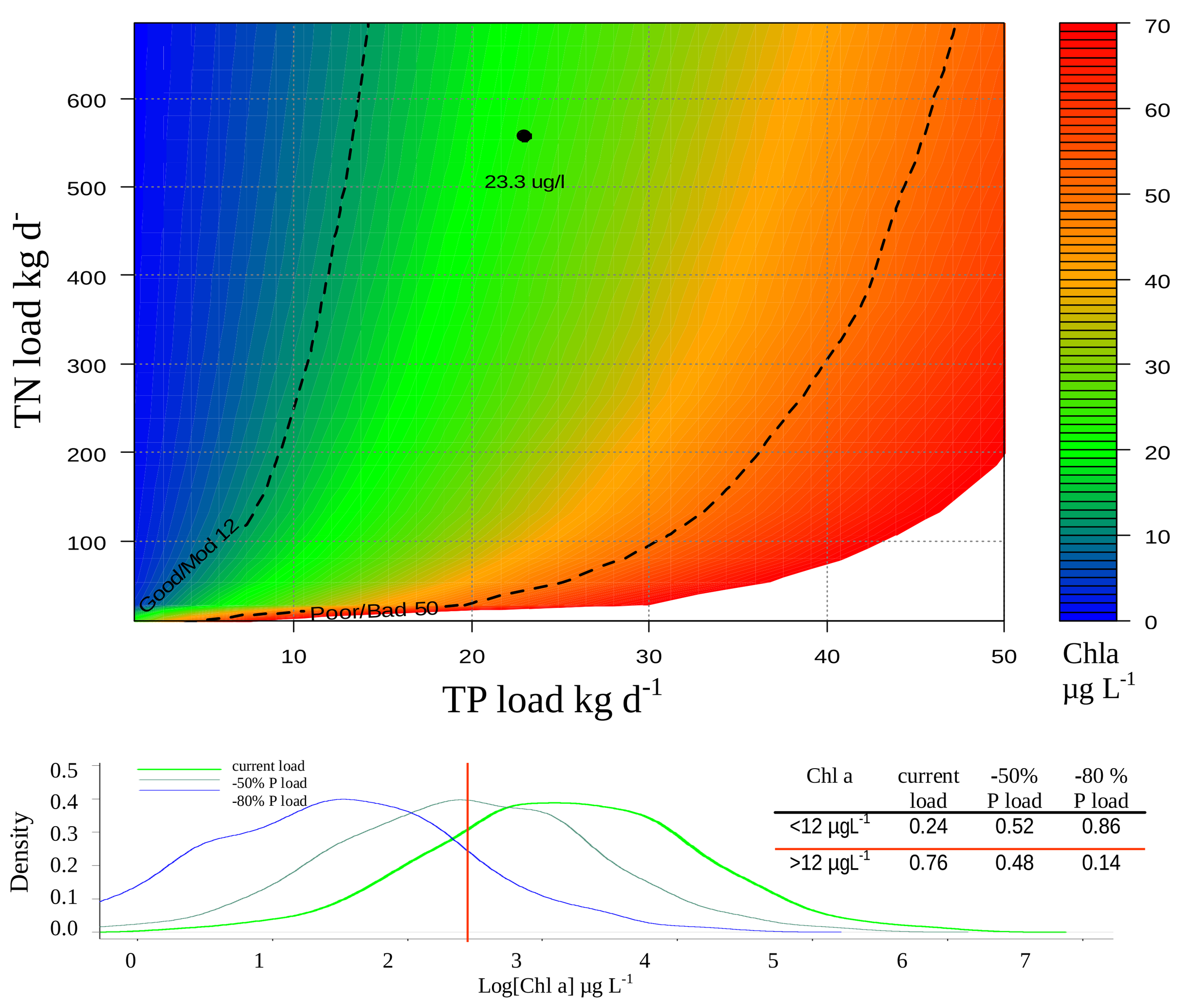


Fig 2. Model fit for chlorophyll *a* (Chla) and total phosphorus (TotP) relation in different types (1-14) of lakes using A) fixed effects model and B) linear mixed model. Finnish lakes are divided into different types depending on the area, depth, and water colour of the lake (for implementation of the Water Framework Directive).



Chl a	current load	-50% P load	-80 % P load
<12 μgL^{-1}	0.24	0.52	0.86
>12 μgL^{-1}	0.76	0.48	0.14

Fig 3. Example of LLR output (upper). The black dot is the average chlorophyll *a* (Chla) estimate as a function of phosphorus (TP) and nitrogen (TN) loading with prediction probability 0.5. The density plot demonstrates the distribution of Chla estimate from MCMC simulations with present loading and reduced TP loading. The red vertical on density plot indicates the good/ moderate class boundary of Chla concentration, and listed are the probabilities to have concentrations below or above the boundary with different loading levels.

RESULTS

By selecting the fixed effects and covariance structure properly we got more reliable estimates of chlorophyll *a* concentrations (Fig 2B) than by using model with only fixed effects (Fig 2A).

After implementing the model in LLR tool we estimated loading reduction for Lake Kirkkojärvi in SE Finland. With reduction of about 10 kg P d^{-1} the Water Framework Directive affiliated chlorophyll *a* good/ moderate target level of 12 μg L^{-1} is achieved with 50% certainty (Fig 3). Higher level of certainty can also be used, but 50% is often adequate start for management planning and for estimating the amount of reduction needed at the least.

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