# Patternising the Alternate Stable States of Turbid versus Clear-Water Dynamics by Applying Kohonen Artificial Neural Network

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## EXTENDED ABSTRACT

Two data sets of shallow Dutch lakes, Lakes Veluwemeer and Lake Wolderwijd were merged together snd clustered by means of Kohonen artificial neural network (KANN). KANN were applied to map the relationships between physical, chemical and biological time-series data of the two adjacent lakes. An expected outcome of this study was to determine improvements in water quality and changed dominance of phytoplankton populations in both lakes in relation to the consecutive implementation of external phosphorus control and food web manipulation.

The lakes were considered as hyper-eutrophic and have been managed both with bottom-up and top-down management approaches. These control measures include: (1) reduction of external phosphate loadings by a sewage treatment plant, (2) lake flushing during winter in 1979 and during summer in 1985, and (3) biomanipulation in Lake Wolderwijd in 1991 and commercial fishing in Lake Veluwemeer from 1992-1994. The three eutrophication control measures aimed at reduced PO4-P concentrations and the prevention of blooms of the filamentous blue-green algae *Oscillatoria agardhii.*

Results using nutrients, pH and secchi depths ranges, have demonstrated that KANN allow to elucidate the complex ecological processes of the alternate stable states (turbid versus clear water conditions) in both lakes. The results have shown similar patterns of abundances within (1) the phytoplankton functional groups; diatom, green algae and blue-green algae (2) the specific genus, *Oscillatoria* and *Scenedesmus*, possibly the combination of external nutrient control and in-lake food web manipulation of the two lakes achieved to control eutrophication.

When applied to complex ecological data KANN provided a realistic image of the changes in *Oscillatoria* and *Scenedesmus* abundances and assemblages of diatoms, green algae and blue-green algae during clear-water and turbid-phase dynamics in relation to pH, Secchi depths , nitrate and phosphate concentrations. *Oscillatoria* and blue-green algae are dominant during turbid phase, with high pHs and N-limitation while green algae and diatoms predominate under clear-water conditions of low pHs and with P-limitation. *Scenedesmus* were mostly abundant under clear-water conditions specified by the ranges.

The results from this study support the assumption that top-down food web manipulation can efficiently complement the primary eutrophication control of decreasing external phosphorus loads.

## 1. INTRODUCTION

Shallow lakes such as Lakes Wolderwijd and Veluwemeer are usually less than 3m in depth with surface area ranging from less than a hectare to over $100km^2$. Shallow lakes have largely shifted from clear to turbid (Scheffer, 1998) due to eutrophication. Research is ongoing to understand the ecological processes that govern the shift from turbid to clear-water also known as the “alternate stable states” (Scheffer *et al*, 1993: Scheffer, 1989: 2001). The sequence of changes during eutrophication is rarely documented well although some elements are common (Moss, 1998). In order to understand the changes in the biotic community and water quality, it is important to identify the factors that affect both. The factors affecting algal growth are multidimensional and closely linked to physical factors (water temperature, light radiation, turbidity, turbulence and other conditions such as precipitation and flow), chemical factors (pH, nutrient loading, humic substances, dissolved oxygen content) as well as biotic interactions (species specific competition, predation, grazing). As a consequence of high phosphorus and nitrogen loading together with suitable physical factors such as retention time and other environmental factors, algal biomass increases with a succession of algal groups during eutrophication. In turbid shallow lakes the concentration of suspended particles depends strongly on the continuous process of sedimentation and resuspension as they have no thermocline to trap sinking particles. Apart from this, there are many factor interactions that occur in shallow lakes that are continually wind mixed or experiencing high external loadings of nutrient (Scheffer, 1998). The concept proposed by Scheffer *et al* (1993), states that shallow lakes can occur in either clear-water or turbid states and is stabilized by feedback loops over a broad range of nutrients. The recovery and restoration of freshwater lakes is often the main target for managers. Until recently, the management strategies include reducing point source and non-point source emissions or by in-lake measures to reduce nutrient availability (Sas, 1989). This ‘bottom-up’ approach was supplemented by ‘top-down’ approach, to accelerate restoration by food web manipulations (Gulati *et al.*, 1990). They produced varying successes yet still failed to pinpoint the underlying mechanisms that control water quality. Various models have been used to study these two lakes including one that demonstrated a climate-related regime shift e.g., Scheffer (2001).

Ecological time-series data of lakes have previously been ordinated and clustered by conventional multivariate statistics (e.g. Varis *et al*., 1989; Varis, 1991; Van Tongeren *et al*., 1992) but failed to cope with the multiple non-linear nature of the data. By contrast data ordination and clustering by KANN (Kohonen, 1989) proves to be applicable to highly complex and non-linear data including limnological time-series (Chon *et al*., 1996; Recknagel *et al*., 2006). Recently this modelling technique has been applied to various ecological problems and is an alternative tool for ordination and classification of community data (Chon *et al*. 1996; Recknagel *et al*., 2006). In this study, we model the alternative stable states in relation to abundances of algae functional groups such as diatoms, green and blue green algae, *Oscillatoria* and *Scenedesmus* in both lakes by using clustering and ordination of KANN to test hypotheses with defined ranges of nutrients, pH and Secchi depths.

## 2. DATA AND PREPROCESSING

KANN were applied to the ordination, clustering and mapping of relationships between physical, chemical and biological time-series data of the two adjacent lakes. An expected outcome of this research was to determine improvements in water quality and changed dominance of phytoplankton populations in both lakes in relation to the consecutive implementation of external phosphorus control and food web manipulation. The ordination and clustering of the phytoplankton communities of the two lakes was applied hierarchically to chlorophyll-a, functional algal groups and taxa of algal species. Three 3-years periods of data from 1976 to 1978, 1983 to 1985, and 1991 to 1993 were selected under the assumption that they reflect changes in the phytoplankton communities and water quality in response to different stages and management of eutrophication.

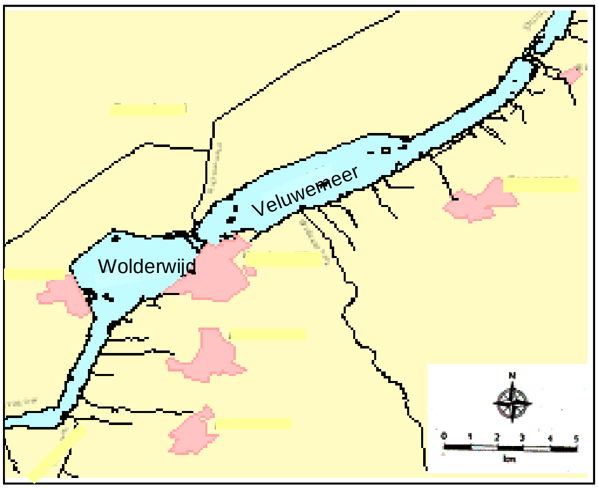


**Figure 1.** Locations of Lake Veluwemeer and Wolderwijd in central Netherlands

## 3. METHOD

Time series data from Lakes Veluwemeer and Wolderwijd, of Netherlands (see Figure 1) were preprocessed to create consistent data sets, with same variables over same time period. Linearly interpolated data sets and 9 years of consistently "clean" data were selected from both lakes for KANN training. Table 1 lists the water quality variables that were considered for the present study. For training, the lake data sets are merged into 18 years of data (see Table 2). Partitioning of the data sets are based on ranges of NO3-N, PO4-P, Secchi and pH (see Table 3).

**Table 1.** Limnological variables of Lake Veluwemeer and Lake Wolderwijd

| | Lake Veluwemeer (1976-1993) | Lake Wolderwijd (1976-1993) |
|---|---|---|
| Limnological variables | Mean/Min/Max | Mean/Min/Max |
| Nitrate $NO_3$-N mg/l | 0.86/0.001/5.77 | 0.24/0.001/7.24 |
| Phosphate $PO_4$-P mg/l | 0.04/0.0001/0.42 | 0.01/0.0001/0.12 |
| Silica mg/l | 2.6/0.05/7.05 | 2.06/0.01/19.1 |
| pH | 8.5/7.3/10.5 | 8.5/7.1/9.7 |
| Ammonium $NH_4$ mg/l | 0.11/0.001/1.77 | 0.05/0.001/0.85 |
| Temperature $^oC$ | 10.8/-1.7/25 | 11.0/0/23.9 |
| Secchi Depth m | 0.4/0.1/1.7 | 0.4/0.15/1.3 |
| Chlorophyll-a µg/l | 111.8/12.6/459 | 95.6/9/265 |
| Blue-Green algae $mm^3/l$ | 84.2/0/390.6 | 113/0/390.6 |
| Green Algae $mm^3/l$ | 4.7/0/37.1 | 4.2/0/34.6 |
| Diatoms $mm^3/l$ | 9.3/0/168.6 | 6.8/0/110.3 |
| *Oscillatoria* cells/ml | 17658/25/95850 | 26970/0/97650 |
| *Scenedesmus* cells/ml | 2216/0/17250 | 1299/0/12688 |

**Table 2.** Distinctive management periods of Lake Veluwemeer and Lake Wolderwijd

| Eutrophication Control | Lake Veluwemeer | Lake Wolderwijd |
|---|---|---|
| None | 1976-1978 | 1976-1978 |
| Wastewater Treatment and Flushing in Winter and Summer | 1983-1985 | 1983-1985 |
| Flushing, Commercial Fishing and Biomanipulation | 1991 - 1993 | 1991-1993 |

**Table 3.** Defining ranges based on nutrients, pH and Secchi depth for model training.

| Water Quality Ranges | Lake Veluwemeer and Wolderwijd (1976-1992) |
|---|---|
| pH | <= 8.5; 8.5 > and =<9.5;.> 9.5 |
| Secchi depth m | < =0.25; 0.25 > and =< 0.5;.> 0.5 |
| NO3-N mg/l | < =0.01; 0.01> and =<0.3;.> 0.3 |
| PO4-P mg/l | < = 0.001; 0.001 > and =<0.015 ;.> 0.015 |

The KANN models were developed by using the MatLab 5.3 SOM Toolbox functions (Vesanto, 1999) developed at the Laboratory of Computer and Information Science at Helsinki University of Technology. The KANN are also called Self-Organizing Maps (SOM) or Kohonen networks referring to Kohonen (1995) who invented principles of unsupervised training of ANN.

### 3.1 K-means Clustering

Clustering was carried out by the K-means method. Clustering can be done either through a hierachical or partitative approach. In the case where the number of clusters is unknown the partitative algorithm is repeated for a set of different values from 2 to $\sqrt{n}$, where n is the number of samples in the data set. The K-means method is the most commonly used partitative algorithm (MacQueen, 1967; Vesanto, 2000).

The KANN algorithm using the K-means method has separated 18 years of the merged lake data sets from the two lakes into three clusters corresponding with the following water quality ranges:

Cluster 1: pH>9.5; SD <=0.25 m; PO4-P > 0.015 mg/l; NO3-N <= 0.01 mg/l.

Cluster 2: 8.5 < pH<=9.5; 0.25 m < SD <=0.5 m; 0.001 mg/l< PO4-P <= 0.015 mg/l; 0.01 mg/l<NO3-N <= 0.3 mg/l.

Cluster 3: pH<=8.5; SD >0.5 m; PO4-P <= 0.001 mg/l; NO3-N >0.3 mg/l.

The U-matrix identified overlapping areas at the borders of the clusters, and is shown in Figure 2 together with the K-means clusters (Figure 3). The plane quality was very good with a low quantization error of 0.0176 and a topographic error of 0.061.

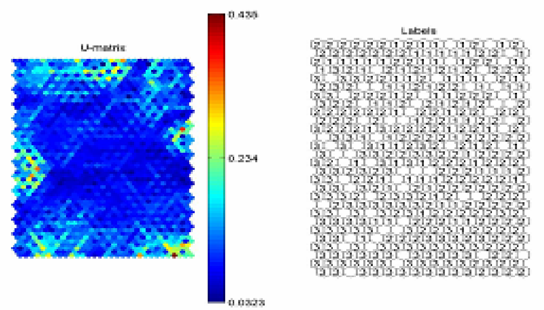

**Figure 2.** Distance matrix map (U-matrix) of ranges

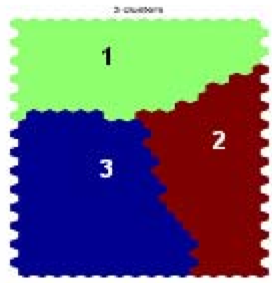


**Figure 3.** Partitioned map (K-means) of ranges cluster

## 4. RESULTS AND DISCUSSION

The results of the K-means clusters and the component planes can be visualized in Figure 4 to Figure 7. The results in Figure 4 and Figure 5 were mapped in terms of pH and secchi depth (SD) ranges for both phytoplankton functional groups and *Oscillatoria* and *Scenedesmus*. The hypotheses tested is that phytoplankton functional groups of blue green algae, green algae and diatoms, *Oscillatoria agardhii* and *Scenedesmus* show succession and competition for light conditions (Secchi depths) that relate to the long-term occurrence of turbid or clear-water phases. The component planes for functional groups have shown patterns that for both Lakes Veluwemeer and Wolderwijd, blue-green algae and *Oscillatoria*, tolerate high pH (>9.5) under turbid water conditions (SD <=0.25 m). The KANN clustering using ranges have shown that green algae and diatoms prefer lower pH (<= 8.5) and clear-water conditions (SD > 0.5 m). Similarly, *Scenedesmus* thrived under a range from low pH, to slightly higher pH (8.5<pH<=9.5) and under various degrees of clear-water conditions (0.25 m < SD <=0.5 m).

Another hypothesis tested is that the blue green and green algae, diatoms, *Oscillatoria* and *Scenedesmus* show succession and competition for P and N that relate to the long-term occurrence of turbid and clear-water phases for both Lakes Veluwemeer and Wolderwijd. Based on the ranges of PO4-P and NO3-N tested (see Figure 6 and 7), blue-green algae and *Oscillatoria* are dominant during turbid phase, with high PO4-P ( > 0.015 mg/l ) and low NO3-N (<= 0.01 mg/l) while diatoms and green algae are abundant under conditions of low PO4-P (<= 0.001mg/l) and with high NO3-N (>0.3 mg/l).

*Scenedesmus*, a green algae show preference for clear-water conditions with low PO4-P and high NO3-N with a range of nutrient conditions of

PO4-P (0.001 mg/l< PO4-P <= 0.015 mg/l) and NO3-N (0.01 mg/l<NO3-N <= 0.3 mg/l).

Because of the consistent results obtained for all the pH, Secchi depths, NO3-N and PO4-P ranges tested our results suggest N: P limitation based on the N: P mass ratio of 7: 2, a conversion from Reynolds (1984) Redfield Ratio of atomic N: P of 16. The N: P limitation is strongly correlated to pH and light limitations, leading to distinct alternate successional patterns between the phytoplankton functional groups and individual species of *Oscillatoria* and *Scenedesmus*. While diatoms and green algae are dominant during clear-water periods of low pH concomitant with P-limitation blue-green algal blooms of *Oscillatoria* were predominant in turbid water, high pH, and under N-limitation. It is well known that annual average biomass of the non-nitrogen fixing *Oscillatoria agardhii* changed in parallel to altered N/P loading ratios, as they are sensitive to N-deficiency as any other phytoplankton (Reynolds, 1994). Previous field studies and physiology-based models indicate that dominance of Oscillatoriaceae can be the alternative stable state of the algal community of shallow lakes because the blue-green algae are shade tolerant (Reynolds, 1994) and can cause an increase in turbidity, which favours their competitive advantage (Scheffer *et al*., 1997). The overall results shown lend evidence that the dynamics in both Lake Veluwemeer and Wolderwijd involve the alternate stable states of turbid versus clear-water conditions as postulated earlier by Scheffer *et al* (1993).

Nutrients concentrations, pH and phytoplankton dynamics in Lake Veluwemeer and Wolderwijd are both affected by the long-term eutrophication and the various management measures. The long-term dynamics, in terms of a reduction in pH, orthophosphate PO4-P and an increase in nitrate NO3-N concentrations together with an increase in *Scenedesmus*, green algae and diatom abundances from turbid phase to clear-phase, can therefore be attributed to the success of these restoration measures.

Although for Lake Veluwemeer originally only lake flushing was the management focal point and for Lake Wolderwijd biomanipulation (Hosper, 1997), at the end flushing affected both lakes because of their physical connections, and commercial fishing in Lake Veluwemeer took principles of trophic cascade effects into account. The prolonged control of external phosphorus loadings from period 1979 onwards has significantly improved the water quality in both lakes and set the course for seasonal changes in phytoplankton dominance. The importance of biomanipulation and commercial fishing towards these phytoplankton community changes is emphasised.

The approach adopted here of comparative analysis using ranges of nutrients, Secchi depths and pH may contribute as a useful framework for predicting the alternate stable states in other temperate shallow lakes. Merging of the two lake data sets provided visualisation of the alternate stable states of turbid and clear-water periods for both lakes. The results of this KANN model can be used as a basis for integration with other modelling studies to better understand the functioning of shallow lakes as an aid to management measures. KANN ordination and clustering study strongly suggest that top-down approach of food web manipulation and commercial fishing in addition to the bottom-up approach of flushing and external phosphate reduction could play an important role in breaking blue-green algae dominance, creating the desirable clear-water state.

## 5. CONCLUSION

KANN with the use of ranges of phosphate, nitrate , Secchi depth and pH have proven to be a suitable tool for patternising complex ecological temporal patterns of the “alternate stable states” (turbid versus clear-water phases) for the two highly eutrophic lakes, Veluwemeer and Wolderwijd. The results from this study support the assumption that top-down food web manipulation can efficiently complement the primary eutrophication control by decreasing external phosphorus loads. KANN can be successfully applied to merged lake datasets and provided a realistic image of the dynamics of *Oscillatoria* and *Scenedesmus* abundance and assemblages of algae functional groups with reference to specific ranges of nitrate, phosphate, water transparency and pH tracking the turbid or clear-water phases in both lakes.

## 6. ACKNOWLEDGEMENTS

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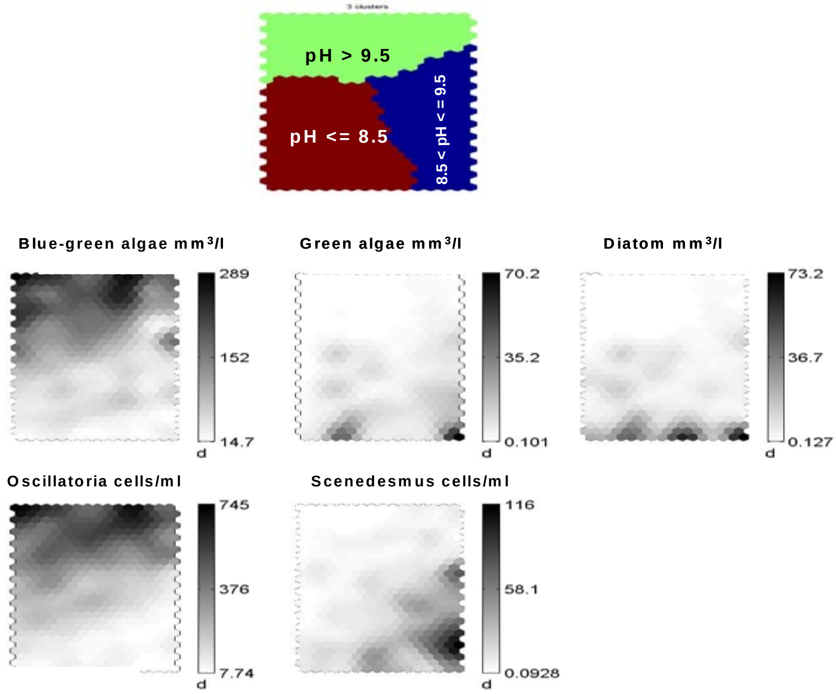


**Figure 4.** KANN clustering of phytoplankton functional groups, *Oscillatoria* and *Scenedesmus* in relation to pH ranges of Lake Veluwemeer and Wolderwijd

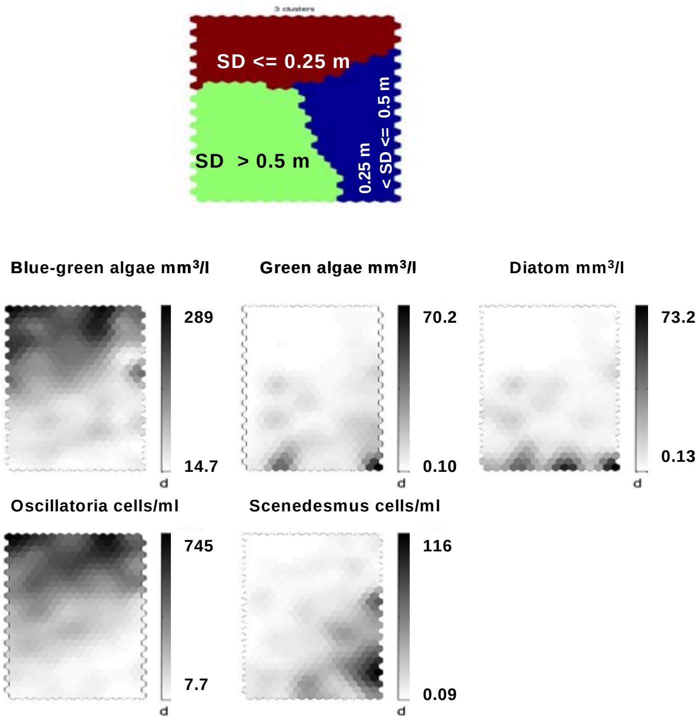


**Figure 5.** KANN clustering of phytoplankton functional groups, *Oscillatoria* and *Scenedesmus* in relation to Secchi depth ranges of Lake Veluwemeer and Wolderwijd

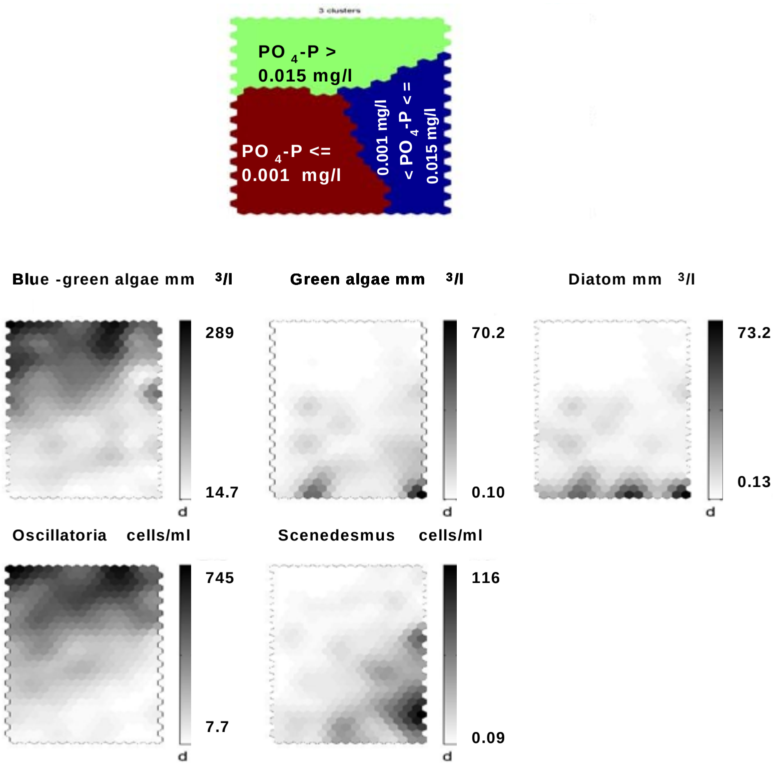


**Figure 6.** KANN clustering of phytoplankton functional groups, *Oscillatoria* and *Scenedesmus* in relation to $PO_4$-P ranges of Lake Veluwemeer and Wolderwijd

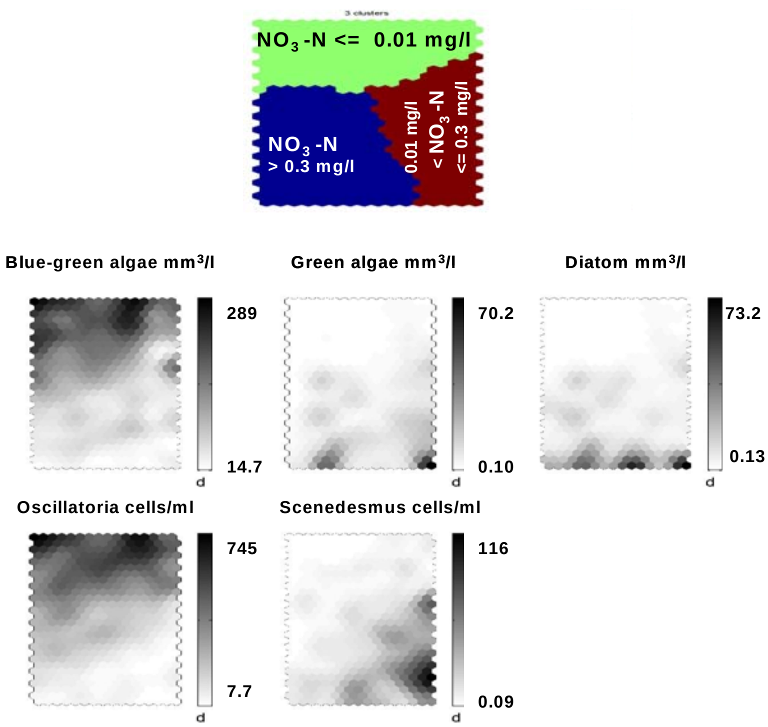


**Figure 7.** KANN clustering of phytoplankton functional groups, *Oscillatoria* and *Scenedesmus* in relation to $NO_3$-N ranges of Lake Veluwemeer and Wolderwijd

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