LakeN

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Introduction

This model was written as a project for course 68806 Eco-hydrologic modelling with R This model illustrates the annual N cycle in a lake in northern Israel, and simulates the transitions from oxydized species into reduced species

Background

Anthropogenic effects of the recent years has largely affected the nitrogen cycle during the last decades. Increased N inputs, primarily as river-born nitrate, originating in soils, encourage eutrophication, anoxic conditions and blooms of harmful algae, interrupting the ecological cycle.

The nitrogen cycle includes several key processes, which include its cycling between several species and affect its bioavailability. Rivers are efficient N sinks, but in its inorganic forms, it is removed from the water through assimilation and adsorption onto sediments. In addition, the precipitation of organic N and denitrification are two major processes that remove N from the water. In the studied lake, an N-fixing algae of the cyanobacteria phylum appeared for the first time during the autumn of 1994. It reappears every year since that time, and was recently accompanied by another cyanobacteria specie since 2005. This dramatic change in lake ecology is the likely result of changes in the availability of water-soluble nutrients, which provided the N-fixing species with a relative ecological advantage.

It is important to remember that the measurment process provides a "snapshot" of lake conditions in a specific day, and that all coocuring processes create interchanging fluxes of nitrogen between the nitrogen pools. While the modelling of the molecular process is difficult to configure, because it involves complex biological processes, the net transformation of species between pools can be modelled through a "net-gross" approach, where molecular transformations are summed into simplistic, time-dependent processes, that are arithmatically disconnected. If each of these processes is modelled properly, the N cycle can be modelled in terms of net fluxes, without taking into account all possible processes and their complexities.

The N cycle in the studied lake

Several key process dominate the N cycle of the studied lake. These include nitrification, denitrification, the fixation of atmospheric nitrogen by cycanobacteria and N recycling through consumption of primary producer up the food chasin. These processes are inherintly biologically mediated, and their relative role in the transformation of one specie to another greatly depends on physical conditions including radiation and temperature as well as the chemical properties of the lake, which are largely dependent on its limnological cycle. The consideration of these parameters in a limnological perspective is essential for the consideration of the dominant processes and their ecological impact. These processes are briefly described in the section below:

Nitrification

Nitrification includes the oxidation of ammonia into nitrite in a two-stage process mediated by the nitrosomonas bacteria followed by the oxidation of nitrate through the mediation of the nitrobacteria, that can be summarized as:

$$NH_4^+ ßNH_3 ßNO_2^- ßNO_3$$

This process largely depends on oxygen availability, ambient conditions and the size of bacterial populations. The process has been documented to be carried quickly and directly into nitrate in some years, whereas in others the increase in nitrite preceded the transformation into nitrate by several days and up to a couple of weeks.

The nitrification takes places in oxic conditions, and largely depends on the mixing of the water column during the winter, and is halted in the hypolimnion during the well-stratified conditions that develop from spring to autumn. Nitrification is however possible still possible in the interface of the hypolimnion with the epilimnion, where dissolved oxygen is present to some extent. Nitrate concentrations are highest at the end of January after the mixing of the lake is most effective, as well as additions of from surface runoff. Correspondingly, nitrite and ammonium are low during this interval.

Data preparation

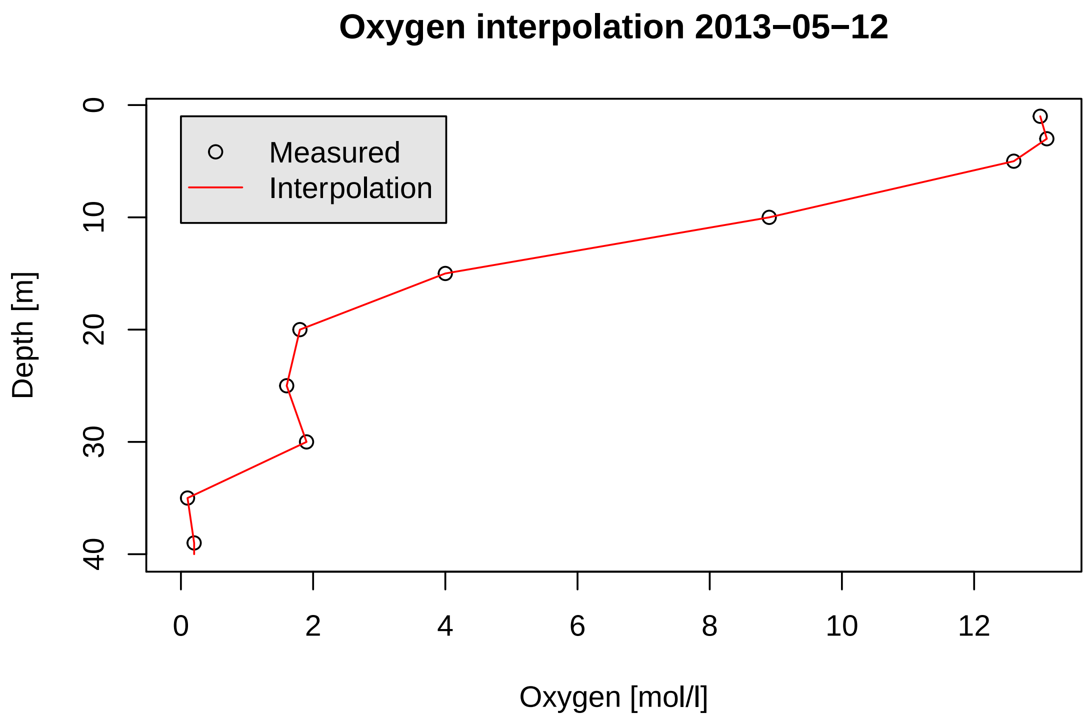
The data is provided in discrete form of concentration measurments. The depths of the measurments are not constant, and the time intervals between measurments are also not constant, and range from several days to several weeks.

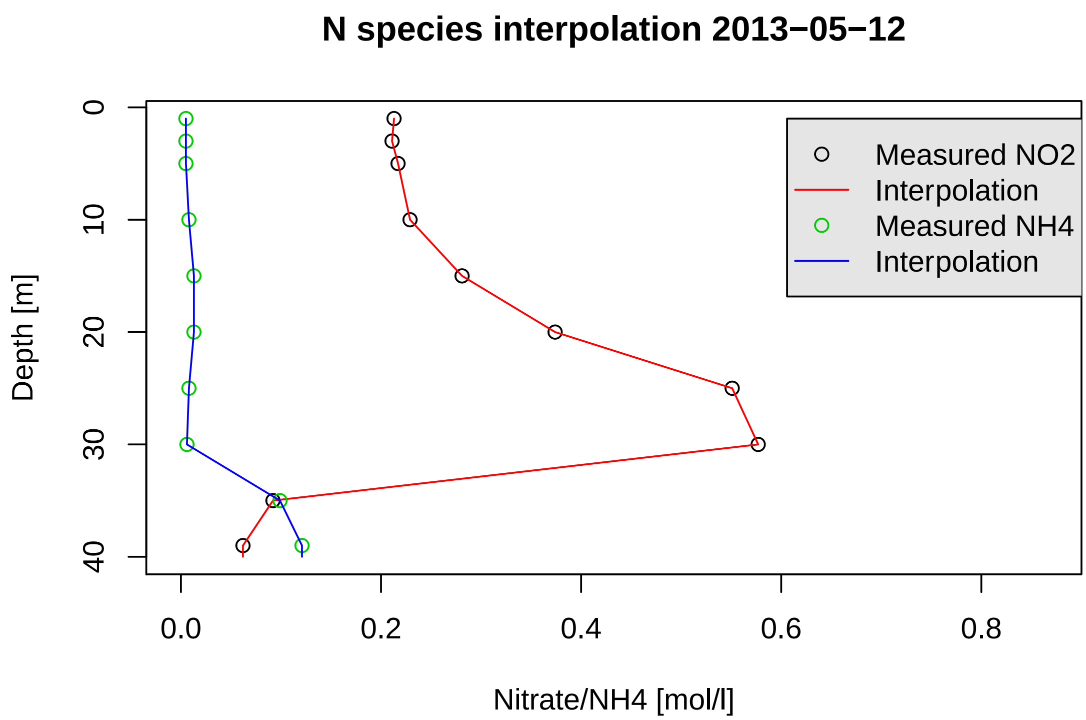
read the data and load relevant libraries

Interpolate the Data into 1 m Intervals

Use the function "depthinterp"" to interpolate the data into uniform length for every 1 m. This is essential for later calculating the volume of each depth interval and the mass of each N specie measured in this depth.

Demonstrate interpolations of randomly selected data

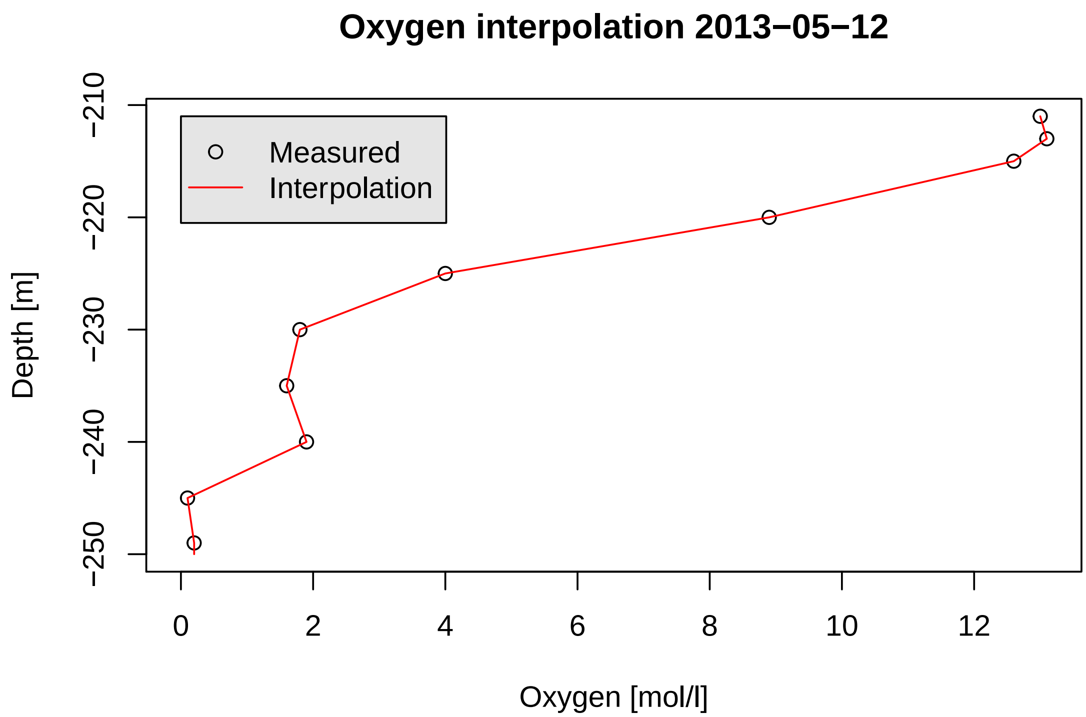


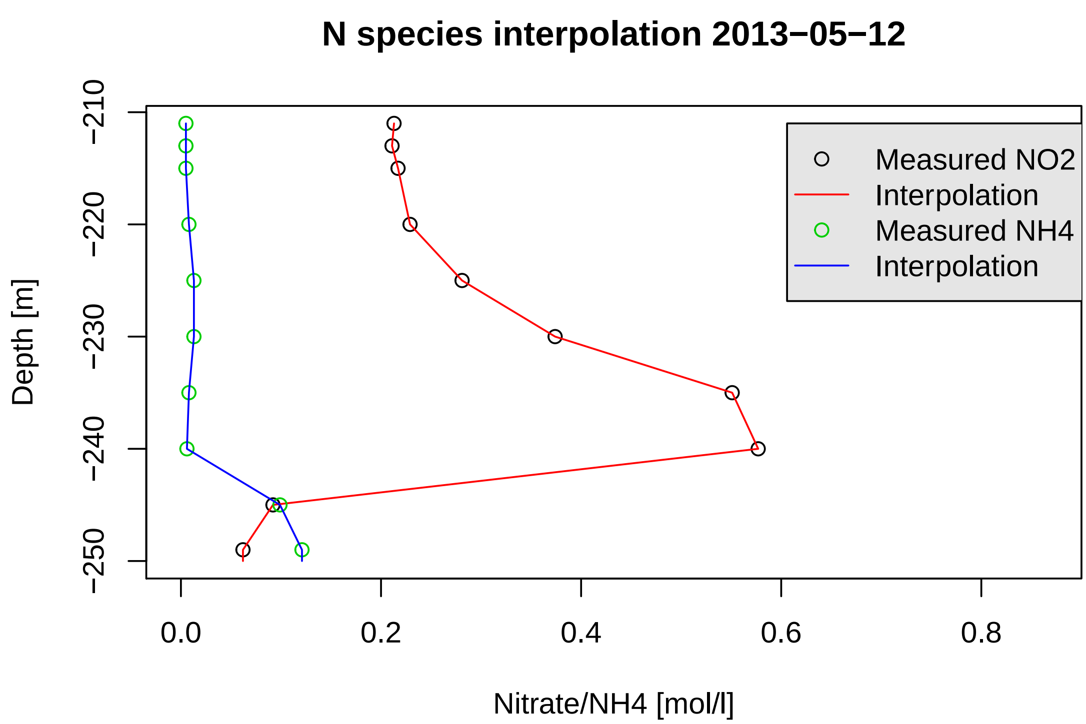


Depth and Level Corrections

Calculate the appropriate depth for each measurment using available daily level measurments. Use function "realdepth" and use closest day if no level measurment of that day is available. This correction is essential for later calculation of depth to volume and concentration quantification of N species in the lake.

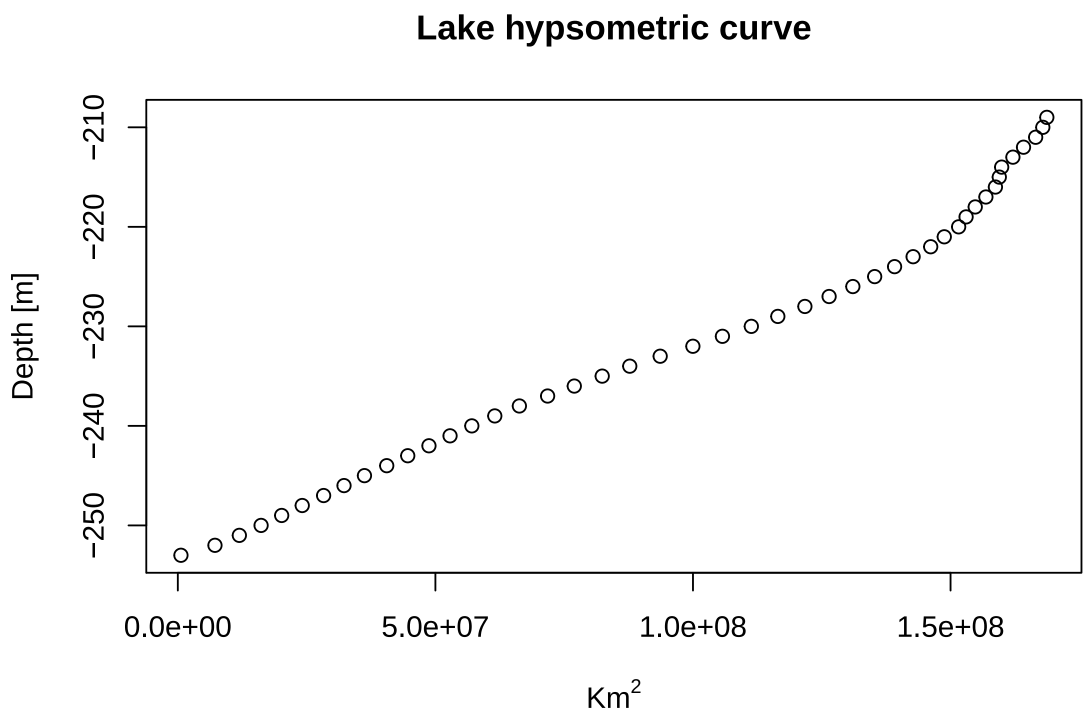
demonstrate the results according to the new depth scale of randomly selected data



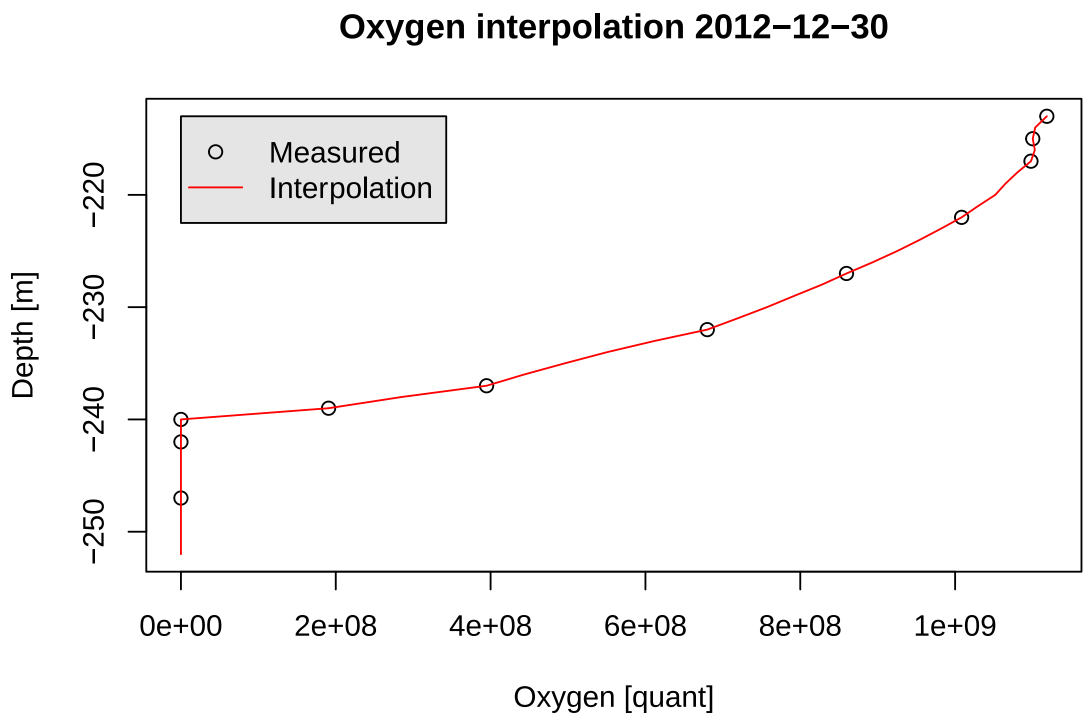


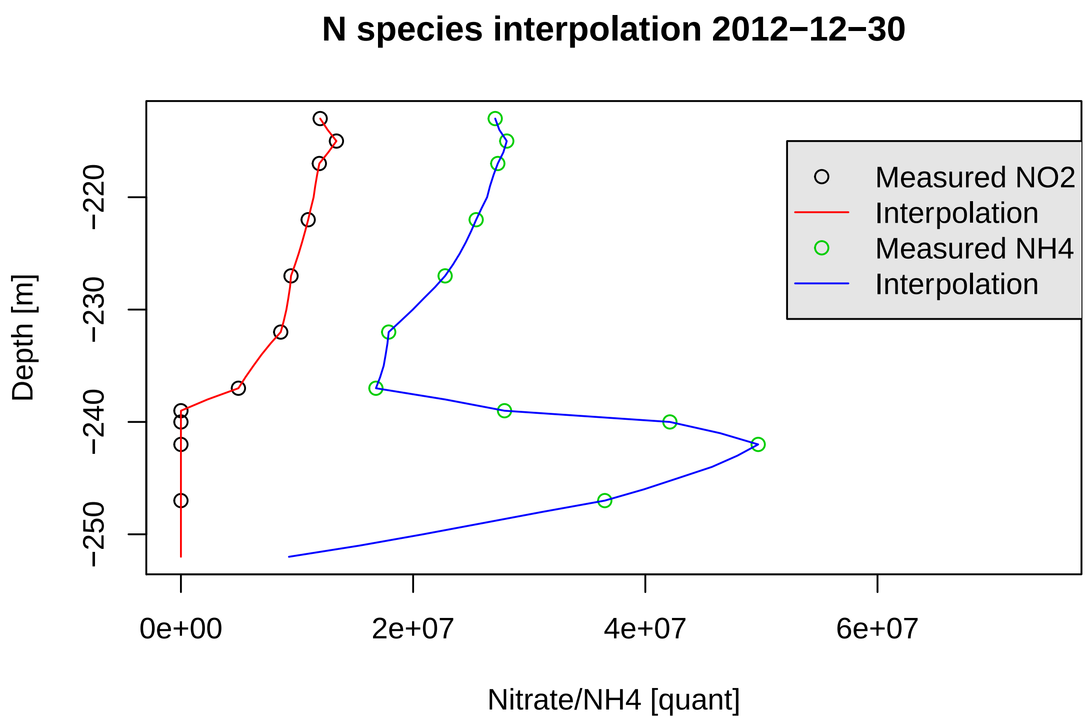
Quantify the data using lake hypsometric curve

The use of concentrations has limitiations because it may enhance or demise a processes that is inhernently "mass-based".Quantify the amount of measured species using the hypsomentric curve of the lake using function "conctoquant". Multiply each depth value with its corresponding hypsometric value to



demonstrate the results according to the new depth scale of randomly selected data

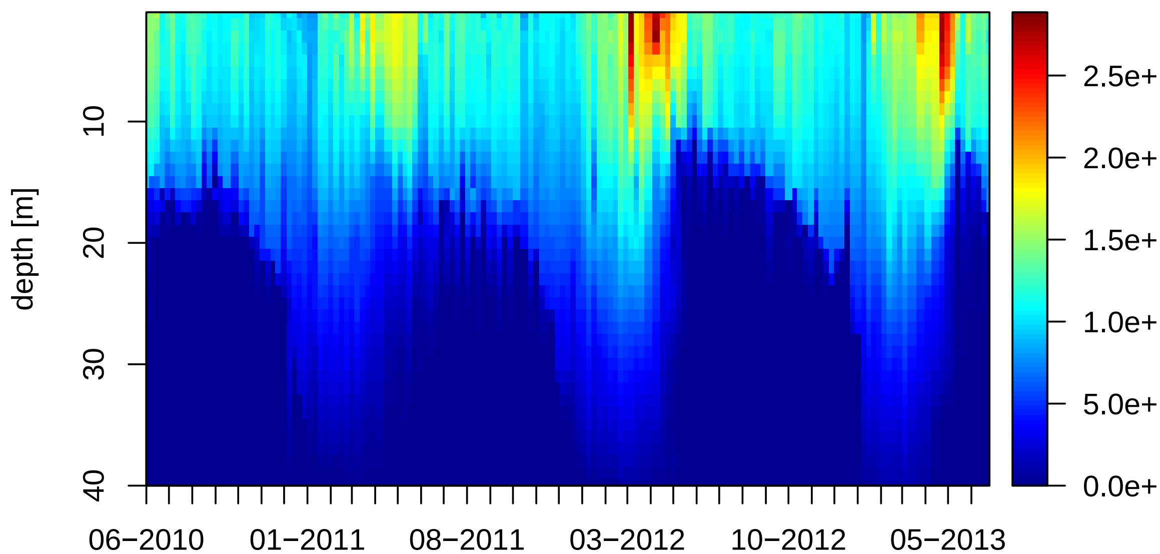




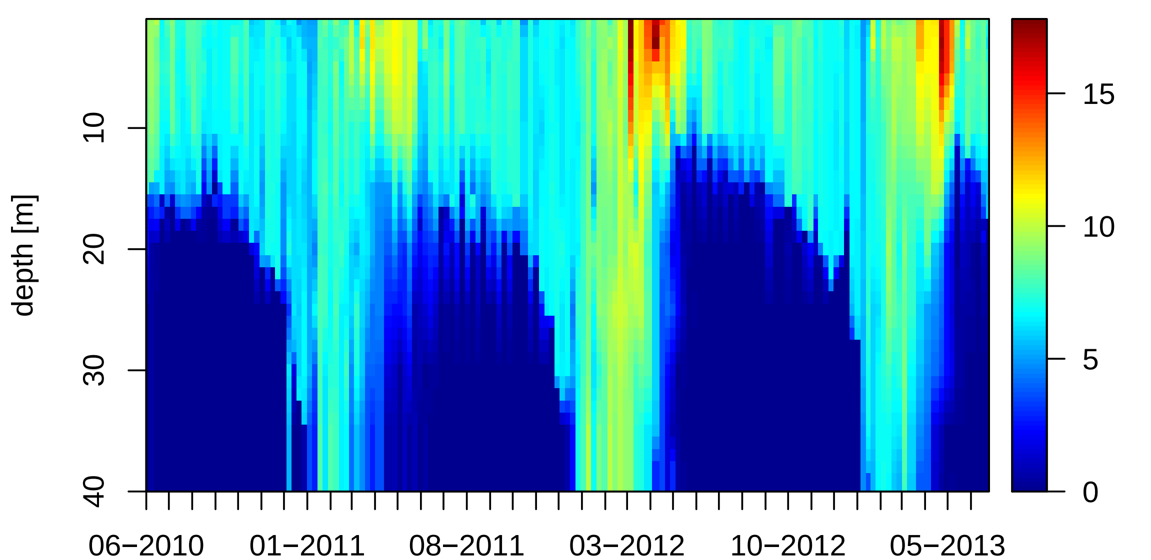
Time series plots

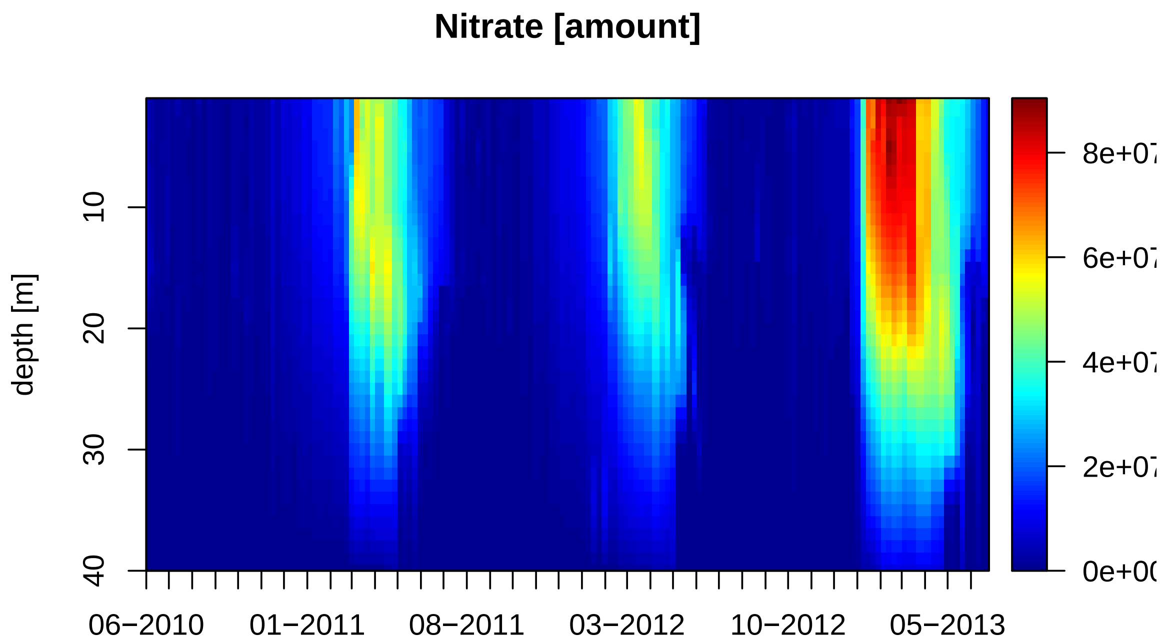
The following plots provide some visual estimation of the data to visualize time-depth processes for further considerations for the modelling of the processes

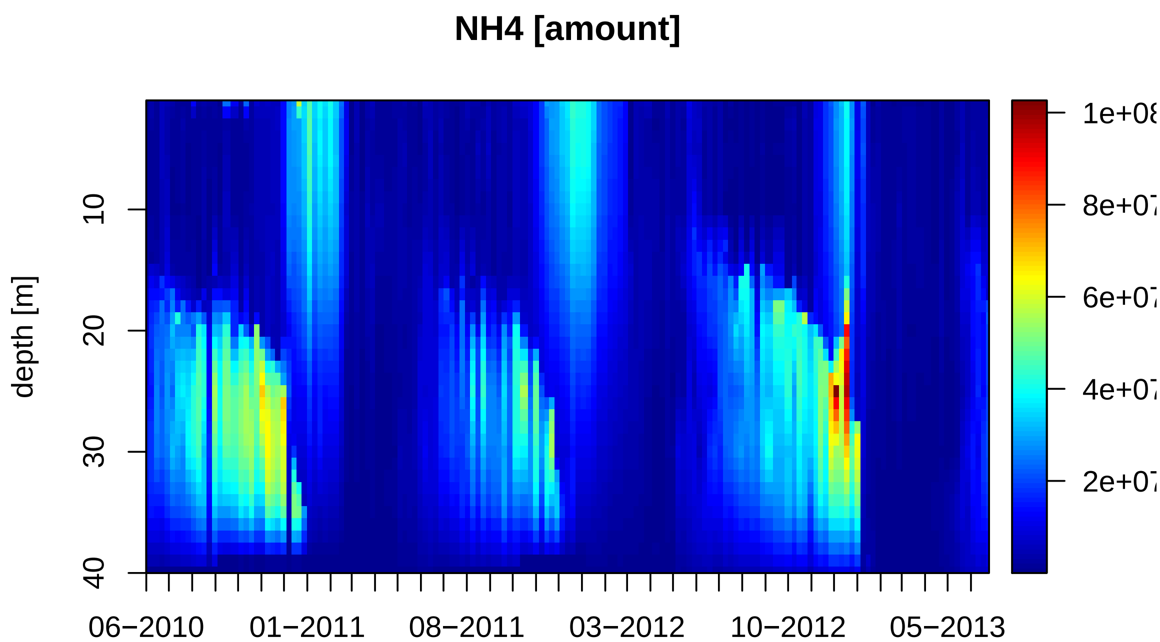
Oxygen [amount]

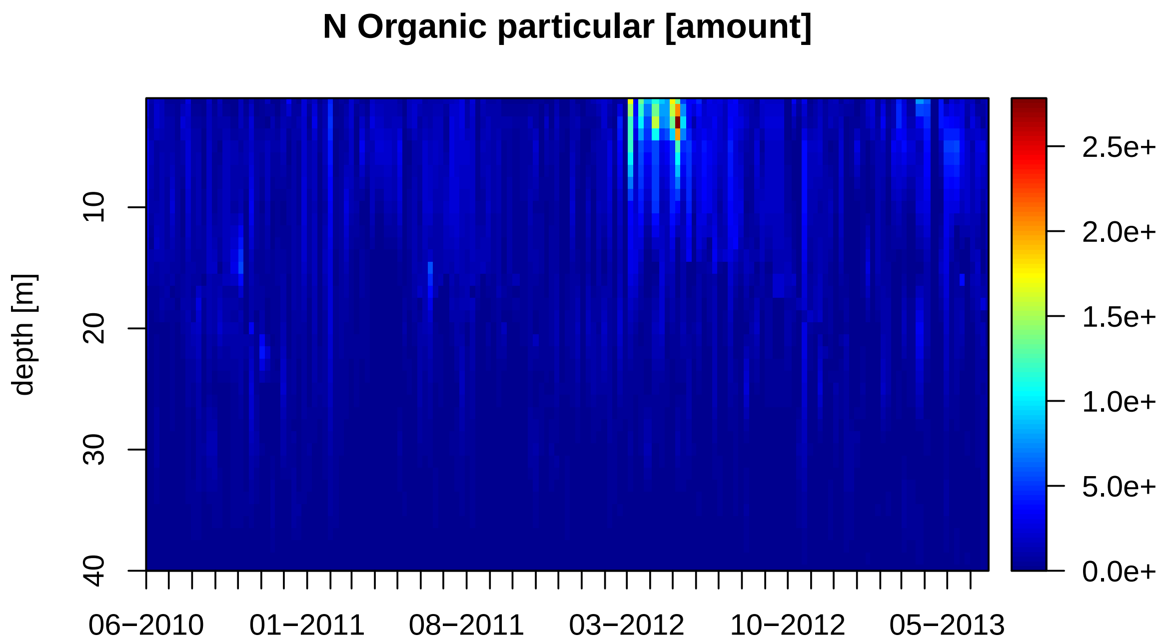


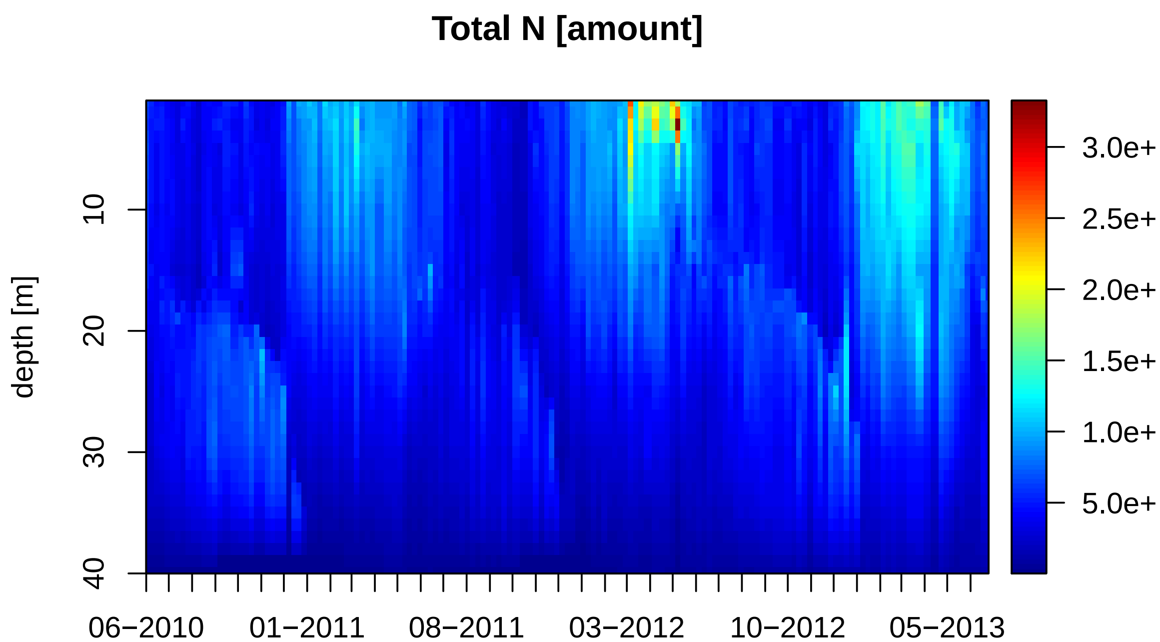
Oxygen [concentration]



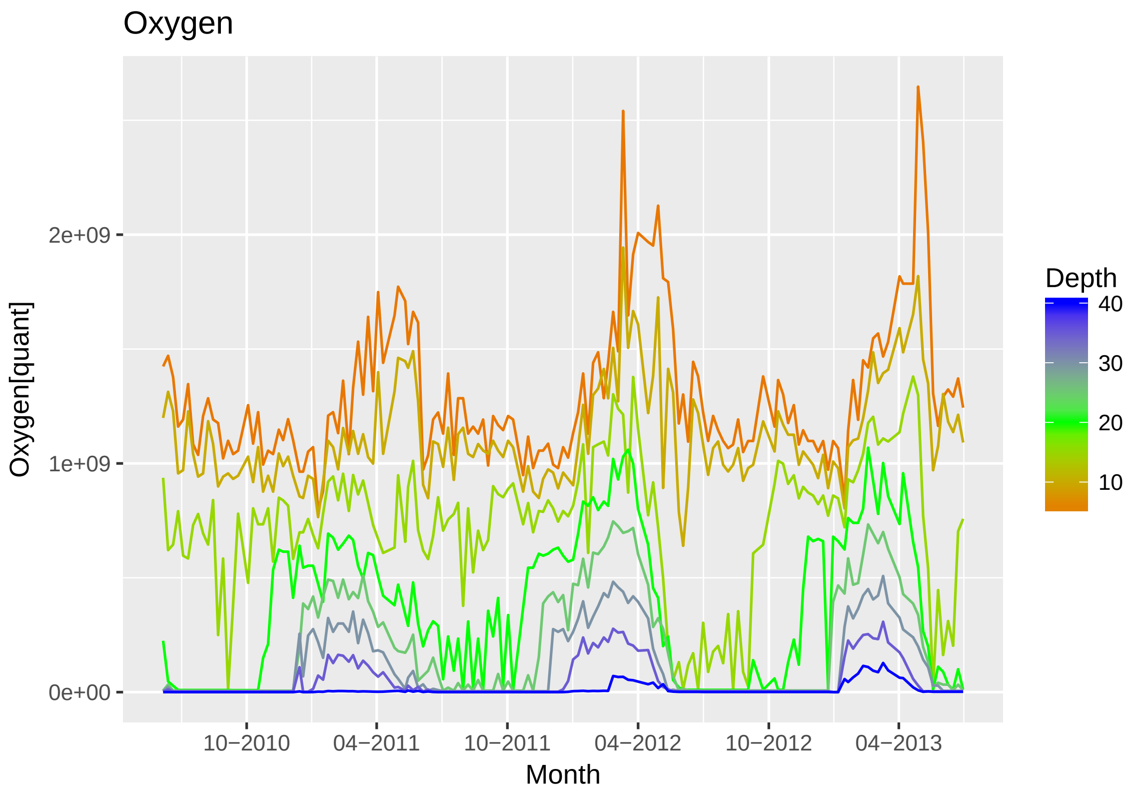

Nitrate [amount]
depth [m]
10
20
30
40
06−2010
01−2011
08−2011
03−2012
10−2012
05−2013
8e+07
6e+07
4e+07
2e+07
0e+00

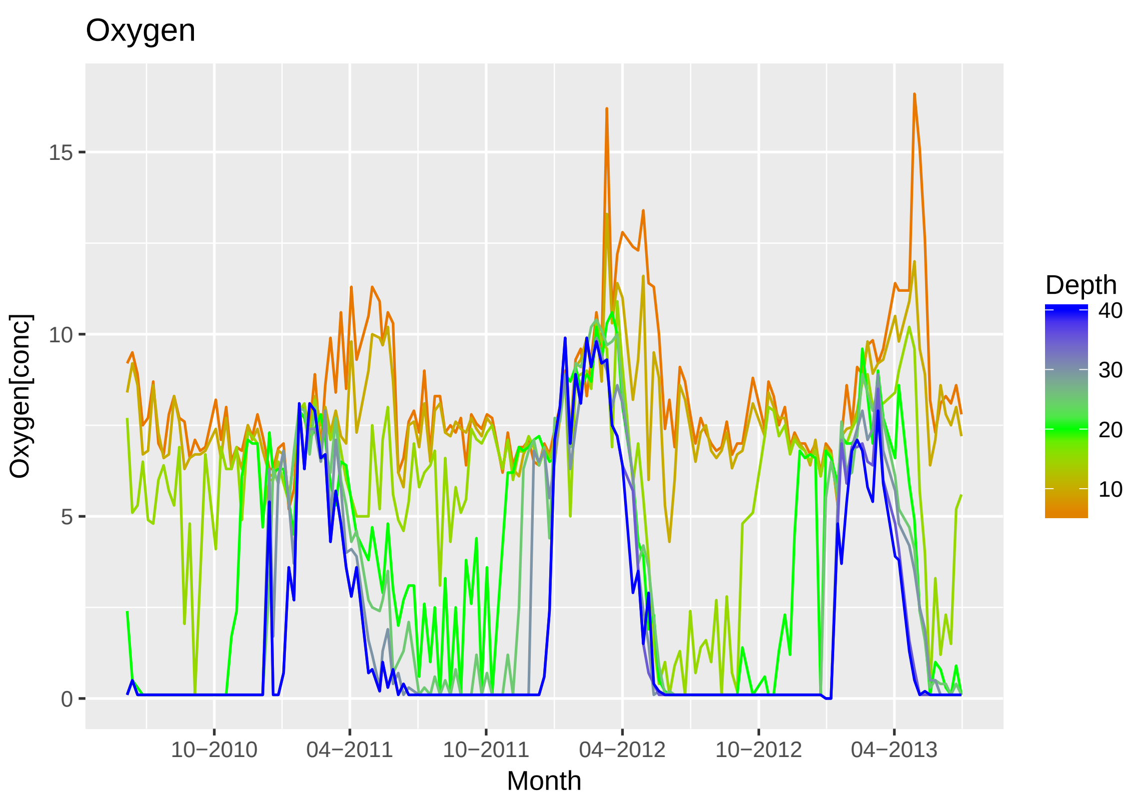

NH4 [amount]
depth [m]
10
20
30
40
06−2010
01−2011
08−2011
03−2012
10−2012
05−2013
1e+08
8e+07
6e+07
4e+07
2e+07

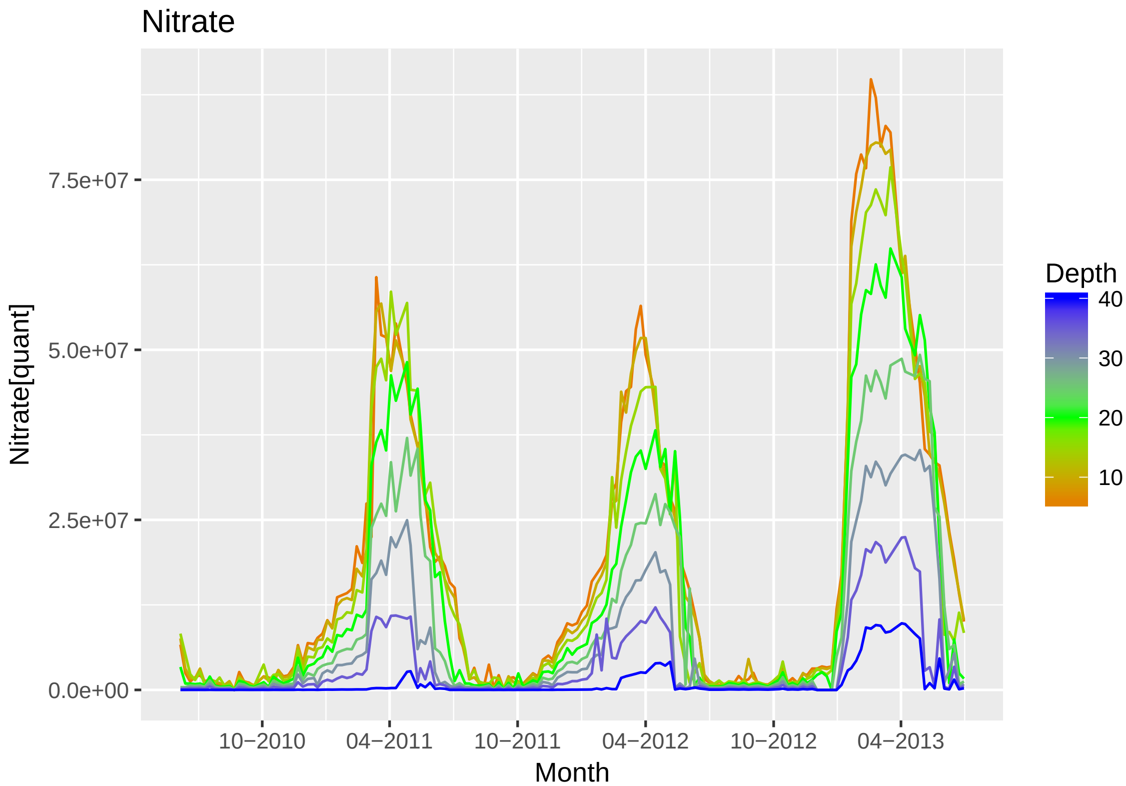

N Organic particular [amount]
depth [m]
10
20
30
40
06−2010
01−2011
08−2011
03−2012
10−2012
05−2013
2.5e+
2.0e+
1.5e+
1.0e+
5.0e+
0.0e+

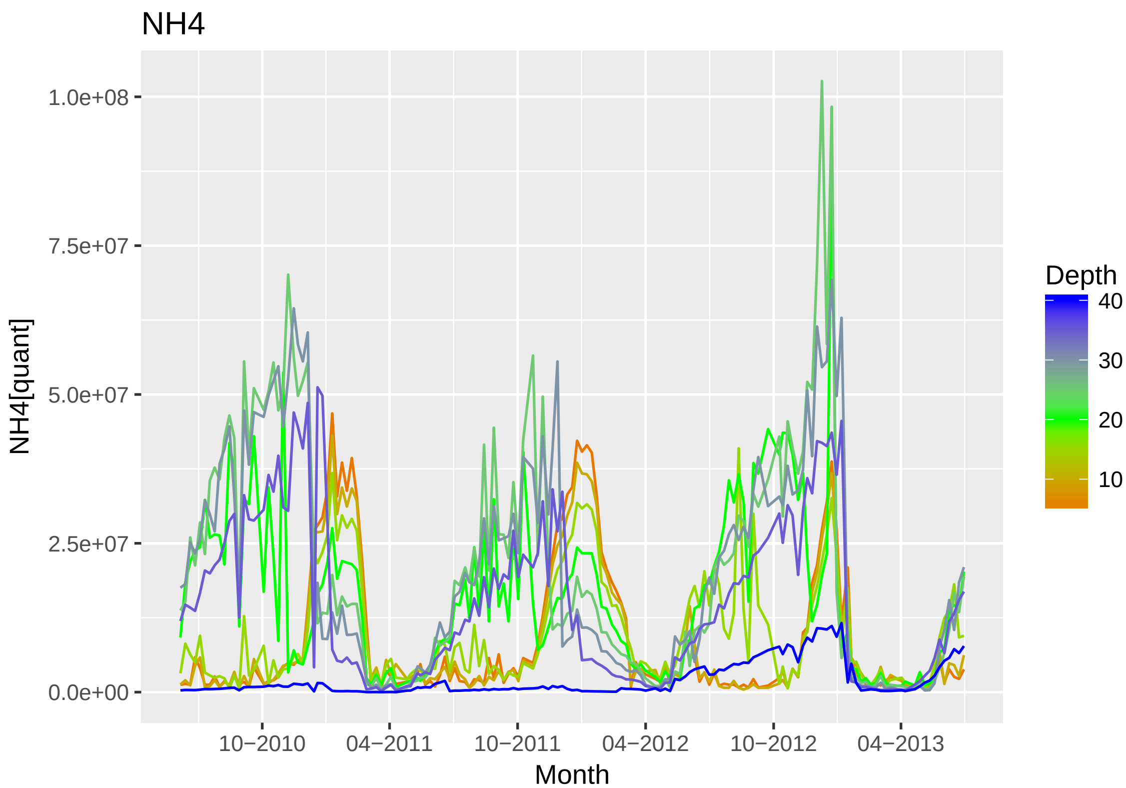

Total N [amount]
depth [m]
10
20
30
40
06−2010
01−2011
08−2011
03−2012
10−2012
05−2013
3.0e+
2.5e+
2.0e+
1.5e+
1.0e+
5.0e+

Time-depth cross sections



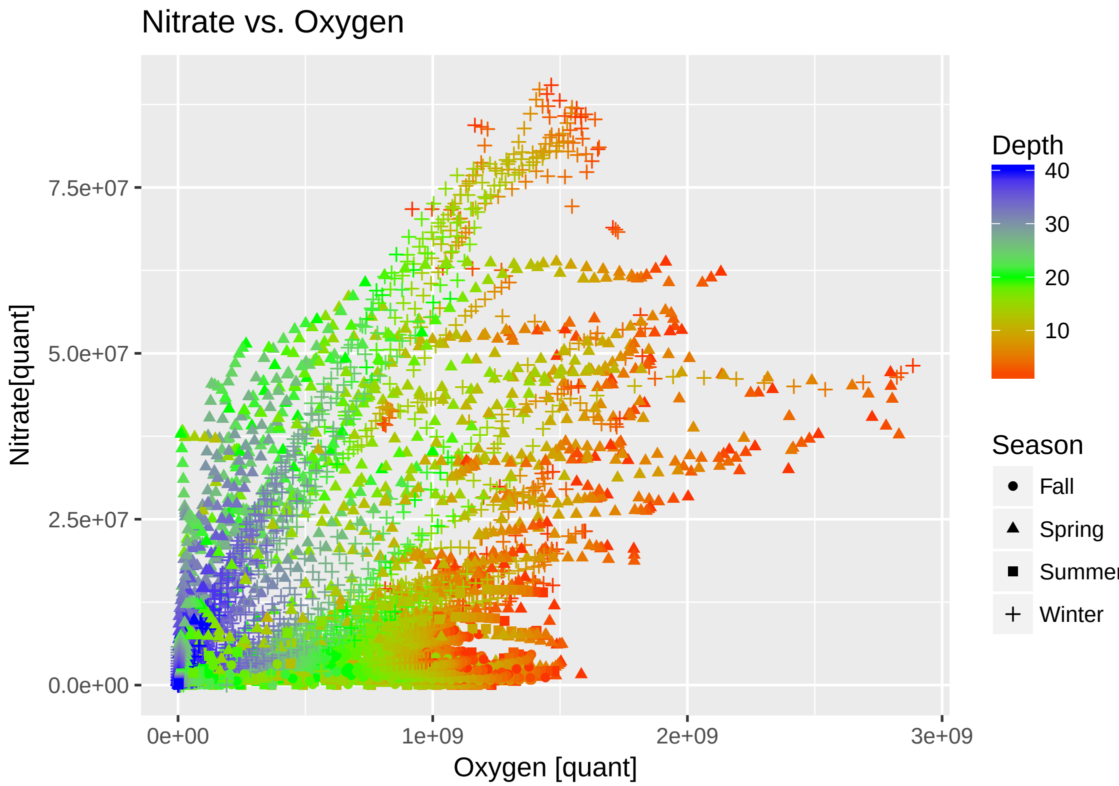


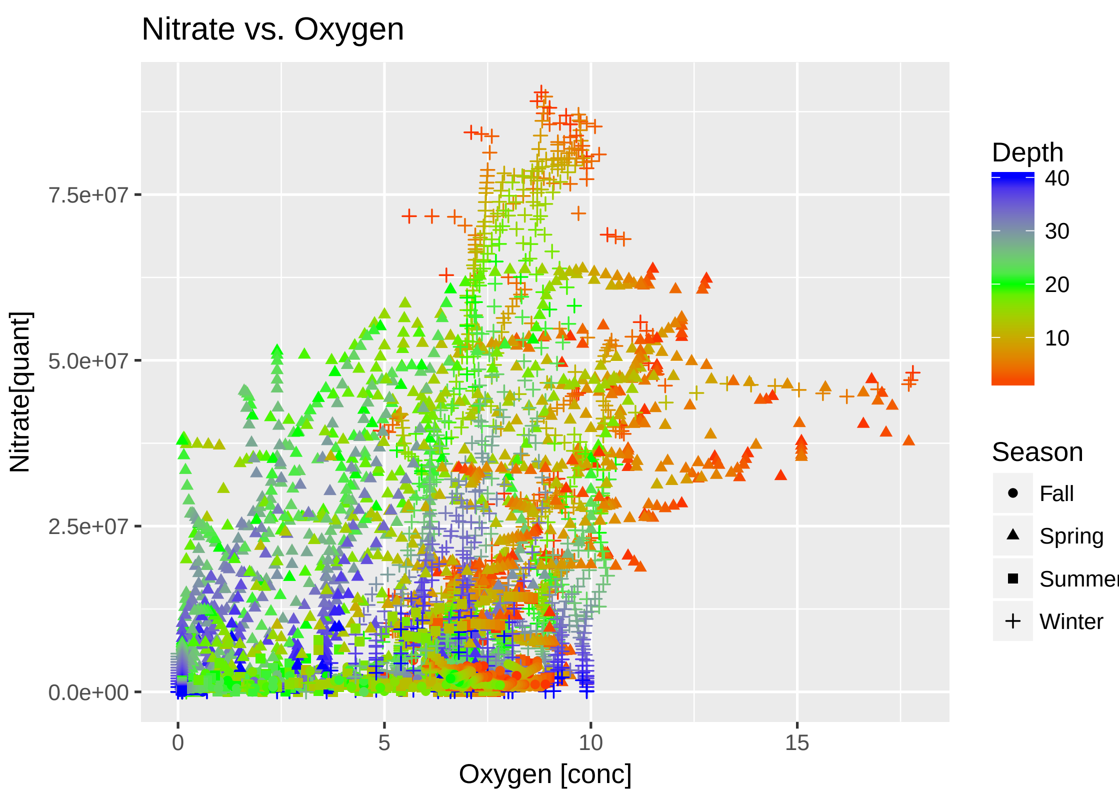

Nitrate
Nitrate[quant]
7.5e+07
5.0e+07
2.5e+07
0.0e+00
10−2010
04−2011
10−2011
04−2012
10−2012
04−2013
Month
Depth
40
30
20
10

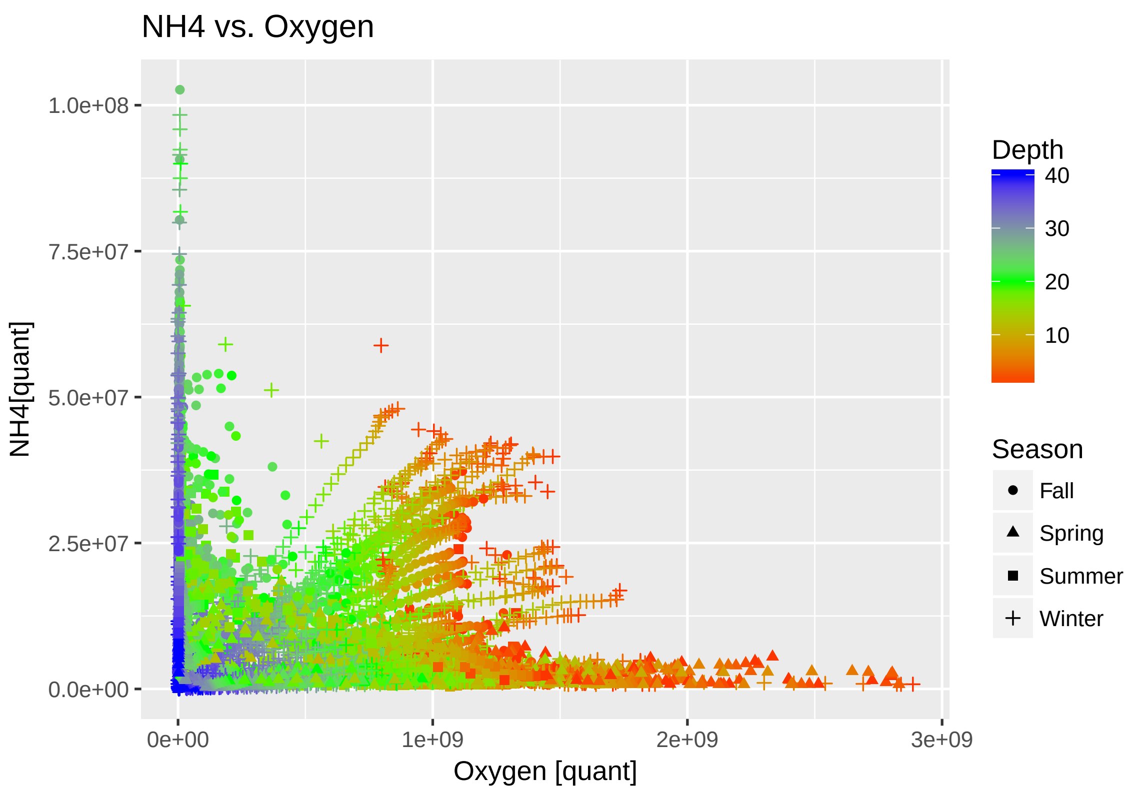

NH4
NH4[quant]
1.0e+08
7.5e+07
5.0e+07
2.5e+07
0.0e+00
10−2010
04−2011
10−2011
04−2012
10−2012
04−2013
Month
Depth
40
30
20
10

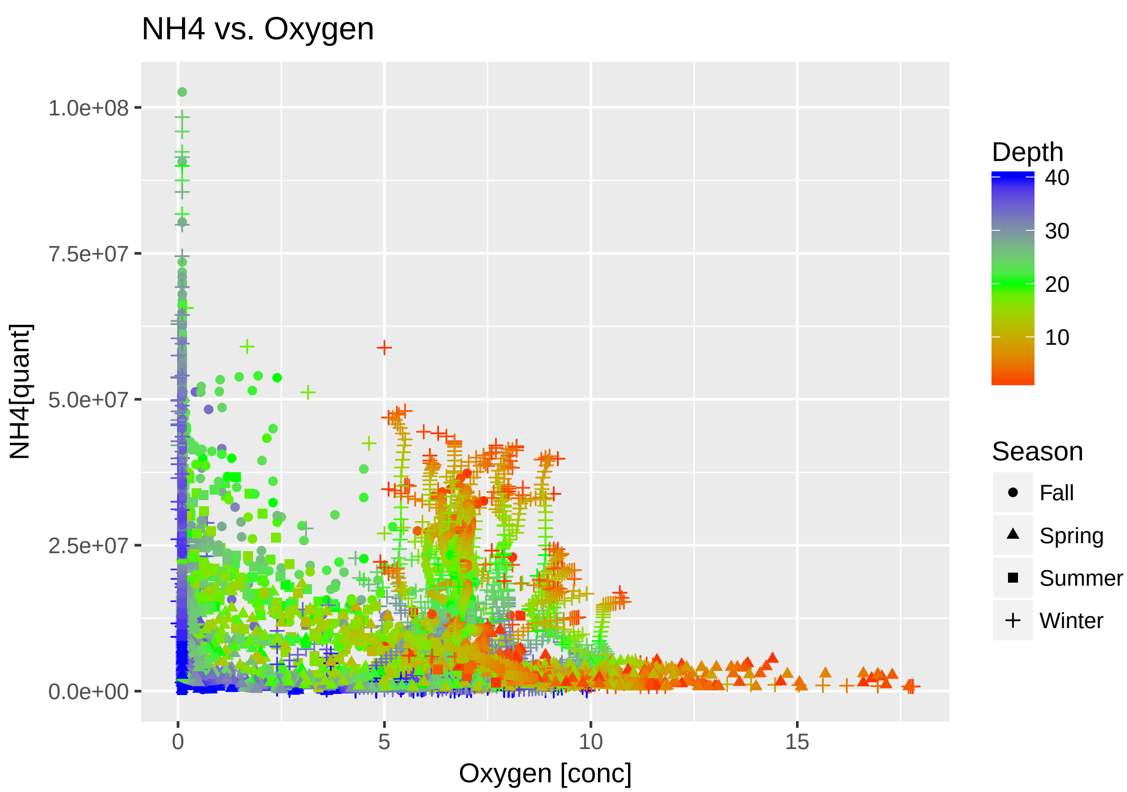
Correlation plots

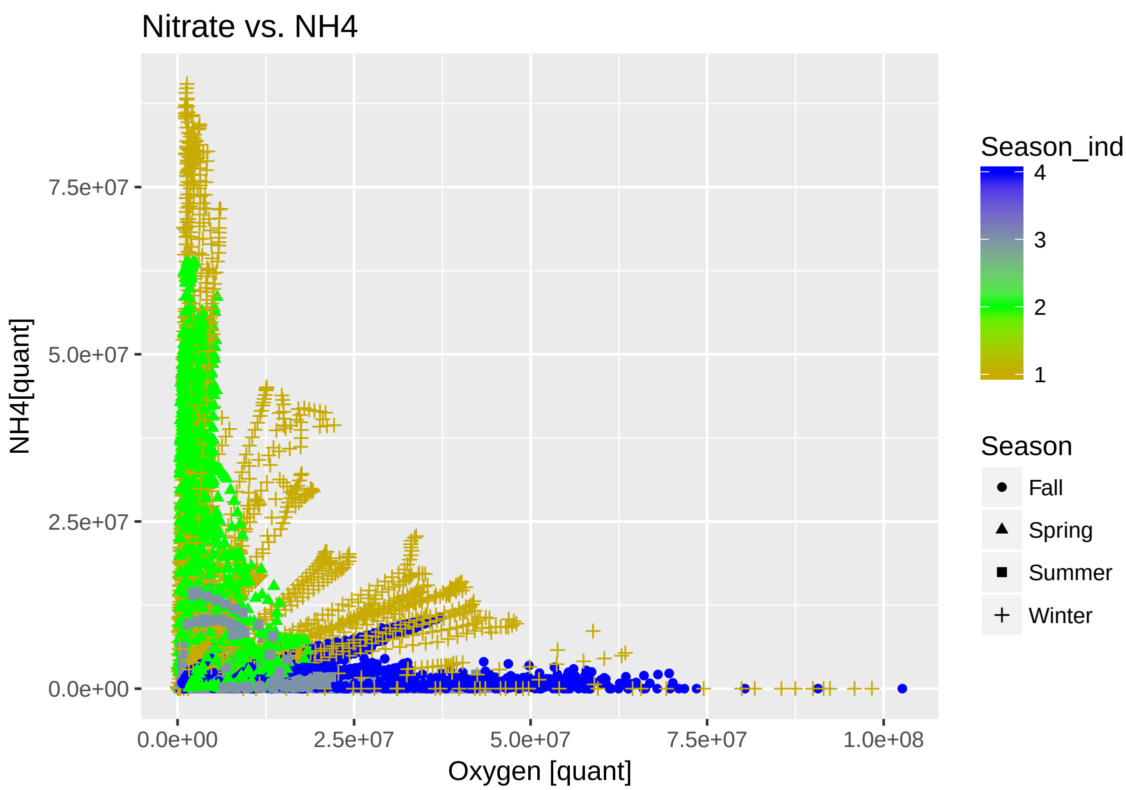
The following plots provide some visual estimation of data correlation



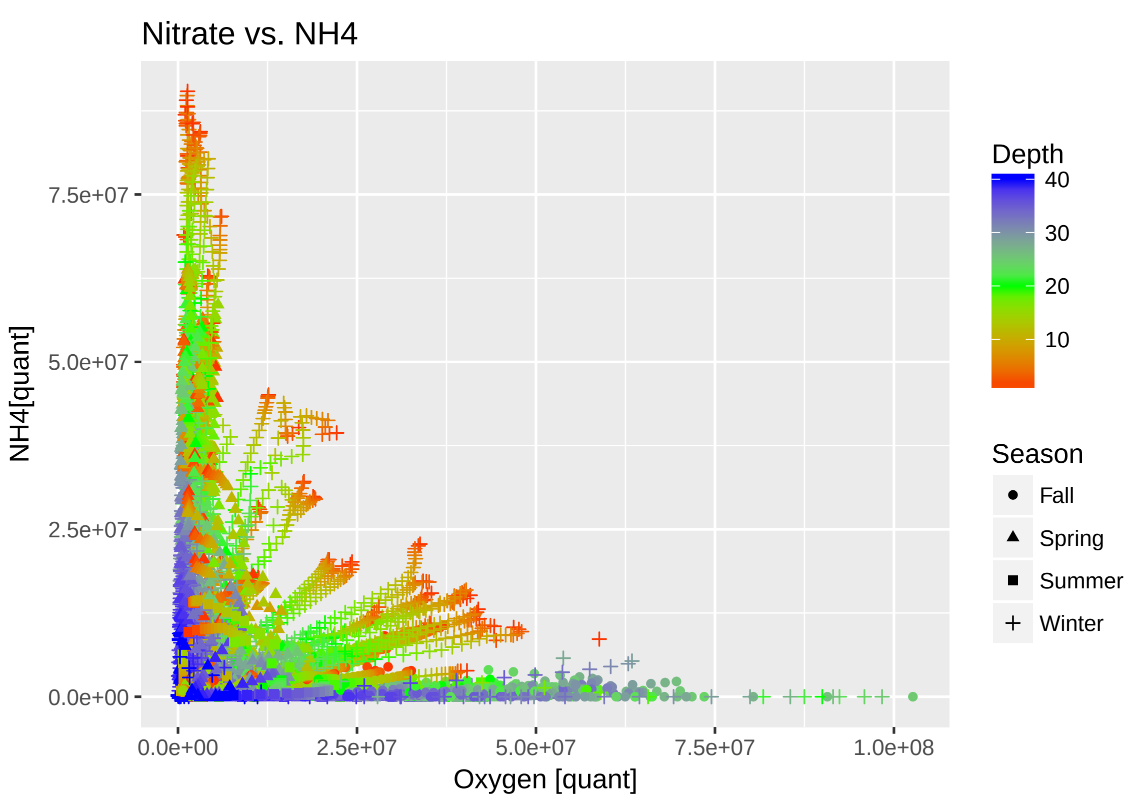



NH4 vs. Oxygen
NH4[quant]
1.0e+08
7.5e+07
5.0e+07
2.5e+07
0.0e+00
0e+00
1e+09
2e+09
3e+09
Oxygen [quant]
Depth
40
30
20
10
Season
Fall
Spring
Summer
Winter


NH4 vs. Oxygen
NH4[quant]
1.0e+08
7.5e+07
5.0e+07
2.5e+07
0.0e+00
0
5
10
15
Oxygen [conc]
Depth
40
30
20
10
Season
Fall
Spring
Summer
Winter



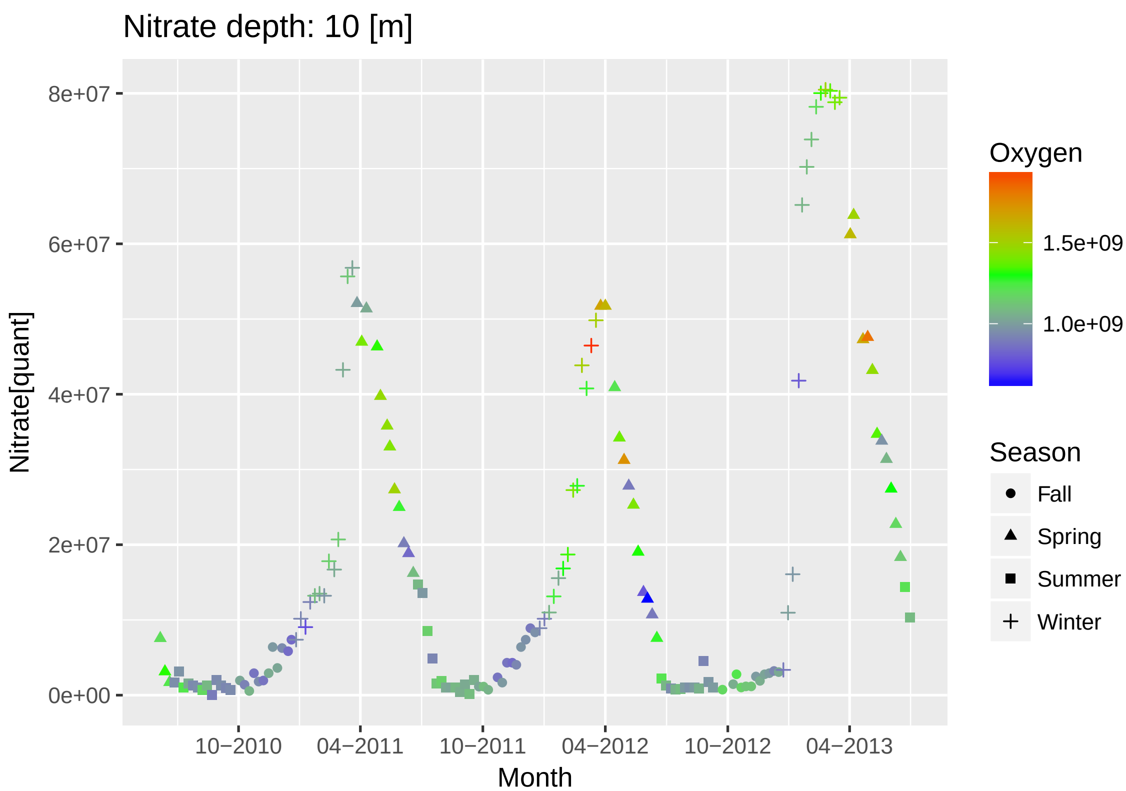
Nitrate vs. NH4
NH4[quant]
7.5e+07
5.0e+07
2.5e+07
0.0e+00
0.0e+00
2.5e+07
5.0e+07
7.5e+07
1.0e+08
Oxygen [quant]
Season_ind
4
3
2
1
Season
Fall
Spring
Summer
Winter

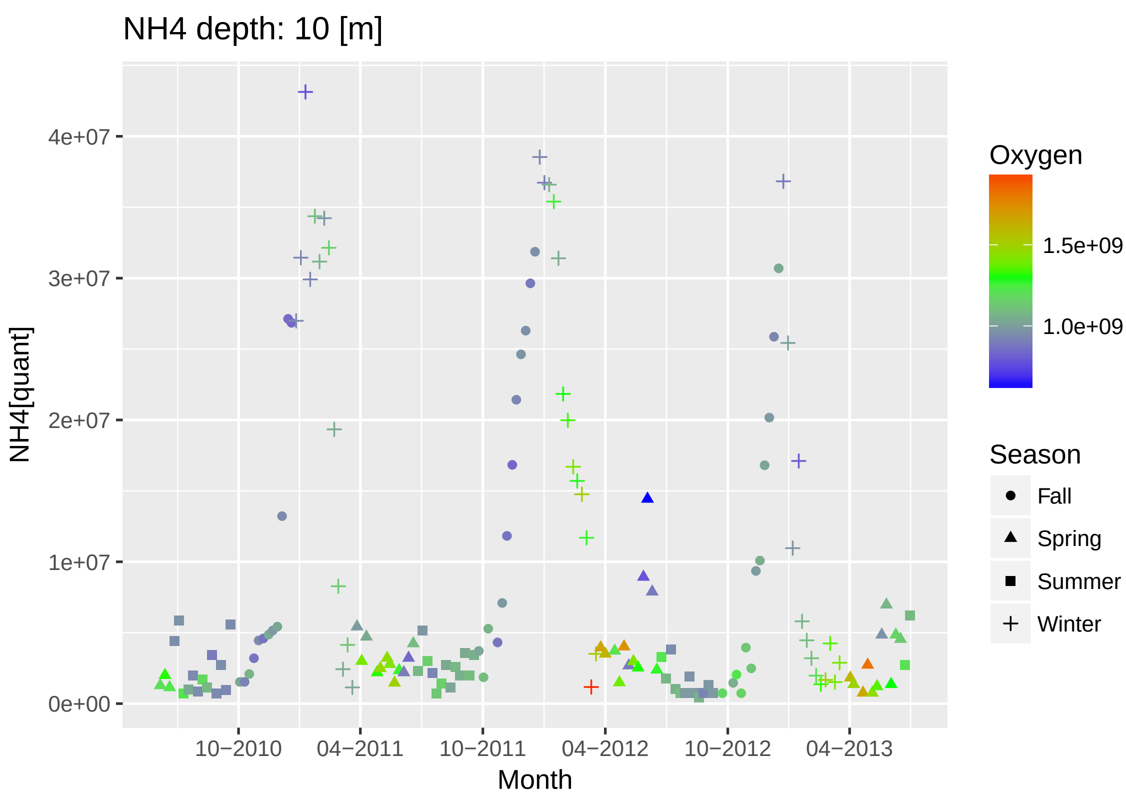


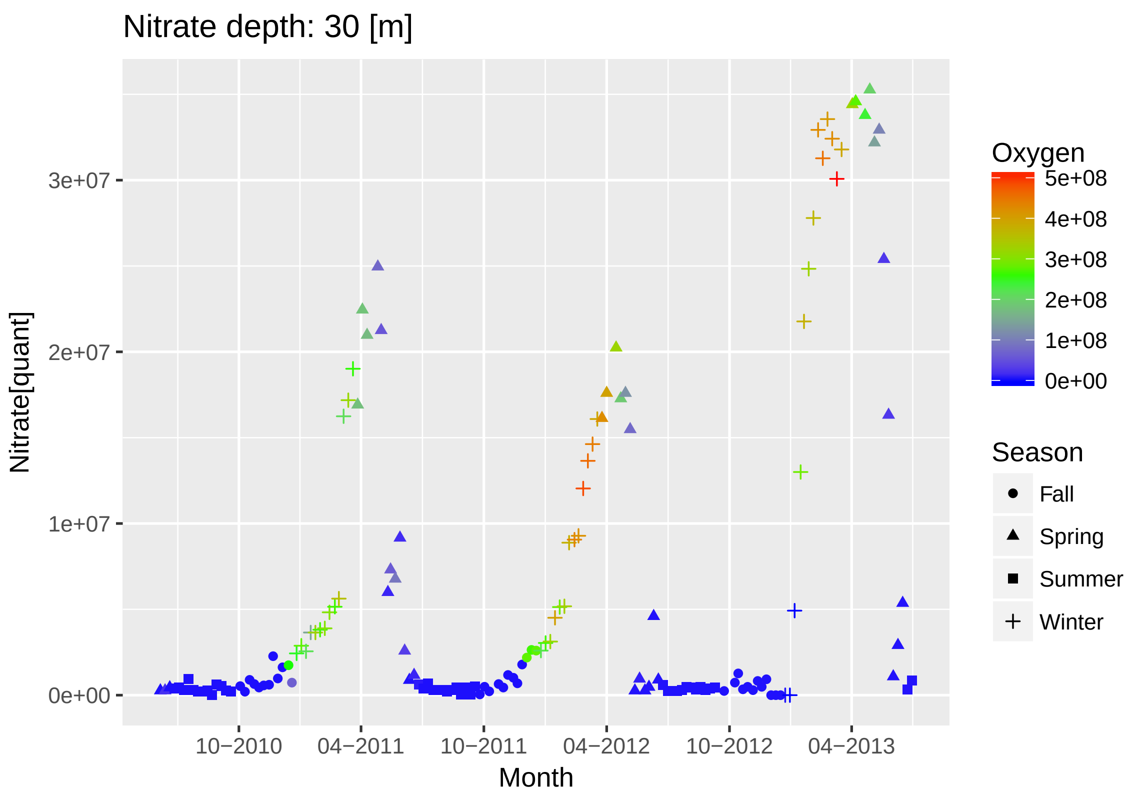
Nitrate vs. NH4
NH4[quant]
7.5e+07
5.0e+07
2.5e+07
0.0e+00
0.0e+00
2.5e+07
5.0e+07
7.5e+07
1.0e+08
Oxygen [quant]
Depth
40
30
20
10
Season
Fall
Spring
Summer
Winter

Model fitting estimation

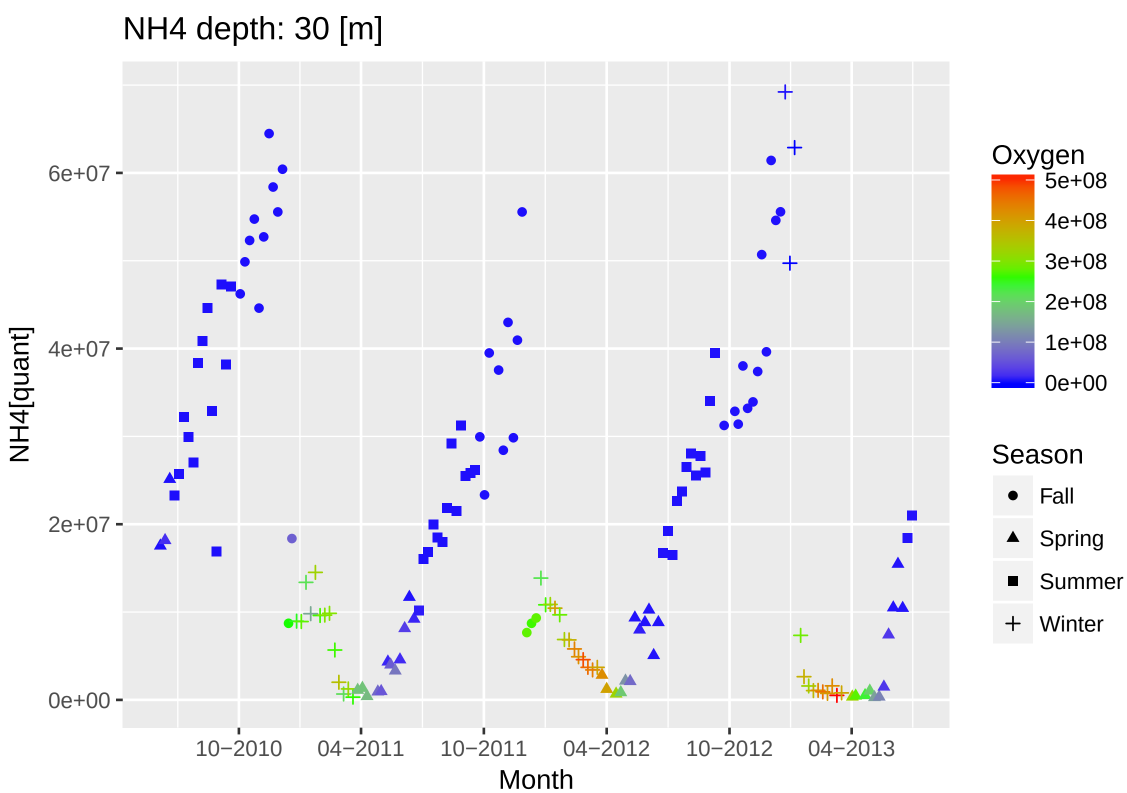
Nitrification and denitrification are two oposing processes that take place in the present or absence of oxygen. They therefore develop in the upper (nitrification) and lower (denitrification) parts of the lake during episodes of a stratified water column. The model therefore relies on the assumprion that their development depends on the presence of oxygen and the time available for their accumulation. Lake mixing, which takes place during winter, disrupts thier build-up, and uniformly distribute them across the lake, and mixing propagates towards the lake bottom. These two proceeses (stratification and mixing)can be examined in detail in two representative depths of 10m (nitrification) and 30m (denitrification).


Nitrate depth: 10 [m]
Nitrate[quant]
8e+07
6e+07
4e+07
2e+07
0e+00
10−2010
04−2011
10−2011
04−2012
10−2012
04−2013
Month
Oxygen
1.5e+09
1.0e+09
Season
Fall
Spring
Summer
Winter


NH4 depth: 10 [m]
NH4[quant]
4e+07
3e+07
2e+07
1e+07
0e+00
10−2010
04−2011
10−2011
04−2012
10−2012
04−2013
Month
Oxygen
1.5e+09
1.0e+09
Season
Fall
Spring
Summer
Winter



Nitrate depth: 30 [m]
Nitrate[quant]
3e+07
2e+07
1e+07
0e+00
10−2010
04−2011
10−2011
04−2012
10−2012
04−2013
Month
Oxygen
5e+08
4e+08
3e+08
2e+08
1e+08
0e+00
Season
Fall
Spring
Summer
Winter

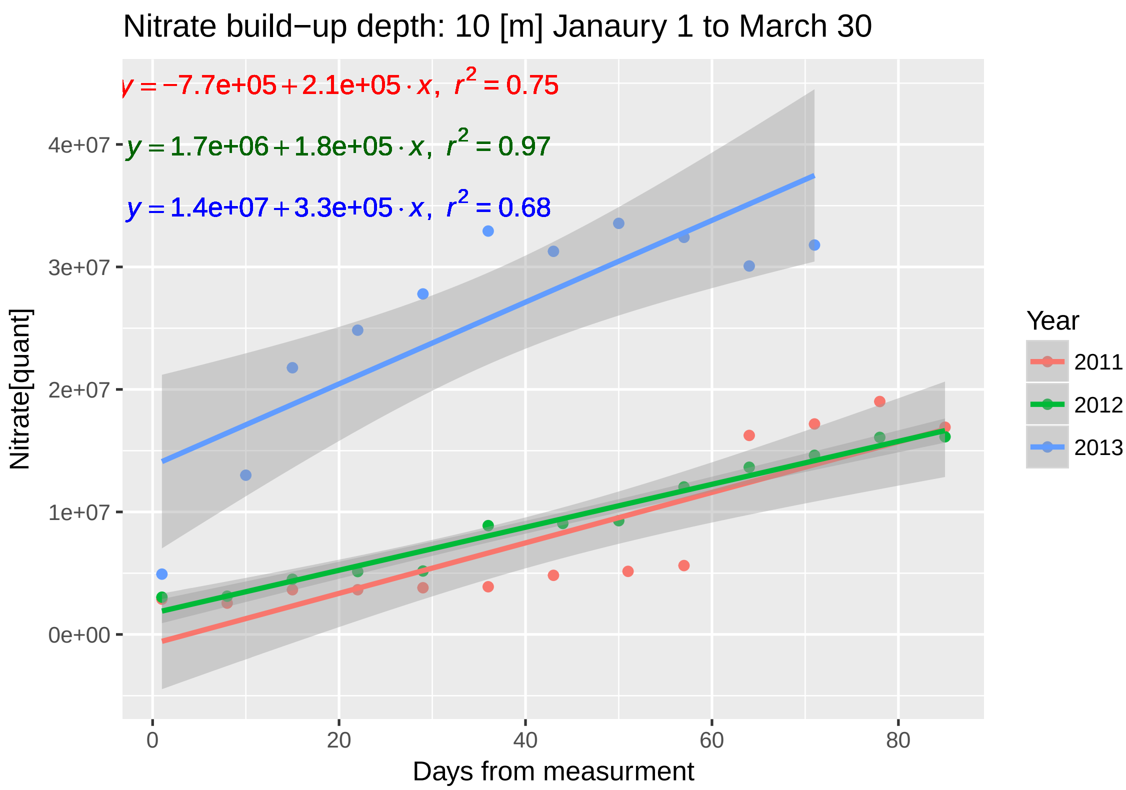


NH4 depth: 30 [m]
NH4[quant]
6e+07
4e+07
2e+07
0e+00
10−2010
04−2011
10−2011
04−2012
10−2012
04−2013
Month
Oxygen
5e+08
4e+08
3e+08
2e+08
1e+08
0e+00
Season
Fall
Spring
Summer
Winter

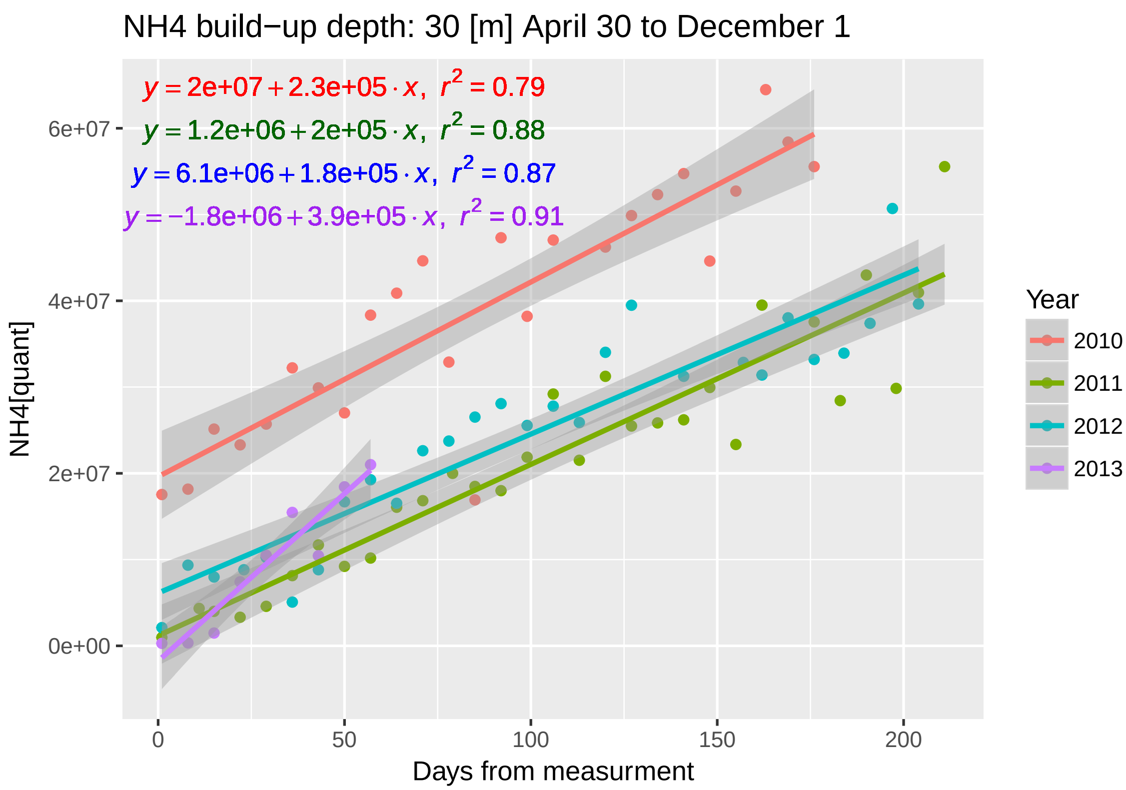
Process rate estimation

It can be observed from the figures presented above that nitrification is dominant in the upper portions of the lake (depicted for 10m depth), primarily between January and April, when the mixing of the lake decreases its content through a down-ward propagating mixing of the oxygenated epilimnion with the lower, oxygen-depleted hypolimnion. Ammonium, on the other hand, develops during the stratified lake conditions in its hypolimnion (depicted for depth 30 m), and peaks at the begining of May, right before the mixing of the lake reaches the deeper parts of the lake, denitrification is halted, and the deeper lake is oxygenated once more.

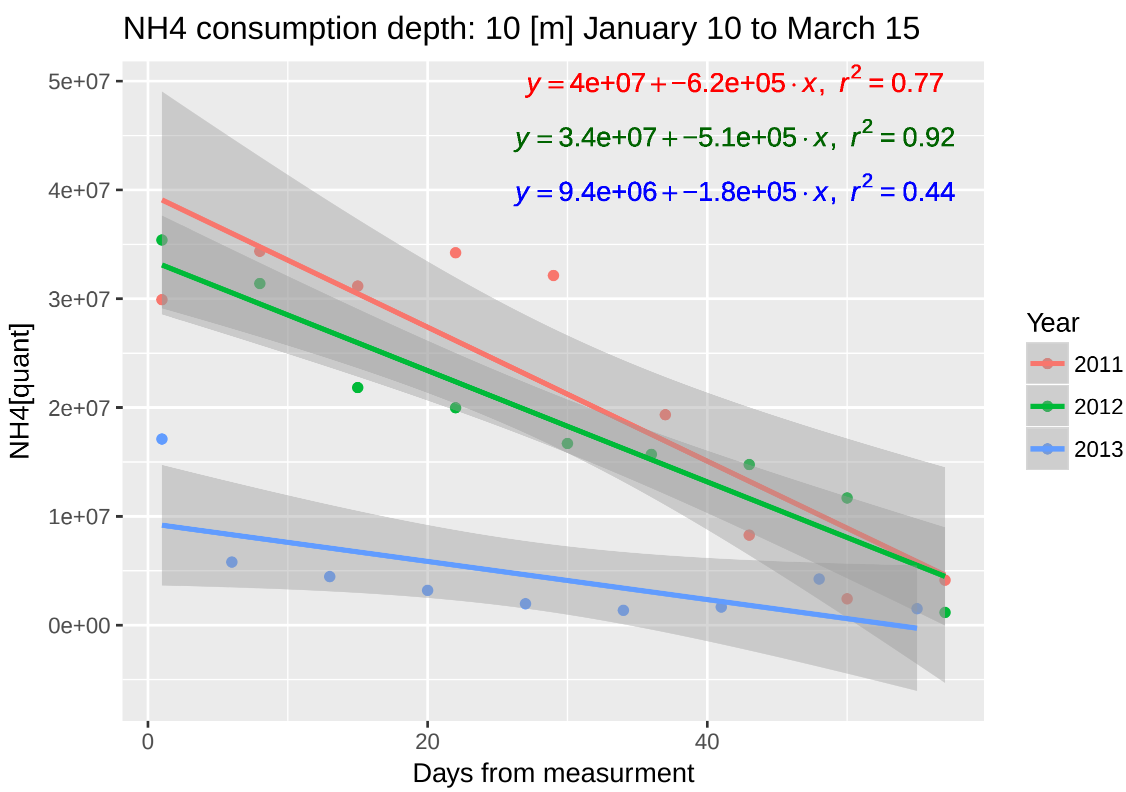
Simulate Nitrate build-up between November 1^{st} and April 30^{st} in 10m depth in order to estimate processes rate



simulate NH4 build-up between April 30^{st} and December 1^{st} in 30m depth in order to estimate reaction rate



simulate NH4 consumption between January 10^{th} and March 15^{th} in 30m depth in order to estimate reaction rate



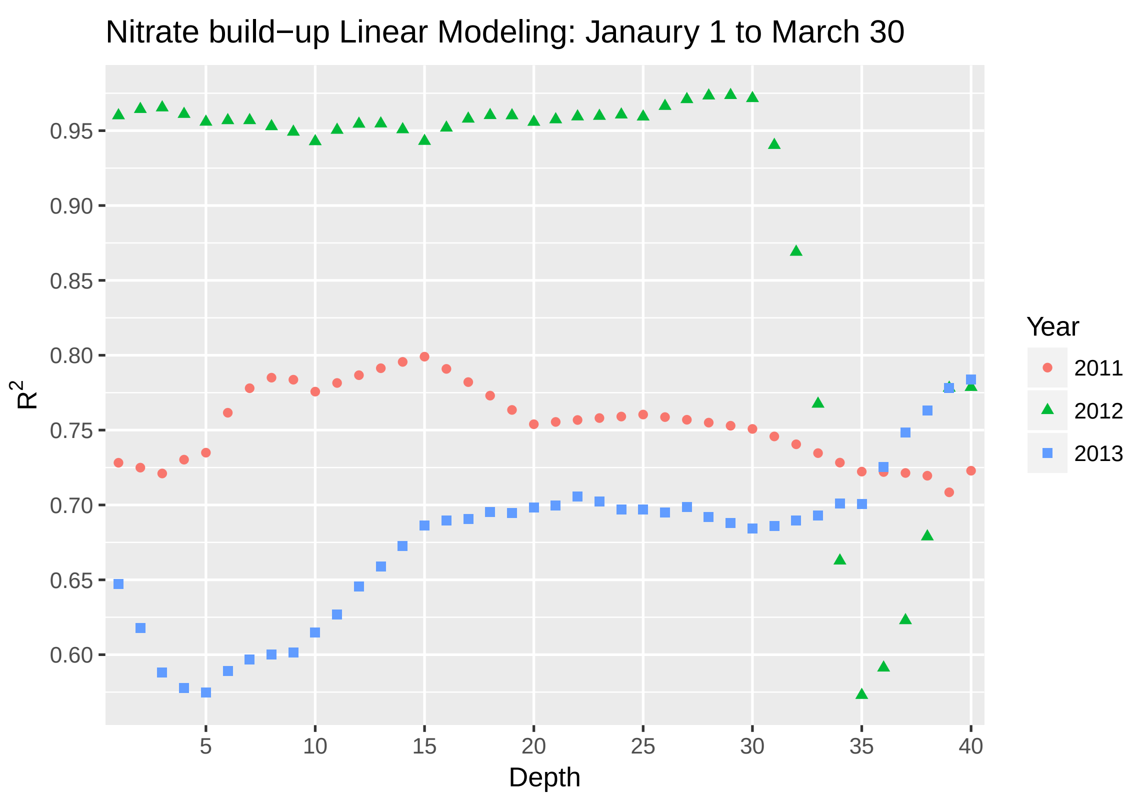
Coeffiecients assement for all depths

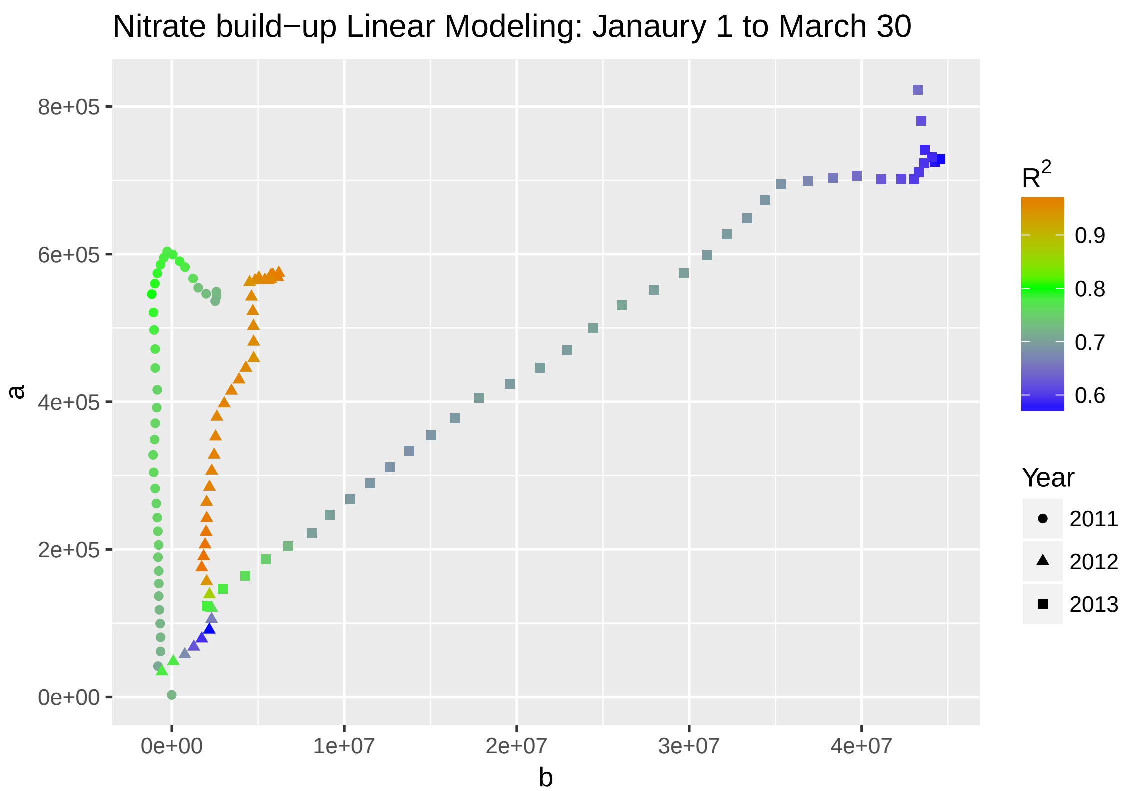
After consideration of the dominant processes that control nitrate and ammonium content in the lake, the following section provides an assesment of the processes and their fit to a linear model in each depth. The R^2 value can be used to asses the best fit of the model for each depth. It can be observed that nitrate buildup fits a linear model in most depths, although some intraannual changes illustrate the complexity of the system and its divergence from linearity. The coefficients of the model also show a wide range, and illustrate that the best R^2 values were found for the year 2012 (triangles) and values of ca. $a = 5 * 10^6$ and $b = 4 * 10^5$ that describe nitrate build up between Novemebr 1^{st} and April 31^{st} using the following equation:

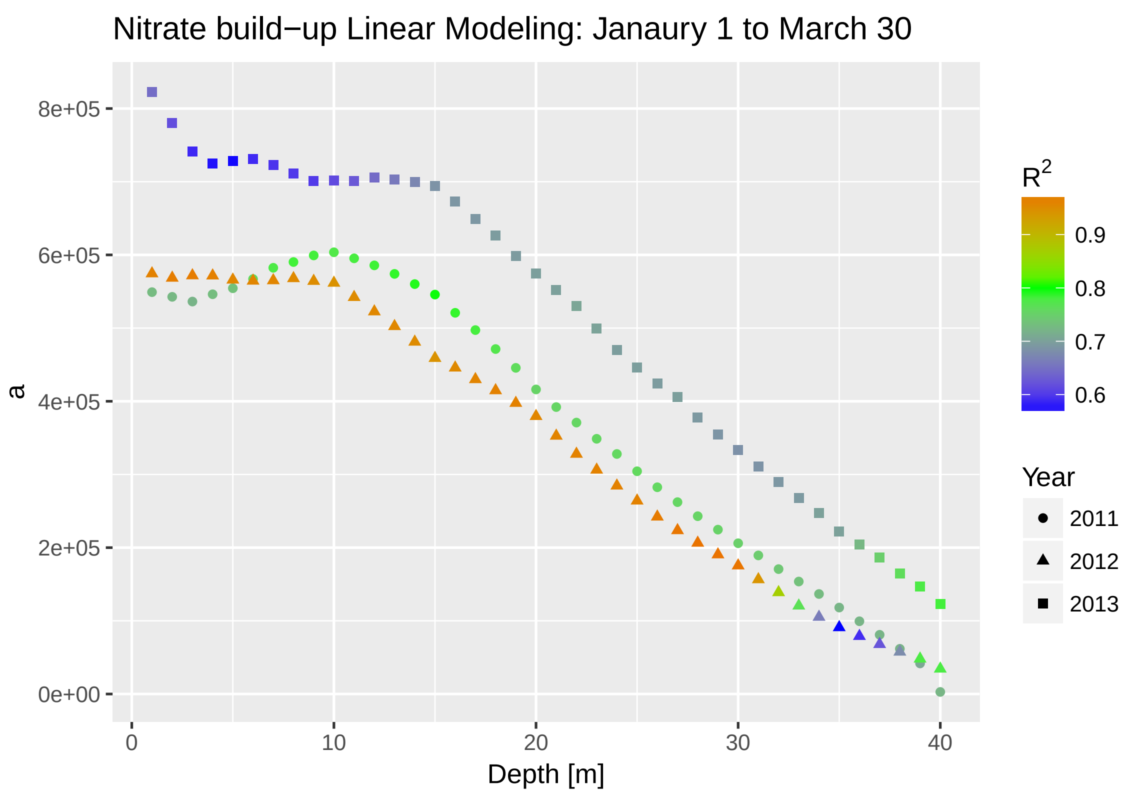
$$NO_3 = 5 * 10^6 * t + 4 * 10^5$$

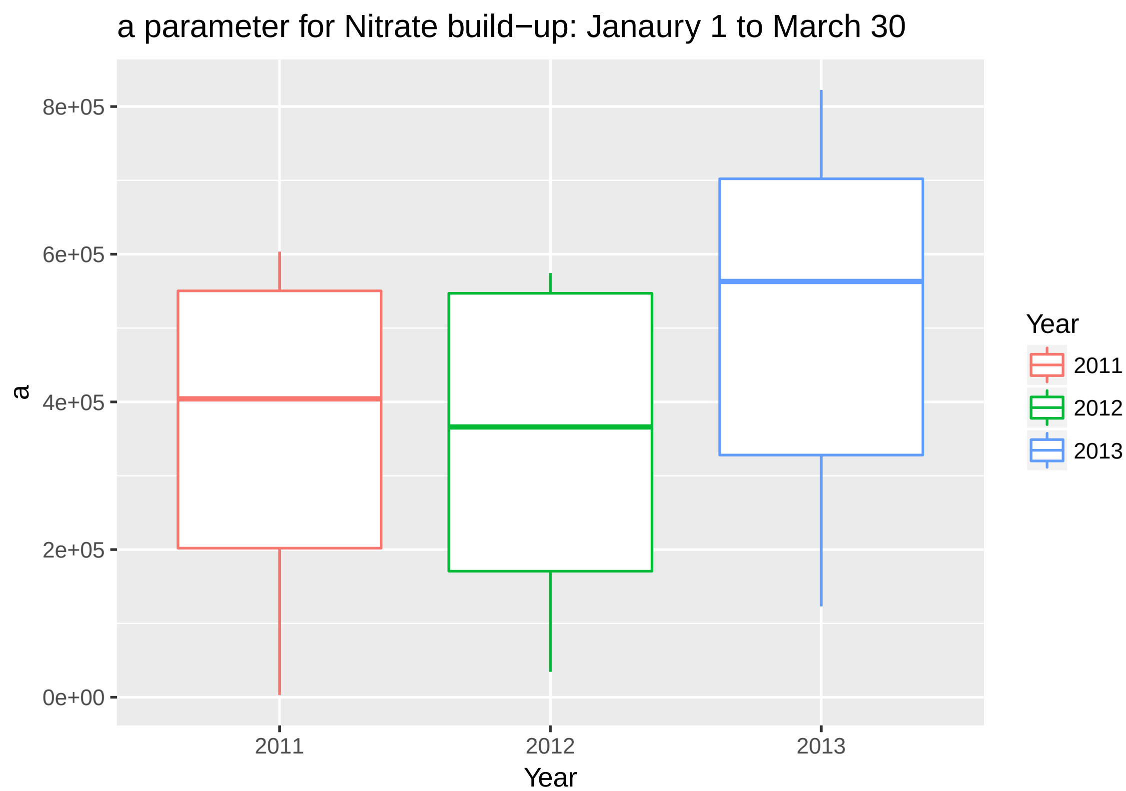
, where t is provided in days.

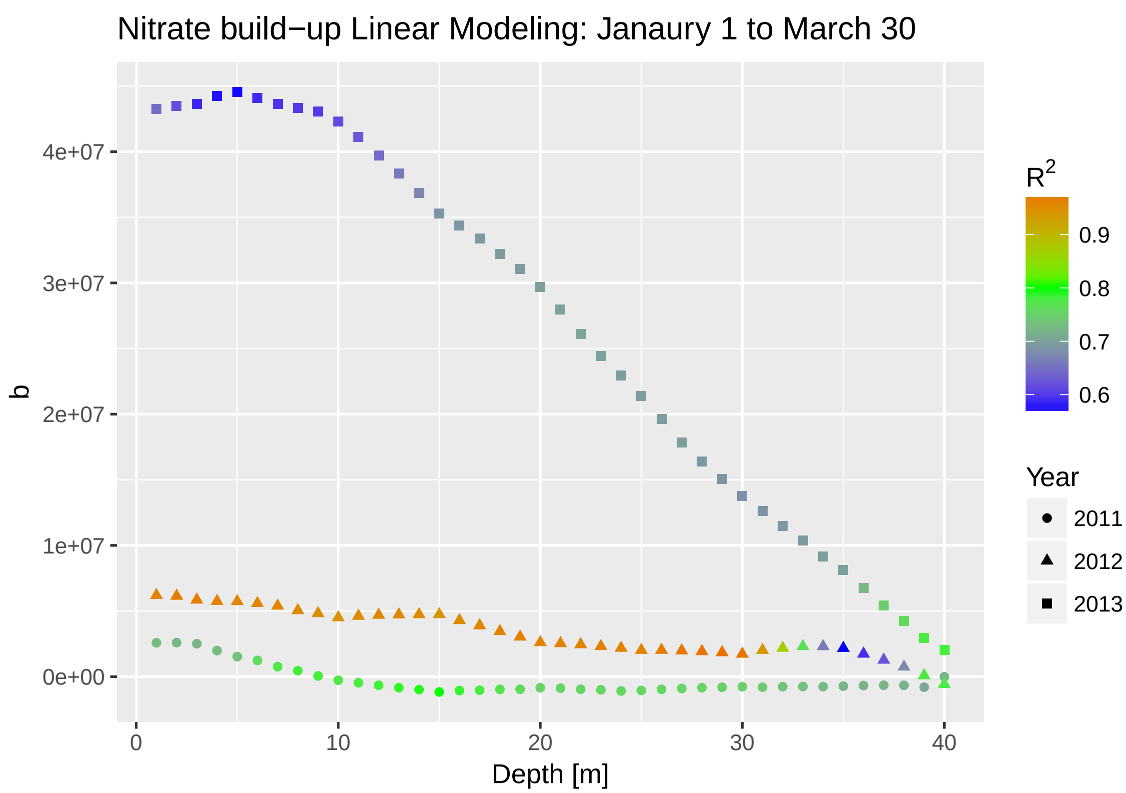
```
##      Depth             a                  b                    r2
##  Min.   : 1.00   Min.   :  2837   Min.   :-1163352   Min.   :0.5730
##  1st Qu.:10.75   1st Qu.:223195   1st Qu.: -315929   1st Qu.:0.6953
##  Median :20.50   Median :437797   Median : 2589163   Median :0.7545
##  Mean   :20.50   Mean   :409771   Mean   : 9884307   Mean   :0.7765
##  3rd Qu.:30.25   3rd Qu.:569284   3rd Qu.:12924573   3rd Qu.:0.9409
##  Max.   :40.00   Max.   :822536   Max.   :44544584   Max.   :0.9737
```

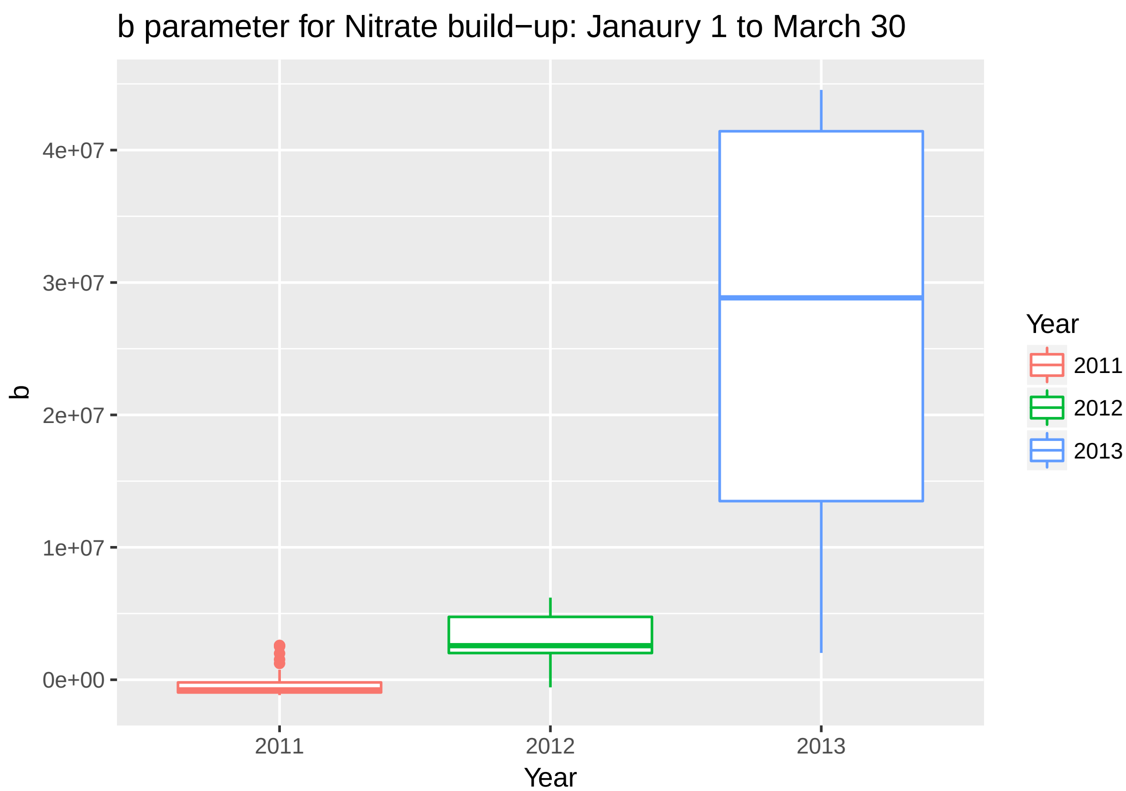


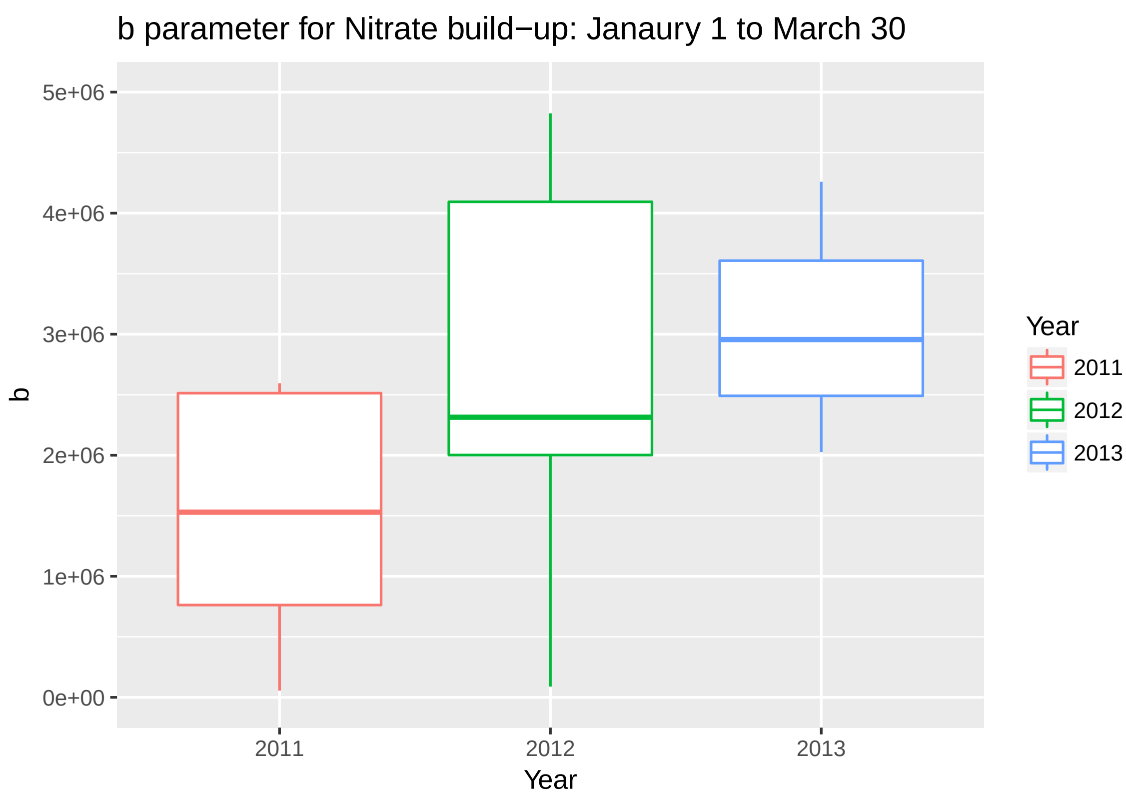

Nitrate build−up Linear Modeling: Janaury 1 to March 30
a
b
8e+05
6e+05
4e+05
2e+05
0e+00
0e+00
1e+07
2e+07
3e+07
4e+07
R2
0.9
0.8
0.7
0.6
Year
2011
2012
2013


Nitrate build−up Linear Modeling: Janaury 1 to March 30
a
Depth [m]
8e+05
6e+05
4e+05
2e+05
0e+00
0
10
20
30
40
R2
0.9
0.8
0.7
0.6
Year
2011
2012
2013


a parameter for Nitrate build−up: Janaury 1 to March 30
8e+05
6e+05
4e+05
2e+05
0e+00
a
2011
2012
2013
Year
Year
2011
2012
2013


Nitrate build−up Linear Modeling: Janaury 1 to March 30
4e+07
3e+07
2e+07
1e+07
0e+00
b
0
10
20
30
40
Depth [m]
R2
0.9
0.8
0.7
0.6
Year
2011
2012
2013





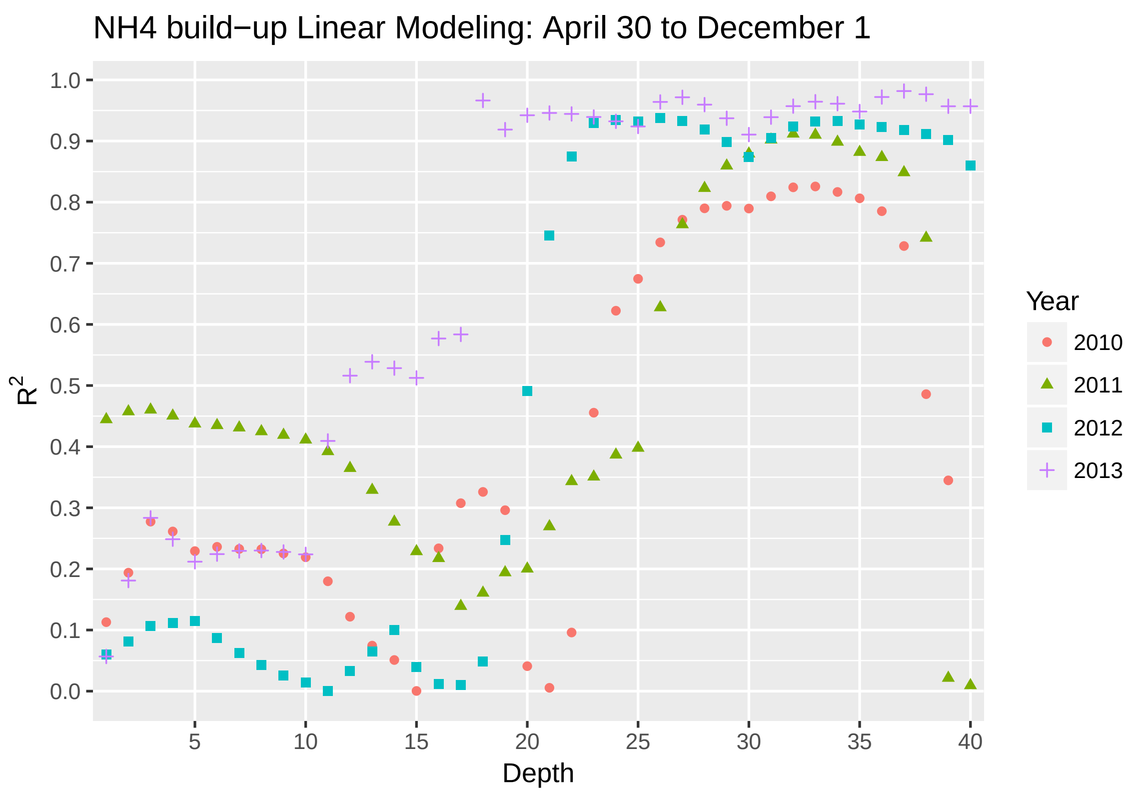
It can be observed that ammonium buildup does fit the linear model in most depths as nicely as nitrate. Intraannual changes are significatn, and once more illustrate the complexity of the system and its divergence from linearity. The coefficients of the model show a slightly smaller range, and illustrate that the best R^2

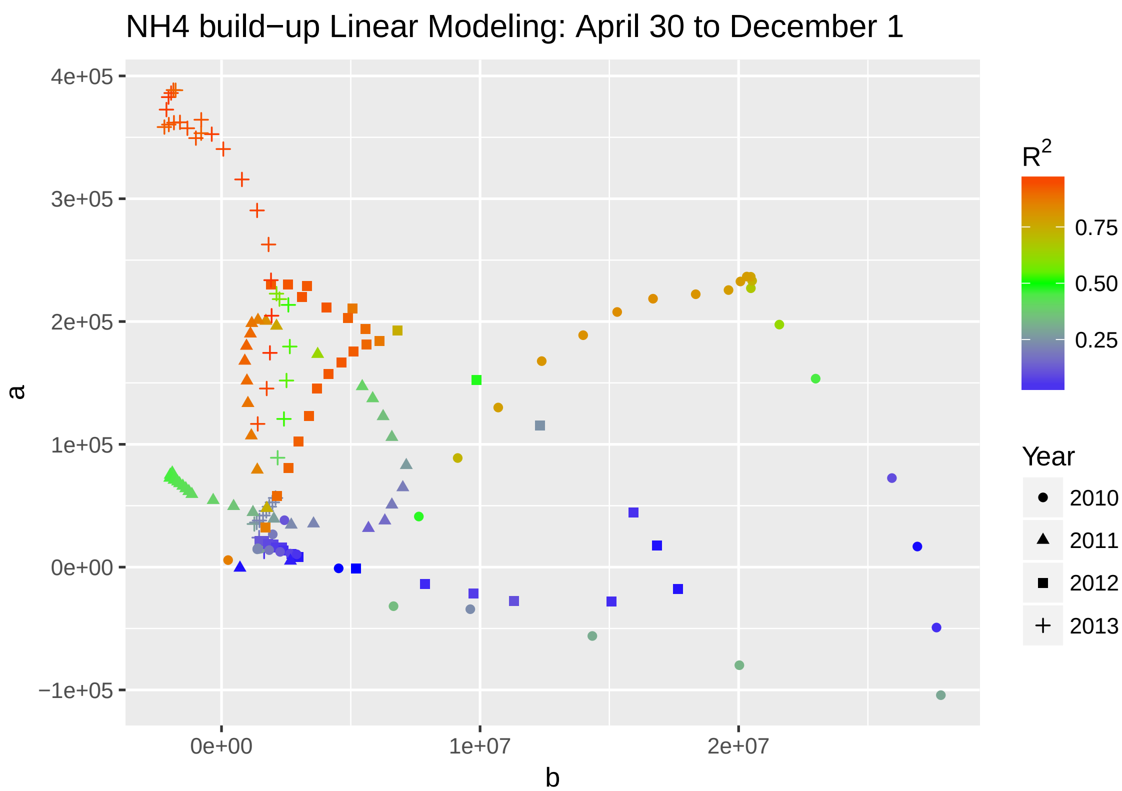
values of ca. $a = 5 * 10^6$ and $b = 5 * 10^5$ that describe ammonium build up between April 30^{th} and December 1^{st} using the following equation:

$$NH_4 = 5 * 10^6 t + 5 * 10^5$$

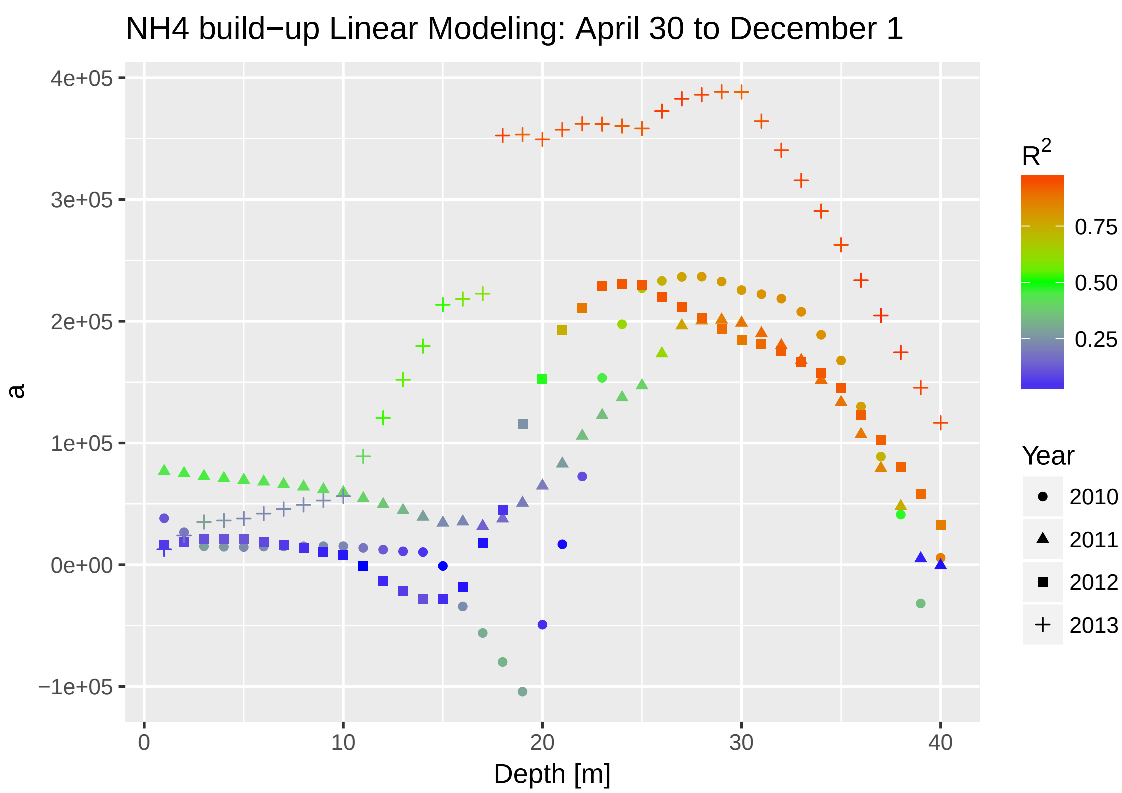
, where t is provided in days. Unsurprisingly, the model has the best fit for depths of 20 to 35m, where oxygenation is solely depends on annual stratification and monomictic mixing.

```
##      Depth             a                  b                   r2
##  Min.   : 1.00   Min.   :-104262   Min.   :-2209182   Min.   :0.0003153
##  1st Qu.:10.75   1st Qu.:  21419   1st Qu.: 1373549   1st Qu.:0.2240937
##  Median :20.50   Median :  81791   Median : 2140742   Median :0.4588809
##  Mean   :20.50   Mean   : 120362   Mean   : 4868893   Mean   :0.5247795
##  3rd Qu.:30.25   3rd Qu.: 200613   3rd Qu.: 6149996   3rd Qu.:0.9020609
##  Max.   :40.00   Max.   : 388468   Max.   :27822019   Max.   :0.9818000
```

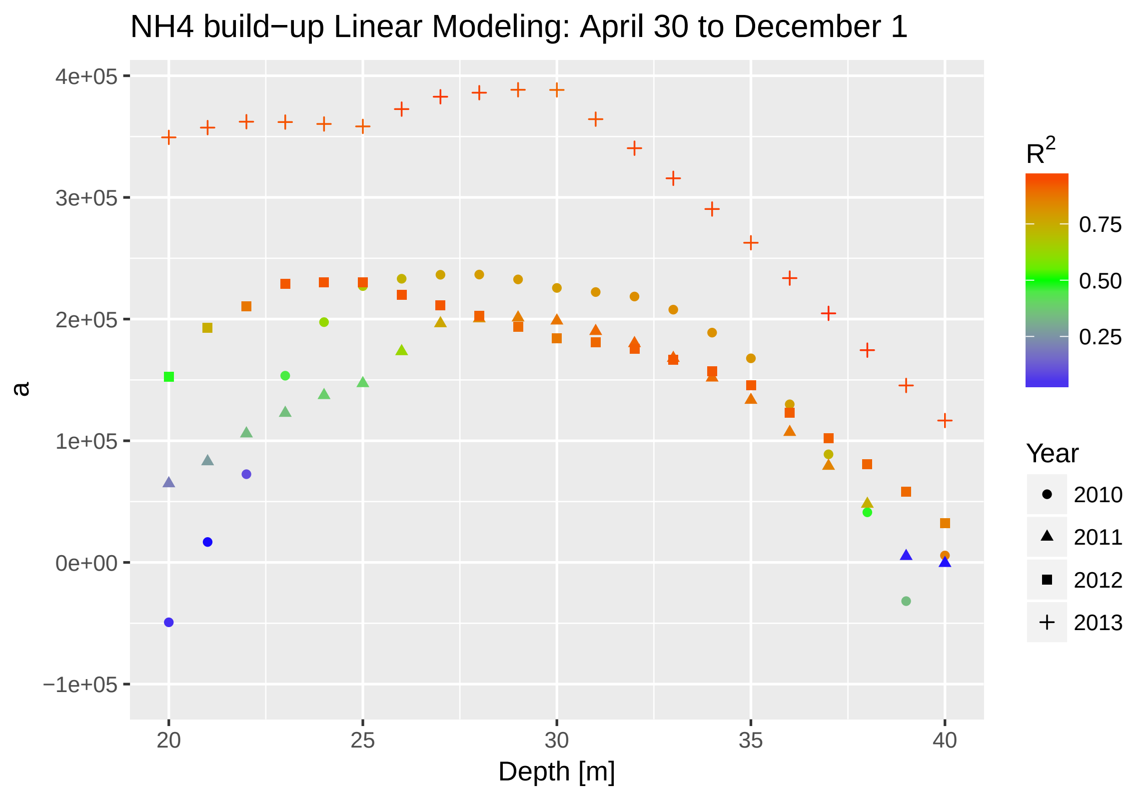


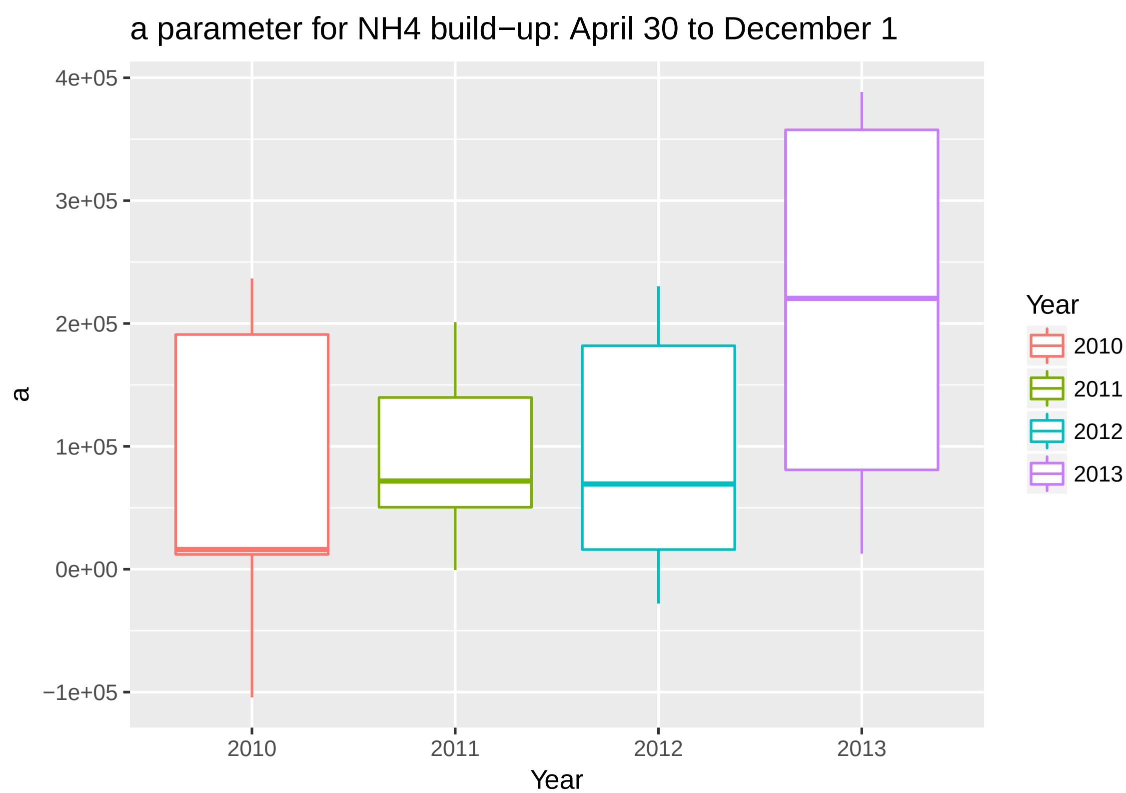


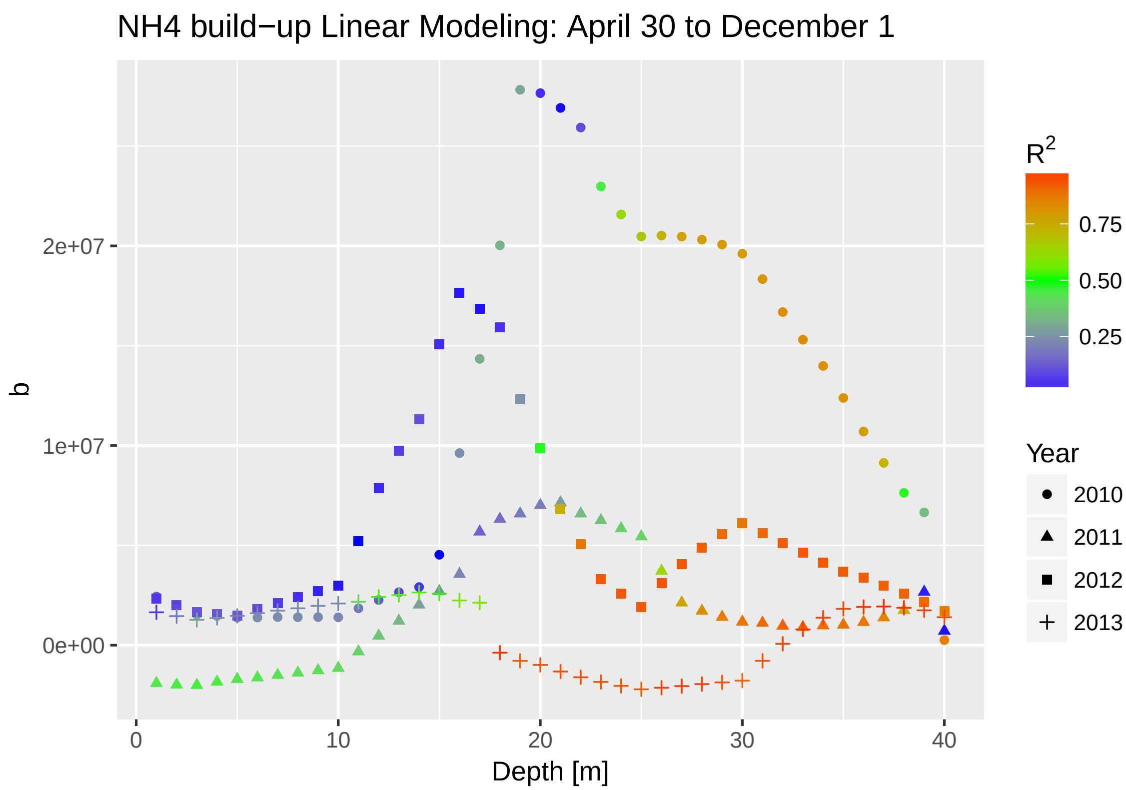
NH4 build−up Linear Modeling: April 30 to December 1
4e+05
3e+05
2e+05
1e+05
0e+00
−1e+05
a
0e+00
1e+07
2e+07
b
R^2
0.75
0.50
0.25
Year
2010
2011
2012
2013



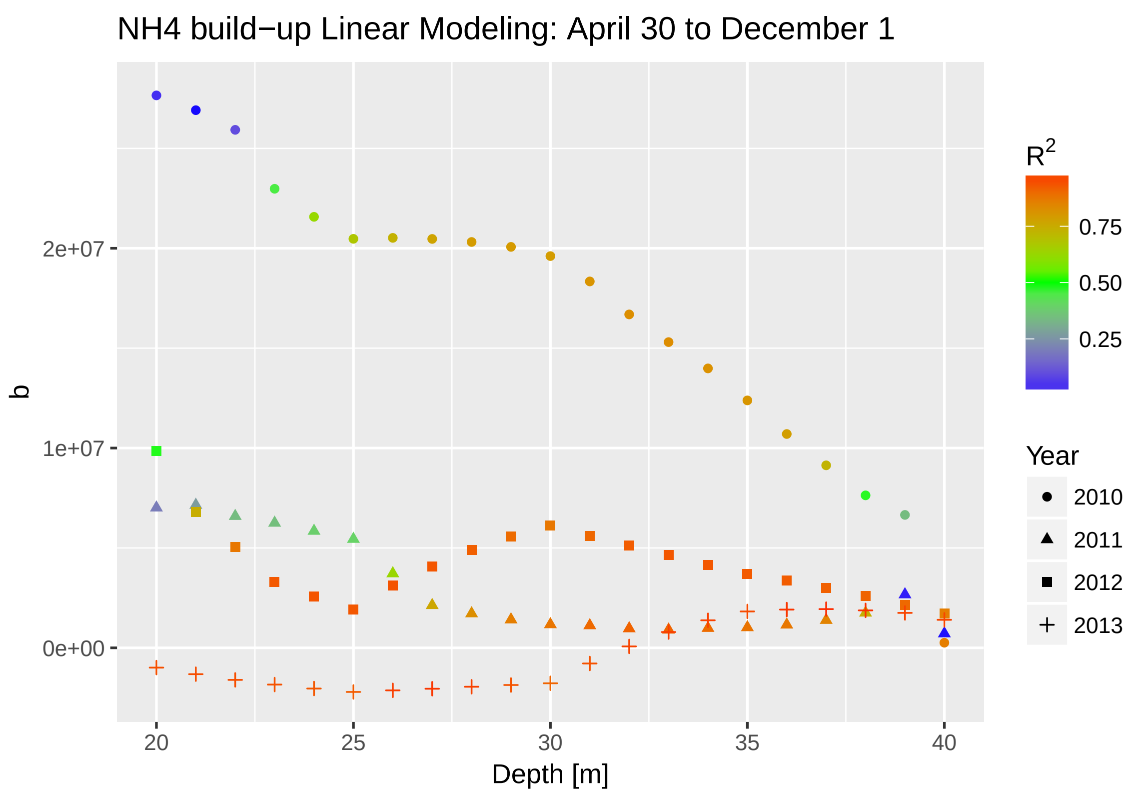
NH4 build−up Linear Modeling: April 30 to December 1
4e+05
3e+05
2e+05
1e+05
0e+00
−1e+05
a
0
10
20
30
40
Depth [m]
R^2
0.75
0.50
0.25
Year
2010
2011
2012
2013


NH4 build−up Linear Modeling: April 30 to December 1
4e+05
3e+05
2e+05
1e+05
0e+00
−1e+05
a
20
25
30
35
40
Depth [m]
R2
0.75
0.50
0.25
Year
2010
2011
2012
2013

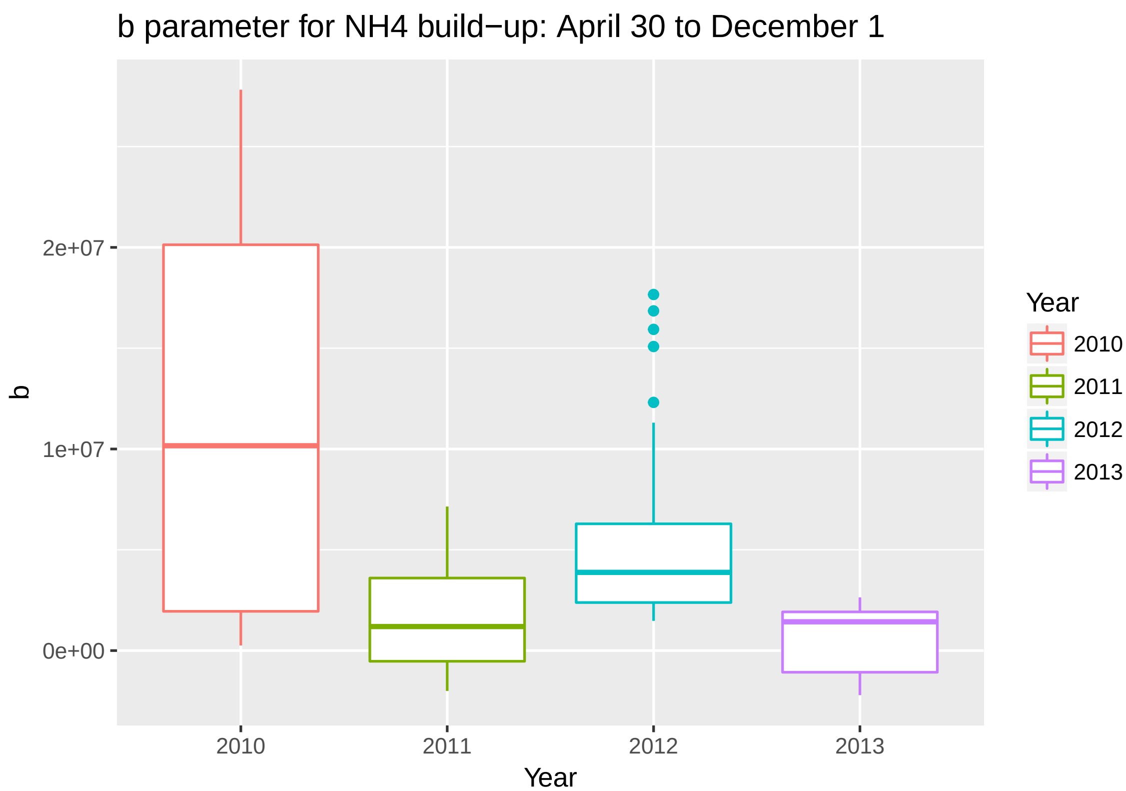

a parameter for NH4 build−up: April 30 to December 1
4e+05
3e+05
2e+05
1e+05
0e+00
−1e+05
a
2010
2011
2012
2013
Year
Year
2010
2011
2012
2013

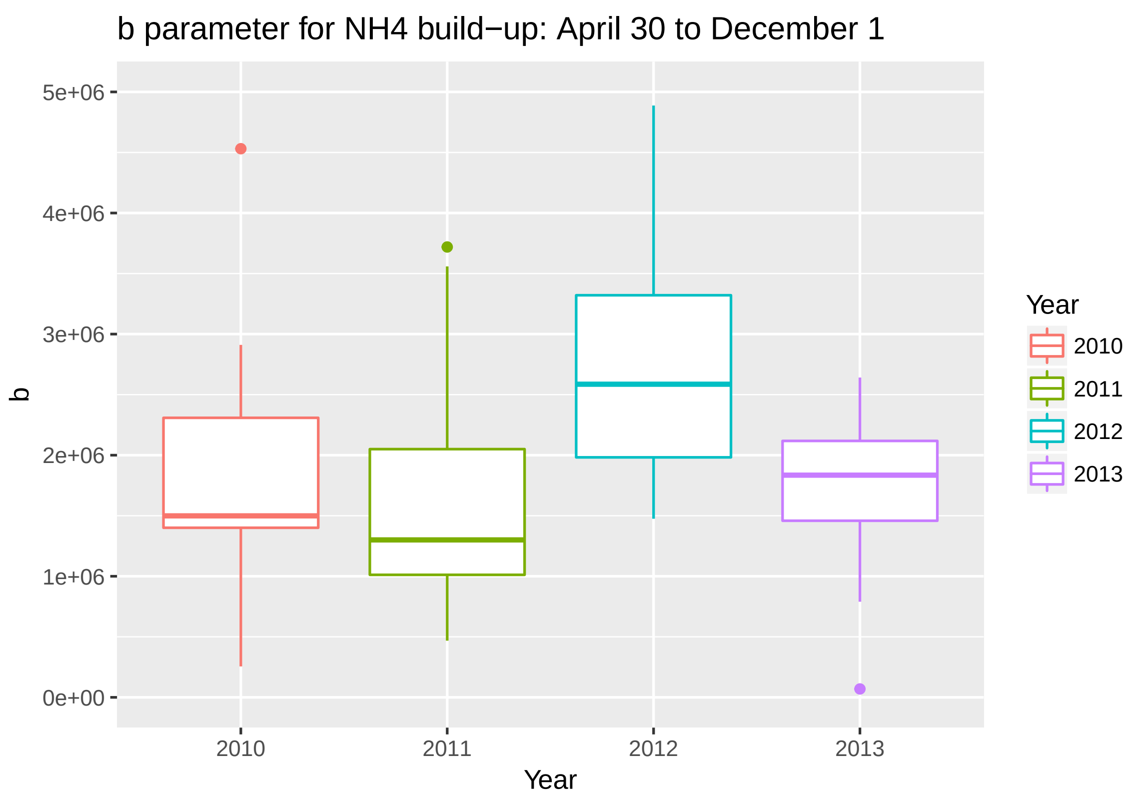


NH4 build−up Linear Modeling: April 30 to December 1
b
2e+07
1e+07
0e+00
0
10
20
30
40
Depth [m]
R^2
0.75
0.50
0.25
Year
2010
2011
2012
2013



NH4 build−up Linear Modeling: April 30 to December 1
b
2e+07
1e+07
0e+00
20
25
30
35
40
Depth [m]
R^2
0.75
0.50
0.25
Year
2010
2011
2012
2013

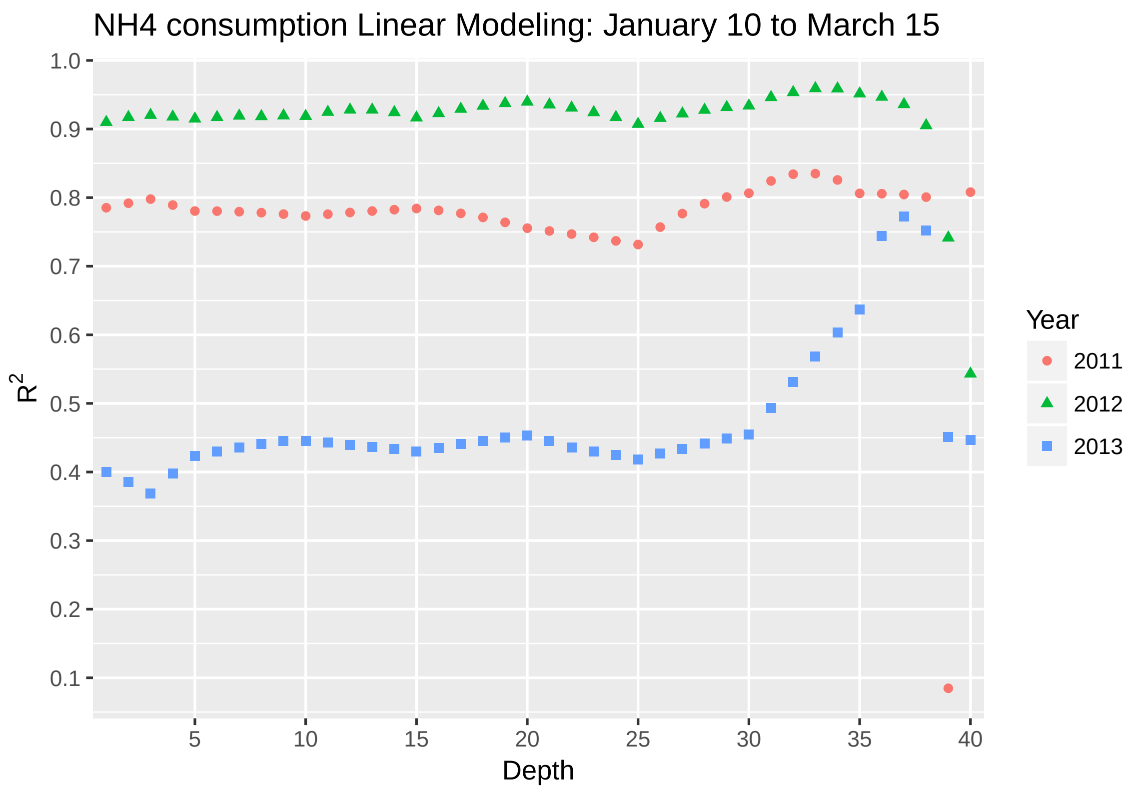


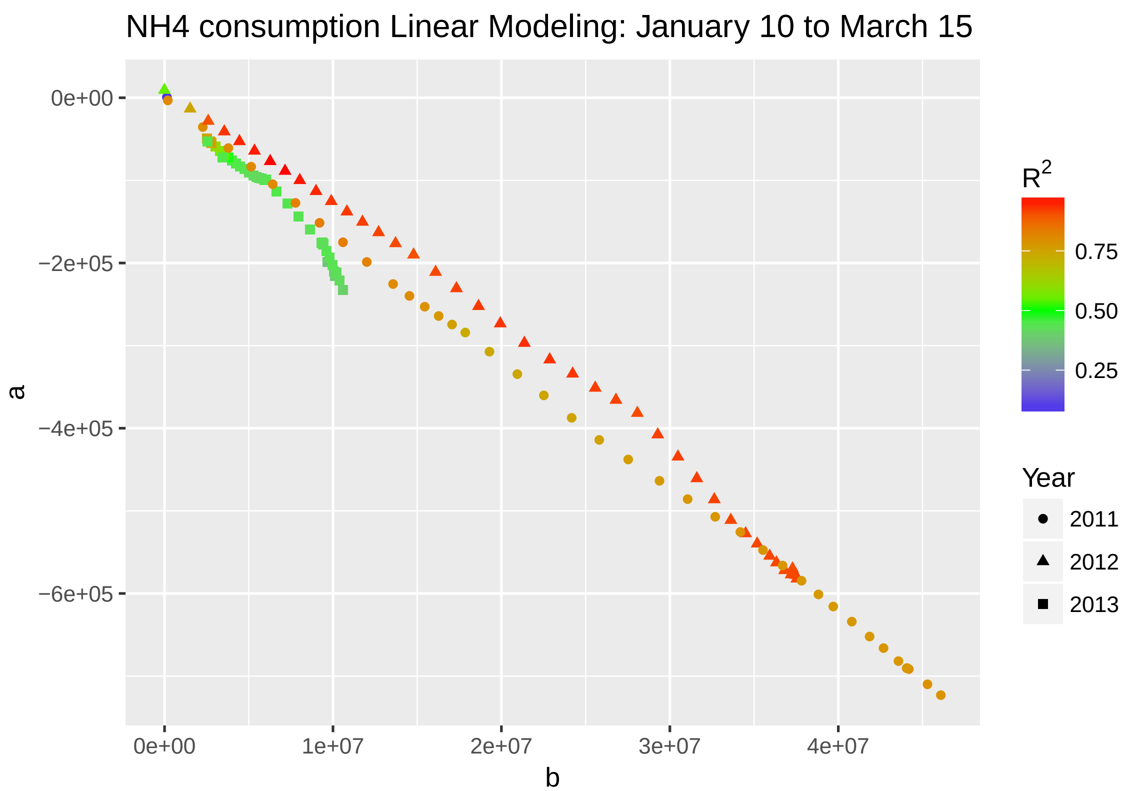


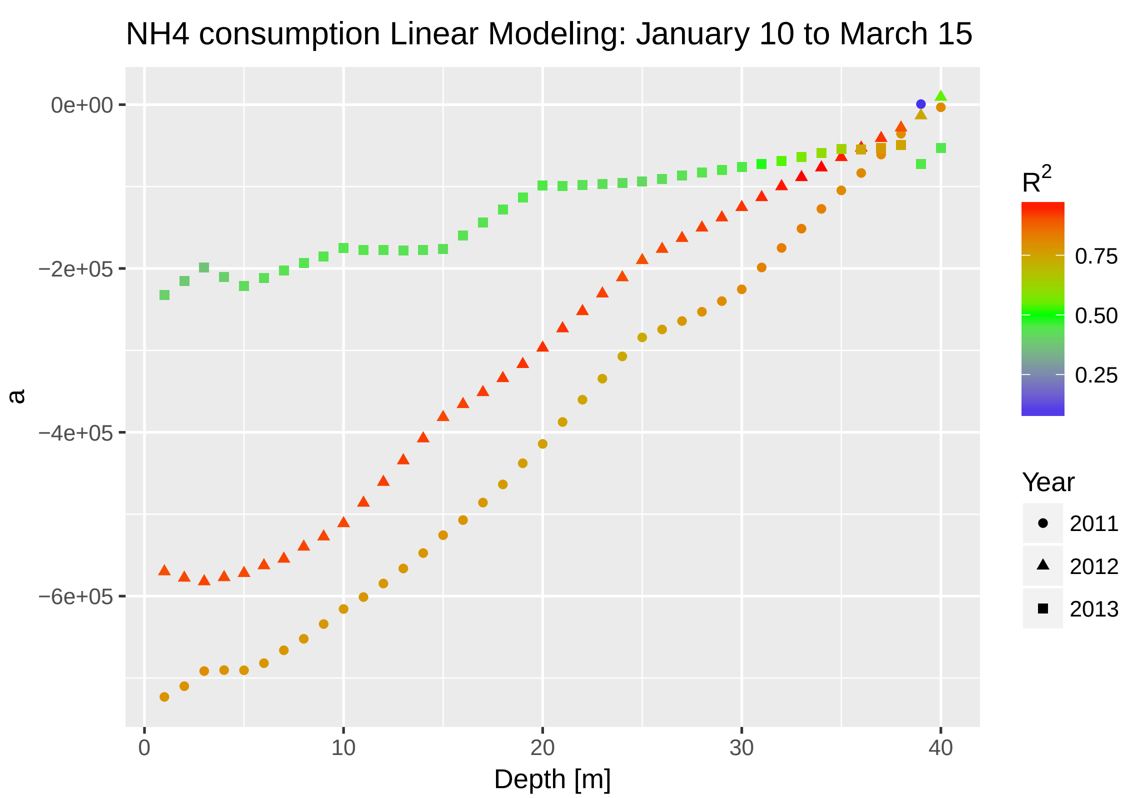
Ammonium consumption after mixing between January 10^{th} to March 15^{th}

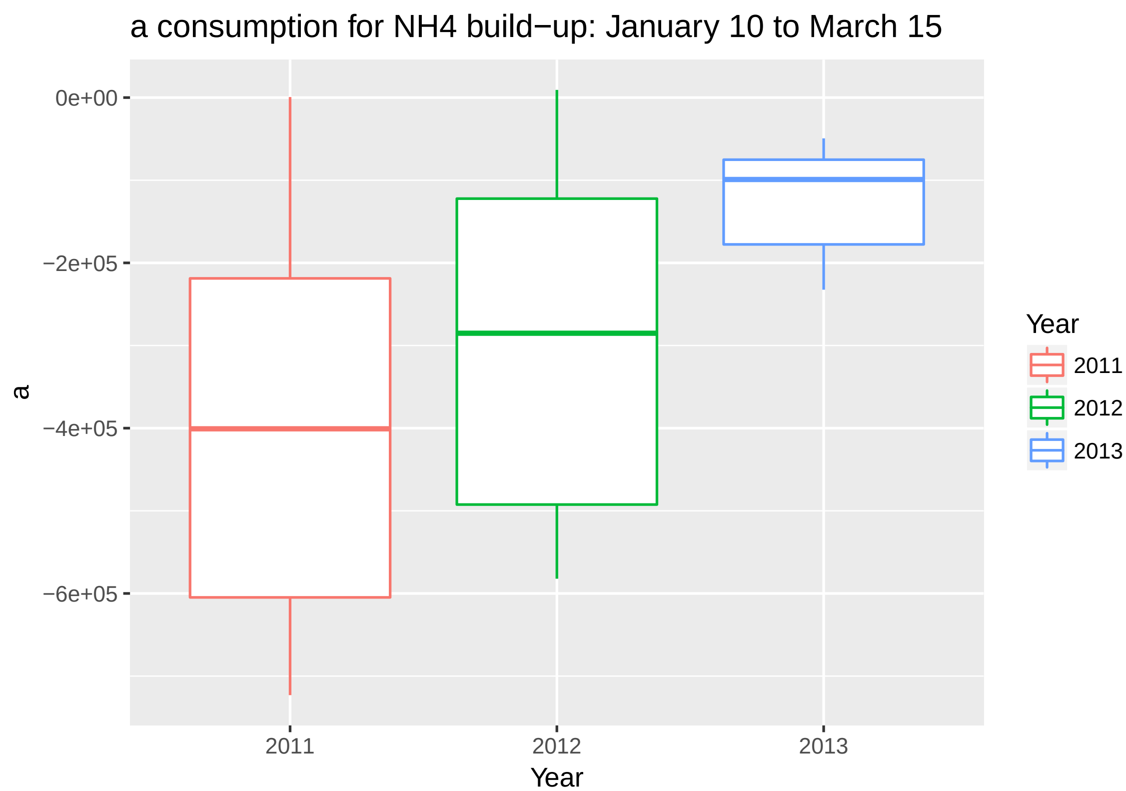
```
##      Depth              a                 b                  r2
```

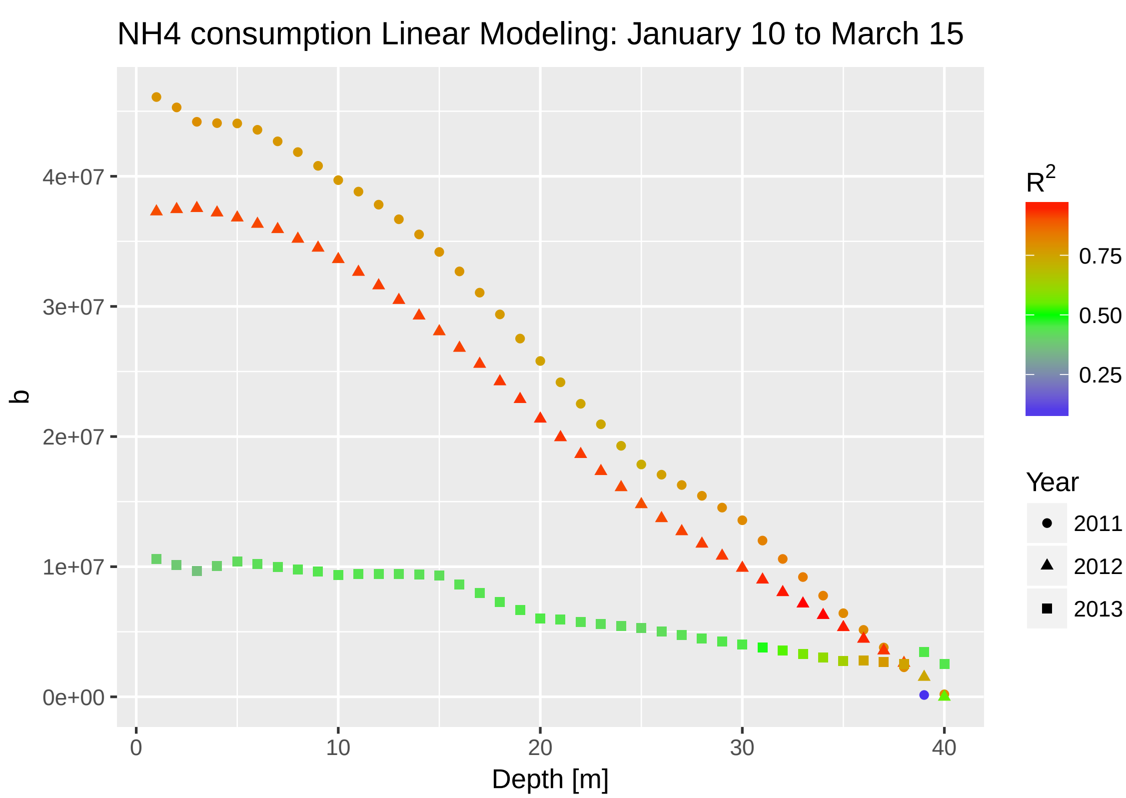
```
##  Min.   : 1.00   Min.   :-723066   Min.   :   -9510   Min.   :0.08467
##  1st Qu.:10.75   1st Qu.:-443545   1st Qu.: 5888522   1st Qu.:0.45085
##  Median :20.50   Median :-200589   Median :10710844   Median :0.77990
##  Mean   :20.50   Mean   :-272712   Mean   :17447156   Mean   :0.71780
##  3rd Qu.:30.25   3rd Qu.: -96653   3rd Qu.:29659587   3rd Qu.:0.91716
##  Max.   :40.00   Max.   :   9290   Max.   :46089838   Max.   :0.95925
```

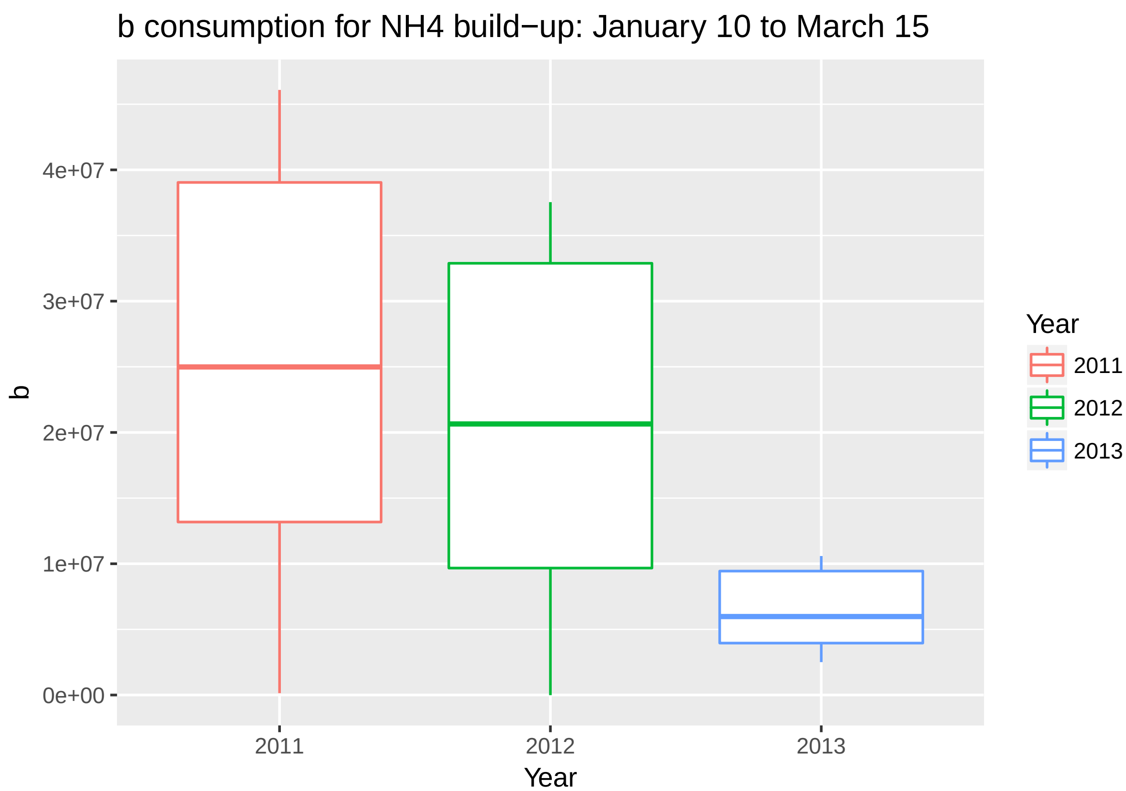



NH4 consumption Linear Modeling: January 10 to March 15
0e+00
−2e+05
−4e+05
−6e+05
a
0e+00
1e+07
2e+07
3e+07
4e+07
b
R^2
0.75
0.50
0.25
Year
2011
2012
2013


NH4 consumption Linear Modeling: January 10 to March 15
0e+00
−2e+05
−4e+05
−6e+05
a
0
10
20
30
40
Depth [m]
R^2
0.75
0.50
0.25
Year
2011
2012
2013


a consumption for NH4 build−up: January 10 to March 15
0e+00
−2e+05
−4e+05
−6e+05
a
2011
2012
2013
Year
Year
2011
2012
2013


NH4 consumption Linear Modeling: January 10 to March 15
4e+07
3e+07
2e+07
1e+07
0e+00
b
0
10
20
30
40
Depth [m]
R2
0.75
0.50
0.25
Year
2011
2012
2013


b consumption for NH4 build−up: January 10 to March 15
4e+07
3e+07
2e+07
1e+07
0e+00
b
2011
2012
2013
Year
Year
2011
2012
2013