

Supplementary Information: A calculator for  
peatland volume and carbon stock to support  
area planners and decision makers.

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# Chapter 1

## Analyses of peatland carbon stocks

Here I document the data and analyses behind the manuscript *A calculator for peatland volume and carbon stock to support area planners and decision makers.* (Fandrem et al. in prep). The documentation exists both as a dynamic web page, and as a static pdf that came with the original publication.

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Figure 1.1: The analyses described in this book makes it possible, with minimal effort, to estimate the carbon content of peatlands such as this one.. Photo: Anders L. Kolstad.

# Chapter 2

## Test data

### 2.1 Peat depth and peatland delineation

To create the methodology for mapping peatland depth profiles, and estimating peat volume, carbon stocks and sensitivity to sampling effort, I will use two contrasting test sites: *Tydal* and *Geilo*. Later, in chapter 7 I will validate the generality of this method on an additional four sites. For more details on the justification and the methods used, please see the manuscript.

Libraries used:

```
library(tmap)
library(sf)
library(readr)
library(tmaptools)
library(basemaps)
library(ggplot2)
library(ggpubr)
library(gstat)
library(matrixStats)
library(ggtext)
library(tidyverse)
library(osmplotr)
```

Import shape files with peatland delineations and fix the CRS.

```
SHP_tydal <- sf::read_sf("Data/Tydal/stasjon_Setermyra.shp")
SHP_geilo <- sf::read_sf("Data/Geilo/geilo-dybdef.shp")

# st_crs(SHP_tydal) st_crs(SHP_geilo) # NA I found CRS
```

```
# through trial and error. It is UTM 32
st_crs(SHP_geilo) <- 25832

# Transform to UTM33N
SHP_geilo <- st_transform(SHP_geilo, 25833)
```

Import peat depth measurements for the two sites.

```
depths_tydal <- readr::read_csv("Data/Tydal/Torvdybder_Tydal_stasjon.csv")
depths_geilo <- read.csv("Data/Geilo/torvdybder.csv", sep = ";")

# convert data.frames to simple features.
depths_tydal <- sf::st_as_sf(x = depths_tydal, coords = c("coords.x1",
  "coords.x2"), crs = "+init=epsg:25833")
depths_geilo <- st_as_sf(x = depths_geilo, coords = c("x", "y"),
  crs = "+init=epsg:25832")

# Tranbsform to UTM33, same as the shape file
depths_geilo <- st_transform(depths_geilo, 25833)
```

```
# Confirm overlap. Using base plotting to avoid
# auto-transformation
plot(SHP_geilo$geometry, col = "red")
plot(depths_geilo$geometry, pch = 16, col = "grey", cex = 0.1,
  add = T)
```

That looks fine.

Download basemaps for some context.

```
# osmplotr want bbboxes in latlong
SHP_geilo_ll <- sf::st_transform(SHP_geilo, 4326)
SHP_tydal_ll <- sf::st_transform(SHP_tydal, 4326)

bb_Geilo <- sf::st_bbox(SHP_geilo_ll)
bb_Tydal <- sf::st_bbox(SHP_tydal_ll)

# GEILO
base_geilo_hw <- osmplotr::extract_osm_objects(bbox = bb_Geilo,
  key = c("highway"), sf = T)
base_geilo_building <- osmplotr::extract_osm_objects(bbox = bb_Geilo,
  key = c("building"), sf = T)
base_geilo_ww <- osmplotr::extract_osm_objects(bbox = bb_Geilo,
  key = c("waterway"), sf = T, return_type = "line")
```

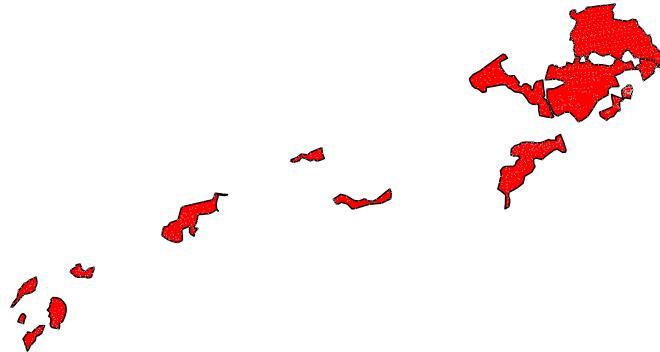


Figure 2.1: Confirming overlap between shape file and depth measurements

```
# TYDAL
base_tydal_hw <- osmplotr::extract_osm_objects(bbox = bb_Tydal,
    key = "highway", sf = T)
base_tydal_building <- osmplotr::extract_osm_objects(bbox = bb_Tydal,
    key = c("building"), sf = T)
base_tydal_ww <- osmplotr::extract_osm_objects(bbox = bb_Tydal,
    key = c("waterway"), sf = T, return_type = "line")
```

Plot static map

```
# GEILO
static_geilo <- tm_shape(SHP_geilo_ll) + tm_polygons(col = "green") +
    tm_shape(depths_geilo) + tm_dots() + tm_shape(base_geilo_hw) +
    tm_lines() + tm_shape(base_geilo_ww) + tm_lines(col = "blue",
        size = 2) + tm_shape(base_geilo_building) + tm_polygons(col = "black",
        alpha = 0.3) + tm_compass() + tm_scale_bar() + tm_layout(title = "Geilo")

# TYDAL
static_tydal <- tm_shape(SHP_tydal_ll) + tm_polygons(col = "green") +
```

```

tm_shape(depths_tydal) + tm_dots(size = "Dybde", col = "Dybde",
palette = "-viridis") + tm_shape(base_tydal_ww) + tm_lines(col = "blue",
size = 2) + tm_compass() + tm_scale_bar() + tm_layout(title = "Tydal",
legend.show = F, inner.margins = c(0.1, 0.02, 0.1, 0.02))

tmap_arrange(static_geilo, static_tydal)

```

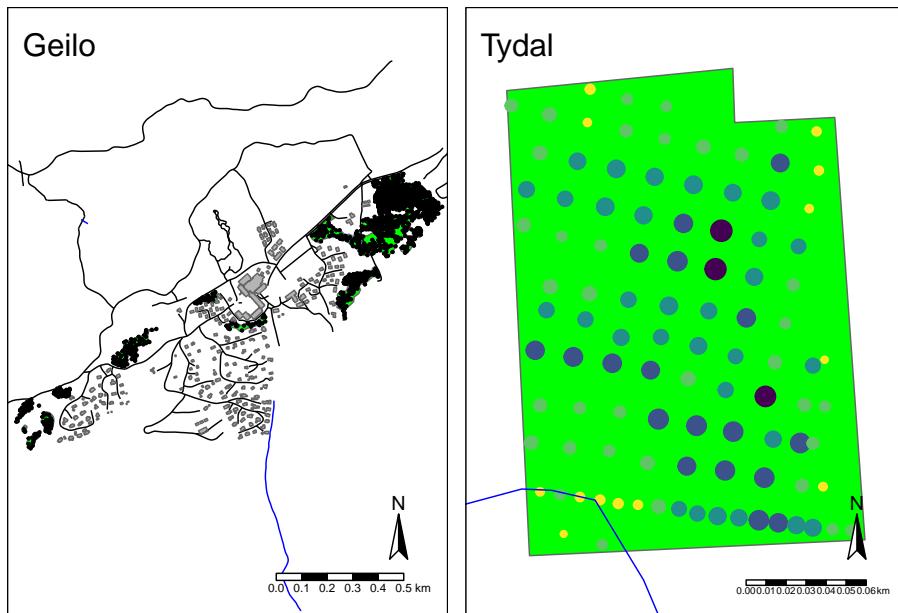


Figure 2.2: Map of Geilo and Tydal test sites. The peatland is delimited as a green polygon(s). Dots are depth measurements and for Tydal the colour and size of the dots reflects the measured peat depths in meters.

These two test cases are very different. Geilo is a set of several unique mire polygons. Usually, in development projects, one would estimate the peat volume and C stock for each of these separately, but we will try now to see if it can be done in one operation. Tydal is a more typical example of a clear peatland delineation. Both cases have dense peat depth measurements taken.

# Chapter 3

## Find best model

We want to interpolate values from the depth measurement on to a raster grid. From this we can estimate the total volume of the peatland, and also visualize the depth profiles.

The main task in this chapter is the determination of optimal power for IDW by cross validation

### 3.1 Raster grid

Create raster grid based on the extent of the peatland

```
# Create empty raster grid (stars object) based on the
# extent of the peatland shape files. Resolution 1 = 1 m
# (because crs is UTM)
grid_Tydal_stars <- starsExtra::make_grid(SHP_tydal, 1)
grid_Geilo_stars <- starsExtra::make_grid(SHP_geilo, 1)
```

Visualise the grid

```
# To plot the grid we can convert the stars objects to sf.
# That way we can plot as polygons and visualise the
# individual cells. This takes too long to perform for
# Geilo, but we can do it for Tydal:
grid_Tydal_sf <- st_as_sf(grid_Tydal_stars)

tm_shape(grid_Tydal_sf) + tm_polygons() + tm_shape(SHP_tydal) +
  tm_polygons(col = "yellow", alpha = 0.5)
```

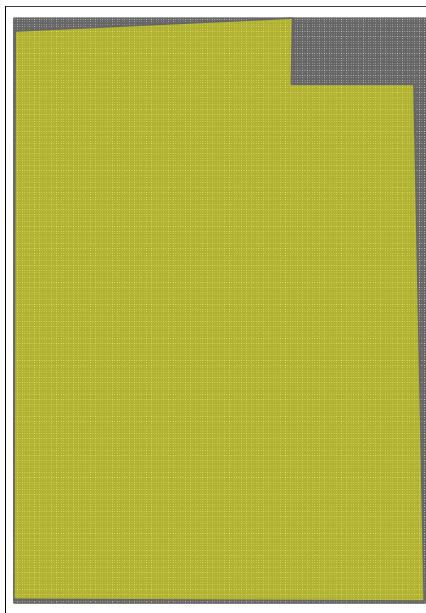


Figure 3.1: A 1x1 m raster grid in grey, overlayed with the peatland delineation in yellow.

Crop raster grid using the peatland delineation

```
grid_Tydal_stars_crop <- sf::st_crop(grid_Tydal_stars, SHP_tydal)
grid_Geilo_stars_crop <- sf::st_crop(grid_Geilo_stars, SHP_geilo)

tmap_arrange(tm_shape(grid_Geilo_stars_crop) + tm_raster(palette = "blue") +
  tm_layout(title = "Geilo", legend.show = F), tm_shape(grid_Tydal_stars_crop) +
  tm_raster(palette = "red") + tm_layout(title = "Tydal", legend.show = F))
```

## 3.2 Inverse distance weighting

We chose to use Inverse distance weighting (IDW) for the interpolation instead of for example kriging. This is because we do not want to include a separate step with for example calculating a variogram, and the functions for automatically fitting a variogram seems unstable.

The IDW requires setting the number of neighboring points to consider. We could set this to consider all points in the dataset (the default), but this increases calculation times and it is also not sensible in general. I will start by considering

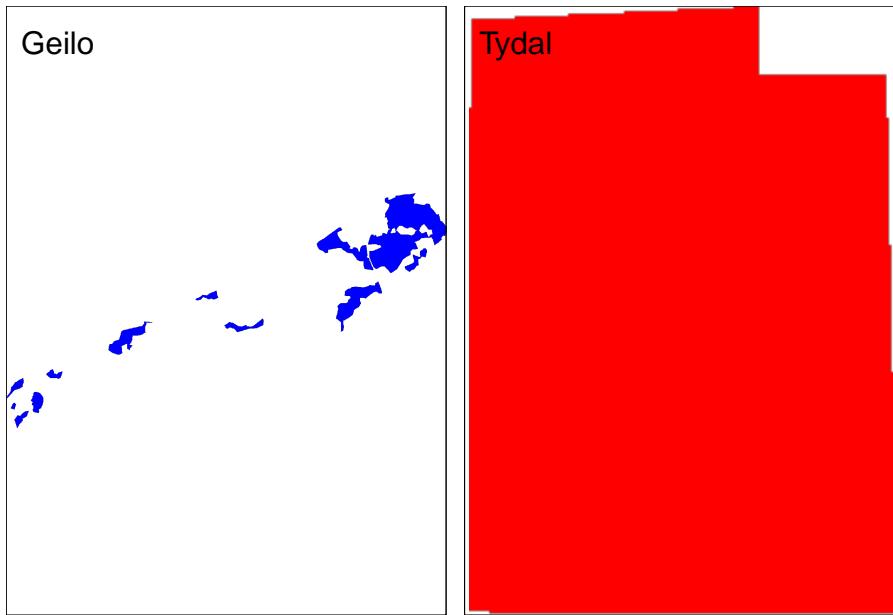


Figure 3.2: Preview of the cropped raster grids.

the 9 nearest points, as this would mean all the 8 closest points in a systematic grid around a point is included.

```
nmax <- 9
```

IDW also has a power parameter, and this is where we can tune the results by down-weighting data points that are further away. This parameter needs to be optimized for each model. We will fit a model with power varying from 0 to 10 and explore the model fit as a result of the chosen power.

First, lets explore the idw function and what the parameters mean. Tydal is 4.4 meters at it's deepest point. Depending on the idw setting, the prediction map will be further or closer to this number. For example, if we only consider the closest neighbor, we are essentially performing a nearest neighbor interpolation (Fig. 3.3; left pane). The choice of power then has no effect, and the deepest point in the prediction map equals the deepest point in the measured data.

If we keep the power at zero (ignore distance weighting) and turn up nmax to 9, each raster cell is predicted to be the mean of the nine closest points (Fig. 3.3; middle pane). The overall predicted depth decreases.

If we then also include distance weighting, e.g. by setting power =2, we get smoothing between the points, and a more local prediction than when we had

no power (i.e. the deepest point is again close to its true value) (Fig. 3.3; right pane).

```

temp <- gstat::idw(formula = Dybde ~ 1, locations = depths_tydal,
  newdata = grid_Tydal_stars_crop, idp = 0, nmax = 1)
#> [inverse distance weighted interpolation]

temp2 <- gstat::idw(formula = Dybde ~ 1, locations = depths_tydal,
  newdata = grid_Tydal_stars_crop, idp = 0, nmax = 9)
#> [inverse distance weighted interpolation]

temp3 <- gstat::idw(formula = Dybde ~ 1, locations = depths_tydal,
  newdata = grid_Tydal_stars_crop, idp = 2, nmax = 9)
#> [inverse distance weighted interpolation]

temp4 <- gstat::idw(formula = Dybde ~ 1, locations = depths_tydal,
  newdata = grid_Tydal_stars_crop, idp = 2, nmax = 20)
#> [inverse distance weighted interpolation]

temp4.1 <- gstat::idw(formula = Dybde ~ 1, locations = depths_tydal,
  newdata = grid_Tydal_stars_crop, idp = 2)
#> [inverse distance weighted interpolation]

temp5 <- gstat::idw(formula = Dybde ~ 1, locations = depths_tydal,
  newdata = grid_Tydal_stars_crop, idp = 100, nmax = 9)
#> [inverse distance weighted interpolation]

gg_temp <- tm_shape(temp) + tm_raster(col = "var1.pred", title = "",
  style = "fixed", breaks = seq(0, 5, 1)) + tm_shape(depths_tydal) +
  tm_symbols(shape = 4, col = "black") + tm_layout(legend.outside = F,
  title = paste0("Power = 0\nNmax = 1"))

gg_temp2 <- tm_shape(temp2) + tm_raster(col = "var1.pred", title = "",
  style = "fixed", breaks = seq(0, 5, 1)) + tm_shape(depths_tydal) +
  tm_symbols(shape = 4, col = "black") + tm_layout(legend.outside = F,
  title = paste0("Power = 0\nNmax = 9"))

gg_temp3 <- tm_shape(temp3) + tm_raster(col = "var1.pred", title = "",
  style = "fixed", breaks = seq(0, 5, 1)) + tm_shape(depths_tydal) +
  tm_symbols(shape = 4, col = "black") + tm_layout(legend.outside = F,
  title = paste0("Power = 2\nNmax = 9"))

gg_temp4 <- tm_shape(temp4) + tm_raster(col = "var1.pred", title = "",
  style = "fixed", breaks = seq(0, 5, 1)) + tm_shape(depths_tydal) +
  tm_symbols(shape = 4, col = "black") + tm_layout(legend.outside = F,
  title = paste0("Power = 2\nNmax = 9"))

```

```

title = paste0("Power = 2\nNmax = 20"))

gg_temp4.1 <- tm_shape(temp4.1) + tm_raster(col = "var1.pred",
    title = "", style = "fixed", breaks = seq(0, 5, 1)) + tm_shape(depths_tydal) +
    tm_symbols(shape = 4, col = "black") + tm_layout(legend.outside = F,
    title = paste0("Power = 2\nNmax = Inf"))

gg_temp5 <- tm_shape(temp5) + tm_raster(col = "var1.pred", title = "",
    style = "fixed", breaks = seq(0, 5, 1)) + tm_shape(depths_tydal) +
    tm_symbols(shape = 4, col = "black") + tm_layout(legend.outside = F,
    title = paste0("Power = 100\nNmax = 9"))

tmap_arrange(gg_temp, gg_temp2, gg_temp3, ncol = 3)

```

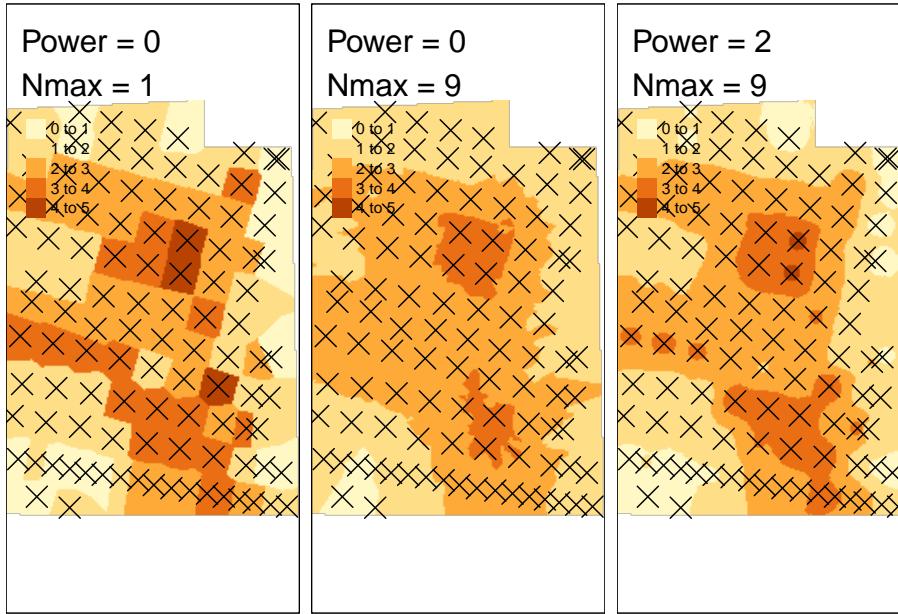


Figure 3.3: IDW with different setting.

```
tmap_arrange(gg_temp4, gg_temp4.1, gg_temp5, ncol = 3)
```

If we increase nmax to 20, and retain the distance weighting, we get a slightly flatter (loss local) estimation than with nmax = 9 (Fig. 3.4; left pane).

If we ramp up the nmax to consider all the points in the dataset, this has little additional effect as long as we have a positive power parameter (Fig. 3.4; middle

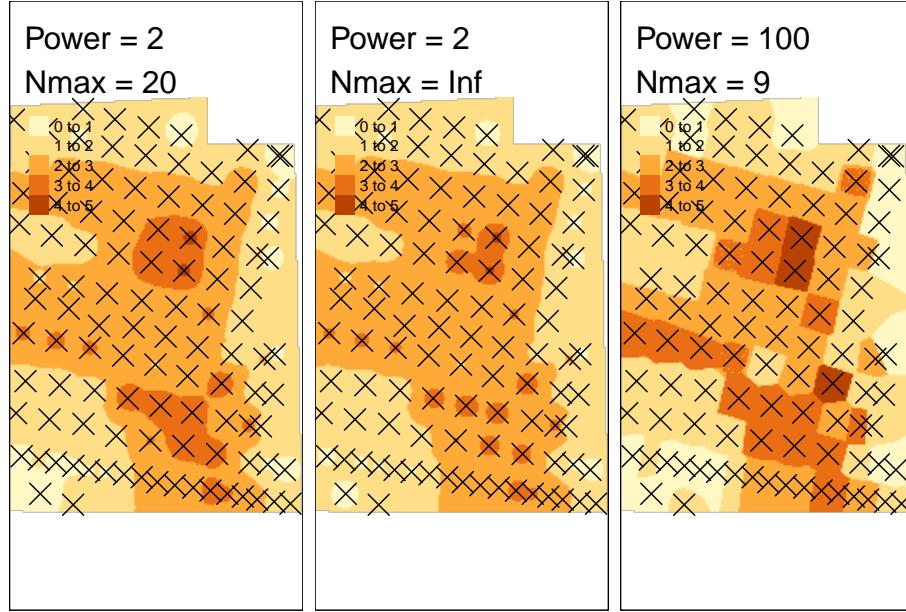


Figure 3.4: IDW with different setting.

pane). For bigger data sets however, the computation time might become an issue.

If we keep nmax at 9, and ramp up the power, we approach what we had at the beginning, that is a nearest neighbor interpolation (Fig. 3.4; right pane).

Of all the examples above, power = 2 and nmax = 9 is probably the best. However, I don't like these little dots on the map. They are artefacts of the model, and do not exist for real. Therefore I think I would prefer a model with a slightly more local focus. We can increase the power a bit to achieve this.

```
temp <- gstat::idw(formula = Dybde ~ 1, locations = depths_tydal,
                     newdata = grid_Tydal_stars_crop, idp = 4, nmax = 9)
#> [inverse distance weighted interpolation]

tm_shape(temp) + tm_raster(col = "var1.pred", title = "", style = "fixed",
                            breaks = seq(0, 5, 1)) + tm_shape(depths_tydal) + tm_symbols(shape = 4,
                            col = "black") + tm_layout(legend.outside = T, title = paste0("Power = 4\nnmax = 9"))
```

After a bit of trial and error, I noticed that by having nmax as low as 9, the optimum power frequently became <2 (which results in model artefacts and biased predictions as you can read about below, esp Fig. 3.9). I therefore increase the nmax.

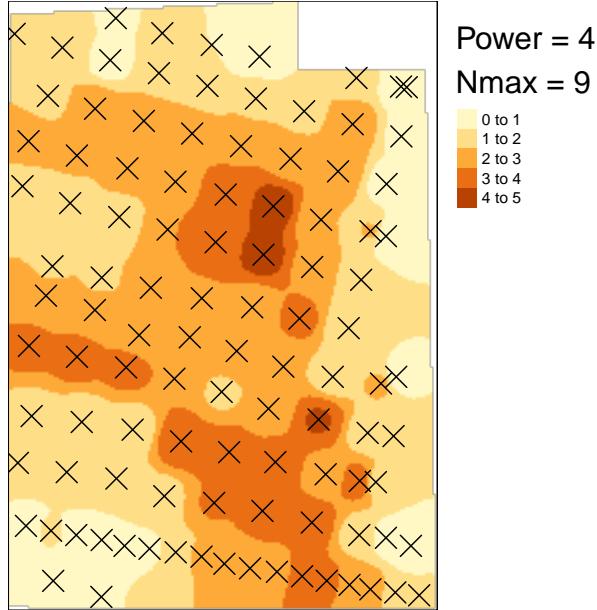


Figure 3.5: IDW with relatively local focus.

```
temp <- gstat::idw(formula = Dybde ~ 1, locations = depths_tydal,
  newdata = grid_Tydal_stars_crop, idp = 5, nmax = 20)
#> [inverse distance weighted interpolation]

tm_shape(temp) + tm_raster(col = "var1.pred", title = "", style = "fixed",
  breaks = seq(0, 5, 1)) + tm_shape(depths_tydal) + tm_symbols(shape = 4,
  col = "black") + tm_layout(legend.outside = T, title = paste0("Power = 4\nNmax = 20"))
```

```
nmax <- 20
```

This tuning of the power parameter is where we will focus now. Here I perform IDW for power between 0 and 10 to compare the results.

```
myPowers <- c(0:10)
for (i in myPowers) {
  temp <- gstat::idw(formula = Dybde ~ 1, locations = depths_tydal,
    newdata = grid_Tydal_stars_crop, idp = i, nmax = nmax)
  assign(paste0("IDW_tydal_", i), temp)
}

# this one takes a couple of minutes to run
```

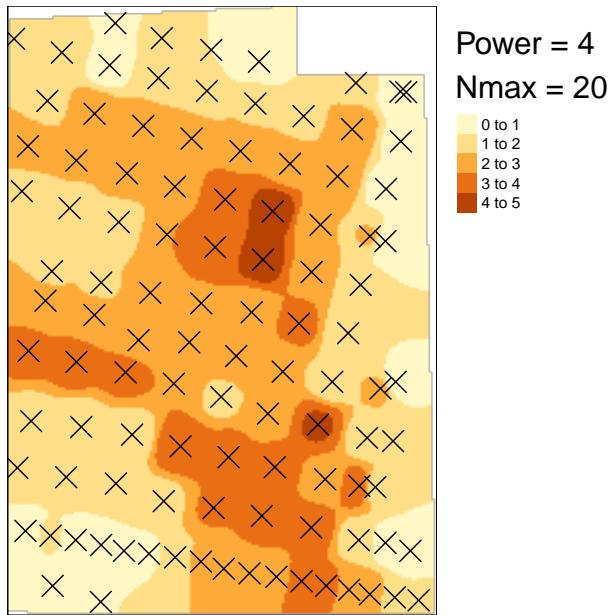


Figure 3.6: IDW with slightly higher nmax and higher power.

```
for (i in myPowers) {
  temp <- gstat::idw(formula = Dybde ~ 1, locations = depths_geilo,
    newdata = grid_Geilo_stars_crop, idp = i)
  assign(paste0("IDW_geilo_", i), temp)
}
```

What do these models look like.

```
for (i in myPowers) {

  temp <- get(paste0("IDW_tydal_", i))

  temp <- tm_shape(temp) + tm_raster(col = "var1.pred", palette = "-viridis",
    title = "Interpolated peat\ndepth (m)") + tm_layout(legend.outside = T,
    title = paste0("Power = ", i)) + tm_shape(depths_tydal) +
    tm_symbols(col = "black", shape = 4, size = 0.5)
  assign(paste0("tmap_IDW_tydal_power_", i), temp)
}
```

```
tmap_arrange(tmap_IDW_tydal_power_0, tmap_IDW_tydal_power_1,
  tmap_IDW_tydal_power_2, tmap_IDW_tydal_power_4, tmap_IDW_tydal_power_6,
  tmap_IDW_tydal_power_8, ncol = 3)
```

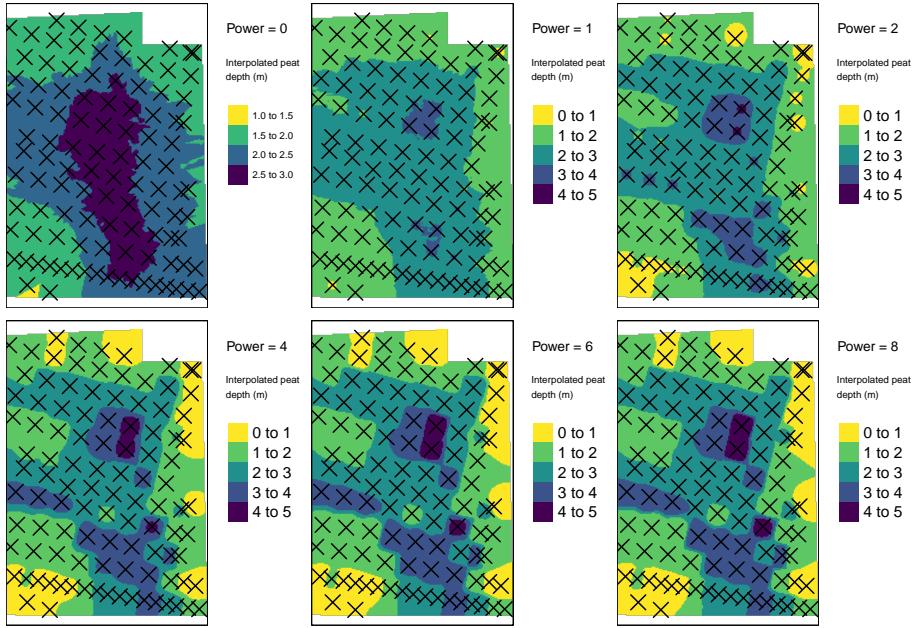


Figure 3.7: First view of how IDW models look like depending on the power parameter. Test site: Tydal.

When plotting Geilo I cannot include the crosses for the depth measurements because there are just too many and the clutter up the image.

```
for (i in myPowers) {

  temp <- get(paste0("IDW_geilo_", i))

  temp <- tm_shape(temp) + tm_raster(col = "var1.pred", palette = "-viridis",
    title = "Interpolated peat\nndepth (m)") + tm_layout(legend.outside = T,
    title = paste0("Power = ", i))
  assign(paste0("tmap_IDW_geilo_power_", i), temp)
}

tmap_arrange(tmap_IDW_geilo_power_1, tmap_IDW_geilo_power_2,
  tmap_IDW_geilo_power_4, ncol = 1)
```

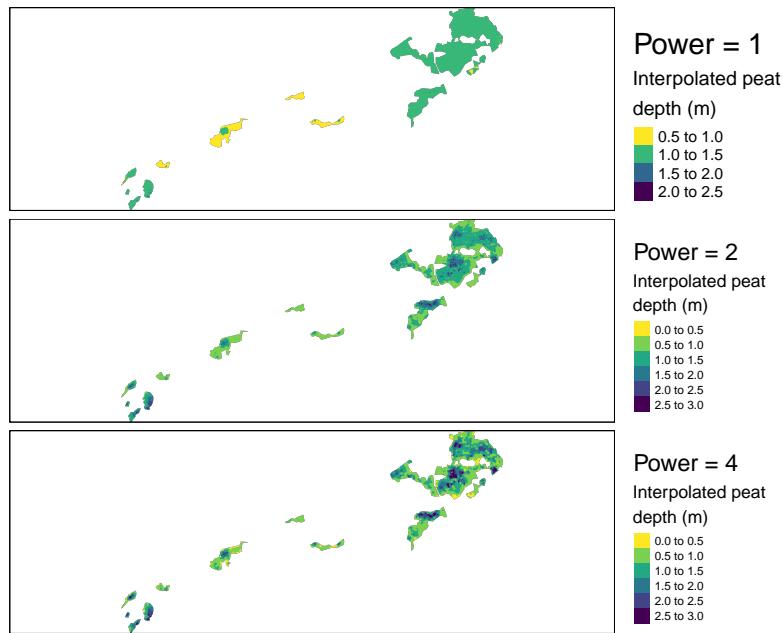


Figure 3.8: First view of how IDW models look like depending on the power parameter. Test site: Geilo.

A low power creates a more flat map where all the depth measurements count equally to any predicted value. With power set to 0 we just predict the average of all the measured peat depths. For both cases, increasing the power beyond 4 has little visual effect.

### 3.3 Original residuals

Let's check the fit with a plot of the residuals.

```
# Prepare data frame with the measured data
resids_tydal <- data.frame(ID = 1:nrow(depths_tydal))
resids_geilo <- data.frame(ID = 1:nrow(depths_geilo))

resids_tydal$measured <- depths_tydal$Dybde
resids_geilo$measured <- depths_geilo$Dybde

# Get the predicted values
for (i in myPowers) {
  temp <- get(paste0("IDW_tydal_", i))
  fit <- stars::st_extract(temp, depths_tydal)
```

```

    resids_tydal[, i + 3] <- resids_tydal$measured - fit$var1.pred
}

for (i in myPowers) {
  temp <- get(paste0("IDW_geilo_", i))
  fit <- stars::st_extract(temp, depths_geilo)
  resids_geilo[, i + 3] <- resids_geilo$measured - fit$var1.pred
}

# Lots of NA's produced for depth measurements taken
# outside the peatland polygons tmap_mode('plot')
# tm_shape(IDW_geilo_10)+ tm_raster(col='var1.pred')+
# tm_shape(fit[is.na(fit$var1.pred),])+ tm_symbols(size =
# .1, col='yellow')

resids_geilo <- resids_geilo[!is.na(resids_geilo$V3), ]

resids_tydal <- tidyr::pivot_longer(resids_tydal, !ID & !measured,
  names_to = "power", values_to = "residual")
resids_geilo <- tidyr::pivot_longer(resids_geilo, !ID & !measured,
  names_to = "power", values_to = "residual")

# Remove V from column names
resids_tydal$power <- gsub(pattern = "V", replacement = "", x = resids_tydal$power)
resids_geilo$power <- gsub(pattern = "V", replacement = "", x = resids_geilo$power)

resids_tydal$power <- as.numeric(resids_tydal$power)
resids_geilo$power <- as.numeric(resids_geilo$power)

resids_tydal$power <- resids_tydal$power - 3
resids_geilo$power <- resids_geilo$power - 3

gg_resids_tydal <- ggplot(resids_tydal, aes(x = factor(power),
  y = residual)) + geom_boxplot(fill = "grey", trim = F) +
  theme_bw(base_size = 12) + xlab("Power") + ggtitle("Tydal")
#> Warning in geom_boxplot(fill = "grey", trim = F): Ignoring
#> unknown parameters: `trim`

gg_resids_geilo <- ggplot(resids_geilo, aes(x = factor(power),
  y = residual)) + geom_boxplot(fill = "grey", trim = F) +
  theme_bw(base_size = 12) + xlab("Power") + ggtitle("Geilo")

```

```
#> Warning in geom_boxplot(fill = "grey", trim = F): Ignoring
#> unknown parameters: `trim`
```

```
ggpubr::ggarrange(gg_resids_geilo, gg_resids_tydal)
```

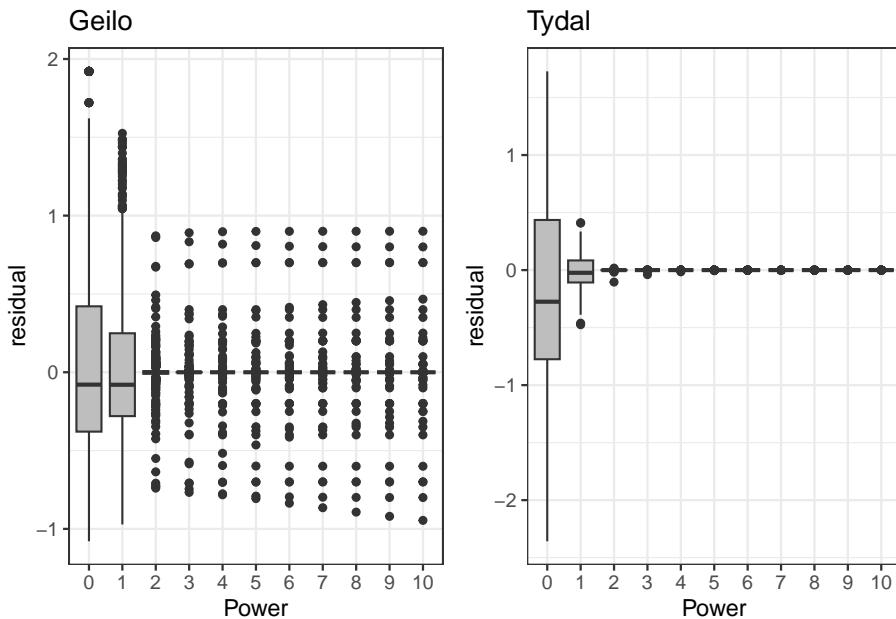


Figure 3.9: Residuals (observed - predicted) stabilize with power greater than 2.

With a power of 2 or greater, the residuals are very stable and unbiased (centered on 0).

### 3.4 Estimated volume

What about the estimated volume - does that change depending on the power setting? Note that because the data are projected in UTM, the mean depth (in meter) of each 1x1 raster cell equals the volume in m<sup>3</sup>.

```
volume_tydal <- NULL
for (i in myPowers) {
  temp <- get(paste0("IDW_tydal_", i))
  volume_tydal <- c(volume_tydal, sum(temp$var1.pred, na.rm = T))
}
```

```

volume_geilo <- NULL
for (i in myPowers) {
  temp <- get(paste0("IDW_geilo_", i))
  volume_geilo <- c(volume_geilo, sum(temp$var1.pred, na.rm = T))
}

volume_tydal <- data.frame(volume = volume_tydal, power = myPowers)
volume_tydal$relative_volume <- volume_tydal$volume/mean(volume_tydal$volume) *
  100

volume_geilo <- data.frame(volume = volume_geilo, power = myPowers)
volume_geilo$relative_volume <- volume_geilo$volume/mean(volume_geilo$volume) *
  100

gg_predVolume_tydal <- ggplot(volume_tydal, aes(x = factor(power),
  y = relative_volume)) + geom_point(size = 10) + xlab("power") +
  ylab("Peat volume as a percentage of\nmean predicted peat volume") +
  theme_bw(base_size = 12) + ggtitle("Tydal")

gg_predVolume_geilo <- ggplot(volume_geilo, aes(x = factor(power),
  y = relative_volume)) + geom_point(size = 10) + xlab("power") +
  ylab("Peat volume as a percentage of\nmean predicted peat volume") +
  theme_bw(base_size = 12) + ggtitle("Geilo")

ggpubr::ggarrange(gg_predVolume_geilo, gg_predVolume_tydal)

```

The values are stabilizing relatively fast, but a power of less than 3 seem like a bad idea. In general though, the difference between the worst and best models is just 2-4%.

This relationship probably depends a bit on the number of data points and the density of peat depth measurements. So we should not generalise just yet.

## 3.5 Model fit LOOCV

Now let's do a proper test of model fit, using leave one out cross validation. I will use the mean absolute deviation as my measure of model fit.

```

MAE_tydal <- data.frame(power = myPowers, MAE = as.numeric(NA))
for (i in myPowers) {
  temp <- krige.cv(Dybde ~ 1, depths_tydal, set = list(idp = i),

```

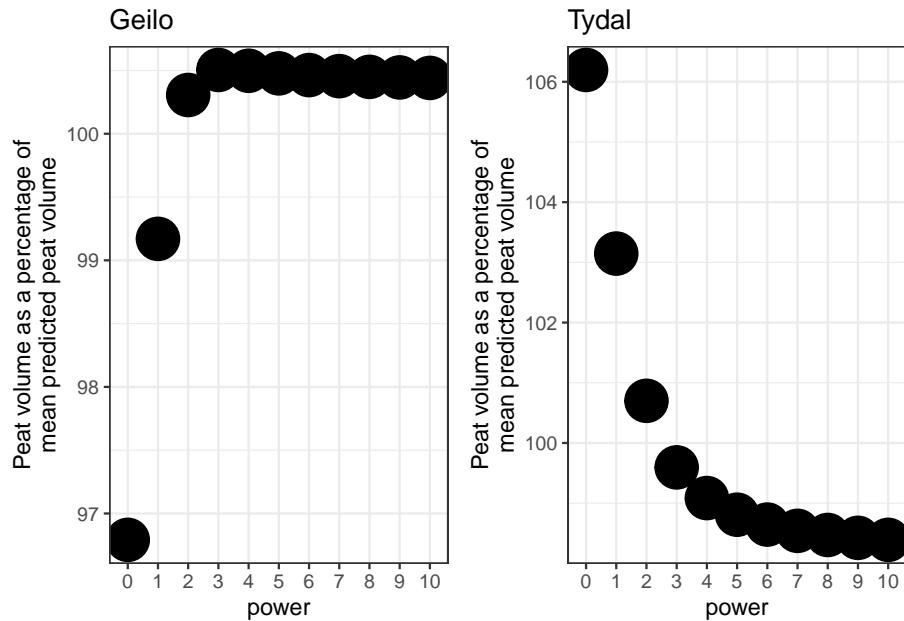


Figure 3.10: Peat volume estimates as a function of the power parameter.

```

# min on my computer, so I will run it once and cache it on
# a local server.
myPowers2 <- seq(0, 5, 1)
# MAE_geilo <- data.frame(power = myPowers2, MAE =
# as.numeric(NA)) for(i in myPowers2){ temp <-
# krige.cv(Dybde ~ 1, depths_geilo, set = list(idp=i), nmax
# = nmax) MAE_geilo$MAE[MAE_geilo$power==i] <-
# mean(abs(temp$residual)) } MAE_geilo$best <-
# ifelse(MAE_geilo$MAE==min(MAE_geilo$MAE), 'best',
# 'not-best') saveRDS(MAE_geilo,
# 'Data/cache/MAE_geilo_cashe.rds')
MAE_geilo <- readRDS("Data/cache/MAE_geilo_cashe.rds")

gg_MAE_tydal <- ggplot(MAE_tydal, aes(x = power, y = MAE, colour = best,
shape = best)) + geom_point(size = 10) + theme_bw(base_size = 12) +
scale_x_continuous(breaks = myPowers) + guides(colour = "none",
shape = "none") + scale_color_manual(values = c("darkgreen",
"grey")) + scale_shape_manual(values = c(18, 19)) + ggtitle("Tydal")

gg_MAE_geilo <- ggplot(MAE_geilo, aes(x = power, y = MAE, colour = best,
shape = best)) + geom_point(size = 10) + theme_bw(base_size = 12) +
scale_x_continuous(breaks = myPowers2) + guides(colour = "none",
shape = "none") + scale_color_manual(values = c("darkgreen",
"grey")) + scale_shape_manual(values = c(18, 19)) + ggtitle("Geilo")

ggpubr::ggarrange(gg_MAE_geilo, gg_MAE_tydal)

```

The mean absolute error is not negligible in any of the two cases. The interpretation is, if you leave out one of the peat depth measurement and predict the peat depth in that point (using just the remaining data points) the models are on average 40-60 cm wrong.

The best models have power = 2 for Geilo and 4 for Tydal. These models also look reasonable in terms of predicted peat volume and the spread of the raw residuals (Figs. 3.7 and 3.8). But the map for Geilo is quite *spotted*, and perhaps a higher power would be smart. I will therefore change it to 3. This is justified also because of the minimal impact in MAE and the predicted volume. For Geilo, we probably would get better results if we analysed each polygon separately.

*Note: A power less than 2 is not recommended as we have seen above. With nmax set to 9, the optimum power for Geilo was actually 1. I therefore went back up in the script and increased nmax to 20.*

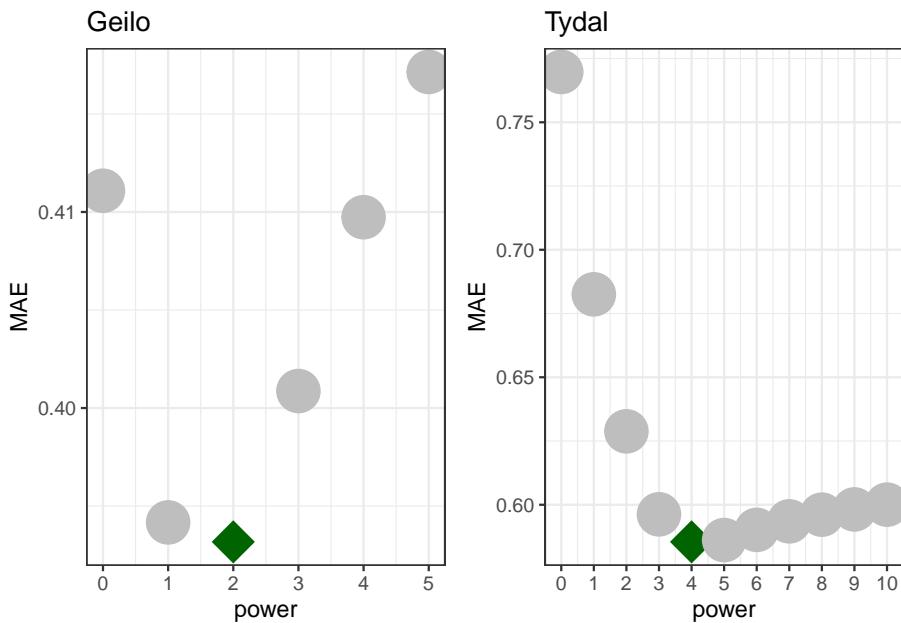


Figure 3.11: Mean absolute error based on leave-one-out cross validation. The optimal power setting is indicated by a green star symbol.

### 3.6 Best models

Based on a criterion of lowest MAE (but above 2) we have identified the best IDW models for the two test sites:

```
tm_tydal <- tm_shape(IDW_tydal_4) + tm_raster(col = "var1.pred",
  palette = "-viridis", title = "Interpolated peat\ndepth (m)") +
  tm_shape(depths_tydal) + tm_symbols(shape = 4, col = "black",
  size = 0.5) + tm_compass(type = "8star", position = c("right",
  "bottom"), size = 2) + tm_scale_bar(position = c("left",
  "bottom"), width = 0.3) + tm_layout(inner.margins = c(0.15,
  0.05, 0, 0.05), legend.outside = T)

# tmap::tmap_save(tm_tydal,
# 'Output/plot_IDW_tydal_bestModel.tiff', width = 1600,
# height = 1600, units = 'px')
tm_tydal
```

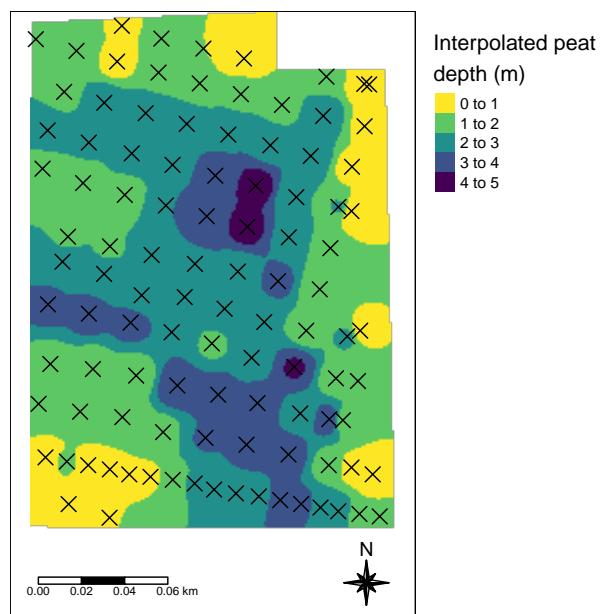


Figure 3.12: Best model for estimating the peat depth profile for the Tydal test site. Dots indicate peat depth sampling points. MAE = 0.59 meters. Power = 4.

```

IDW_geilo_3 <- gstat::idw(formula = Dybde ~ 1, locations = depths_geilo,
  newdata = grid_Geilo_stars_crop, idp = 2, nmax = nmax)

tm_geilo <- tm_shape(IDW_geilo_3) + tm_raster(col = "var1.pred",
  palette = "-viridis", title = "Interpolated peat\\ndepth (m)") +
  tm_compass(type = "8star", position = c("right", "bottom"),
  size = 2) + tm_scale_bar(position = c("right", "bottom"),
  width = 0.3)

# tmap::tmap_save(tm_geilo,
# 'Output/plot_IDW_geilo_bestModel.tiff', width = 1600,
# height = 1600, units = 'px')
tm_geilo
#> stars object downsampled to 1369 by 730 cells. See tm_shape manual (argument raster)

```

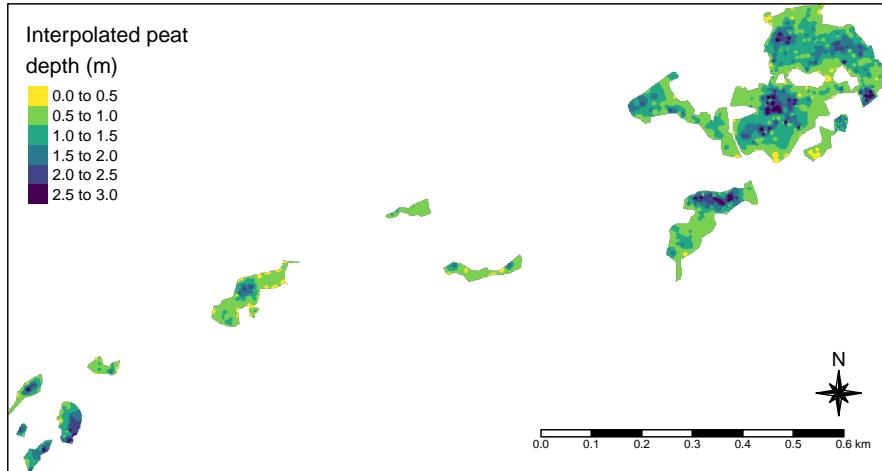


Figure 3.13: Best model for estimating the peat depth profile for the Geilo test site. Dots indicate peat depth sampling points. MAE = 0.4 meters. Power = 3.

Tydal is  $7.7336967 \times 10^4$  m<sup>3</sup> and Geilo is  $1.0246996 \times 10^5$  m<sup>3</sup>. We can get the residuals from LOOCV.

```

SE_tydal <- krige.cv(Dybde ~ 1, depths_tydal, set = list(idp = 4),
  nmax = nmax)
#> /
SE_geilo <- krige.cv(Dybde ~ 1, depths_geilo, set = list(idp = 3),
  nmax = nmax)
#> /
ggplot(SE_tydal, aes(x = residual)) + geom_histogram()

```

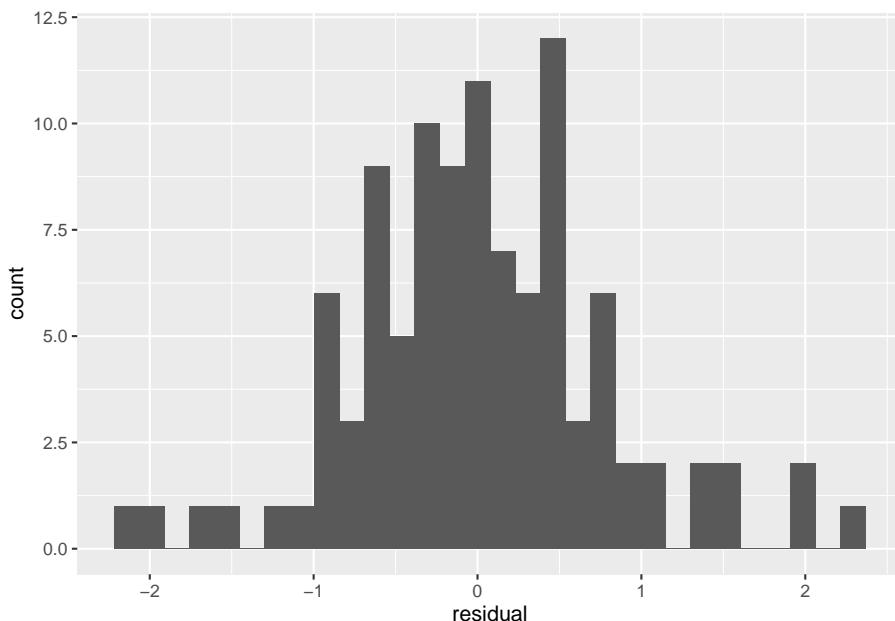


Figure 3.14: Residuals from LOOCV. Test site: Tydal

For any point inside the prediction area, we assume an error equal to the mean residual from LOOCV. For Tydal, this is 0.59 meters. There is no clear way how to predict confidence intervals for IDW. The residuals, and the MAE, represents uncertainty for each grid cell value, and not uncertainty in the sum of all these grid cells. Since the mean of the residuals (not the absolute mean, but the normal mean) is quite close to 0, the uncertainty for each cell cancels out.

We can calculate the peat volume based on the best model

```

volume <- data.frame(site = c("Tydal", "Geilo"), volume = c(sum(IDW_tydal_4$var1.pred,
  na.rm = T), sum(IDW_geilo_3$var1.pred, na.rm = T)))

```

```
library(ggtext) # write superscript as markdown
ggplot(volume, aes(x = site, y = volume)) + geom_bar(stat = "identity",
  colour = "black", fill = "grey") + theme_bw(base_size = 12) +
  theme(axis.title.y = element_markdown()) + ylab("Volume m^(3)")
```

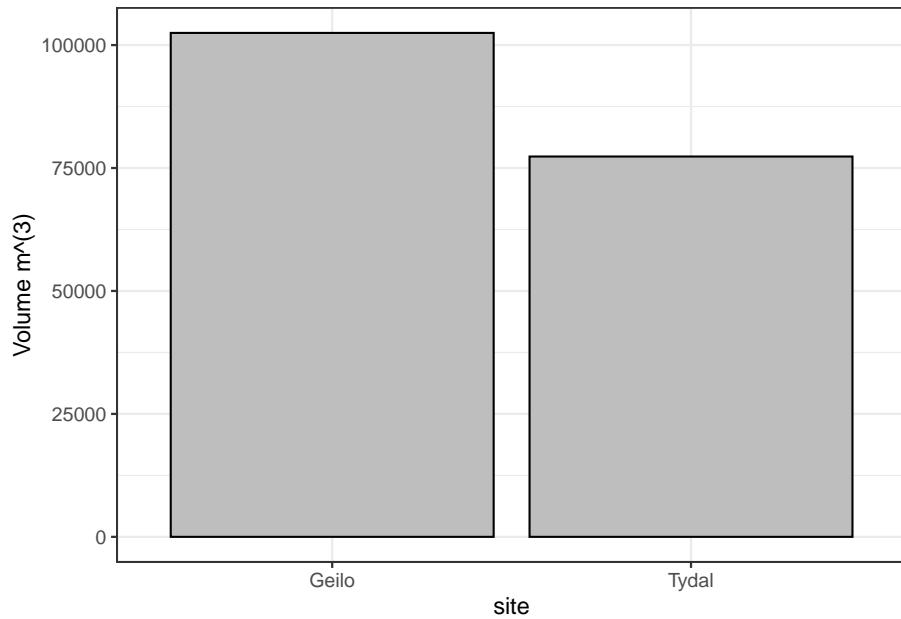


Figure 3.15: Peat volume estimated from IDW.

The rough volume (no iDW) Tydal and Geilo

```
SHP_tydal$myArea <- sf::st_area(SHP_tydal)
mean(depths_tydal$Dybde) * sum(SHP_tydal$myArea)
#> 76994.27 [m^2]
```

```
SHP_geilo$myArea <- sf::st_area(SHP_geilo)
mean(depths_geilo$Dybde) * sum(SHP_geilo$myArea)
#> 98690.12 [m^2]
```

Next I want to try and estimate how many depth measurement I need to get a stable result, both on therm of peat volume and of visual appearance. Then I will also see if the same choice of the power parameter is still the best after removing some data points.

# Chapter 4

## Optimise sampling intensity

Now I want to resample and reduce the dataset, but try to keep the original sampling design. For the Geilo dataset I want to limit this part of the analyses to only consider one polygon. It is obvious that a peat depth measurement from a neighboring mire cannot replace data collection on the actual mire.

### 4.1 Subset Geilo data

```
# select a single mire polygon
SHP_geilo_biggest <- SHP_geilo[which.max(SHP_geilo$AREAL), ]

# drop the depth measurements from the other polygons
depths_geilo_biggest <- sf::st_intersection(depths_geilo, SHP_geilo_biggest)

# Crop the raster grid
grid_Geilo_stars_crop_biggest <- sf::st_crop(grid_Geilo_stars,
                                              SHP_geilo_biggest)

plot(depths_geilo_biggest$Dybde[order(depths_geilo_biggest$Dybde)],
     ylab = "Peat depth (m)")
```

Looking at the depth measurements in Fig. 4.1, we are reminded that the data contains zeros (measurements taken near the edge) and are truncated above 3 (because that was the length of the peat depth probe).

```
tm_shape(SHP_geilo_biggest) + tm_polygons() + tm_shape(depths_geilo_biggest) +
  tm_symbols(col = "black", shape = 4)
```

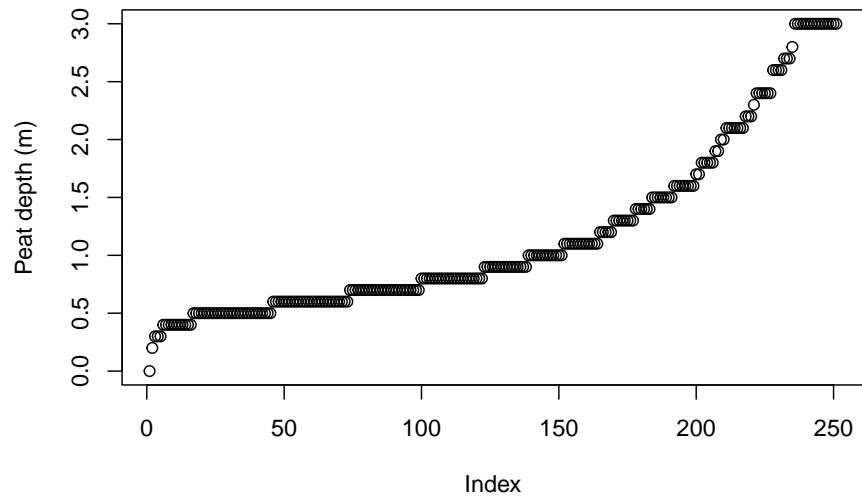


Figure 4.1: Peat depth measurements for the biggest of the Geilo mires.

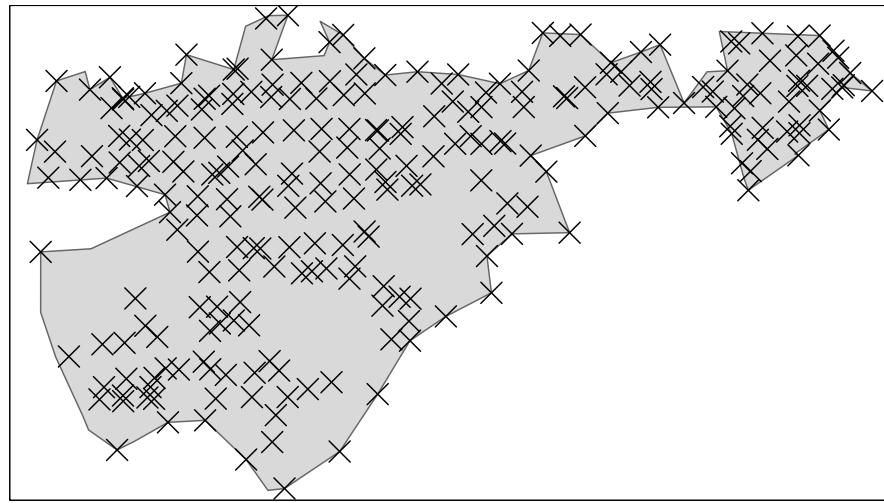


Figure 4.2: One mire polygon from the Geilo test site used in the assessment of minimum sampling.

## 4.2 Repeat the best IDW

Here I simply recalculate the best models, as described in the previous chapter

```
IDW_tydal_4 <- gstat::idw(formula = Dybde ~ 1, locations = depths_tydal,
  newdata = grid_Tydal_stars_crop, idp = 4, nmax = nmax)
#> [inverse distance weighted interpolation]

IDW_geilo_3 <- gstat::idw(formula = Dybde ~ 1, locations = depths_geilo_biggest,
  newdata = grid_Geilo_stars_crop_biggest, idp = 3, nmax = nmax)
#> [inverse distance weighted interpolation]
```

## 4.3 Reduce N

- by gradually removing the closest point.

First we need to set up some temporary files for the for-loop.

```
distMatrix_tydal <- sf::st_distance(depths_tydal)
distMatrix_tydal <- units::drop_units(distMatrix_tydal)
distMatrix_tydal[distMatrix_tydal == 0] <- NA
distMin_tydal <- matrixStats::rowMins(distMatrix_tydal, na.rm = T)

distMatrix_geilo <- sf::st_distance(depths_geilo_biggest)
distMatrix_geilo <- units::drop_units(distMatrix_geilo)
distMatrix_geilo[distMatrix_geilo == 0] <- NA
distMin_geilo <- matrixStats::rowMins(distMatrix_geilo, na.rm = T)
```

Create temporary working files

```
distMin_tydal_temp <- distMin_tydal
depths_tydal_temp <- depths_tydal

distMin_geilo_temp <- distMin_geilo
depths_geilo_temp <- depths_geilo_biggest
```

Get the summed volume

```
est_tydal <- sum(IDW_tydal_4$var1.pred, na.rm = T)
est_geilo <- sum(IDW_geilo_3$var1.pred, na.rm = T)
```

Get the median, mean and skewness of the distances to the closest neighbor

```

medianDist_tydal <- median(distMin_tydal)
meanDist_tydal <- mean(distMin_tydal)
skewDist_tydal <- e1071::skewness(distMin_tydal)

medianDist_geilo <- median(distMin_geilo)
meanDist_geilo <- mean(distMin_geilo)
skewDist_geilo <- e1071::skewness(distMin_geilo)

```

Get the MAE

```

MAE_tydal_allData <- krige.cv(Dybde ~ 1, depths_tydal, set = list(idp = 4),
                                 nmax = nmax)
#>   /
MAE_tydal_allData <- mean(abs(MAE_tydal_allData$residual))

MAE_geilo_allData <- krige.cv(Dybde ~ 1, depths_geilo_biggest,
                                 set = list(idp = 2), nmax = nmax)
#>   /
MAE_geilo_allData <- mean(abs(MAE_geilo_allData$residual))

```

Put it into a dataframe

```

summaryTable_tydal <- data.frame(medianDist = medianDist_tydal,
                                    meanDist = meanDist_tydal, skewness = skewDist_tydal, n = length(distMin_tydal),
                                    estimatedPeatVolume_m3 = est_tydal, MAE = MAE_tydal_allData)

summaryTable_geilo <- data.frame(medianDist = medianDist_geilo,
                                    meanDist = meanDist_geilo, skewness = skewDist_geilo, n = length(distMin_geilo),
                                    estimatedPeatVolume_m3 = est_geilo, MAE = MAE_geilo_allData)

```

Perform a for-loop to gradually remove points based on how close they are to other points. This will hopefully retain most of the systematic design of the points (avoiding clumping of points).

```

# I will not bother going lower than ten data points
for (i in 1:c(nrow(depths_tydal) - 10)) {

  print(paste("run number = ", i))

  toRemove <- which(distMin_tydal_temp == min(distMin_tydal_temp))[1]
  print(paste("Removing row number ", toRemove))

  # get some stats distance between neighbours
  medianDist <- median(distMin_tydal_temp)

```

```

meanDist <- mean(distMin_tydal_temp)
skewDist <- e1071::skewness(distMin_tydal_temp)

depths_tydal_temp <- depths_tydal_temp[-toRemove, ]

# perform interpolation on tempDF
int <- gstat::idw(Dybde ~ 1, depths_tydal_temp, newdata = grid_Tydal_stars_crop,
  nmax = nmax, idp = 4)

# Export some predictions for checks
if (i %in% seq(30, 90, 30)) {
  assign(paste0("IDW_tydal_i", i), int)
}

est <- sum(int$var1.pred, na.rm = T)

# get the MAE as well, even though it takes a long time
# to run
MAE <- krige.cv(Dybde ~ 1, depths_tydal_temp, set = list(idp = 4),
  nmax = nmax)
MAE <- mean(abs(MAE$residual))

# paste into the summary table
summaryTable_tydal[1 + i, "medianDist"] <- medianDist
summaryTable_tydal[1 + i, "meanDist"] <- meanDist
summaryTable_tydal[1 + i, "skewness"] <- skewDist
summaryTable_tydal[1 + i, "n"] <- length(distMin_tydal_temp) -
  1
summaryTable_tydal[1 + i, "estimatedPeatVolume_m3"] <- est
summaryTable_tydal[1 + i, "MAE"] <- MAE

# prepare dataset for next loop
euclidDist <- sf::st_distance(depths_tydal_temp)
euclidDist <- units::drop_units(euclidDist)
euclidDist[euclidDist == 0] <- NA
distMin_tydal_temp <- rowMins(euclidDist, na.rm = T)

}

saveRDS(summaryTable_tydal, "Data/Tydal/tydal_cvAnalysisData.rds")

saveRDS(IDW_tydal_i30, "Output/Tydal/IDW_tydal_i30.rds")
saveRDS(IDW_tydal_i60, "Output/Tydal/IDW_tydal_i60.rds")
saveRDS(IDW_tydal_i90, "Output/Tydal/IDW_tydal_i90.rds")

```

```

# now doing the same for the Geilo test site
for (i in 1:c(nrow(depths_geilo_biggest) - 10)) {

  print(paste("run number = ", i))

  toRemove <- which(distMin_geilo_temp == min(distMin_geilo_temp))[1]
  print(paste("Removing row number ", toRemove))

  # get some stats distance between neighbours
  medianDist <- median(distMin_geilo_temp)
  meanDist <- mean(distMin_geilo_temp)
  skewDist <- e1071::skewness(distMin_geilo_temp)

  depths_geilo_temp <- depths_geilo_temp[-toRemove, ]

  # perform interpolation on tempDF
  int <- gstat::idw(Dybde ~ 1, depths_geilo_temp, newdata = grid_Geilo_stars_crop_big,
                     nmax = nmax, idp = 3)

  # Export some predictions for checks
  if (i %in% seq(40, 240, 50)) {
    assign(paste0("IDW_geilo_i", i), int)
  }

  est <- sum(int$var1.pred, na.rm = T)

  # get the MAE as well, even though it takes a long time
  # to run
  MAE <- krige.cv(Dybde ~ 1, depths_geilo_temp, set = list(idp = 3),
                    nmax = nmax)
  MAE <- mean(abs(MAE$residual))

  # paste into the summary table
  summaryTable_geilo[1 + i, "medianDist"] <- medianDist
  summaryTable_geilo[1 + i, "meanDist"] <- meanDist
  summaryTable_geilo[1 + i, "skewness"] <- skewDist
  summaryTable_geilo[1 + i, "n"] <- length(distMin_geilo_temp) -
    1
  summaryTable_geilo[1 + i, "estimatedPeatVolume_m3"] <- est
  summaryTable_geilo[1 + i, "MAE"] <- MAE

  # prepare dataset for next loop
  euclidDist <- sf::st_distance(depths_geilo_temp)
  euclidDist <- units::drop_units(euclidDist)
  euclidDist[euclidDist == 0] <- NA
}

```

```

distMin_geilo_temp <- rowMins(euclidDist, na.rm = T)

}

saveRDS(summaryTable_geilo, "Data/Geilo/geilo_cvAnalysisData.rds")

saveRDS(IDW_geilo_i40, "Output/Geilo/IDW_geilo_i40.rds")
saveRDS(IDW_geilo_i90, "Output/Geilo/IDW_geilo_i90.rds")
saveRDS(IDW_geilo_i140, "Output/Geilo/IDW_geilo_i140.rds")
saveRDS(IDW_geilo_i190, "Output/Geilo/IDW_geilo_i190.rds")
saveRDS(IDW_geilo_i240, "Output/Geilo/IDW_geilo_i240.rds")

```

Import the data back in

```

summaryTable_tydal <- readRDS("Data/Tydal/tydal_cvAnalysisData.rds")
summaryTable_geilo <- readRDS("Data/Geilo/geilo_cvAnalysisData.rds")

```

A code block just for getting the reduced datasets

```

distMin_tydal_temp <- distMin_tydal
depths_tydal_temp <- depths_tydal

for (i in 1:c(nrow(depths_tydal) - 10)) {

  # print(paste('run number = ', i))

  toRemove <- which(distMin_tydal_temp == min(distMin_tydal_temp))[1]
  # print(paste('Removing row number ', toRemove))

  depths_tydal_temp <- depths_tydal_temp[-toRemove, ]

  # Export some data set for checks
  if (i %in% seq(30, 90, 10)) {
    assign(paste0("depths_tydal_i", i), depths_tydal_temp)
  }

  # prepare dataset for next loop
  euclidDist <- sf::st_distance(depths_tydal_temp)
  euclidDist <- units::drop_units(euclidDist)
  euclidDist[euclidDist == 0] <- NA
  distMin_tydal_temp <- rowMins(euclidDist, na.rm = T)

}

```

```

##### Geilo

distMin_geilo_temp <- distMin_geilo
depths_geilo_temp <- depths_geilo_biggest

for (i in 1:c(nrow(depths_geilo_biggest) - 10)) {

  # print(paste('run number = ', i))

  toRemove <- which(distMin_geilo_temp == min(distMin_geilo_temp))[1]
  # print(paste('Removing row number ', toRemove))

  depths_geilo_temp <- depths_geilo_temp[-toRemove, ]

  # Export some data set for checks
  if (i %in% c(1, 50, 100, 200)) {
    assign(paste0("depths_geilo_i", i), depths_geilo_temp)
  }

  # prepare dataset for next loop
  euclidDist <- sf::st_distance(depths_geilo_temp)
  euclidDist <- units::drop_units(euclidDist)
  euclidDist[euclidDist == 0] <- NA
  distMin_geilo_temp <- rowMins(euclidDist, na.rm = T)

}

tmap_arrange(tm_shape(SHP_tydal) + tm_polygons() + tm_shape(depths_tydal) +
  tm_symbols(col = "black", shape = 4, size = 0.5) + tm_layout(title = "All data points",
  inner.margins = c(0.1, 0.02, 0.1, 0.02)), tm_shape(SHP_tydal) +
  tm_polygons() + tm_shape(depths_tydal_i30) + tm_symbols(col = "black",
  shape = 4, size = 0.5) + tm_layout(title = "-30 data points",
  inner.margins = c(0.1, 0.02, 0.1, 0.02)), tm_shape(SHP_tydal) +
  tm_polygons() + tm_shape(depths_tydal_i60) + tm_symbols(col = "black",
  shape = 4, size = 0.5) + tm_layout(title = "-60 data points",
  inner.margins = c(0.1, 0.02, 0.1, 0.02)), tm_shape(SHP_tydal) +
  tm_polygons() + tm_shape(depths_tydal_i80) + tm_symbols(col = "black",
  shape = 4, size = 0.5) + tm_layout(title = "-80 data points",
  inner.margins = c(0.1, 0.02, 0.1, 0.02)))

tmap_arrange(tm_shape(SHP_geilo_biggest) + tm_polygons() + tm_shape(depths_geilo_biggest) +
  tm_symbols(col = "black", shape = 4, size = 0.5) + tm_layout(title = "All data points",
  inner.margins = c(0.1, 0.02, 0.1, 0.02)), tm_shape(SHP_geilo_biggest) +
  tm_polygons() + tm_shape(depths_geilo_i50) + tm_symbols(col = "black",

```

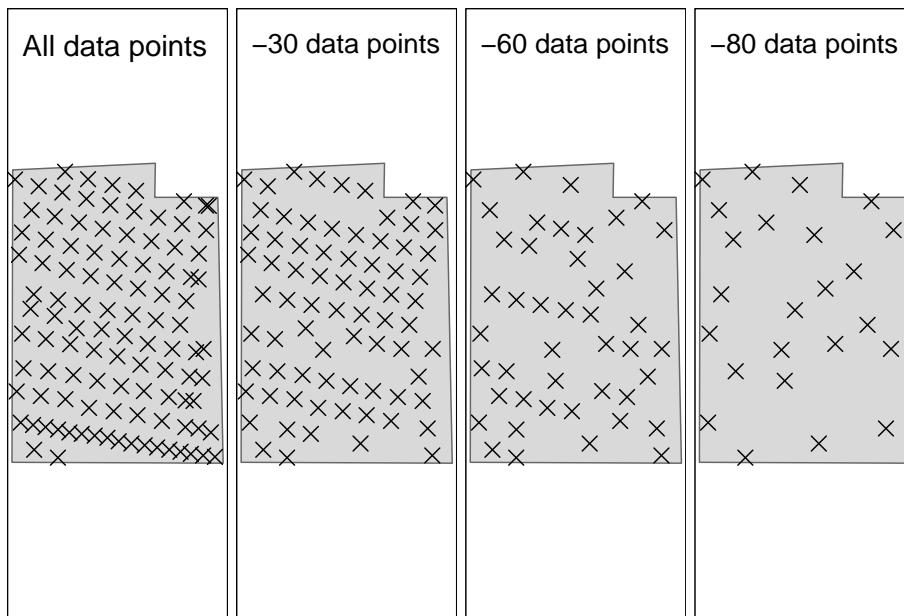


Figure 4.3: Demonstrating the gradual reduction in sampling points. after removing 80 data points, the median distance between the points is 28 meters.  
Test site: Tydal

```
shape = 4, size = 0.5) + tm_layout(title = "-50 data points",
inner.margins = c(0.1, 0.02, 0.1, 0.02)), tm_shape(SHP_geilo_biggest) +
tm_polygons() + tm_shape(depths_geilo_i100) + tm_symbols(col = "black",
shape = 4, size = 0.5) + tm_layout(title = "-100 data points",
inner.margins = c(0.1, 0.02, 0.1, 0.02)), tm_shape(SHP_geilo_biggest) +
tm_polygons() + tm_shape(depths_geilo_i200) + tm_symbols(col = "black",
shape = 4, size = 0.5) + tm_layout(title = "-200 data points",
inner.margins = c(0.1, 0.02, 0.1, 0.02)))
```

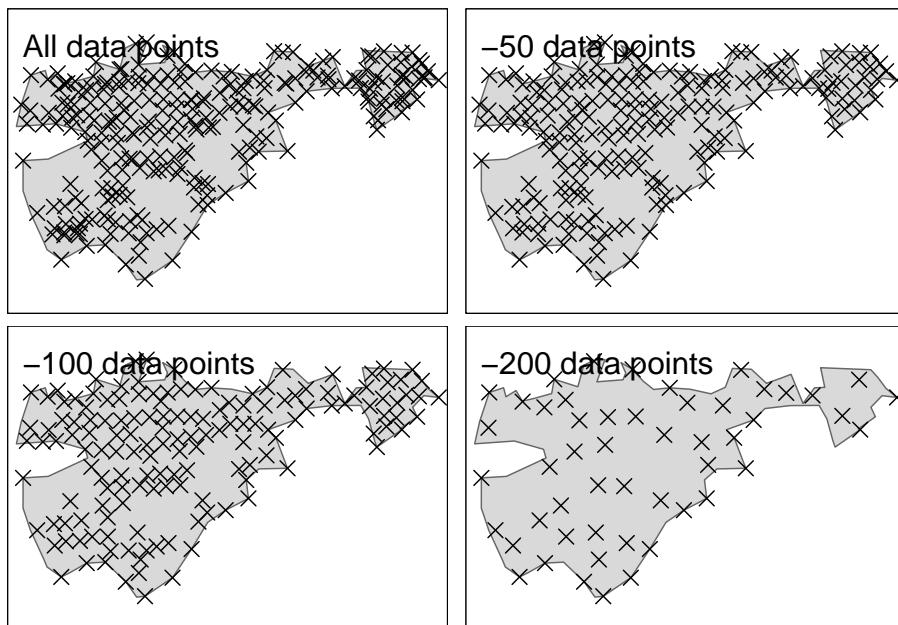


Figure 4.4: Demonstrating the gradual reduction in sampling points. after removinf 200 data poins, the median distance between points is 19 meters. Test site: Geilo

## 4.4 Explore results

### 4.4.1 Sampling design

```
IDW_tydal_i30 <- readRDS("Output/Tydal/IDW_tydal_i30.rds")
IDW_tydal_i60 <- readRDS("Output/Tydal/IDW_tydal_i60.rds")
IDW_tydal_i90 <- readRDS("Output/Tydal/IDW_tydal_i90.rds")
```

```
tmap_arrange(tm_shape(IDW_tydal_i30) + tm_raster(col = "var1.pred",
  palette = "-viridis", title = "Interpolated peat\ndepth (m)",
  tm_shape(IDW_tydal_i60) + tm_raster(col = "var1.pred", palette = "-viridis",
  title = "Interpolated peat\ndepth (m)", tm_shape(IDW_tydal_i90) +
  tm_raster(col = "var1.pred", palette = "-viridis", title = "Interpolated peat\ndepth (m)"
```

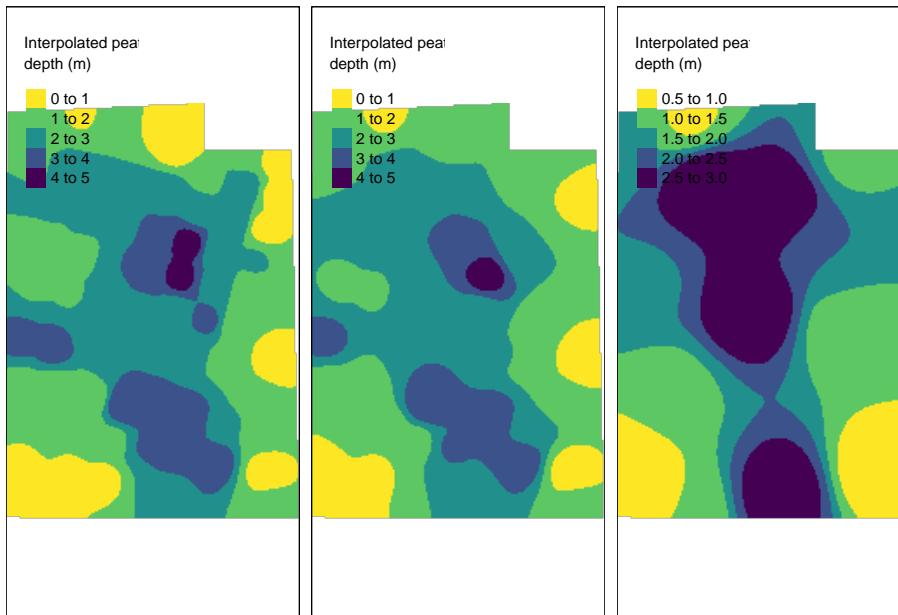


Figure 4.5: IDW with mean distance between data points from left to right: 19.4, 20.2 and 40 m. Test site: Tydal

```
IDW_geilo_i90 <- readRDS("Output/Geilo/IDW_geilo_i90.rds")
IDW_geilo_i140 <- readRDS("Output/Geilo/IDW_geilo_i140.rds")
IDW_geilo_i190 <- readRDS("Output/Geilo/IDW_geilo_i190.rds")
IDW_geilo_i240 <- readRDS("Output/Geilo/IDW_geilo_i240.rds")

tmap_arrange(tm_shape(IDW_geilo_i90) + tm_raster(col = "var1.pred",
  palette = "-viridis", title = "Interpolated peat\ndepth (m)",
  tm_shape(IDW_geilo_i140) + tm_raster(col = "var1.pred", palette = "-viridis",
  title = "Interpolated peat\ndepth (m)", tm_shape(IDW_geilo_i190) +
  tm_raster(col = "var1.pred", palette = "-viridis", title = "Interpolated peat\ndepth (m)",
  tm_shape(IDW_geilo_i240) + tm_raster(col = "var1.pred", palette = "-viridis",
  title = "Interpolated peat\ndepth (m)"))
```

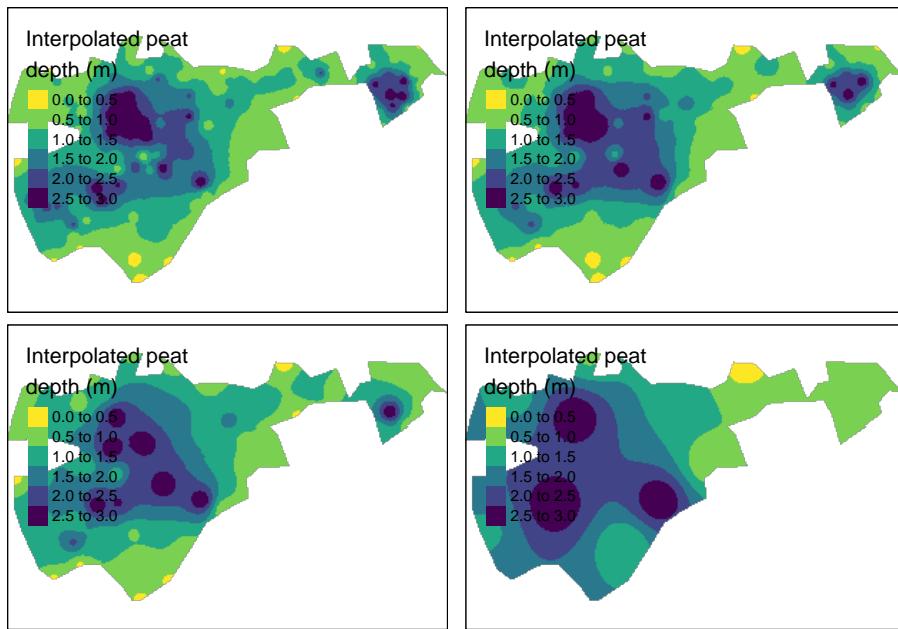


Figure 4.6: IDW with mean distance between data points from left to right, row by row: 9.1, 11.0, 17.3 and 44.5 m. Test site: Geilo

#### 4.4.2 Distance to neighbors

Combine datasets

```
summaryTable_tydal$site <- "Tydal"
summaryTable_geilo$site <- "Geilo"
summaryTable_twoSites <- rbind(summaryTable_tydal, summaryTable_geilo)

ggplot(data = summaryTable_twoSites) + geom_point(aes(x = n,
y = medianDist)) + geom_point(aes(x = n, y = meanDist), pch = 21,
fill = "grey") + theme_bw(base_size = 16) + ylab("Distance to nearest neighbour (m")
ylim(0, 60) + facet_wrap(vars(site), scales = "free_x")
```

This figure tells us that the median (black) and the mean (grey) distance to nearest neighbor are very similar, meaning there is little skew, meaning again that the n reduction process has retained the systematic sampling design.

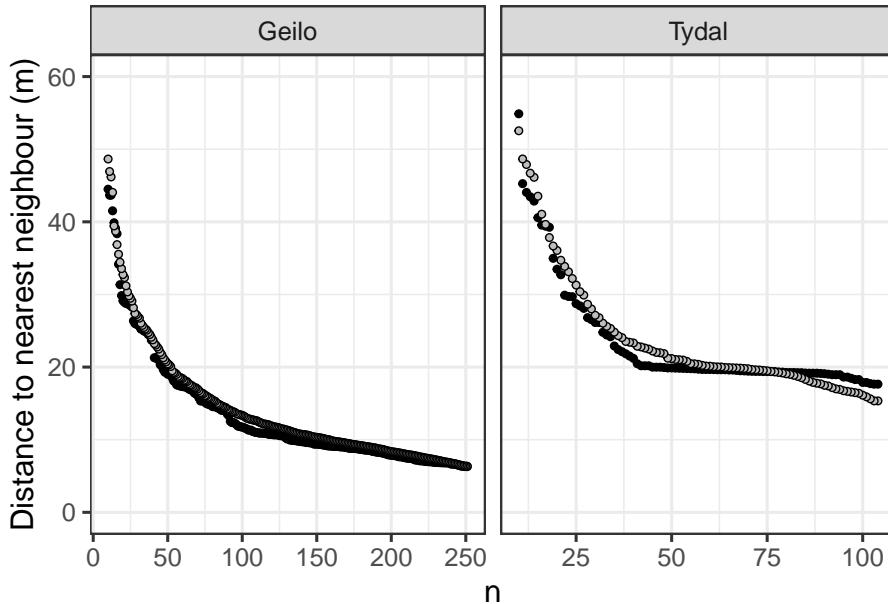


Figure 4.7: Mean (grey) and median (black) distance between peat depth measurements along a gradient of sampling intensity.

#### 4.4.3 Skewness

```
ggplot(data = summaryTable_twoSites) + geom_point(aes(x = n,
  y = skewness), pch = 21, fill = "grey") + theme_bw(base_size = 16) +
  ylab("Skewness") + facet_wrap(vars(site), scales = "free_x")
```

Contrary to the above, this figure indicates perhaps that the sampling designs is compromised when I reduce n. It starts out with a negative skew due to some points being very close together. There are then ‘weeded out’ first, and the skew is flipped around to become positive. I will mostly rely on figure 4.3 and 4.4 and say that the reduction in sampling intensity retains the systematic design.

#### 4.4.4 Peat volume estimates

```
gg_volume <- ggplot(data = summaryTable_twoSites, aes(x = medianDist,
  y = estimatedPeatVolume_m3)) + geom_point(pch = 21, fill = "grey",
  size = 2) + theme_bw(base_size = 16) + ylab(expression("Est. peat volume (m"^3 *
```

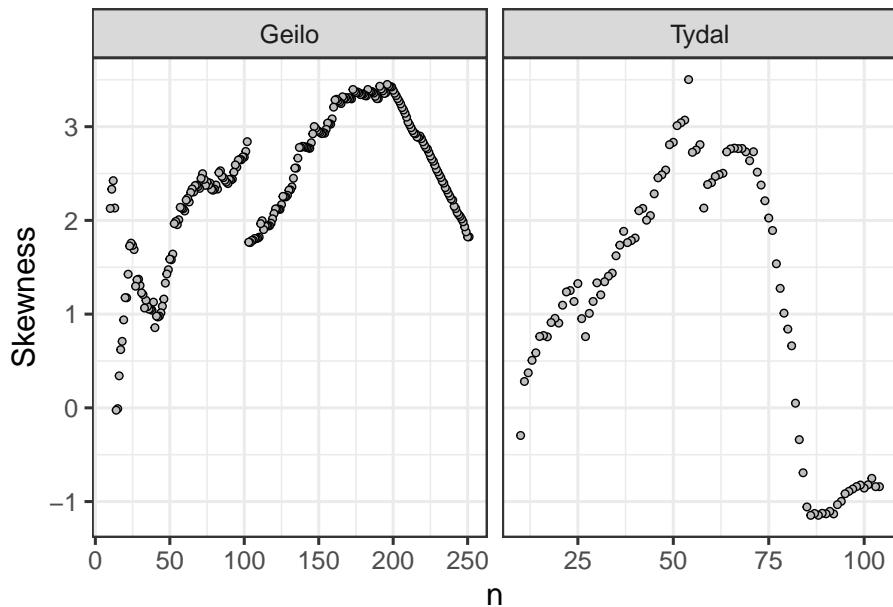


Figure 4.8: Skewness in the distribution of euclidian distances as a response to varying sapling intensity.

```

    ")))) + xlab("Median distance to nearest neighbour (m)") +
    coord_trans(x = "log2") + facet_wrap(vars(site), scales = "free")

ggsave("Output/plot_distanceAgainstVolume.tiff", gg_volume, width = 1600,
       height = 1200, units = "px")

gg_volume

```

For Tydal, the estimated peat volume is quite stable up to around 25 meter between sampling points. For Geilo, the estimated volume increases from zero to 10-12 meters, before stabilizing and finally increasing again with distances above 29 meters. The most correct prediction comes with a median distance between 12-20 meters. The original sampling density was biased towards the edges, resulting in a disproportionate large number of samples from shallow areas (Fig. 4.4). The IDW does not seem to be able to adequately control for this, and care should be taken to ensure a balanced and systematic sampling design.

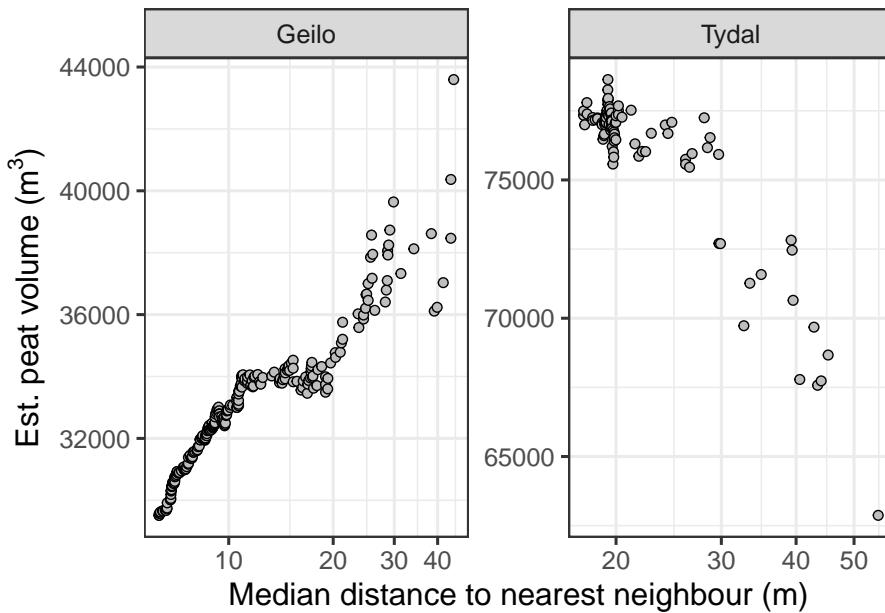


Figure 4.9: Estimated peat volume as a response of the median distance between sampling points.

#### 4.4.5 CV

In addition to seeing the peat volume estimates becoming biased with increasing distance between sampling points, we also see the variation increasing. Now we will calculate this in terms of the coefficient of variation.

```
max(summaryTable_tydal$medianDist)
#> [1] 54.87518

max(summaryTable_geilo$medianDist)
#> [1] 44.49275

tydal_cv <- summaryTable_tydal
tydal_cv$group <- ifelse(tydal_cv$medianDist < 10, "<10 m", ifelse(tydal_cv$medianDist < 15, "10-15 m", ifelse(tydal_cv$medianDist < 20, "15-20 m", ifelse(tydal_cv$medianDist < 25, "20-25 m", ifelse(tydal_cv$medianDist < 30, "25-30 m", ifelse(tydal_cv$medianDist < 35, "30-35 m", ifelse(tydal_cv$medianDist < 40, "35-40 m", "40-55 m"))))))))
tydal_cv <- tydal_cv[tydal_cv$medianDist < 100, ]
(tydal_n <- table(tydal_cv$group))
```

```
#>
#> 15-20 m 20-25 m 25-30 m 30-35 m 35-40 m 40-55 m
#>      60       13       10       3       3       6
```

There's quite few data points in the higher categories. Perhaps too few.

```
geilo_cv <- summaryTable_geilo
geilo_cv$group <- ifelse(geilo_cv$medianDist < 10, "<10 m", ifelse(geilo_cv$medianDist < 15, "10-15 m", ifelse(geilo_cv$medianDist < 20, "15-20 m", ifelse(geilo_cv$medianDist < 25, "20-25 m", ifelse(geilo_cv$medianDist < 30, "25-30 m", ifelse(geilo_cv$medianDist < 35, "30-35 m", ifelse(geilo_cv$medianDist < 40, "35-40 m", "40-55 m"))))))))
geilo_cv <- geilo_cv[geilo_cv$medianDist < 100, ]
(geilo_n <- table(geilo_cv$group))
#>
#> <10 m 10-15 m 15-20 m 20-25 m 25-30 m 30-35 m 35-40 m
#>      120       56       29       13       15       2       3
#> 40-55 m
#>      4
```

CV function

```
cv <- function(x) {
  sd(x)/mean(x)
}

tydal_cv_tbl <- tapply(tydal_cv$estimatedPeatVolume_m3, tydal_cv$group,
  cv)
tydal_cv_tbl <- data.frame(cv = tydal_cv_tbl, label = names(tydal_cv_tbl),
  order = c(3, 4, 5, 6, 7, 8))
tydal_cv_tbl <- tydal_cv_tbl[order(tydal_cv_tbl$order), ]
tydal_cv_tbl$n <- tydal_n

geilo_cv_tbl <- tapply(geilo_cv$estimatedPeatVolume_m3, geilo_cv$group,
  cv)
geilo_cv_tbl <- data.frame(cv = geilo_cv_tbl, label = names(geilo_cv_tbl),
  order = c(1, 2, 3, 4, 5, 6, 7, 8))
geilo_cv_tbl <- geilo_cv_tbl[order(geilo_cv_tbl$order), ]
geilo_cv_tbl$n <- geilo_n
```

Join tables

```

tydal_cv_tbl$site = "Tydal"
geilo_cv_tbl$site = "Geilo"
cvTab <- rbind(tydal_cv_tbl, geilo_cv_tbl)

gg_cv <- ggplot(data = cvTab, aes(x = order, y = cv, fill = site,
  shape = site)) + geom_line(lty = 2) + scale_shape_manual(values = c(21,
  24)) + geom_point(size = 3, stroke = 1.5, position = position_dodge(width = 0.2)) +
  theme_bw(base_size = 16) + scale_x_continuous(breaks = cvTab$order,
  labels = cvTab$label) + theme(axis.text.x = element_text(angle = 90)) +
  xlab("")

ggsave("Output/plot_distanceAgainstCV.tiff", gg_cv, width = 1600,
       height = 1200, units = "px")

gg_cv

```

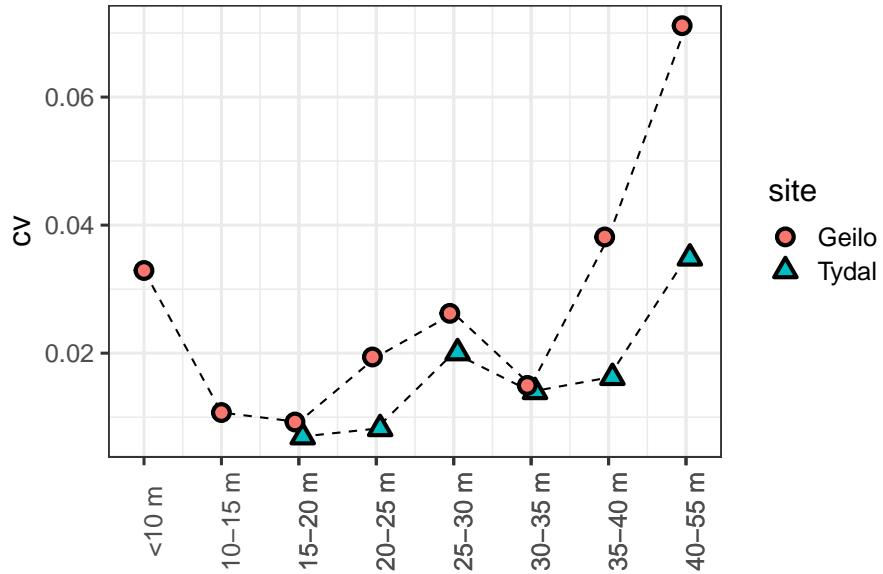


Figure 4.10: Coefficient of variation in peat volume estimates as a response to median distance between sampling points

## 4.5 MAE

```
gg_mae <- ggplot(data = summaryTable_twoSites, aes(x = medianDist,
y = MAE)) + geom_point(pch = 21, fill = "grey", size = 2) +
theme_bw(base_size = 16) + ylab("Mean absolute error (m)") +
xlab("Median distance to nearest neighbour (m)") + coord_trans(x = "log2") +
facet_wrap(vars(site), scales = "free")

ggsave("Output/plot_distanceAgainstMAE.tiff", gg_mae, width = 1600,
height = 1200, units = "px")

gg_mae
```

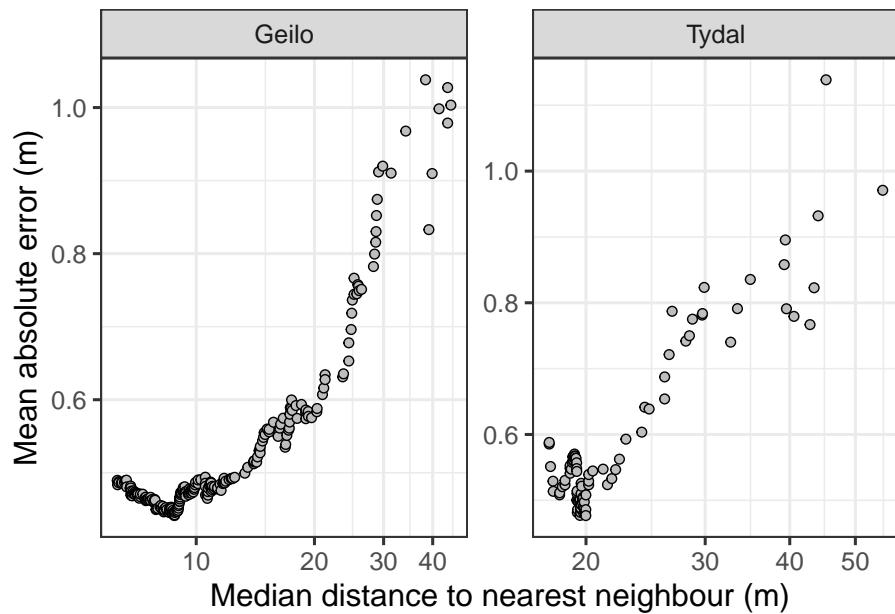


Figure 4.11: MAE in IDW predictions as a response of median distance between sampling points.

This figure I think also support that sampling distances above about 25 m is a bad idea.

# Chapter 5

## Validate using reduced sampling data

In chapter 2 we found the optimal power settings for the Tydal and Geilo sites. Now I just want to look at how this might have changed when we have removed *superfluous* data points as in chapter 3.

Lets say for Tydal that we want to have 20 meters between the sampling points.

```
tm_shape(SHP_tydal) + tm_polygons() + tm_shape(depths_tydal_i60) +
  tm_dots(size = "Dybde", scale = 2, col = "Dybde", palette = "-viridis",
  title = "Measured peat depth (m)") + tm_layout(legend.outside = T)
```

Confirm the median distance is 20 meters

```
temp <- sf::st_distance(depths_tydal_i60)
temp <- units::drop_units(temp)
temp[temp == 0] <- NA
temp <- rowMins(temp, na.rm = T)
median(temp)
#> [1] 20.18216
```

Then we determine the optimal power setting.

```
ccalc_optimumPower <- function(powerRange = 1:6, nmax = 20, peatDepths,
  peatlandDelimitation, title) {
  temp <- data.frame(power = powerRange, MAE = as.numeric(NA))
```

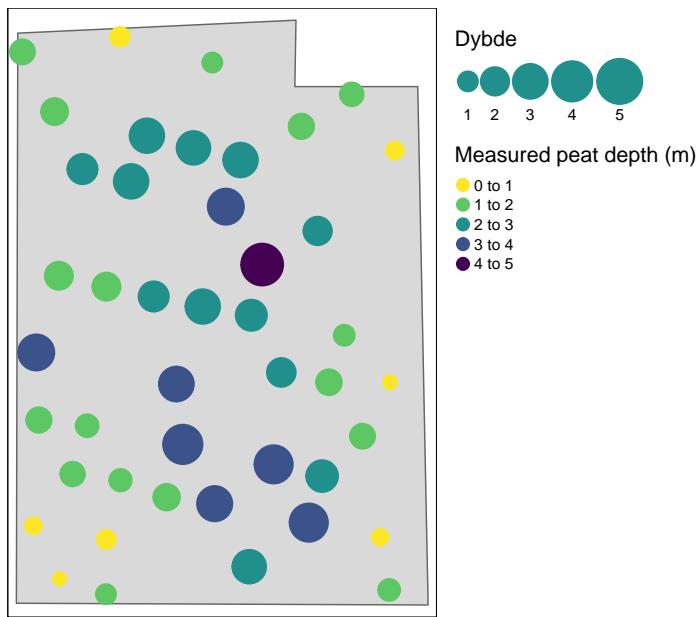


Figure 5.1: Peat depth measurements in the Tydal test site, after trimming the data points so that the median distance between them is 20 meters.

```

vol <- NULL

myGrid <- starsExtra::make_grid(peatlandDelimitation, 1)
myGrid <- sf::st_crop(myGrid, peatlandDelimitation)

for (i in powerRange) {

  # Get the MAE
  temp2 <- krige.cv(Dybde ~ 1, peatDepths, set = list(idp = i),
                      nmax = nmax)
  temp$MAE[temp$power == i] <- mean(abs(temp2$residual))

  # Get the volume
  vol_temp <- gstat::idw(Dybde ~ 1, peatDepths, newdata = myGrid,
                          nmax = nmax, idp = i)

  vol <- c(vol, sum(vol_temp$var1.pred, na.rm = T))
}

ifelse(temp$power[which.min(temp$MAE)] < 2, temp$best <- ifelse(temp$power ==

```

That's good. The optimum power is the same as when we had all the data points.

Let's plot the IDW predictions for Tydal based on all the data points and based on the reduced set of data points.

```
IDW_tydal_4_red <- gstat::idw(formula = Dybde ~ 1, locations = depths_tydal_i60,
  newdata = grid_Tydal_stars_crop, idp = 4, nmax = nmax)
```

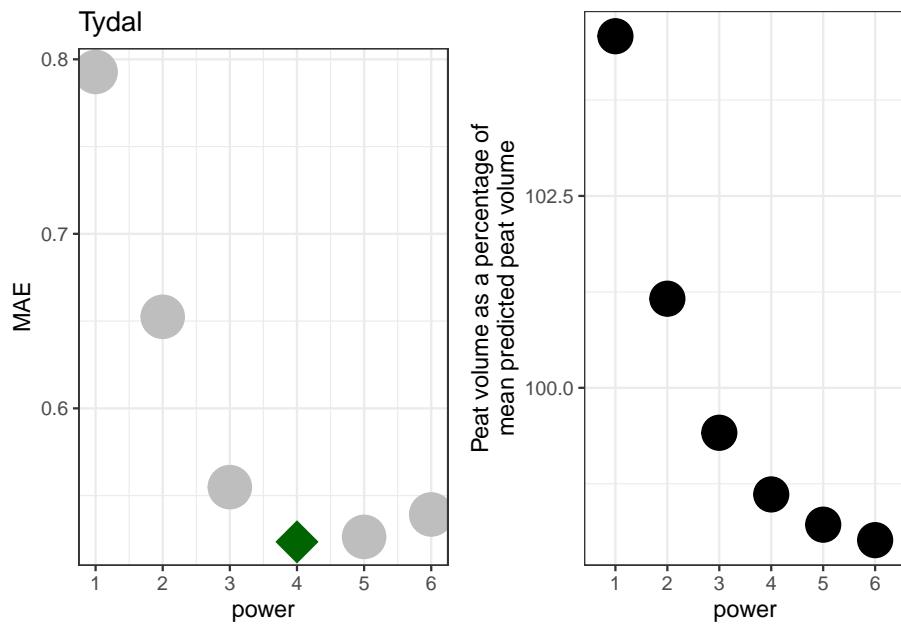


Figure 5.2: Determining the optimal power setting for IDW using a reduced dataset from the Tydal test site.

```
#> [inverse distance weighted interpolation]
```

```
tm_tydal_red <- tm_shape(IDW_tydal_4_red) + tm_raster(col = "var1.pred",
  palette = "-viridis", title = "Interpolated peat\nndepth (m)") +
  tm_shape(depths_tydal_i60) + tm_symbols(shape = 4, col = "black",
  size = 0.5) + tm_compass(type = "8star", position = c("right",
  "bottom"), size = 2) + tm_scale_bar(position = c("left",
  "bottom"), width = 0.3) + tm_layout(inner.margins = c(0.15,
  0.05, 0, 0.05), legend.outside = T)

tmap_arrange(tm_tydal, tm_tydal_red)
```

The two maps in Fig. 5.3 are qualitatively similar.

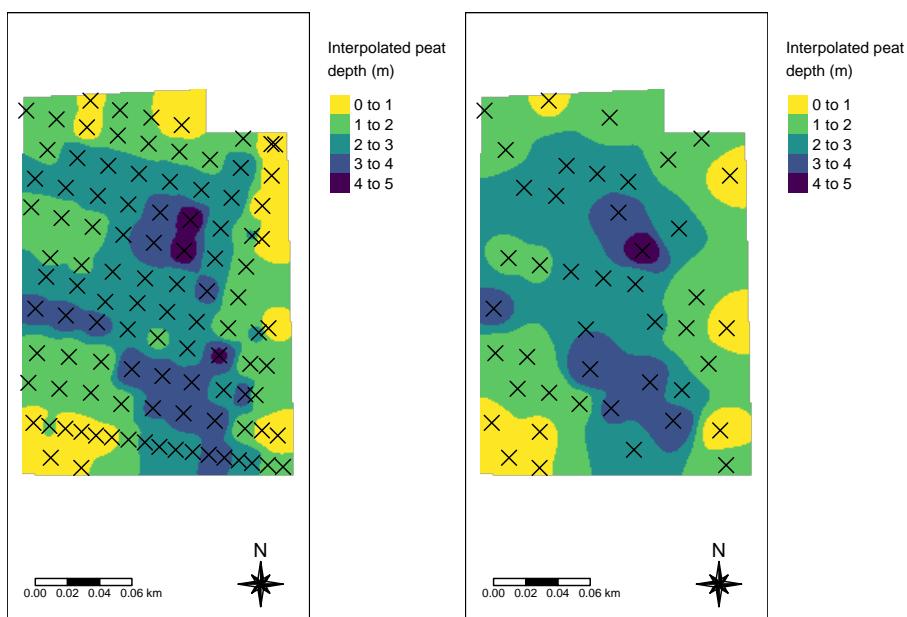


Figure 5.3: Comparing IDW prediction using all data points (left) and a reduced set of data points with median distance between point set to 20 meters.



# Chapter 6

## Carbon stocks

Now I want to convert the peat volumes into estimates of carbon stock. This conversion depends on the values of some peat characteristics, such as bulk density and C concentrations. We have a data set with these values.

Import dataset with peat characteristics.

```
peatCharacteristics <- read_delim("Data/peatCharacteristics.csv",
  delim = ";", escape_double = FALSE, locale = locale(encoding = "ISO-8859-1"),
  trim_ws = TRUE)
dim(peatCharacteristics)
#> [1] 88 30
```

Each sample consists of multiple sub samples from different depths. Here we will ignore the depth aspect, and simply take the mean from each sample core. This part of the analyses can be improved.

```
peatCharacteristics_summedDepths <- peatCharacteristics %>%
  mutate(perc_SOM = as.numeric(`% SOM`)) %>%
  mutate(BD = as.numeric(`BD (t/m3)`)) %>%
  dplyr::select(`SAMPLE ID2`, perc_SOM, BD) %>%
  group_by(`SAMPLE ID2`) %>%
  summarise(across(.fns = list(mean = ~mean(., na.rm = TRUE))))  
  

# Getting the other variables that I also want to keep
df_info <- peatCharacteristics %>%
  dplyr::select(`SAMPLE ID2`, `General Peatland Type`, `Specific Peatland Type`) %>%
  group_by(`SAMPLE ID2`) %>%
  unique()  

# and join together again (this two-step procedure could
```

```
# be simplified)
df = full_join(peatCharacteristics_summedDepths, df_info, by = "SAMPLE ID2") %>%
  drop_na()
head(df)
#> # A tibble: 6 x 5
#>   `SAMPLE ID2` perc_SOM_mean BD_mean General Peatl~1 Speci~2
#>   <chr>           <dbl>    <dbl> <chr>          <chr>
#> 1 0029            98.3     0.05  fen            poor f~
#> 2 0030            99.5     0.102 fen            interm~
#> 3 0031            98.2     0.0527 bog            bog
#> 4 0032            95.9     0.0555 fen            poor f~
#> 5 0033            96.6     0.067  fen            interm~
#> 6 0034            99.3     0.066  fen            rich f~
#> # ... with abbreviated variable names
#> #   1: `General Peatland Type`, 2: `Specific Peatland Type`
```

We have 12 samples from bogs, and 14 from fens:

```
table(df$`General Peatland Type`)
#>
#> bog  fen
#> 12   14
```

We do not perhaps have enough data points to really compare the different specific peatland types:

```
table(df$`Specific Peatland Type`)
#>
#>      bog intermediate fen      oceanic bog
#>      3             5             2
#>      poor fen      raised bog      rich fen
#>      5             7             4
```

Let's get the total peat volumes for Tydal (and Geilo, but I will not look at Geilo here).

```
volume
#>   site   volume
#> 1 Tydal  77336.97
#> 2 Geilo 102469.96
```

Calculating the c stocks (tons C) for the Tydal site without specifying the mire type

```
c_stock_tydal_uninformed <- volume$volume[volume$site == "Tydal"] *
  mean(df$perc_SOM_mean/100) * mean(df$BD_mean) * 0.5  #* 1000 # removing the original conversion
c_stock_tydal_uninformed
#> [1] 3519.665
```

I think we also need to estimate the uncertainties around this number. Note that for the peat volume estimation, we did not calculate an uncertainty. But for the peat characteristics we have an uncertainty in terms of variation within and between samples points. I will calculate the uncertainty between individual peat cores only.

```
c_stock_tydal_uninformed <- NULL
for (i in 1:1000) {
  temp <- volume$volume[volume$site == "Tydal"] * mean(sample(df$perc_SOM_mean,
    replace = T)/100) * mean(sample(df$BD_mean, replace = T) *
    0.5)

  c_stock_tydal_uninformed <- c(c_stock_tydal_uninformed, temp)
}
hist(c_stock_tydal_uninformed, main = "", xlab = "C stock")
```

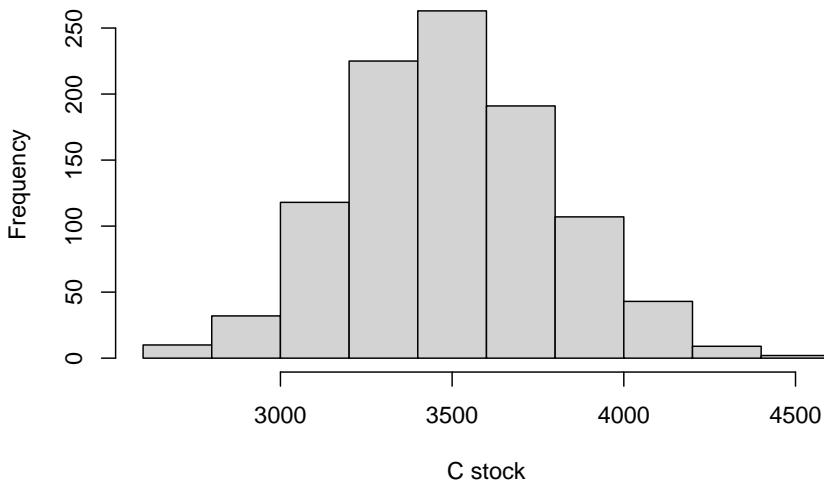


Figure 6.1: Estimated carbon stock in the Tydal peatland

This distribution is quite wide. Let's summarize the distribution.

```
c(quantile(c_stock_tydal_uninformed, c(0.05, 0.5, 0.95)), mean = mean(c_stock_tydal_uninformed),
   sd = sd(c_stock_tydal_uninformed))
#>      5%      50%      95%     mean      sd
#> 3028.6522 3495.0599 4013.9842 3496.2167 302.8956
```

We can put this stuff into a more generic function.

```
ccalc_cStocks <- function(volume, peatlandType = c("fen", "bog"),
  peatData) {
  temp_stocks <- NULL
  temp_peatData <- peatData[peatData$`General Peatland Type` %in%
    peatlandType, ]

  for (i in 1:1000) {
    temp <- volume * mean(sample(peatData$perc_SOM_mean,
      replace = T)/100) * mean(sample(peatData$BD_mean,
      replace = T) * 0.5)

    temp_stocks <- c(temp_stocks, temp)
  }
  return(c(quantile(temp_stocks, c(0.05, 0.5, 0.95)), mean = mean(temp_stocks),
    sd = sd(temp_stocks)))
}
```

Calculating summary statistics for the carbon stocks in Tydal, using both general peatland types.

```
(cstocks_tydal_unspecified <- ccalc_cStocks(volume = volume$volume[volume$site ==
  "Tydal"], peatData = df))
#>      5%      50%      95%     mean      sd
#> 3002.0563 3513.2232 4023.2218 3522.4050 306.8462
```

And using only the *bog* data.

```
(cstocks_tydal_bog <- ccalc_cStocks(volume = volume$volume[volume$site ==
  "Tydal"], peatData = df, peatlandType = "bog"))
#>      5%      50%      95%     mean      sd
#> 3034.3316 3527.9250 4013.8360 3522.1516 301.4506
```

And finally, also the *fen* data.

```
(cstocks_tydal_fen <- ccalc_cStocks(volume = volume$volume[volume$site ==
  "Tydal"], peatData = df, peatlandType = "fen"))
#>      5%      50%      95%     mean      sd
#> 2997.2640 3488.9693 4029.7993 3502.1825 315.8093
```

```

cstocks_tydal_unspecified_df <- as.data.frame(cstocks_tydal_unspecified)
names(cstocks_tydal_unspecified_df) <- "C stocks"
cstocks_tydal_unspecified_df$summary <- row.names(cstocks_tydal_unspecified_df)
cstocks_tydal_unspecified_df$information <- "Unspecified"

cstocks_tydal_bog_df <- as.data.frame(cstocks_tydal_bog)
names(cstocks_tydal_bog_df) <- "C stocks"
cstocks_tydal_bog_df$summary <- row.names(cstocks_tydal_bog_df)
cstocks_tydal_bog_df$information <- "Bog"

cstocks_tydal_fen_df <- as.data.frame(cstocks_tydal_fen)
names(cstocks_tydal_fen_df) <- "C stocks"
cstocks_tydal_fen_df$summary <- row.names(cstocks_tydal_fen_df)
cstocks_tydal_fen_df$information <- "Fen"

cstocks_tydal_compare <- rbind(cstocks_tydal_fen_df, cstocks_tydal_bog_df,
                                cstocks_tydal_unspecified_df)

# Pivot
cstocks_tydal_compare <- pivot_wider(cstocks_tydal_compare, names_from = summary,
                                       values_from = "C stocks")

ggplot(cstocks_tydal_compare, aes(x = information)) + geom_point(aes(y = mean),
                                                               shape = 15, size = 10) + geom_linerange(aes(ymax = `5%`,
                                                               ymin = `95%`), size = 2) + theme_bw(base_size = 16) + labs(x = "Peat characteristics",
                                                                 y = "Carbon stocks (tons)")

```

Specifying the peatland type makes no difference!

Let's just get the (non-informed) C stock estimates for Geilo as well

```

ccalc_cStocks(volume = volume$volume[volume$site == "Geilo"],
               peatData = df)
#>      5%     50%    95%   mean      sd
#> 4023.5538 4662.4745 5349.3607 4674.1840 406.5653

```

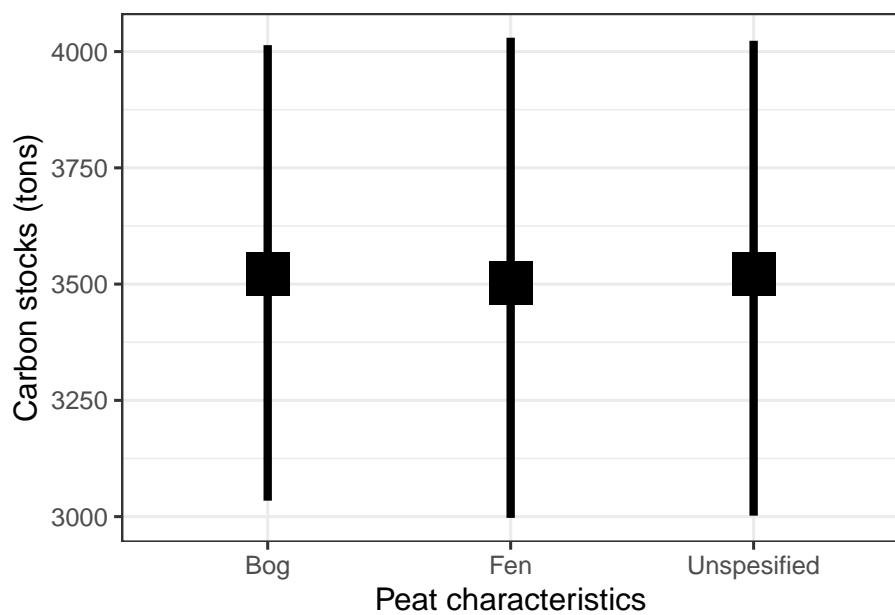


Figure 6.2: Mean ( $\pm$  95 CI) carbon stock for the Tydal test site.

# Chapter 7

## Additional test sites

We used two contrasting sites, Tydal and Geilo, for the main analyses and testing. Now I will bring in an additional four sites to validate the generality of these finding.

### 7.1 Modalen

Import shape files with peatland delineations.

```
SHP_modalen <- sf::read_sf("Data/Modalen/Modalen_myrareal.shp")
# st_crs(SHP_modalen) #OK
```

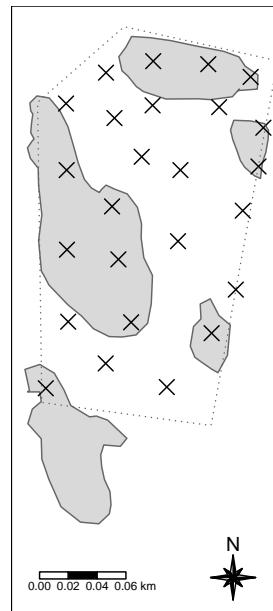
Another shape file with the project area (see below)

```
SHP_modalen_project <- sf::read_sf("Data/Modalen/modalen_shp.shp")
# st_crs(SHP_modalen_project) # OK
```

Import depth samples

```
depths_modalen <- sf::read_sf("Data/Modalen/modalen_punkter.shp")
# st_crs(depths_modalen) #OK

tm_shape(SHP_modalen) + tm_polygons() + tm_shape(depths_modalen) +
  tm_symbols(col = "black", size = 0.5, shape = 4) + tm_shape(SHP_modalen_project) +
  tm_borders(lty = "dotted") + tm_compass(type = "8star", position = c("right",
  "bottom"), size = 2) + tm_scale_bar(position = c("left",
  "bottom"), width = 0.3) + tm_layout(inner.margins = c(0.15,
  0.05, 0.05, 0.05))
```



The peatland delineation (five peatland inside the project area) is mapped using aerial photos and other base maps. There may be peat also between these polygons, however, there si for sure areas between the polygons that are not peat. The depth measurements are performed systematically inside the project area. I don't think we should include points that are taken from smaller isolated mire fragments that are clearly separated from the main peatlands. This example illustrates the importance of appropriate sampling. We are now limited to just a few data points. The smaller mires have only one or two datapoints.

Calculating the combined area of the five mires.

```
SHP_modalen$myArea <- sf::st_area(SHP_modalen)
sum(SHP_modalen$myArea)
#> 16752.75 [m^2]
```

And the area of the project delineation

```
SHP_modalen_project$myArea <- sf::st_area(SHP_modalen_project)
SHP_modalen_project$myArea
#> 36179.43 [m^2]
```

Removing the depth measurement from outside the peatland delinitaion

```

depths_modalen_reduced <- sf::st_intersection(depths_modalen,
                                              SHP_modalen)
#> Warning: attribute variables are assumed to be spatially
#> constant throughout all geometries

tm_shape(SHP_modalen) + tm_polygons() + tm_shape(depths_modalen_reduced) +
  tm_symbols(col = "black", size = 0.5, shape = 4) + tm_shape(SHP_modalen_project) +
  tm_borders(lty = "dotted") + tm_compass(type = "8star", position = c("right",
  "bottom"), size = 2) + tm_scale_bar(position = c("left",
  "bottom"), width = 0.3) + tm_layout(inner.margins = c(0.15,
  0.05, 0.05, 0.05))

```

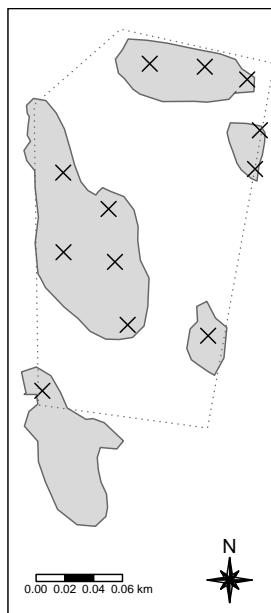


Figure 7.1: The Modalen test site with peatland delineated as grey polygons. Crosses are peat depth samples, contained within the project area (dotted line). Only depth measurements that intersect the mire polygons are included

Create a raster grid

```

# First fix polygon closure
SHP_modalen <- sf::st_make_valid(SHP_modalen)

grid_Modalen_stars_crop <- starsExtra::make_grid(SHP_modalen,

```

```
1) %>%
sf::st_crop(SHP_modalen)

tm_shape(grid_Modalen_stars_crop) + tm_raster()
```

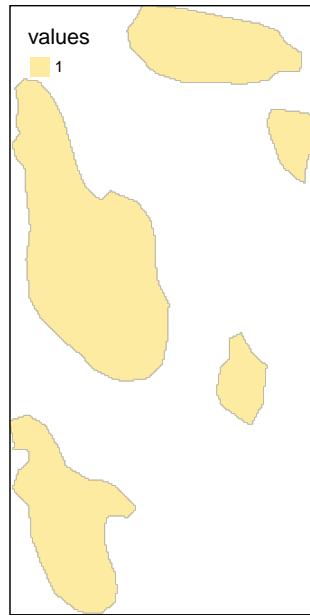
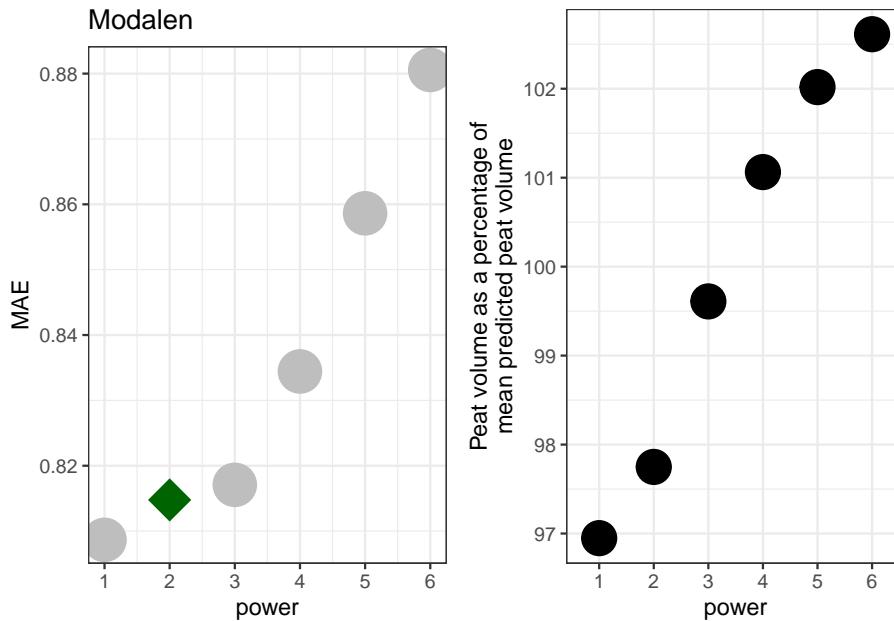


Figure 7.2: Checking that the raster grid for Modalen looks correct.

## Predict peat depth



Unsurprising, when we have so few data points, the optimum power is very low. I will predict using power 1 through 3 to compare, just because I don't trust power 1 is the best choice.

```
IDW_Modalen_1 <- gstat::idw(formula = Dybde ~ 1, locations = depths_modalen_reduced,
  newdata = grid_Modalen_stars_crop, idp = 1, nmax = 20) # nmax > than the number of points
#> [inverse distance weighted interpolation]

IDW_Modalen_2 <- gstat::idw(formula = Dybde ~ 1, locations = depths_modalen_reduced,
  newdata = grid_Modalen_stars_crop, idp = 2, nmax = nrow(depths_modalen_reduced))
#> [inverse distance weighted interpolation]

IDW_Modalen_3 <- gstat::idw(formula = Dybde ~ 1, locations = depths_modalen_reduced,
  newdata = grid_Modalen_stars_crop, idp = 3, nmax = nrow(depths_modalen_reduced))
#> [inverse distance weighted interpolation]

tmap_arrange(
tm_shape(IDW_Modalen_1)+ 
  tm_raster(col="var1.pred",
    palette = "-viridis",
    title = "Power = 1\nInterpolated peat\ndepth (m)",
    breaks = seq(0,3,.5))+ 
  tm_compass(type="8star", position = c("right", "bottom"), size = 2) + 
  tm_scale_bar(position = c("right", "bottom"), width = 0.3)+ 
  tm_shape(depths_modalen_reduced)+
```

```

tm_symbols(shape=4,
           col="black",
           size=.5)+
tm_layout(legend.outside = T)
,
tm_shape(IDW_Modalen_2)+
  tm_raster(col="var1.pred",
             palette = "-viridis",
             title = "Power = 2\nInterpolated peat\ndepth (m)",
             breaks = seq(0,3,.5))+ 
  tm_compass(type="8star", position = c("right", "bottom"), size = 2) +
  tm_scale_bar(position = c("right", "bottom"), width = 0.3) +
  tm_shape(depths_modalen_reduced) +
  tm_symbols(shape=4,
             col="black",
             size=.5) +
  tm_layout(legend.outside = T)
,
tm_shape(IDW_Modalen_3) +
  tm_raster(col="var1.pred",
             palette = "-viridis",
             title = "Power = 3\nInterpolated peat\ndepth (m)",
             breaks = seq(0,3,.5))+ 
  tm_compass(type="8star", position = c("right", "bottom"), size = 2) +
  tm_scale_bar(position = c("right", "bottom"), width = 0.3) +
  tm_shape(depths_modalen_reduced) +
  tm_symbols(shape=4,
             col="black",
             size=.5) +
  tm_layout(legend.outside = T)
)

#> Legend labels were too wide. The labels have been resized to 0.41, 0.41, 0.41, 0.41
#> Legend labels were too wide. The labels have been resized to 0.41, 0.41, 0.41, 0.41
#> Legend labels were too wide. The labels have been resized to 0.41, 0.41, 0.41, 0.41

```

I think power 3 looks more accurate because of the way it gives weight to local points. The recommended practice for this case I think would be to analyse each polyong or mire separately because of how the point from neighboring mires affect the depth predictions.

Summary stats for the peat depth at Modalen.

```

summary(depths_modalen_reduced$Dybde)
#>   Min. 1st Qu. Median  Mean 3rd Qu.   Max.

```

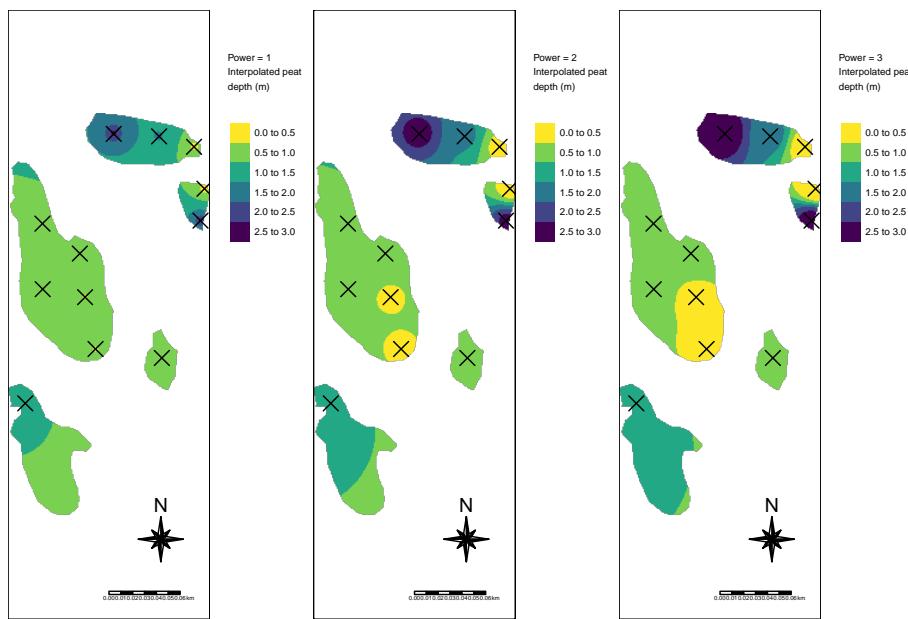


Figure 7.3: IDW for peat depth at Modalen test site.

```
#> 0.000 0.400 0.600 1.017 1.475 2.800
```

The MAE for the power =3 prediction is 0.82 m.

The rough volume (in m<sup>3</sup>), that is the mean peat depth multiplied by the area, is

```
mean(depths_modalen_reduced$Dybde) * sum(SHP_modalen$myArea)
#> 17031.97 [m^2]
```

Number of depth samples per 100 m<sup>2</sup>:

```
12/(sum(SHP_modalen$myArea)/100)
#> 0.07163001 [1/m^2]
```

Interpolated volume

```
(volume_modalen <- sum(IDW_Modalen_3$var1.pred, na.rm = T))
#> [1] 16792.6
```

Estimated carbon stocks for the Modalen site:

```
ccalc_cStocks(volume_modalen, peatData = df)
#>      5%      50%     95%    mean      sd
#> 651.1035 765.6464 878.4216 764.9719 67.3035
```

## 7.2 Opelandsmarka

Import shape file

```
SHP_opelandsmarka <- sf::read_sf("Data/Opelandsmarka/Opelandsmarka_Voss.shp")
# st_crs(SHP_opelandsmarka) #32632 UTM 32
```

The depth measurements are in three different files.

```
depths_opelandsmarka1 <- read_delim("Data/Opelandsmarka/Torvdybder_Opelandsmarka_myr1",
  delim = ";", escape_double = FALSE, locale = locale(encoding = "ISO-8859-1"),
  trim_ws = TRUE)
depths_opelandsmarka2 <- read_delim("Data/Opelandsmarka/Torvdybder_Opelandsmarka_myr2",
  delim = ";", escape_double = FALSE, locale = locale(encoding = "ISO-8859-1"),
  trim_ws = TRUE)
depths_opelandsmarka3 <- read_delim("Data/Opelandsmarka/Torvdybder_Opelandsmarka_myr3",
  delim = ";", escape_double = FALSE, locale = locale(encoding = "ISO-8859-1"),
  trim_ws = TRUE)
# The last one is missing a column

depths_opelandsmarka <- bind_rows(depths_opelandsmarka1, depths_opelandsmarka2,
  depths_opelandsmarka3)

depths_opelandsmarka <- sf::st_as_sf(depths_opelandsmarka, coords = c("UTM_N_ZONE32N",
  "UTM_E_ZONE32N"), crs = 32632)

tm_shape(SHP_opelandsmarka) + tm_polygons() + tm_shape(depths_opelandsmarka) +
  tm_symbols(col = "black", size = 0.5, shape = 4)
```

I think we can ignore that top mire as it was not sampled nearly as intensive as the other two.

```
SHP_opelandsmarka_twoMires <- SHP_opelandsmarka[-1, ]
```

It could be a good idea sometimes to include depth measurements outside the mire polygons (with a depth of 0). Here it is easier for me to just exclude all points outside any polygon.



Figure 7.4: Test site: Opelandsmarka. Crosses are peat depth measurements.

```
depths_opelandsmarka <- st_intersection(depths_opelandsmarka,
                                         SHP_opelandsmarka_twoMires)
#> Warning: attribute variables are assumed to be spatially
#> constant throughout all geometries

tm_shape(SHP_opelandsmarka_twoMires) + tm_polygons() + tm_shape(depths_opelandsmarka) +
  tm_symbols(col = "black", size = 0.5, shape = 4)
```

There is one NA in the depth data which we have to remove

```
depths_opelandsmarka <- depths_opelandsmarka[!is.na(depths_opelandsmarka$Dybde),
                                             ]
```

Try again:

```
ccalc_optimumPower(peatDepths = depths_opelandsmarka, title = "Opelandsmarka",
                   peatlandDelimitation = SHP_opelandsmarka_twoMires)
#> /
#> [inverse distance weighted interpolation]
#> /
```

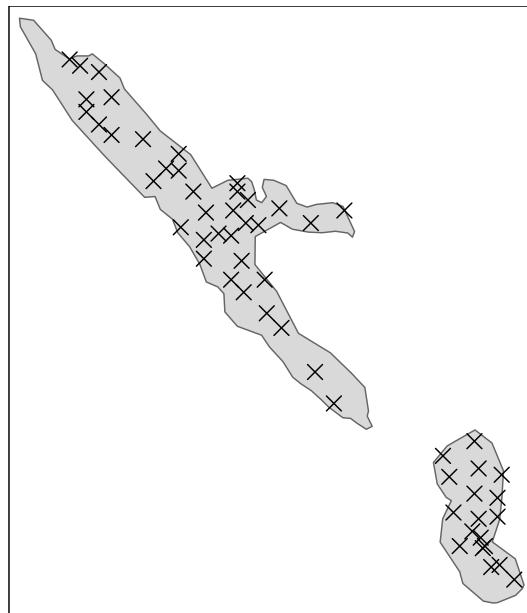


Figure 7.5: Opelandsmarka with two out of three mires. Crosses are peat depth measurements.

```
#> [inverse distance weighted interpolation]
#> /
#> [inverse distance weighted interpolation]
```

Again the lowest MAE is obtained from a power of 1, but as we have seen, the power should probably be set higher. The predicted peat volume for example is quite unstable at low power settings.

Create a raster grid for the predictions

```
grid_Opelandsmarka_stars_crop <- starsExtra::make_grid(SHP_opelandsmarka_twoMires,
  1) %>%
  sf::st_crop(SHP_opelandsmarka_twoMires)
```

The depths are recorded as cm not meters. Converting to m.

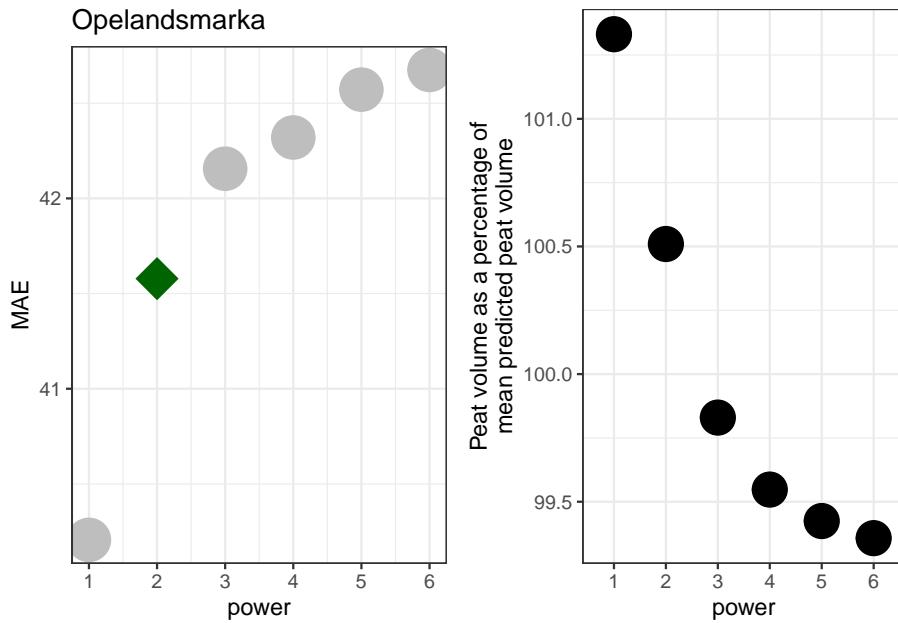


Figure 7.6: Determining the optimal power for the Opelandsmarka test site.

```

depths_opelandsmarka$Dybde <- depths_opelandsmarka$Dybde/100

IDW_opelandsmarka_1 <- gstat::idw(Dybde ~ 1, depths_opelandsmarka,
  newdata = grid_Opelandsmarka_stars_crop, nmax = nmax, idp = 1)
#> [inverse distance weighted interpolation]

IDW_opelandsmarka_2 <- gstat::idw(Dybde ~ 1, depths_opelandsmarka,
  newdata = grid_Opelandsmarka_stars_crop, nmax = nmax, idp = 2)
#> [inverse distance weighted interpolation]

IDW_opelandsmarka_3 <- gstat::idw(Dybde ~ 1, depths_opelandsmarka,
  newdata = grid_Opelandsmarka_stars_crop, nmax = nmax, idp = 3)
#> [inverse distance weighted interpolation]

myBreaks <- seq(0,3,.5)
myPos <- c("left", "bottom")

tmap_arrange(
  tm_shape(IDW_opelandsmarka_1)+
    tm_raster(col="var1.pred",
              palette = "-viridis",

```

```

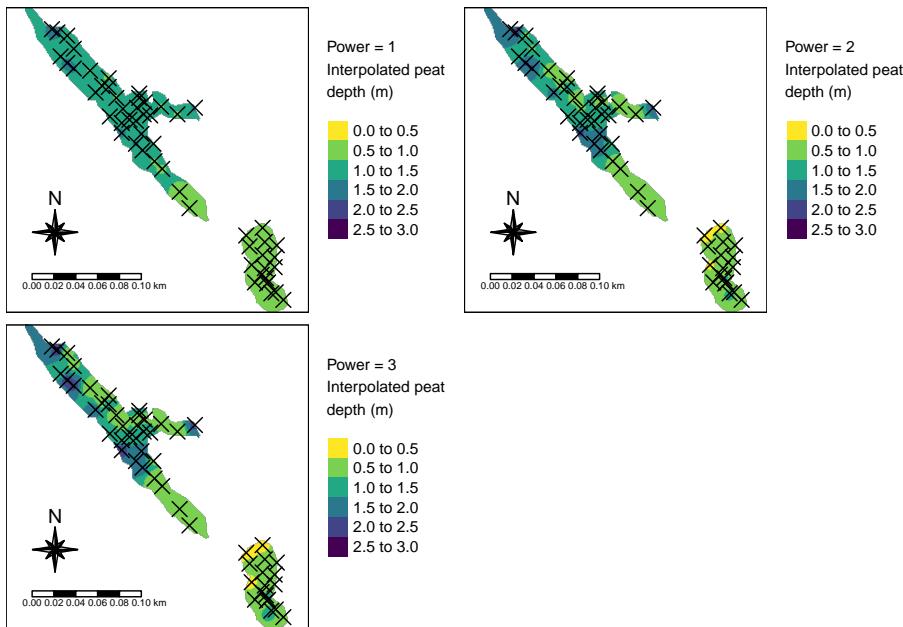
        title = "Power = 1\nInterpolated peat\ndepth (m)",
        breaks = myBreaks) +
tm_compass(type="8star", position = myPos, size = 2) +
tm_scale_bar(position = myPos, width = 0.3) +
tm_shape(depths_opelandsmarka) +
tm_symbols(shape=4,
           col="black",
           size=.5) +
tm_layout(legend.outside = T)

,
tm_shape(IDW_opelandsmarka_2) +
tm_raster(col="var1.pred",
           palette = "-viridis",
           title = "Power = 2\nInterpolated peat\ndepth (m)",
           breaks = myBreaks) +
tm_compass(type="8star", position = myPos, size = 2) +
tm_scale_bar(position = myPos, width = 0.3) +
tm_shape(depths_opelandsmarka) +
tm_symbols(shape=4,
           col="black",
           size=.5) +
tm_layout(legend.outside = T)

,
tm_shape(IDW_opelandsmarka_3) +
tm_raster(col="var1.pred",
           palette = "-viridis",
           title = "Power = 3\nInterpolated peat\ndepth (m)",
           breaks = myBreaks) +
tm_compass(type="8star", position = myPos, size = 2) +
tm_scale_bar(position = myPos, width = 0.3) +
tm_shape(depths_opelandsmarka) +
tm_symbols(shape=4,
           col="black",
           size=.5) +
tm_layout(legend.outside = T),
ncol = 2

)

```



With power set to 1 the model is too flat, and the deep areas are not identified correctly. Power 2 or 3 makes less of a difference. Because the MAE and volume estimates are so similar, I will choose the modest local model (power = 3)

Getting the total peatland area

```
SHP_opelandsmarka_twoMires$myArea <- sf::st_area(SHP_opelandsmarka_twoMires)
sum(SHP_opelandsmarka_twoMires$myArea)
#> 8700.213 [m^2]
```

Getting the mean peat depth (after excluding points outside the polygons)

```
mean(depths_opelandsmarka$Dybde)
#> [1] 1.058333
```

Rough volume

```
mean(depths_opelandsmarka$Dybde) * sum(SHP_opelandsmarka_twoMires$myArea)
#> 9207.725 [m^2]
```

Number of peat depth measurements

```
nrow(depths_opelandsmarka)
#> [1] 54
```

Depth measurement density (points per 100 m<sup>-2</sup>)

```
nrow(depths_opelandsmarka)/(sum(SHP_opelandsmarka_twoMires$myArea)/100)
#> 0.6206745 [1/m^2]
```

Interpolated peat volume (best model)

```
(vol_temp <- sum(IDW_opelandsmarka_3$var1.pred, na.rm = T))
#> [1] 9270.232
```

Estimated C stocks

```
ccalc_cStocks(volume = vol_temp, peatData = df)
#>      5%      50%      95%     mean      sd
#> 359.29722 421.40733 481.56878 420.93027 37.14581
```

### 7.3 Kinn 1

```
# import peatland delineation
SHP_kinn1 <- sf::st_read("Data/Kinn/rikmyr_avgrensing.shp")
#> Reading layer 'rikmyr_avgrensing' from data source
#>   'C:/Users/anders.kolstad/Github/carbonCalculator/Data/Kinn/rikmyr_avgrensing.shp'
#>   using driver 'ESRI Shapefile'
#> Simple feature collection with 1 feature and 27 fields
#> Geometry type: POLYGON
#> Dimension:     XY
#> Bounding box: xmin: 5.099473 ymin: 61.48336 xmax: 5.102058 ymax: 61.48463
#> Geodetic CRS:  WGS 84

# import peat deth data
depths_kinn1 <- read_delim("Data/Kinn/data_rikmyr_torvdybder.csv",
  delim = ";", escape_double = FALSE, locale = locale(encoding = "ISO-8859-1"),
  trim_ws = TRUE)
#> Rows: 36 Columns: 4
#> -- Column specification -----
#> Delimiter: ;"
#> chr (2): Lokalitet, Notat
#> dbl (2): name, Dybde
#>
#> i Use `spec()` to retrieve the full column specification for this data.
#> i Specify the column types or set `show_col_types = FALSE` to quiet this message.
```

The peat depth data doesn't contain coordinates. Importing those now.

```
depths_kinn1_spatial <- sf::st_read("Data/Kinn/rikmyr_punkter.shp")
#> Reading layer `rikmyr_punkter' from data source
#>   `C:/Users/anders.kolstad/Github/carbonCalculator/Data/Kinn/rikmyr_punkter.shp'
#>   using driver `ESRI Shapefile'
#> Simple feature collection with 37 features and 24 fields
#> Geometry type: POINT
#> Dimension:      XYZ
#> Bounding box:  xmin: 5.099712 ymin: 61.48347 xmax: 5.101931 ymax: 61.48458
#> z_range:        zmin: 18.489 zmax: 44.38
#> Geodetic CRS:  WGS 84
```

The column `name` is shared between the two datasets so I can use this to merge them. First I need to remove leading zeros.

```
depths_kinn1_spatial$name <- as.numeric(depths_kinn1_spatial$name)

depths_kinn1_spatial$Dybde <- depths_kinn1$Dybde[match(depths_kinn1_spatial$name,
  depths_kinn1$name)]
rm(depths_kinn1)
```

There is still one NA to remove

```
depths_kinn1_spatial <- depths_kinn1_spatial[!is.na(depths_kinn1_spatial$Dybde),
  ]
```

Check CRS

```
# st_crs(depths_kinn1_spatial) # lat long st_crs(SHP_kinn1)
# # also lat long

depths_kinn1_spatial <- sf::st_transform(depths_kinn1_spatial,
  25833)
SHP_kinn1 <- sf::st_transform(SHP_kinn1, 25833)

tm_shape(SHP_kinn1) + tm_polygons() + tm_shape(depths_kinn1_spatial) +
  tm_symbols(col = "black", size = 0.5, shape = 4)
```

This is a nice example data set. I notice however, there are few points near the edges.

Getting the rough volume

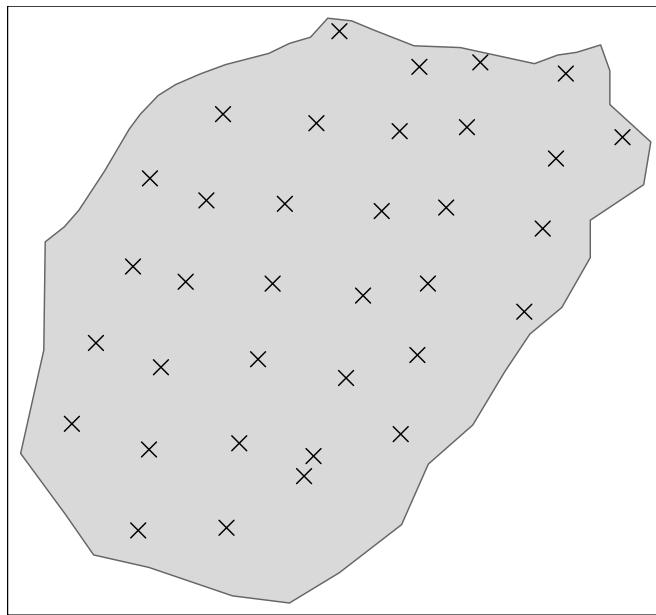


Figure 7.7: Test site Kinn1.

```
SHP_kinn1$myArea <- sf::st_area(SHP_kinn1)
SHP_kinn1$myArea
#> 13541.53 [m^2]
```

Mean depth

```
mean(depths_kinn1_spatial$Dybde, na.rm = T)
#> [1] 244.1429
```

The depths are in cm. Converting to m.

```
depths_kinn1_spatial$Dybde <- depths_kinn1_spatial$Dybde/100
```

Number of depth measurements

```
nrow(depths_kinn1_spatial)
#> [1] 35
```

Point density (100 m<sup>-2</sup>)

```
nrow(depths_kinn1_spatial)/(SHP_kinn1$myArea) * 100
#> 0.2584641 [1/m^2]
```

Finding optimum power

```
ccalc_optimumPower(peatDepths = depths_kinn1_spatial, peatlandDelimitation = SHP_kinn1,
  title = "Kinn1")
#> /
#> [inverse distance weighted interpolation]
```

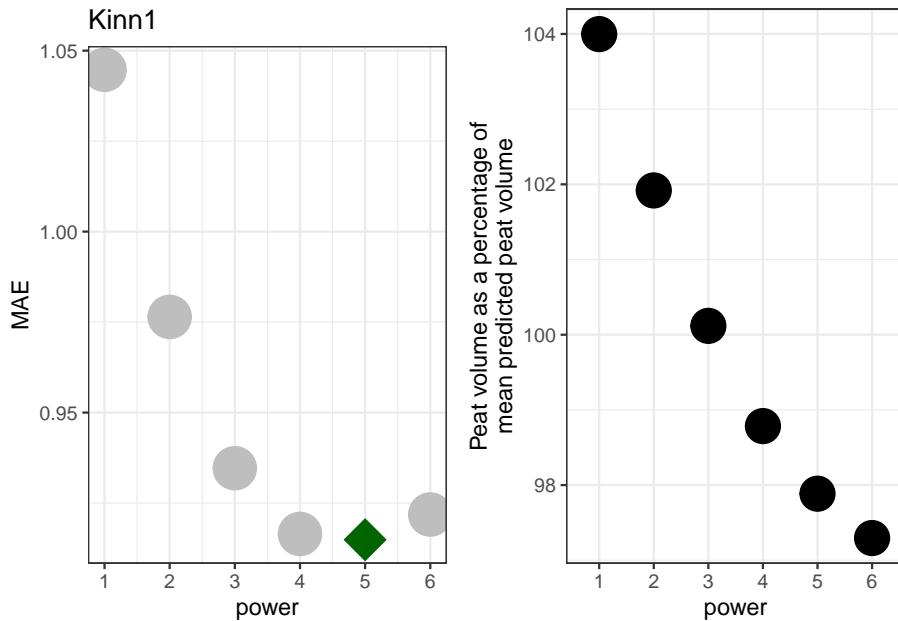


Figure 7.8: Finding the best power setting for the Kinn1 test site.

The optimal power is 5.

Create a raster grid for the predictions

```
grid_kinn1_stars_crop <- starsExtra::make_grid(SHP_kinn1, 1) %>%
  sf::st_crop(SHP_kinn1)

IDW_kinn1_5 <- gstat::idw(Dybde ~ 1, depths_kinn1_spatial, newdata = grid_kinn1_stars_
  nmax = nmax, idp = 5)
#> [inverse distance weighted interpolation]
```

Max peat depth

```
max(depths_kinn1_spatial$Dybde)
#> [1] 4.7
```

```
myBreaks <- seq(0, 5, 1)
myPos <- c("right", "bottom")

tm_shape(IDW_kinn1_5) + tm_raster(col = "var1.pred", palette = "-viridis",
  title = "Power = 5\nInterpolated peat\\ndepth (m)", breaks = myBreaks) +
  tm_compass(type = "8star", position = myPos, size = 2) +
  tm_scale_bar(position = myPos, width = 0.3) + tm_shape(depths_kinn1_spatial) +
  tm_symbols(shape = 4, col = "black", size = 0.5) + tm_layout(legend.outside = T)
```

Predicted peat volume

```
(vol_temp <- sum(IDW_kinn1_5$var1.pred, na.rm = T))
#> [1] 33530.09
```

Carbon stocks

```
ccalc_cStocks(volume = vol_temp, peatData = df)
#>      5%      50%      95%      mean      sd
#> 1318.5341 1526.4497 1738.2737 1528.2790 128.9279
```

## 7.4 Kinn2

```
SHP_kinn2 <- sf::st_read("Data/Kinn/maroy_avgrensing.shp")
#> Reading layer `maroy_avgrensing' from data source
#>   `C:/Users/anders.kolstad/Github/carbonCalculator/Data/Kinn/maroy_avgrensing.shp'
#>   using driver `ESRI Shapefile'
```

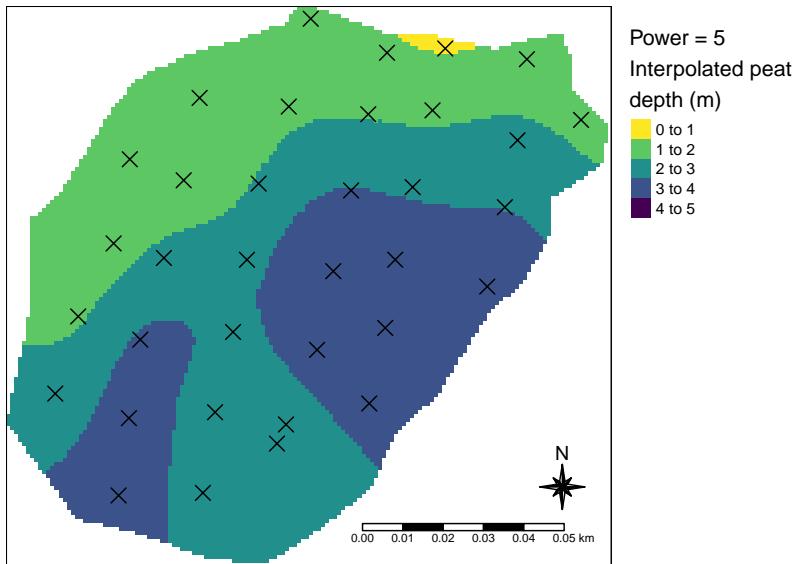


Figure 7.9: Best model for test site Kinn1

```
#> Simple feature collection with 1 feature and 27 fields
#> Geometry type: POLYGON
#> Dimension: XY
#> Bounding box: xmin: 5.102353 ymin: 61.50691 xmax: 5.107625 ymax: 61.50866
#> Geodetic CRS: WGS 84

depths_kinn2 <- read_delim("Data/Kinn/data_maroy_torvdybder.csv",
  delim = ";", escape_double = FALSE, locale = locale(encoding = "ISO-8859-1"),
  trim_ws = TRUE)
#> Rows: 78 Columns: 4
#> -- Column specification -----
#> Delimiter: ;
#> chr (2): Lokalitet, Notat
#> dbl (2): name, Dybde
#>
#> i Use `spec()` to retrieve the full column specification for this data.
#> i Specify the column types or set `show_col_types = FALSE` to quiet this message.
```

As before, the depths have no coordinates.

```
depths_kinn2_spatial <- sf::st_read("Data/Kinn/maroy_punkter.shp")
#> Reading layer `maroy_punkter' from data source
#>   `C:/Users/anders.kolstad/Github/carbonCalculator/Data/Kinn/maroy_punkter.shp'
#>     using driver 'ESRI Shapefile'
#> Simple feature collection with 78 features and 24 fields
#> Geometry type: POINT
#> Dimension:      XYZ
#> Bounding box:  xmin: 5.102523 ymin: 61.50698 xmax: 5.10742 ymax: 61.5086
#> z_range:        zmin: 8.484 zmax: 17.732
#> Geodetic CRS:  WGS 84
```

```
depths_kinn2_spatial$name <- as.numeric(depths_kinn2_spatial$name)
depths_kinn2_spatial$Dybde <- depths_kinn2$Dybde[match(depths_kinn2_spatial$name,
  depths_kinn2$name)]
rm(depths_kinn2)
```

Transform to UTF33

```
depths_kinn2_spatial <- sf::st_transform(depths_kinn2_spatial,
  25833)
SHP_kinn2 <- sf::st_transform(SHP_kinn2, 25833)

tm_shape(SHP_kinn2) + tm_polygons() + tm_shape(depths_kinn2_spatial) +
  tm_symbols(col = "black", size = 0.5, shape = 4)
```

The mean depth

```
summary(depths_kinn2_spatial$Dybde, na.rm = T)
#>   Min. 1st Qu. Median Mean 3rd Qu. Max.
#>   0.00  41.25  71.00  90.26 130.25 282.00
```

Converting from cm to m

```
depths_kinn2_spatial$Dybde <- depths_kinn2_spatial$Dybde/100
```

Area

```
SHP_kinn2$myArea <- st_area(SHP_kinn2)
nrow(depths_kinn2_spatial)
#> [1] 78
```

Number of peat depth measurements

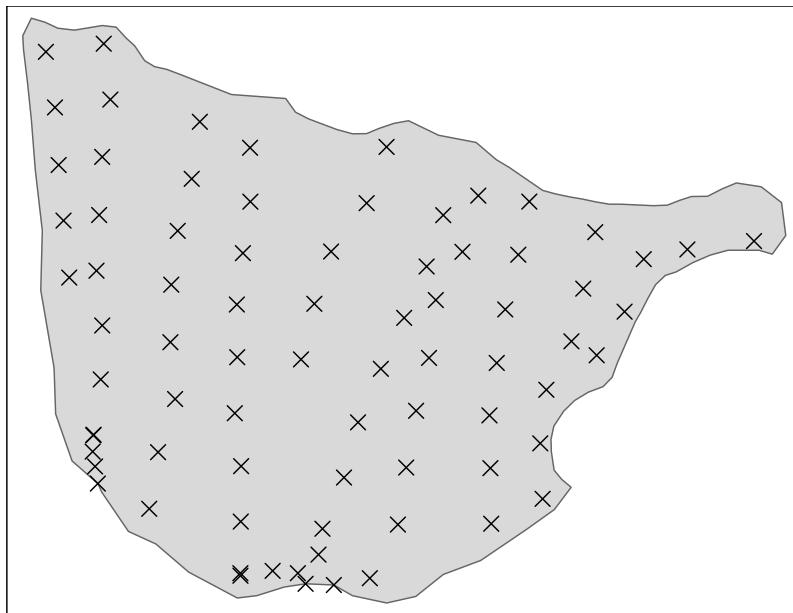


Figure 7.10: Test site Kinn2.

```
nrow(depths_kinn2_spatial)
#> [1] 78
```

Density of points (100 m<sup>-2</sup>)

```
nrow(depths_kinn2_spatial)/SHP_kinn2$myArea * 100
#> 0.2346467 [1/m^2]
```

Find optimal power

```
ccalc_optimumPower(peatDepths = depths_kinn2_spatial, peatlandDelimitation = SHP_kinn2,
  title = "Kinn2")
#> /
#> [inverse distance weighted interpolation]
```

```
#> [inverse distance weighted interpolation]
#> /
#> [inverse distance weighted interpolation]
```

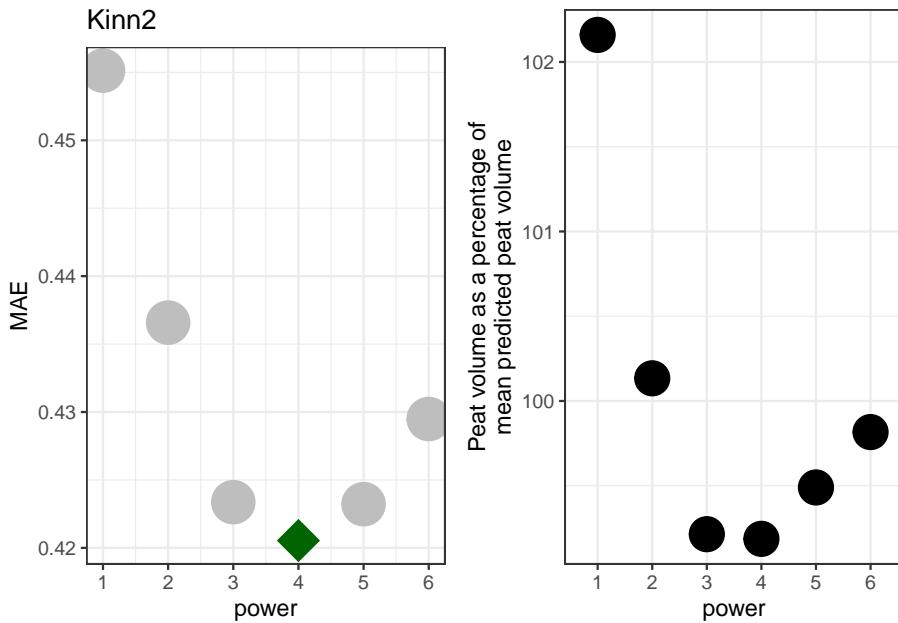


Figure 7.11: Finding the best power setting for the Kinn2 test site.

Power = 4 is best.

Create a raster grid for the predictions

```
grid_kinn2_stars_crop <- starsExtra::make_grid(SHP_kinn2, 1) %>%
sf::st_crop(SHP_kinn2)
```

Interpreted peat volume

```
IDW_kinn2_4 <- gstat::idw(Dybde ~ 1, depths_kinn2_spatial, newdata = grid_kinn2_stars_c
nmax = nmax, idp = 4)
#> [inverse distance weighted interpolation]
```

```
myBreaks <- seq(0, 3, 0.5)
myPos <- c("right", "bottom")

tm_shape(IDW_kinn2_4) + tm_raster(col = "var1.pred", palette = "-viridis",
```

```
title = "Power = 4\nInterpolated peat\\ndepth (m)", breaks = myBreaks) +
tm_compass(type = "8star", position = myPos, size = 2) +
tm_scale_bar(position = myPos, width = 0.3) + tm_shape(depths_kinn2_spatial) +
tm_symbols(shape = 4, col = "black", size = 0.5) + tm_layout(legend.outside = T)
```

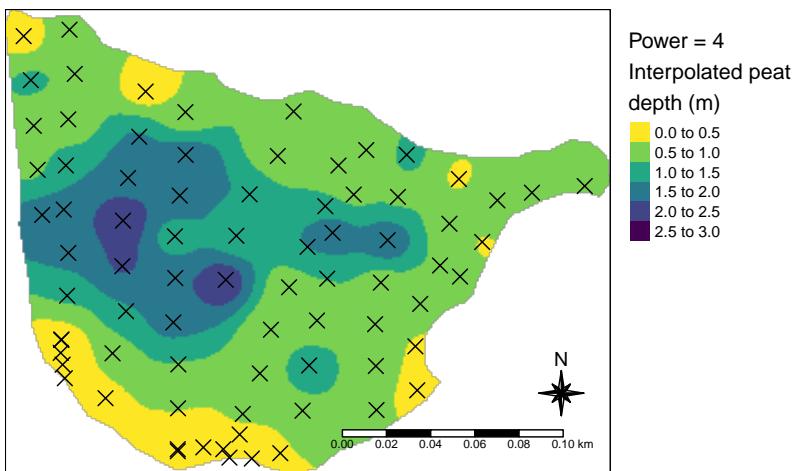


Figure 7.12: Best model for test site Kinn2

And the volume is

```
(vol_temp <- sum(IDW_kinn2_4$var1.pred, na.rm = T))
#> [1] 33037.11
```

And the C stock

```
ccalc_cStocks(volume = vol_temp, peatData = df)
#>      5%      50%      95%     mean      sd
#> 1275.9898 1502.9623 1713.9566 1499.0585 132.0889
```



# Chapter 8

## Session Info

```
sessionInfo()
#> R version 4.2.2 (2022-10-31 ucrt)
#> Platform: x86_64-w64-mingw32/x64 (64-bit)
#> Running under: Windows 10 x64 (build 19045)
#>
#> Matrix products: default
#>
#> locale:
#> [1] LC_COLLATE=Norwegian_Norway.1252
#> [2] LC_CTYPE=Norwegian_Norway.1252
#> [3] LC_MONETARY=Norwegian_Norway.1252
#> [4] LC_NUMERIC=C
#> [5] LC_TIME=Norwegian_Norway.1252
#> system code page: 65001
#>
#> attached base packages:
#> [1] stats      graphics   grDevices  utils      datasets
#> [6] methods    base
#>
#> other attached packages:
#> [1] osmplotr_0.3.3.022 formatR_1.14
#> [3] forcats_1.0.0     stringr_1.5.0
#> [5] dplyr_1.0.10      purrrr_1.0.1
#> [7] tidyverse_1.3.0     tibble_3.1.8
#> [9] tidyverse_1.3.2     ggtext_0.1.2
#> [11] matrixStats_0.63.0 ggpibr_0.5.0
#> [13] ggplot2_3.4.0      basemaps_0.0.5
#> [15] tmaptools_3.1-1    readr_2.1.3
```

```
#> [17] sf_1.0-9           tmap_3.3-3
#> [19] bookdown_0.32      gstat_2.1-0
#>
#> loaded via a namespace (and not attached):
#> [1] utf8_1.2.2          spatstat.explore_3.0-6
#> [3] tidyselect_1.2.0     htmlwidgets_1.6.1
#> [5] grid_4.2.2          devtools_2.4.5
#> [7] munsell_0.5.0        ragg_1.2.5
#> [9] codetools_0.2-18    units_0.8-1
#> [11] miniUI_0.1.1.1    withr_2.5.0
#> [13] spatstat.random_3.1-3 colorspace_2.1-0
#> [15] highr_0.10         knitr_1.42
#> [17] rstudioapi_0.14    wk_0.7.1
#> [19] ggsignif_0.6.4     tensor_1.5
#> [21] labeling_0.4.2      httr2_0.2.2
#> [23] polyclip_1.10-4    farver_2.1.1
#> [25] bit64_4.0.5        rprojroot_2.0.3
#> [27] vctrs_0.5.2        generics_0.1.3
#> [29] xfun_0.36          timechange_0.2.0
#> [31] markdown_1.4         R6_2.5.1
#> [33] slippymath_0.3.1   spatstat.utils_3.0-1
#> [35] cachem_1.0.6       assertthat_0.2.1
#> [37] promises_1.2.0.01  scales_1.2.1
#> [39] vroom_1.6.1         googlesheets4_1.0.1
#> [41] gtable_0.3.1        lwgeom_0.2-11
#> [43] processx_3.8.0     goftest_1.2-3
#> [45] rlang_1.0.6         systemfonts_1.0.4
#> [47] osmdata_0.2.0       splines_4.2.2
#> [49] rstatix_0.7.1      gargle_1.3.0
#> [51] dichromat_2.0-0.1   spatstat.geom_3.0-6
#> [53] broom_1.0.3         s2_1.1.2
#> [55] yaml_2.3.7          abind_1.4-5
#> [57] modelr_0.1.10      crosstalk_1.2.0
#> [59] backports_1.4.1     httpuv_1.6.8
#> [61] gridtext_0.1.5      tools_4.2.2
#> [63] usethis_2.1.6       ellipsis_0.3.2
#> [65] raster_3.6-14      RColorBrewer_1.1-3
#> [67] proxy_0.4-27        sessioninfo_1.2.2
#> [69] Rcpp_1.0.10          base64enc_0.1-3
#> [71] classInt_0.4-8       ps_1.7.2
#> [73] prettyunits_1.1.1   rpart_4.1.19
#> [75] deldir_1.0-6         pbapply_1.7-0
#> [77] cowplot_1.1.1        urlchecker_1.0.1
#> [79] zoo_1.8-11           haven_2.5.1
#> [81] fs_1.6.0              leafem_0.2.0
```

```
#> [83] tinytex_0.43           magrittr_2.0.3
#> [85] magick_2.7.3          spacetime_1.2-8
#> [87] reprex_2.0.2          googledrive_2.0.0
#> [89] pkgload_1.3.2          hms_1.1.2
#> [91] mime_0.12             evaluate_0.20
#> [93] xtable_1.8-4          XML_3.99-0.13
#> [95] leaflet_2.1.1          readxl_1.4.1
#> [97] compiler_4.2.2         maps_3.4.1
#> [99] KernSmooth_2.23-20    crayon_1.5.2
#> [101] htmltools_0.5.4       mgcv_1.8-41
#> [103] later_1.3.0          tzdb_0.3.0
#> [105] lubridate_1.9.1       DBI_1.1.3
#> [107] dbplyr_2.3.0          rappdirs_0.3.3
#> [109] Matrix_1.5-3          car_3.1-1
#> [111] cli_3.6.0            parallel_4.2.2
#> [113] pkgconfig_2.0.3        sp_1.6-0
#> [115] terra_1.7-3          spatstat.sparse_3.0-0
#> [117] xml2_1.3.3            rvest_1.0.3
#> [119] callr_3.7.3           digest_0.6.31
#> [121] starsExtra_0.2.7       spatstat.data_3.0-0
#> [123] rmarkdown_2.20          cellranger_1.1.0
#> [125] leafsync_0.1.0         intervals_0.15.2
#> [127] curl_5.0.0             commonmark_1.8.1
#> [129] shiny_1.7.4            lifecycle_1.0.3
#> [131] nlme_3.1-161           jsonlite_1.8.4
#> [133] carData_3.0-5          mapproj_1.2.11
#> [135] desc_1.4.2             viridisLite_0.4.1
#> [137] fansi_1.0.4            pillar_1.8.1
#> [139] spatstat.linnet_3.0-4 lattice_0.20-45
#> [141] fastmap_1.1.0          httr_1.4.4
#> [143] pkgbuild_1.4.0          glue_1.6.2
#> [145] xts_0.12.3             remotes_2.4.2
#> [147] FNN_1.1.3.1            spatstat_3.0-3
#> [149] png_0.1-8              bit_4.0.5
#> [151] class_7.3-20            stringi_1.7.12
#> [153] profvis_0.3.7          textshaping_0.3.6
#> [155] spatstat.model_3.1-2   stars_0.6-0
#> [157] memoise_2.0.1           e1071_1.7-12
```