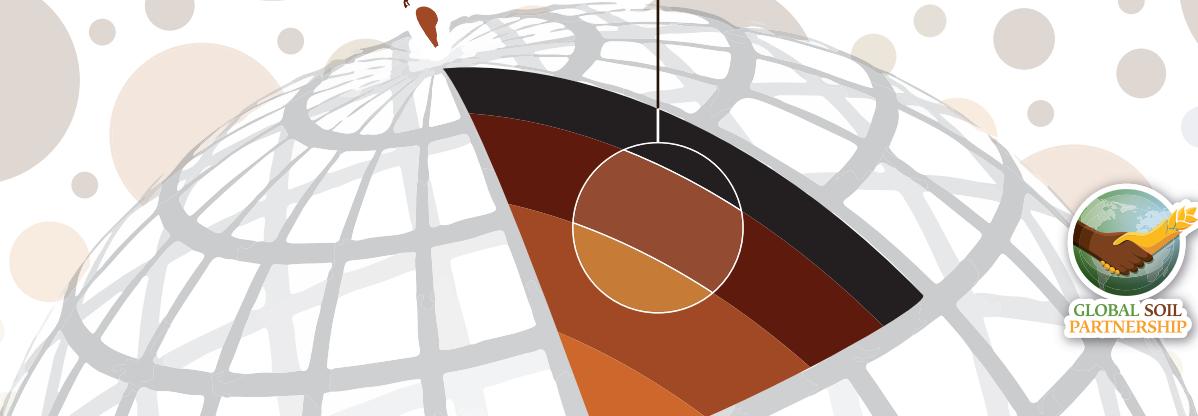




Food and Agriculture
Organization of the
United Nations



SOIL ORGANIC CARBON MAPPING *Cookbook*





Copyright and disclaimer

Recommended citation:

FAO. 2018. Soil Organic Carbon Mapping Cookbook. Y Yigini, GF Olmedo, K Viatkin, R Baritz, and RR Vargas, (Eds). 2nd edition, 2018.

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations (FAO) concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned.

The views expressed in this information product are those of the author(s) and do not necessarily reflect the views or policies of FAO.

ISBN [insert number]

©FAO, 2018

FAO encourages the use, reproduction and dissemination of material in this information product. Except where otherwise indicated, material may be copied, downloaded and printed for private study, research and teaching purposes, or for use in non-commercial products or services, provided that appropriate acknowledgement of FAO as the source and copyright holder is given and that FAO's endorsement of users' views, products or services is not implied in any way.

All requests for translation and adaptation rights, and for resale and other commercial use rights should be made via www.fao.org/contact-us/licence-request or addressed to copyright@fao.org.

FAO information products are available on the FAO website (www.fao.org/publications) and can be purchased through publications-sales@fao.org.

Foreword

This cookbook provides step-by-step guidance for developing 1 km grids for soil carbon stocks. It includes the preparation of local soil data, the compilation and pre-processing of ancillary spatial data sets, upscaling methodologies, and uncertainty assessments. Guidance is mainly specific to soil carbon data, but also contains many generic sections on soil grid development, as it is relevant for other soil properties.

Therefore, this first edition is the beginning of a series of updates and extensions, necessary to cover a larger variety of upscaling approaches. Experiences gained throughout 2017 during the GSOC map programme, through applications at country scale and various trainings scheduled for 2017, shall be considered in the next editions. Also, the section on uncertainties will be adjusted to more practical implementation steps.

Editorial Board

- Yusuf Yigini, Guillermo Federico Olmedo, Kostiantyn Viatkin, Rainer Baritz, Ronald R. Vargas Global Soil Partnership, Food and Agriculture Organization of the United Nations

Contributing Authors



Rainer Bartiz - Food and Agriculture Organization of the United Nations



Dick Brus - Department of Plant Sciences, Wageningen University, the Netherlands



Mario Guevara - University of Delaware, USA



Tomislav Hengl - ISRIC - World Soil Information, Wageningen, the Netherlands



Gerard Heuvelink - World Soil Information, Wageningen, the Netherlands



Bas Kempen - ISRIC, World Soil Information, Wageningen, the Netherlands



Titia VL Mulder - Wageningen University, Department of Environmental Sciences, the Netherlands



Guillermo Federico Olmedo - Instituto Nacional de Tecnología Agropecuaria, Mendoza, Argentina



Laura Poggio - The James Hutton Institute, Craigiebuckler Aberdeen, Scotland UK



Eloi Ribeiro - ISRIC , World Soil Information, Wageningen, the Netherlands



Christian Thine Omuto - Department of Environmental and Biosystems Engineering, University of Nairobi, Kenya



Yusuf Yigini - Food and Agriculture Organization of the United Nations



Ronald R Vargas - Food and Agriculture Organization of the United Nations

Contents

Copyright and disclaimer	i
Foreword	iii
Editorial Board	iv
Contributing Authors	iv
1 Presentation	9
2 Soil Property Maps	11
2.1 Definitions and Objectives	11
2.2 Generic Mapping of Soil Grids: Upscaling of Plot-Level Measurements and Estimates	12
3 Preparation of Local Soil Data	13
3.1 Soil Profiles and Soil Augers	13
3.2 Soil Database	13
3.2.1 Technical Steps - Loading Data from Tables in R	15
3.3 Completeness of Measurements and Estimates	16
3.3.1 Stones	16
3.3.2 Bulk density	17
3.3.3 Soil Carbon Analysis	20
3.3.4 Carbonates	21
3.3.5 Depth	21
3.4 Completeness of Depth Estimate	21
3.4.1 Technical Steps - Equal-Area Splines Using R	22
4 Setting-Up the Software Environment	27
4.1 Use of R, RStudio and R Packages	27
4.1.1 Obtaining and Installing R	27
4.1.2 Obtaining and Installing R Studio	27
4.1.3 Getting Started with R	28
4.2 R Packages	28
4.2.1 Finding R Packages	28
4.2.2 Most Used R Packages for Digital Soil Mapping	28
4.3 R and Spatial Data	30

4.3.1	Reading Shapefiles	30
4.3.2	Coordinate Reference Systems (CRS) in R	31
4.3.3	Working with Rasters	32
4.4	Other DSM Related Software and Tools	32
5	Preparation of Spatial covariates	33
5.1	DEM-Derived Covariates	33
5.1.1	DEM Source Data Sets	33
5.2	Parent Material	34
5.3	Soil Maps	36
5.3.1	Technical Steps - Rasterizing a Vector Layer in R	37
5.4	Land Cover and Land use	37
5.4.1	GlobCover (Global)	38
5.4.2	Landsat GeoCover (Global)	38
5.4.3	Globeland30 (Global)	39
5.4.4	CORINE Land Cover (Europe Only)	39
5.5	Climate	39
5.5.1	WorldClim V1.4 and V2 (Global)	39
5.5.2	Gridded Agro-Meteorological Data in Europe (Europe)	41
5.6	GSOCMap - Data Repository (ISRIC, 2017)	41
5.6.1	Covariates and Empty Mask	41
5.6.2	Data Specifications	41
5.6.3	Data Access	42
5.7	Extending the Soil Property Table for Spatial Statistics	42
5.8	Preparation of a Soil Property Table for Spatial Statistics	42
5.9	Technical Steps - Overlay Covariates and Soil Points Data	42
5.9.1	Load soil sample data and covariates	43
5.9.2	Combine the covariates provided with the raster version of the soil map	43
5.9.3	Overlay Covariates and Spatial Data	44
5.9.4	Convert result to data.frame and save as a csv table	46
6	Mapping Methods	47
6.1	Conventional Upscaling Using Soil Maps	47
6.1.1	Overview	47
6.1.2	Technical Steps: Class-matching	48
6.1.3	Technical Steps: Geo-Matching	49
6.2	Regression-Kriging	59
6.2.1	Overview	59
6.2.2	Assumptions	59
6.2.3	Pre-Processing of Covariates	60
6.2.4	The Terminology	60
6.2.5	Interpret the Key Results of Multiple Regression	62
6.2.6	Using the Results of a Regression Analysis to Make Predictions	63
6.2.7	Technical Steps - Regression Kriging	63
6.2.8	Technical Steps - Cross-validation of Regression Kriging models	75

6.3	Data mining: Random Forest	76
6.3.1	Overview	76
6.3.2	Random forests	76
6.3.3	Conceptual model and data preparation	78
6.3.4	Software	78
6.3.5	Tunning Random forest parameters	79
6.3.6	Technical steps - Random forest	79
6.3.7	Modelling Uncertainty Using Random Forest	85
6.4	Data mining: Support Vector Machines	90
6.4.1	Overview	90
6.4.2	Technical Steps - Fitting an SVM Model to Predict the SOC	91
7	Validation	101
7.1	What is Validation?	101
7.2	Map Quality Measures	102
7.2.1	Quality Measures for Quantitative Soil Maps	102
7.2.2	Quality Measures for Qualitative Soil Maps	105
7.2.3	Estimating the Map Quality Measures and Associated Uncertainty	107
7.3	Graphical Map Quality Measures	108
7.4	Validation Methods and Statistical Inference	108
7.4.1	Additional Probability Sampling	109
7.4.2	Data-Splitting	114
7.4.3	Cross-Validation	115
7.5	Technical steps - Validation	116
7.5.1	Prediction error	116
7.5.2	Estimating the Map Quality Measures	117
7.5.3	Graphical Map Quality Measures	118
7.5.4	Data-Splitting	119
8	Model Evaluation in Digital Soil Mapping	125
8.1	Technical steps - Model correlations and spatial differences	126
8.2	Technical steps - Model evaluation	128
9	Uncertainty	135
9.1	Sources of Uncertainty	135
9.1.1	Attribute Uncertainty of Soil Measurements	136
9.1.2	Positional Uncertainty of Soil Measurements	136
9.1.3	Uncertainty in Covariates	137
9.1.4	Uncertainty in Models Predicting Soil Properties From Covariates and Soil Point Data	137
9.2	Uncertainty and Spatial Data Quality	138
9.3	Quantifying Prediction Uncertainty	139
9.3.1	Uncertainty Characterised by Probability Distributions	139
9.3.2	Propagation of Model Uncertainty	140
9.3.3	Propagation of Attribute, Positional and Covariate Uncertainty	142

10 Data Sharing	145
10.1 Export Formats	145
10.1.1 Type of Soil Data and Their Formatting	145
10.1.2 General GIS Data Formats: Vector, Raster, Table	148
10.1.3 Recommended GIS Data Exchange Formats	150
10.2 Web Services - Serving Soil Data Using Web Technology	152
10.2.1 Third-Party Services	152
10.2.2 GeoServer (Web Serving and Web Processing)	153
10.2.3 Visualizing Data Using Leaflet and/or Google Earth	154
10.3 Preparing Soil Data for Distribution	154
10.3.1 Metadata	154
10.3.2 Exporting Data — Final Tips	156
10.4 Export Formats	157
11 Technical Overview and the Checklist	159
11.1 Point Dataset	159
11.2 Covariates	159
11.3 Statistical Inference	160
11.4 Spatial Interpolation	160
11.5 Calculation of Stocks	160
11.6 Evaluation of Output and Quality Assessment	160
12 Deliverables	163
13 Compendium of the code examples included in the cookbook	165
13.1 Overview	165
13.2 Data Preparation for Soil Profiles	167
13.3 Data Preparation for Top Soil or Auger Samples	170
13.4 Merging Top Soil and Soil Profiles Databases	172
13.5 Data-Splitting	173
13.6 Rasterizing a Vector Layer in R	174
13.7 Overlay Covariates and Soil Points Data	175
13.8 Fitting a Regression-Kriging model to predict the OCS	176
13.8.1 Cross-validation of Regression Kriging models	179
13.9 Fitting a random forest model to predict the SOC	180
13.10 Using Quantile Regression Forest to estimate uncertainty	182
13.11 Fitting a svm model to predict the SOC	184
13.12 Validation	187
13.13 Graphical Map Quality Measures	188
Bibliography	195

List of Figures

3.1	Histogram of bulk density values	20
3.2	Statistical distribution of original OCS values vs log-transformed values	26
5.1	SRTM 90m, resampled to 1km for FYROM	35
5.2	soil map of MK	36
5.3	Two layers included in the climate covariates	40
6.1	QGIS Desktop with the browser panel on the upper left, the layer information on the bottom left and the display of your layers on the right	50
6.2	Changing layer properties for the FYROM Soil Map	51
6.3	Project properties and projection settings	52
6.4	Join attributes by location	53
6.5	Example field calculator	53
6.6	Calculate group statistics	54
6.7	Change the legend style to display the SOC values	55
6.8	Example of the Map composer	56
6.9	Change the projection of a raster file	57
6.10	Linear regression model	61
6.11	Workflow for Regression Kriging	61
6.12	Schematical representation of data splitting data to generate the random subsets used to train regression trees within a Random forest model (ensemble of regression trees)	77
6.13	Model Decreasing Error and Node Purity	84
6.14	select ntree	85
6.15	SOC prediction using a randomForest model	86
6.16	Performance of the different svm models in the parameter tuning procedure	97
6.17	SOC prediction using a support vector machines model	99

7.1 Scatterplot of predicted versus observed soil organic matter content for Rwanda (left) and spatial bubble plot of cross-validation error for soil organic matter (right) (Kempen et al., 2015). The black line in the scatter plot represents the 1:1 line of prediction versus observed, the blue line represents the regression between observed and predicted values	108
7.2 Sample error matrix	112
7.3 Sample error matrix for a hypothetical soil class map	113
7.4 Scatter plots of predicted against observed values	120
7.5 Spatial bubble of the prediction errors for RK	121
7.6 Spatial bubble of the prediction errors for rf	122
7.7 Spatial bubble of the prediction errors for svm	123
7.8 Statistical distribution of train and test datasets	124
8.1 Taylor diagram used in the evaluation of the 3 digital soil mapping models	131
8.2 Effectiveness of the different digital soil mapping models across the full distribution of SOC observed values	132
9.1 Scatter plots of 500 paired soil property values drawn from a two-dimensional normal distribution	140
10.1 Soil texture triangle plot. An example of soil science specific data.	147
10.2 Some frequently required soil variables (sorted by number of studies) based on the study by Keller et al. (2014). This list is probably country/project specific but illustrates the differences considering the interest in soil data.	148
10.3 Displaying point dataset eberg (used in the previous example) in Google Fusion Tables.	151
10.4 SoilGrids (Hengl et al. 2017) WCS opened in QGIS.	153
10.5 Sampled locations and produced predictions visualized using Leaflet package.	155

List of Tables

3.1	Example for site-level data table	14
3.2	Example for profile-description table	14
5.1	Code and name of example covariates provided with the cookbook.	34
7.1	Map unit purity and class representation statistics for an hypothetical example.	113
7.2	Summary of prediction errors for 3 different mapping methods . .	117
7.3	Summary of map quality measures for 3 different mapping methods	118
8.1	Summary of Different Model Evaluation Statistics for the 3 Models Compared	130

Chapter 1

Presentation

Soils provide ecosystem services critical to life on Earth. The Food and Agricultural Organization of the United Nations (FAO) recognizes the need to preserve soil resources from degradation and restore them. In 2012, the Global Soil Partnership (GSP) was established to improve soil governance and promote sustainable soil management.

The GSP aims to promote sustainable soil management at all levels globally through normative tools relying on evidence-based science. Understanding the status of a given soil in different land uses, including its properties and functions, and relating this information to the various ecosystem services provided by soils, becomes mandatory for sustainable soil management decisions. As the availability and use of soil data and information is fundamental to underpin these decisions, members of the GSP decided to establish a Global Soil Information System (GLOSIS) based on the development of national soil information systems.

In the process of establishing GLOSIS, a number of tools and networks are being created, including the International Network of Soil Information Institutions (INSII), a *GSP Soil Data Policy* and more. Taking advantage of this process and responding to a request for support in addressing the Sustainable Development Goal Indicators, especially indicator 15.3 which includes the restoration of degraded soils, the GSP Plenary Assembly in 2016 instructed the Intergovernmental Technical Panel on Soils (ITPS) and the GSP Secretariat to develop the first-ever Global Soil Organic Carbon Map (GSOCMap) following the same bottom-up approach as GLOSIS. To this end, members under the INSII umbrella developed guidelines and technical specifications for the preparation of the *GSOCMap* and countries were invited to prepare their national soil organic carbon maps according to these specifications.

Given the scientific advances in tools for mapping soil organic carbon (SOC), many countries requested the GSP Secretariat to support them in the process of preparing national maps, hence an intensive capacity development programme on SOC mapping has been implemented to support countries in this process. Various re-

gional and national training sessions were organized using an on-the-job-training modality to ensure national experts were trained to utilize their own datasets to produce reliable SOC maps. The GSP Secretariat invited a group of experts to prepare a *Soil Organic Carbon Mapping Cookbook* as a comprehensible reference knowledge source to support the capacity development process.

The second edition of the cookbook provides generic methodologies and technical steps to produce SOC maps. This edition has been updated with knowledge and practical experiences gained during the implementation process of GSOCmap V1.0 throughout 2017. The cookbook includes step-by-step guidance for developing 1 km grids for SOC stocks, as well as for the preparation of local soil data, the compilation and preprocessing of ancillary spatial data sets, upscaling methodologies, and uncertainty assessment methods. Guidance is mainly specific to SOC data, but as this cookbook contains generic sections on soil grid development it can be applicable to map various soil properties.

The guidance is focusing on the upscaling of national SOC stocks in order to produce the GSOCMap. Therefore, the cookbook supplements the *GSP Guidelines for Sharing National Data/Information to Compile a Global Soil Organic Carbon (GSOC) Map*, providing technical guidelines to prepare and evaluate spatial soil data sets to:

- Determine SOC stocks from local samples to a target depth of 30 cm;
- Prepare spatial covariates for upscaling; and
- Select and apply the best suitable upscaling methodology.

In terms of statistical upscaling methods, the use of conventional upscaling methods using soil maps and soil profiles is still very common, although this approach is mostly considered empirical by soil mappers. Even though evaluations are based on polygon soil maps, the resulting SOC maps can be rasterized to any target grid. However, a spatially-explicit assessment of uncertainties is impossible. The use of digital soil mapping to upscale local soil information is increasingly applied and recommended.

This cookbook presents two approaches in detail, namely spatial modelling using either regression or data mining analysis, combined with geostatistics such as regression kriging. The second edition includes updates in the section on uncertainty assessment.

It is our hope that this cookbook will fulfill its mandate of easily enabling any user to produce a digital SOC or other soil property map using soil legacy data and modern methods of digital soil mapping with the overall aim for improved decision making on soil management.

Chapter 2

Soil Property Maps

R Baritz

2.1 Definitions and Objectives

Soil property maps represent spatial information about soil properties to a certain depth or for soil horizons. Conventionally, soil property maps are generated as polygon maps, with properties from typical soil profiles representing soil mapping units. Digital Soil Mapping (DSM) allows more accurate spatial mapping of soil properties, including the spatial quantification of the prediction error. The quality of such predictions improves with increasing number of local observations (e.g. soil profiles) available to build the prediction model. Whenever possible, DSM is recommended.

The development of soil property maps via DSM is spatially flexible. For different soil properties (e.g. concentration and stocks of nutrients in the soil, carbon, heavy metals, pH, cation exchange capacity, physical soil properties such as particle sizes and bulk density, etc.), various depth classes and spatial resolution can be modeled depending on project and mapping objectives and available input data. For GSOCmap, a 1 km grid is pursued. The same methodology and input data can also be used to produce higher resolution soil grids.

The mapping of global soil organic carbon (GSOC) stocks will be the first implementation of a series of other soil property grids to be developed for GLOSSIS, based on the typical GSP country-driven system. GSOCmap will demonstrate the capacity of countries all around the globe to compile and manage national soil information systems and to utilize and evaluate these data following agreed international specifications. The GSP Secretariat, FAO, and its regional offices, as well as the Regional Soil Partnerships, are challenged together with the GSP members, especially the members of INSII, to establish national capacity and soil data infrastructures to enable soil property mapping.

2.2 Generic Mapping of Soil Grids: Upscaling of Plot-Level Measurements and Estimates

The following table presents an overview of different geographic upscaling approaches, recommended to produce soil property maps, in particular, GSOCmap.

Conventional upscaling (Lettens et al., 2004)	Class-matching	Derive average SOC stocks per class: soil type for which a national map exists, or combination with other spatial covariates (e.g. land use category, climate type, biome, etc.). This approach is used in the absence of spatial coordinates of the source data.
	Geomatching	Point locations with spatial referencing are overlaid with GIS layers of important covariates (e.g. a soil map). Upscaling is based on averaged SOC values per mapping unit.
Digital soil mapping (Dobos, 2006)	Data mining and geostatistics	Multiple regression, classification tree, random forests, regression kriging, kriging with external drift.

Digital soil mapping is based on the development of functions for upscaling point data (with soil measurements) to a full spatial extent using correlated environmental covariates, for which spatial data are available.

DSM: Concept of environmental correlation that explores the quantitative relationship between environmental variables and soil properties and could be used to predict the latter with multivariate prediction techniques.

Chapter 3

Preparation of Local Soil Data

GF Olmedo & R Baritz

3.1 Soil Profiles and Soil Augers

Soil profiles are complex real-world entities. They are composed of soil layers which form soil horizons; the soil layers have different properties and these properties are evaluated with different methods. As we know, soil and vertical soil properties are landscape elements and part of matter dynamics (water, nutrients, gases, habitat, etc.). Local soil samples or soil profiles add a third dimension into the spatial assessment of soil properties in the landscape.

Most *commonly*, soils are described as vertical profiles using soil pits (sometimes also augerings, but this is less accurate). Soil profiles are described using macro-morphological properties. These properties can be assessed in the field without analysis by making a field inventory or land evaluation. For additional quantitative analysis, soils are then sampled by genetic horizons or by depth class.

The sampling of soils is the basis to obtain quantitative information. Depending on the goal of a project, sampling can be quite diverse. Sampling can follow the description of the soil or can be conducted without, for example using a spade or auger to generate a composite sample (for a certain depth independent of the morphological features such as soil horizons). Sampling locations can be representative of a certain location, project, field, or mapped object, such as a soil type.

3.2 Soil Database

In order to process and evaluate soil information from field assessments, soil profile data and analytical information need to be stored in a database. This can be a set

Table 3.1: Example for site-level data table

ProfID	X_coord	Y_coord	Year	Soil_Type
P1276	7591265	4632108	2012	Complex of Chernozem ...
P1277	7592027	4631664	2012	Complex of Chernozem ...
P1278	7592704	4631941	2012	Complex of Chernozem ...
P1279	7590817	4633115	2013	Complex of Chernozem ...

Table 3.2: Example for profile-description table

ProfID	HorID	top	bottom	SOC	BLD	CRF	Sand	Silt	Clay
P1276	P1276H01	0	50	2.78	1.05	11	52	39	9
P1276	P1276H02	50	76	1.75	1.45	4	56	31	14
P1276	P1276H03	76	100	1.19	1.22	2	43	35	22
P1277	P1277H01	0	28	1.93	1.36	8	59	22	18
P1277	P1277H02	28	48	1.60	1.43	9	69	15	16
P1277	P1277H03	48	63	1.26	NA	25	65	21	13
P1277	P1277H04	63	120	0.86	NA	54	63	23	14
P1278	P1278H01	0	40	2.32	1.27	0	50	39	12
P1278	P1278H02	40	68	1.80	1.48	1	46	39	16
P1278	P1278H03	68	120	0.89	1.18	0	47	39	14

of simple *Excel* spreadsheets, or a relational or object-oriented database management system (Baritz et al., 2008). When working in **R**, `SoilProfileCollections` from the **R** `aqp` package are a useful tool. Tables 3.1 and 3.2 are examples of how soil information can be stored. The advantage of such organization is the possibility to develop relational databases which can be easily queried. Such a systematic approach will support the organization of national soil information and will reduce errors in future modeling exercises (Baritz et al., 2008).

Table 3.1 stores site-level data, which describe the location of the soil description and/or sampling site: spatial coordinates, landscape attributes such as slope gradient and slope form, soil class, land cover type, rock type, etc. In this table, every row should hold a single soil profile. One column, usually the first one, should be the soil profile's unique identifier. Using the latter, soil information can be easily linked from one table to another.

Table 3.2 stores information from the soil description, such as horizon name, horizon thickness, organic matter content, carbonate content, soil color, laboratory soil analysis, etc. The first column contains the soil profile's unique identifier. It is important to include the upper and lower limits for each soil layer; in case the sampling strategy deviates from soil layers/soil horizons, the upper and lower depth of the sampling locations should be specified if possible. This information is needed for modeling soil properties over the soil profile.

3.2.1 Technical Steps - Loading Data from Tables in R

This chapter includes two examples for data preparation. The first example is for using soil profiles data. This example is mixed with the text but a copy the code is presented in section 13.2. The second example is using topsoil or auger data and is presented in section 13.3.

```
dat <- read.csv(file = "data/horizons.csv")

# Explore the data
str(dat)
summary(dat)

## 'data.frame': 10292 obs. of 10 variables:
## $ ProfID: Factor w/ 4118 levels "P0000","P0001",...: 1 1 1 2 2 ...
## $ HorID : Factor w/ 9914 levels "P0000H01","P0000H02",...: 1 2 ...
## $ top   : int  4 23 46 2 11 0 22 63 0 3 ...
## $ bottom: int  23 46 59 11 31 22 63 90 19 10 ...
## $ SOC   : num  NA NA NA NA NA ...
## $ BLD   : num  NA NA NA NA NA NA NA NA ...
## $ CRF   : num  54 62 47 66 70 57 77 87 8 4 ...
## $ SAND  : int  52 59 67 45 40 52 48 43 50 48 ...
## $ SILT  : num  34 31 24 39 31 33 36 42 16 35 ...
## $ CLAY  : num  14 11 8 16 28 15 16 16 34 17 ...
##     ProfID          HorID          top
## P2881 : 64  P2881H01: 64  Min.   : 0.00
## P1481 : 32  P0434H02: 8   1st Qu.: 0.00
## P2096 : 32  P1286H01: 8   Median : 20.00
## P3623 : 32  P2056H01: 8   Mean    : 27.48
## P2056 : 24  P2056H02: 8   3rd Qu.: 47.00
## P2142 : 24  P2056H03: 8   Max.    :285.00
## (Other):10084 (Other) :10188
##     bottom          SOC          BLD
## Min.   : 1.00  Min.   : 0.000  Min.   :0.00
## 1st Qu.: 25.00 1st Qu.: 1.090  1st Qu.:1.40
## Median : 45.00 Median : 1.800  Median :1.54
## Mean   : 55.82 Mean   : 2.603  Mean   :1.55
## 3rd Qu.: 80.00 3rd Qu.: 2.940  3rd Qu.:1.66
## Max.   :295.00 Max.   :83.820  Max.   :2.93
##                   NA's   :831    NA's   :7845
##     CRF          SAND          SILT
## Min.   : 0.0  Min.   : 0.00  Min.   : 0.00
## 1st Qu.: 2.0  1st Qu.: 44.00  1st Qu.:16.00
## Median : 8.0  Median : 58.00  Median :24.00
## Mean   : 13.5 Mean   : 57.67  Mean   :25.64
## 3rd Qu.: 21.0 3rd Qu.: 72.00  3rd Qu.:33.00
## Max.   :104.0 Max.   :100.00  Max.   :80.00
## NA's   :3360   NA's   :1049   NA's   :920
```

```

##      CLAY
## Min.   : 0.00
## 1st Qu.: 7.00
## Median :14.00
## Mean   :17.08
## 3rd Qu.:24.00
## Max.   :83.00
## NA's    :927

dat_sites <- read.csv(file = "data/site-level.csv")

# Explore the data
str(dat_sites)

## 'data.frame':   4118 obs. of  6 variables:
## $ X.1       : int  1 2 3 4 5 6 7 8 9 10 ...
## $ ProfID    : Factor w/ 4118 levels "P0000","P0001",...: 1 2 3 ...
## $ soiltype   : Factor w/ 58 levels "Albic Luvisol",...: 3 3 3 57 ...
## $ Land.Cover: int  25 24 25 26 26 27 27 27 22 23 ...
## $ X          : num  20.8 20.8 20.8 20.8 20.8 ...
## $ Y          : num  42 42 42 42 42 ...

```

3.3 Completeness of Measurements and Estimates

The *GSP Guidelines for Sharing National Data/Information to Compile a Global Soil Organic Carbon (GSOC) Map* specify which soil parameters are needed to produce a GSOCmap. Of course, other soil properties can be evaluated and modeled using this cookbook as well.

SOC stocks for soil horizons or targeted soil depths can be calculated using the equations in section 8.4.3 of the *GSP Guidelines for Sharing National Data/Information to Compile a Global Soil Organic Carbon (GSOC) Map*. Carbon concentration, bulk density and stone content for a certain depth or genetic horizon are needed to calculate the amount of carbon stored in that depth interval/soil horizon. In many countries, legacy data from former surveys and projects, as well as from various owners and data sources are compiled. Often, measured bulk densities are either missing, only available for few soil profiles, or are estimated. Stones in the soil profile are usually only estimated, and if augers are used for sampling, stone content is not assessed at all. Pedo-transfer functions can be used to fill data gaps (e.g. bulk density), and interpolation approaches can be used to infer from measured depths to target depths.

3.3.1 Stones

The estimation of stoniness is difficult and time-consuming, and therefore not carried out in many national soil inventories, or only estimated visually in the

profile. Unfortunately, if soil inventories and sampling are done with simple pits or augers rather than standard soil pits, stones are very often not assessed.

As a proxy, it is recommended to derive national default values from well-described soil profile pits by soil type.

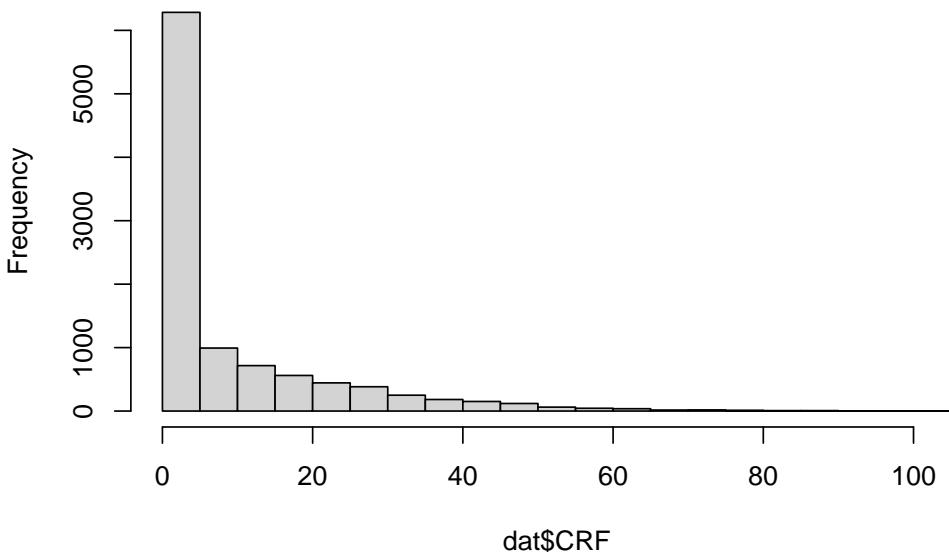
```
# summary of column CRF (Coarse Fragments) in the example data base
summary(dat$CRF)
```

```
##      Min.   1st Qu.    Median      Mean   3rd Qu.      Max.   NA's
##      0.0     2.0     8.0    13.5    21.0   104.0    3360
```

```
# Convert NA's to 0
dat$CRF[is.na(dat$CRF)] <- 0

hist(dat$CRF, col = "light gray")
```

Histogram of dat\$CRF



3.3.2 Bulk density

The amount of fine earth is one of the basic estimation parameters to estimate SOC stocks in the mineral soil as well as in peat layers. It depends on the volume of soil considered (depth \times reference area) and the bulk density (BD). BD expresses the soil weight per unit volume. When determining BD, it is important to subtract stones, if any, from the cylinder samples; if this is not done, BD is underestimated, and the resulting SOC stocks are overestimated. Stones in the cylinders are added to the total stone content in order to correct for the total amount of fine earth per volume of soil in a given area.

Most of the soil profiles in national databases come from agricultural land. Very often, BD estimates do not consider fine stones because top soils (e.g. plough layers) seem to be free of visible stones.

Mineral soil: Default values from *General Guide for Estimating Moist Bulk Density*. If analytical BD is missing, BD can be estimated using pedo-transfer functions (see examples listed below).

For organic soil material, BD_x can be estimated as follows, considering existing litter layers L (or Oi horizon); organic or duff layers, partially decomposed material above the mineral soil and beneath the litter layer; F (fermentation) horizons; H (humus) horizons (Oe and Oa); and peat (P), as described in the *U.S. Soil Taxonomy*.

Forest floor: Default values from Ottmar and Andreu (2007).

- Pine: $BD_L = 0.018 g \cdot cm^{-3}$; $BD_{F,H} = 0.057 g \cdot cm^{-3}$
- Hardwood: $BD_L = 0.012 g \cdot cm^{-3}$ (Barney et al., 1981)
- Birch: $BD_{F,H} = 0.17 g \cdot cm^{-3}$
- Spruce: $BD_L = 0.051 g \cdot cm^{-3}$; $BD_H = 0.13 g \cdot cm^{-3}$

Peat: Default value: $BD_P = 0.31 g \cdot cm^{-3}$. The range of peat BD is generally from 0.02 to 0.3 $t \cdot m^{-3}$ depending on maturity and compaction, as well as the ash content (Agus et al., 2011).@batjes1996total and Agus et al. (2011) distinguish different peat decomposition types (with different C content):

- Sapric: $BD_{P,sapric} = 0.174 g \cdot cm^{-3}$ (48.90% C)
- Hemic: $BD_{P,hemic} = 0.117 g \cdot cm^{-3}$ (52.27% C)
- Fibric: $BD_{P,fibric} = 0.089 g \cdot cm^{-3}$ (53.56% C)

Examples for pedo-transfer functions to estimate BD , based on the soil organic matter (OM) content in percent (%):

$$BD = 1.62 - 0.06 * OM \quad (3.1)$$

Saini (1966)

$$BD = 1/(0.6268 + 0.0361 * OM) \quad (3.2)$$

Drew (1973)

$$BD = 1.482 - 0.6786 * (\log OM) \quad (3.3)$$

Jeffrey (1970)

$$BD = 0.669 + 0.941 * e^{(-0.06 * OM)} \quad (3.4)$$

Grigal et al. (1989)

$$BD = 100/(OM/0.244 + (100 - OM))/MBD \quad (3.5)$$

Adams (1973)

$$BD = 1/(0.564 + 0.0556 * OM) \quad (3.6)$$

Honeysett and Ratkowsky (1989)

where MDB is the mineral particle density, assumed to be the specific gravity of quartz, $2.65 \text{ Mg} \cdot \text{m}^{-3}$. And OM is the organic matter content, estimated as $OM = SOC(\%) \times 1.724$

Each method is derived from a specific set of regional soils that is regionally adapted. Selection of the proper method for a given country shall be based on existing reviews and comparisons.

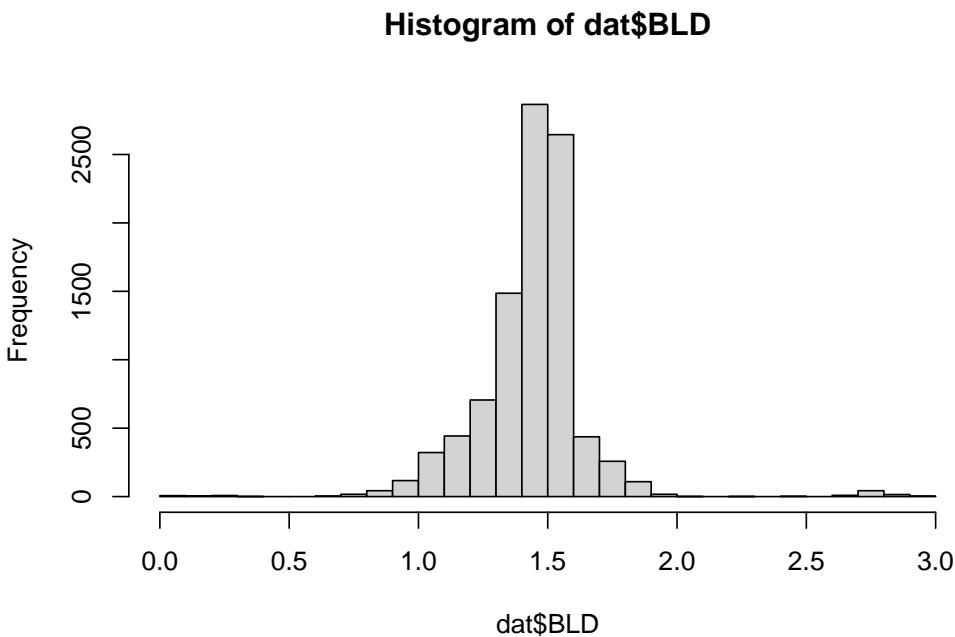


Figure 3.1: Histogram of bulk density values

```
# explore the results
hist(dat$BLD, col = 'light gray', breaks = 32)
```

3.3.3 Soil Carbon Analysis

Rosell et al. (2001) have closely reviewed the different SOC and SOM estimation procedures, and have also drawn some conclusions about the sources of errors. Determination of SOC from dry combustion methods is least susceptible to errors.

- **Dry combustion by Loss on Ignition (LOI):** SOC is re-calculated applying a conversion factor. It is commonly assumed, that organic matter contains an average of 58% organic carbon (so-called Van Bemmelen factor 1.724; for non-organic horizons: $SOC = SOM/1.724$). For organic horizons, conversion factor ranges from 1.9 to 2.5 (Nelson and Sommers, 1982). The inorganic carbon is not resolved, since typically, temperatures between 400°C and 550°C are used.
- **Wet oxidation:** Since wet oxidation is applied without additional (external) heating, low temperatures of around 120°C (internal heat) are typical. Thus, the oxidation of carbon is incomplete, and a so-called oxidation factor needs to be applied. With external heating, the C-recovery of the method becomes improved, up to complete recovery. No correction of the mineral carbon

is needed. Wet oxidation should typically only be applied to samples with < 5% organic matter.

Usually, an average of 76% organic carbon is recovered, leading to a standard oxidation factor or 1.33 (Lettens et al., 2005).

3.3.4 Carbonates

In case the total organic carbon is determined with temperatures higher than 600°C to 800°C, the proportion of mineral soil in $CaCO_3$ has to be subtracted in order to derive the amount of organic carbon (inorganic carbon is also oxidized). The pH value gives the first indication whether the sample has to be analyzed for inorganic carbon or not.

It is crucial to report in the metadata whether national SOC values refer to total C or if the inorganic component has been considered.

3.3.5 Depth

The standard depth for GSOCmap is **0 to 30 cm**. Subdivisions are possible depending on the available data, by genetic horizons or depth classes. The following depths are additionally considered for GSOCmap (optional): * Forest floor: thickness (cm) subdivision in horizons depending on national soil inventory method (e.g. L, F, H) * Peat: >30 , <100 depending on national data

3.4 Completeness of Depth Estimate

Soil properties are commonly collected from field inventories (see Table 2.2) or from sampling and analyzing horizons and/or fixed depths. Since a fixed target depth of 30 cm is required for GSOC (other depth classes will be recommended in the future, following the *GSP Guidelines for Sharing National Data/Information to Compile a Global Soil Organic Carbon (GSOC) Map*, data holders are confronted with the following options:

- **Option 1:** Soil sampling has already considered this depth, data can be directly used for upscaling (see chapter 6).
- **Option 2:** Horizons or layers/depth classes are sampled but aggregation is needed over the 0 to 30 cm.
- **Option 3:** The target depth (0 to 30 cm) was not completely covered by sampling, e.g. only the A horizon or a topsoil layer (e.g. 0 to 20 cm) has been sampled.

For both **Options 2** and **3**, the transformation is needed, using e.g. equal-area splines. In the case of **Option 2**, the use of equal-area splines was first proposed by Ponce Hernandes et al. (1986), and later tested against real data (Bishop et al., 1999). This technique is based on fitting continuous depth functions for modeling

the variability of soil properties with depth. Thus, it is possible to convert soil profiles to standard depths, but also to fill gaps. The equal-area spline function consists of a series of local quadratic polynomials that join at so-called knots, located at the horizon boundaries, whereby the mean value of each horizon is maintained by the spline fit. They are called equal-area splines because the area to the left of the fitted spline curve is equal to the area to the right of the curve. In case of **Option 3**, additional information on the vertical distribution of carbon in the soils is required for accurate recalculation from the sampling depth to target depth, e.g. as was shown by Bernoux et al. (1998).

3.4.1 Technical Steps - Equal-Area Splines Using R

In **R** environment, the easiest way to apply equal-area splines is using the function `GSIF::mpspline` from the **R** package **GSIF** (Hengl (2016), see section 4.2.2.1). For illustration, a sample dataset has been used (see chapter 5). This function requires data stored as `SoilProfileCollection` (SPC) using package **aqp**. Nevertheless, data in any local soil database or in tables like the ones proposed before (Tables @ref(tab:example table for site-level), @ref(tab:example table for horizon-level)) can be transformed to an SPC.

The function `GSIF::mpspline` has several arguments. One of the arguments is the lambda value mentioned before. The proposed default value is 0.1. Another argument for this function is the target standard depths. The function produces spline-estimated values at these depths. However, this function also produces spline-estimated values at 1 cm increments.

The following technical steps require **R** and the named packages.

3.4.1.1 Promote table dat to SoilProfileCollection

```
# Load aqp package
library(aqp)

# Promote to SoilProfileCollection
# The SoilProfileCollection is a object class in R designed to
# handle soil profiles
depths(dat) <- ProfID ~ top + bottom

## Warning: converting IDs from factor to character
```

3.4.1.2 Add site-level data and coordinates

```
# Merge the soil horizons information with the site-level
# information from dat_sites
site(dat) <- dat_sites
```

```

# Set spatial coordinates
coordinates(dat) <- ~ X + Y

# A summary of our SoilProfileCollection
dat

## Object of class SoilProfileCollection
## Number of profiles: 4118
## Depth range: 5-295 cm
##
## Horizon attributes:
##   ProfID    HorID top bottom SOC BLD CRF SAND SILT CLAY
## 1 P0000 P0000H01 4     23  NA  NA  54  52  34  14
## 2 P0000 P0000H02 23    46  NA  NA  62  59  31  11
## 3 P0000 P0000H03 46    59  NA  NA  47  67  24   8
## 4 P0001 P0001H01 2     11  NA  NA  66  45  39  16
## 5 P0001 P0001H02 11    31  NA  NA  70  40  31  28
## 6 P0002 P0002H01 0     22  NA  NA  57  52  33  15
##
## Sampling site attributes:
##   ProfID X.1                               soiltype Land.Cover
## 1 P0000  1                                 Cambisol  25
## 2 P0001  2                                 Cambisol  24
## 3 P0002  3                                 Cambisol  25
## 4 P0003  4                                 Rendzic Leptosols 26
## 5 P0004  5                                 Rendzic Leptosols 26
## 6 P0005  6 Complex of Rendzic Leptosol and Leptosol 27
##
## Spatial Data:
##      min      max
## X 20.46434 23.01039
## Y 40.68543 42.35932
## [1] NA

```

3.4.1.3 Run mass preserving splines for all the needed properties

```

library(GSIF)

## Estimate 0-30 standard horizon usin mass preserving splines
try(SOC <- mpspline(dat, 'SOC', d = t(c(0,30))))
try(BLD <- mpspline(dat, 'BLD', d = t(c(0,30))))
try(CRFVOL <- mpspline(dat, 'CRF', d = t(c(0,30))))

```

3.4.1.4 Convert back to table

```
## Prepare final data frame
dat <- data.frame(id = dat@site$ProfID,
                   Y = dat@sp@coords[, 2],
                   X = dat@sp@coords[, 1],
                   SOC = SOC$var.std[, 1],
                   BLD = BLD$var.std[, 1],
                   CRFVOL = CRFVOL$var.std[, 1])

dat <- dat[complete.cases(dat),]

## Take a look at the results
head(dat)

##      id        Y        X       SOC       BLD     CRFVOL
## 4 P0003 42.02828 20.81819 26.380000 0.7304483 8.000000
## 5 P0004 42.02747 20.81464 24.561667 0.8955320 6.305316
## 7 P0006 42.02885 20.82757 19.940000 0.7886235 14.000000
## 8 P0007 42.02279 20.83165 6.149114 1.1653355 18.633590
## 9 P0008 42.05014 20.82036 3.940352 1.2962582 31.875748
## 10 P0009 42.02047 20.93529 3.258545 1.3446297 21.714059
```

3.4.1.5 Estimate the soil organic carbon stock using the virtual horizons

Finally, the estimation of the soil organic carbon stock (OKS) can be done using the **GSIF** package.

```
library(GSIF)
# Estimate Organic Carbon Stock
# SOC must be in g/kg
# BLD in kg/m3
# CRF in percentage
OCSKGM <- OCSKGM(ORCDRC = dat$SOC, BLD = dat$BLD*1000,
                  CRFVOL = dat$CRFVOL, HSIZE = 30)

dat$OCSKGM <- OCSKGM
dat$meaERROR <- attr(OCSKGM, "measurementError")
dat <- dat[dat$OCSKGM>0,]
summary(dat)

##      id        Y        X       SOC
##  P0003 : 1  Min.  :40.69  Min.  :20.46  Min.  : 0.080
##  P0004 : 1  1st Qu.:41.19  1st Qu.:21.35  1st Qu.: 1.750
##  P0006 : 1  Median :41.42  Median :21.49  Median : 2.603
##  P0007 : 1  Mean   :41.49  Mean   :21.66  Mean   : 3.539
##  P0008 : 1  3rd Qu.:41.83  3rd Qu.:22.14  3rd Qu.: 4.089
```

```

## P0009 : 1 Max. :42.36 Max. :23.01 Max. :86.510
## (Other):3880
##      BLD          CRFVOL          OCSKGM
## Min. :0.05353  Min. : 0.00000  Min. : 0.0111
## 1st Qu.:1.28089 1st Qu.: 0.00516 1st Qu.: 0.6951
## Median :1.39549 Median : 5.01397 Median : 0.9866
## Mean   :1.38073 Mean  :11.02257 Mean  : 1.1399
## 3rd Qu.:1.47612 3rd Qu.:17.69065 3rd Qu.: 1.3997
## Max.  :2.92191  Max. :93.95013 Max. : 7.4302
##
##      meaERROR
## Min. :0.172
## 1st Qu.:3.160
## Median :3.840
## Mean   :3.715
## 3rd Qu.:4.260
## Max.  :8.770
##

```

Soil organic carbon tends to have a log-normal distribution with a right-skew, and transforming the original values to its natural logarithm would generate a normal distribution of soil organic carbon values. Here we will test if the log transformation of the response variable (*SOC*) tends to normality and 2) if this transformation increases the simple correlation of *SOC* and its prediction factors.

```

# Generate a new column with the transformed OCSKGM to its natural
# logarithm
dat$OCSKGMlog <- log(dat$OCSKGM)

## plot the next two plots as one
par(mfrow=c(1,2))
plot(density(dat$OCSKGM),
     main='original values')

plot(density(dat$OCSKGMlog),
     main='log transformed values')

par(mfrow=c(1,1))

## We can save our processed data as a table
write.csv(dat, "data/dataproc.csv", row.names = FALSE)

```

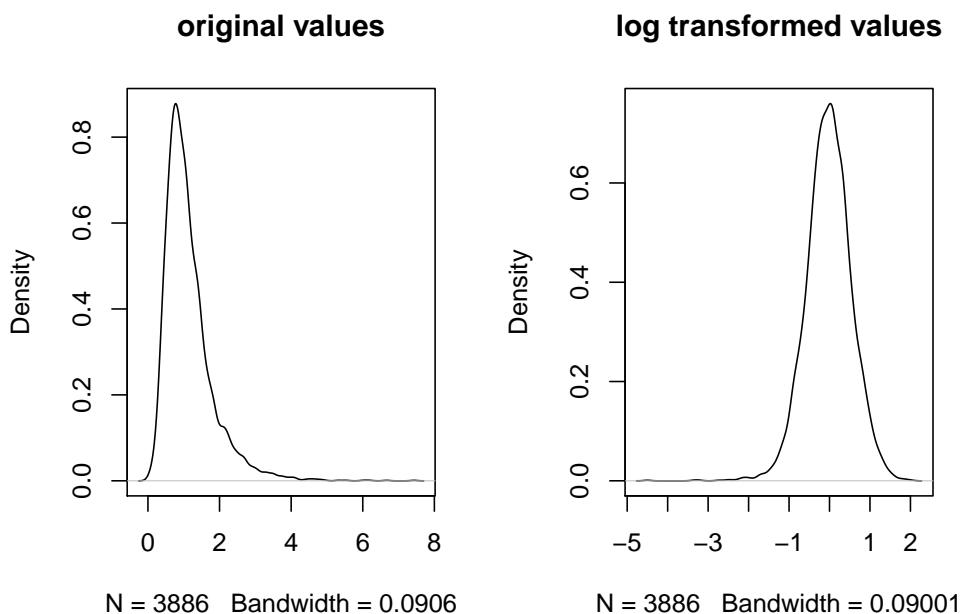


Figure 3.2: Statistical distribution of original OCS values vs log-transformed values

Chapter 4

Setting-Up the Software Environment

Y Yigini

This cookbook focuses on SOC modeling using open source digital mapping tools. The instructions and screen-captures in this section will guide you through installing and manually configuring the software to be used for digital soil mapping procedures for *Microsoft Windows* desktop platform. Instructions for the other platforms (e.g. *Linux Flavours*, *MacOS*) can be found through free online resources.

4.1 Use of R, RStudio and R Packages

R is a language and environment for statistical computing. It provides a wide variety of statistical (e.g. linear modeling, statistical tests, time-series, classification, clustering, etc.) and graphical methods, and is highly extensible.

4.1.1 Obtaining and Installing R

- Go to <https://cloud.r-project.org/index.html> to download and install **R**.
- Pick an installation file for your platform.

4.1.2 Obtaining and Installing R Studio

Beginners will find it very hard to start using **R** because it has no Graphical User Interface (GUI). There are some GUIs which offer some of the functionality of **R**. **RStudio** makes **R** easier to use. It includes a code editor, debugging and

visualization tools, therefore, in this cookbook we would like to focus on the latter including a GUI. You can follow very similar steps to install **RStudio**.

- Go to <https://www.rstudio.com/products/rstudio/download/> to download and install **RStudio**'s open source edition.
- On the download page, *RStudio Desktop, Open Source License* option should be selected.
- Pick an installation file for your platform.

4.1.3 Getting Started with R

- **R** Manuals: <http://cran.r-project.org/manuals.html>
- Contributed Documentation: <http://cran.r-project.org/other-docs.html>
- Quick-**R**: <http://www.statmethods.net/index.html>
- Stackoverflow **R** Community: <https://stackoverflow.com/questions/tagged/r>

4.2 R Packages

When you download **R**, you get the basic **R** system which implements the **R** language. **R** becomes more useful with the large collection of packages that extend the basic functionality of it. **R** packages are developed by the **R** community.

4.2.1 Finding R Packages

The primary source for **R** packages is *CRAN*'s official website, where currently about 12.000 available packages are listed. For spatial applications, various packages are available. You can obtain information about the available packages directly on *CRAN* with the `available.packages()` function. The function returns a matrix of details corresponding to packages currently available at one or more repositories. An easier way to browse the list of packages is using the *Task Views* link, which groups together packages related to a given topic.

4.2.2 Most Used R Packages for Digital Soil Mapping

As was previously mentioned, **R** is extensible through packages. **R** packages are collections of **R** functions, data, documentation and compiled code easy to share with others. In the following subsections, we are going to present the most used packages related to digital soil property mapping.

4.2.2.1 Soil Science and Pedometrics

aqp: Algorithms for quantitative pedology. A collection of algorithms related to modeling of soil resources, soil classification, soil profile aggregation, and visualization.

GSIF: Global Soil Information Facility (GSIF). Tools, functions and sample datasets for digital soil mapping. GSIF tools (standards and functions) and sample datasets for global soil mapping.

ithir: A collection of functions and algorithms specific to pedometrics. The package was developed by Brendan Malone at the University of Sydney.

soiltexture: The *Soil Texture Wizard* is a set of **R** functions designed to produce texture triangles (also called texture plots, texture diagrams, texture ternary plots), classify and transform soil textures data. These functions virtually allow to plot any soil texture triangle (classification) into any triangle geometry (isosceles, right-angled triangles, etc.). The set of functions is expected to be useful to people using soil textures data from different soil texture classification or different particle size systems. Many (> 15) texture triangles from all around the world are predefined in the package. A simple text-based GUI is provided: `soiltexture_gui()`.

4.2.2.2 Spatial Analysis

sp: The package provides classes and methods for spatial data. The classes document where the spatial location information resides, for 2D or 3D data.

raster: Reading, writing, manipulating, analyzing and modeling of gridded spatial data. The package implements basic and high-level functions, processing of very large files is supported.

rgdal: Provides bindings to Frank Warmerdam's Geospatial Data Abstraction Library (GDAL).

RSAGA: The package provides access to geocomputing and terrain analysis functions of *SAGA GIS* from within **R** by running the command line version of *SAGA*.

4.2.2.3 Modeling

caret: Extensive range of functions for training and plotting classification and regression models.

Cubist: Regression modeling using rules with added instance-based corrections. Cubist models were developed by Ross Quinlan.

C5.0: C5.0 decision trees and rule-based models for pattern recognition. Another model structure developed by Ross Quinlan.

gam: Functions for fitting and working with generalized additive models.

nnet: Software for feed-forward neural networks with a single hidden layer, and for multinomial log-linear models.

gstat: Variogram modeling with simple, ordinary and universal point or block (co)kriging, sequential Gaussian or indicator (co)simulation. The package includes variogram and variogram map plotting utility functions.

automap: This package performs an automatic interpolation by automatically estimating the variogram and then calling **gstat**.

4.2.2.4 Mapping and Plotting

Both **raster** and **sp** have handy functions for plotting spatial data. Besides using the base plotting functionality, another useful plotting package is **ggplot2**.

plotKML: Writes sp-class, spatiotemporal-class, raster-class and similar spatial and spatiotemporal objects to KML following some basic cartographic rules.

leaflet: Create and customize interactive maps using the Leaflet JavaScript library and the **htmlwidgets** package. These maps can be used directly from the **R** console, from **RStudio**, in **Shiny** apps and **RMarkdown** documents.

4.3 R and Spatial Data

R has a large and growing number of spatial data packages. We recommend taking a quick browse on **R**'s official website to see the spatial packages available: <http://cran.r-project.org/web/views/Spatial.html>

4.3.1 Reading Shapefiles

ESRI's shapefile format is widely used for storing vector-based spatial data (i.e., points, lines, polygons). This example demonstrates use of **raster** package that provides functions for reading and/or writing shapefiles.

```
library(raster)
# load the soil map from a shapefile file
soilmap <- shapefile("MK_soilmap_simple.shp")
```

We may want to use these data in other GIS environments such as *ArcGIS*, *QGIS*, *SAGA GIS*, etc. This means we need to export the **SpatialPointsDataFrame** to an appropriate spatial data format such as a shapefile.

```
# For example, we can select the soil units classified as
# Fluvisols according to WRB
Fluvisols <- soilmap[soilmap$WRB == "Fluvisol",]

# and save this as a new shapefile
```

```
shapefile(Fluvisols, filename = 'results/fluvisols.shp',
          overwrite = TRUE)
```

4.3.2 Coordinate Reference Systems (CRS) in R

We need to define the CRS (Coordinate Reference System) to be able to perform any sort of spatial analysis in **R**. To clearly tell **R** this information we define the CRS which describes a reference system in a way understood by the PROJ.4 projection library <http://trac.osgeo.org/proj/>.

An interface to the PROJ.4 library is available in the **rgdal** package. An alternative to using Proj4 character strings, we can use the corresponding yet simpler EPSG (European Petroleum Survey Group) code. **rgdal** also recognizes these codes. If you are unsure of the Proj4 or EPSG code for the spatial data that you have but know the CRS, you should consult <http://spatialreference.org/> for assistance.

```
## print the CRS for the object soilmap
soilmap@proj4string

## CRS arguments:
## +proj=longlat +datum=WGS84 +no_defs +ellps=WGS84
## +towgs84=0,0,0
```

The following example shows how you can create a spatial object from a .csv file. We can use the **coordinates()** function from the **sp** package to define which columns in the data frame refer to actual spatial coordinates—here the coordinates are listed in columns X and Y.

```
# load the table with the soil observations site information
dat_sites <- read.csv(file = "data/site-level.csv")

# convert from table to spatial points object
coordinates(dat_sites) <- ~ X + Y

# check the coordinate system:
dat_sites@proj4string

## CRS arguments: NA
# as the CRS is not defined, we can assign the correct CRS is we
# have information about it. In this case, it should be EPSG:4326
dat_sites@proj4string <- CRS("+init=epsg:4326")

# check the CRS again:
dat_sites@proj4string

## CRS arguments:
## +init=epsg:4326 +proj=longlat +datum=WGS84 +no_defs
```

```
## +ellps=WGS84 +towgs84=0,0,0
```

4.3.3 Working with Rasters

Most of the functions for handling raster data are available in the **raster** package. There are functions for reading and writing raster files from and to different formats. In digital soil mapping, we mostly work with data in table format and then rasterize this data so that we can produce a continuous map. For doing this in **R** environment, we will load raster data in a data frame. This data is a digital elevation model (DEM) provided by *ISRIC* for Former Yugoslav Republic of Macedonia (FYROM).

```
#For handling raster data, we load raster package
library(raster)

#load DEM from tif file
DEM <- raster("cova/DEMENV5.tif")
```

We may want to export this raster to a suitable format to work in a standard GIS environment. See the help file for writing a raster `?writeRaster` to get information regarding the supported grid types that data can be exported into. Here, we will export our raster to *ESRI* Ascii, as it is a common and universal raster format.

We may also want to export our mac.dem to KML file using the `KML()` function. `KML()` is a handy function from the **raster** package for exporting grids to kml format. Note that we need to re-project the data to WGS84 geographic. The raster re-projection is performed using the `projectRaster()` function. Look at the help file `?projectRaster` for this.

4.4 Other DSM Related Software and Tools

- *QGIS*: Available at <http://www.qgis.org/en/site/forusers/download.html>
- *SAGA GIS*: Available at <https://sourceforge.net/projects/saga-gis/files/>

Chapter 5

Preparation of Spatial covariates

R Baritz & Y Yigini

The example covariates from this chapter were prepared by *ISRIC*. The access and use limitations are presented in section 5.6. A small subset of these covariates, comprising most of the soil forming factors, will be used for the examples. This subset is presented in the following table.

5.1 DEM-Derived Covariates

5.1.1 DEM Source Data Sets

Currently, two global level 30 m DEMs are freely available: the Shuttle Radar Topographic Mission (SRTM) and the ASTER Global Digital Elevation Model (GDEM). They provide topographic data at the global scale, which are freely available for users. Both DEMs were compared by Wong et al. (2014). Comparison against high-resolution topographic data of Light Detection and Ranging (LiDAR) in a mountainous tropical montane landscape showed that the SRTM (90 m) produced better topographic data in comparison with ASTER GDEM.

- Recommended for national level applications: 30 m GDEM / SRTM.
- Recommended for global level applications: SRTM 90 m, resampled 1 kilometer.

In both cases, noise and artefacts need to be filtered out. ASTER seems to contain more large artifacts (e.g. peaks), particularly in flat terrain, which are very difficult to remove through filtering.

Table 5.1: Code and name of example covariates provided with the cookbook.

CODE	ATTRIBUTE_TITLE
DEMENV5	Land surface elevation
SLPMRG5	Terrain slope
VBFMRG5	Multiresolution Index of Valley Bottom Flatness (MRVBF)
VDPMRG5	Valley depth
TWIMRG5	SAGA Wetness Index
TMDMOD3	Mean annual LST (daytime) MODIS
TMNMOD3	Mean annual LST (nighttime) MODIS
PRSCHE3	Total annual precipitation at 1 km
B04CHE3	Temperature seasonality at 1 km
B07CHE3	Temperature Annual Range at 1 km
B13CHE3	Precipitation of wettest month [mm]
B14CHE3	Precipitation of driest month [mm] at 1 km
LCEE10	ESA land cover map 2010

```
#For handling raster data, we load raster package
library(raster)

#load DEM from tif file
DEM <- raster("cobs/DEMENV5.tif")
plot(DEM)
```

GRASS GIS or GDAL: Use “mdenoise” module/utility to remove noise while preserving sharp features like ridges, lines, and valleys.

SRTM contains many gaps (pixels with no-data). These gaps could be filled using splines. SAGA GIS has a module called ‘Close Gaps with Splines’ and other similar tools for doing this.

5.2 Parent Material

Parent material has a crucial impact on soil formation, soil geochemistry, and soil physics. Parent material, if not specifically mapped by soil mappers and included in soil maps, is usually available from geological maps. These maps focus on rock formation, mineral components, and age, and often lack younger surface sediments (even in quaternary maps). Parent material/rock types classified by soil mappers considers more strongly geochemistry and rock structure. Its geochemistry has an essential impact on the soil chemistry, e.g. cation exchange capacity, base saturation, and nutrient stock. The rock structure determines the ability to disintegrate, which has an impact on soil physical properties, like texture, skeleton content, permeability, and soil thickness.

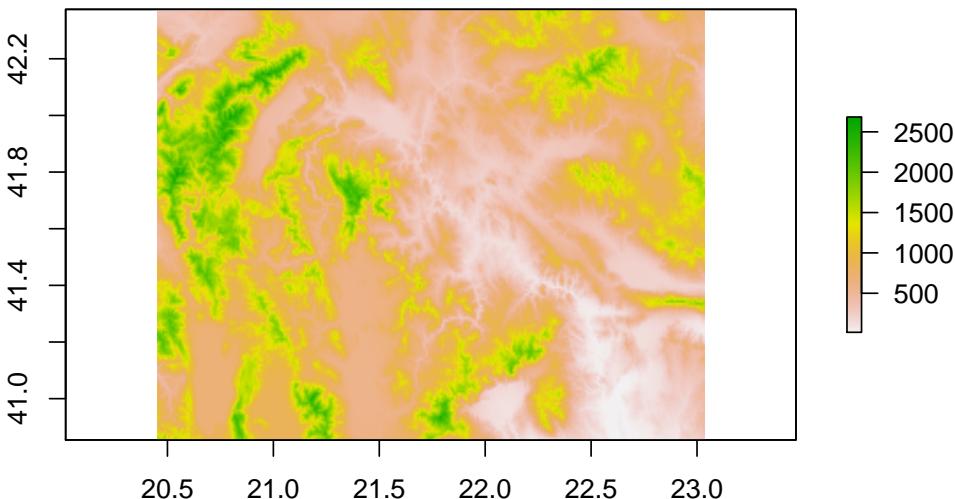


Figure 5.1: SRTM 90m, resampled to 1km for FYROM

National parent material and geological maps may be used. Other available datasets and data portals are given on the *ISRIC WorldGrids* website.

- OneGeology: The world geological maps are now being integrated via the OneGeology project which aims at producing a consistent geological map of the world in approximate scale 1:1M ([Jackson, 2007](#)); Link: <http://www.onegeology.org/>.
- *USGS* has several data portals, e.g. that allows browsing of the International Surface Geology (split into South Asia, South America, Iran, Gulf of Mexico, Former Soviet Union, Europe, Caribbean, Bangladesh, Asia Pacific, Arctic, Arabian Peninsula, Africa and Afghanistan); Link: <https://mrdata.usgs.gov/geology/world/>.
- Hartmann and Moosdorf ([2012](#)) have assembled a global, purely lithological database called GLiM (Global Lithological Map). GLiM consists of over 1.25 million digital polygons that are classified into three levels (a total of 42 rock-type classes); Link: <https://www.geo.uni-hamburg.de/en/geologie/forschung/geochemie/glim.html>.
- *USGS* jointly with *ESRI* has released in 2014 a Global Ecological Land Units map at 250 m resolution. This also includes world layer of rock types. This data can be downloaded from the USGS site (<http://rmgsc.cr.usgs.gov/outgoing/ecosystems/Global/>).

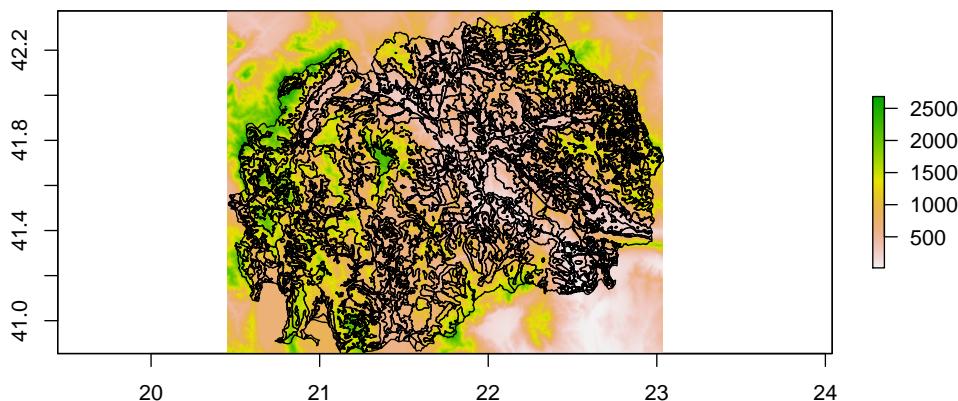


Figure 5.2: soil map of MK

5.3 Soil Maps

Soil maps play a crucial role for upscaling soil property data from point locations. They can be the spatial layer for conventional upscaling, they can also serve as a covariate in digital soil mapping. Predicted soil property maps have lower quality in areas where the covariates such as relief, geology, and climate do not correlate well with the dependent variable, here SOC stocks. This is especially true for soils under groundwater or stagnic water influence. This information is well-represented in soil maps.

FAO, IIASA, ISRIC, ISS CAS and JRC produced a gridded 1 km soil class map (HWSD). Global HWSD-derived soil property maps can be downloaded as geotiffs at http://worldgrids.org/doku.php/wiki:layers#harmonized_world_soil_database_images_5_km (see section 5.6).

```
# load the soil map from a shapefile file
soilmap <- shapefile("MK_soilmap_simple.shp")

# plot the DEM together with the soil types
plot(DEM)
lines(soilmap)
```

Digitized small-scale national soil maps are the most important spatial layer for soil property mapping. The higher its resolution, the better soil maps contribute to high-quality soil property maps - considering that the map should cover the target area/full country coverage.

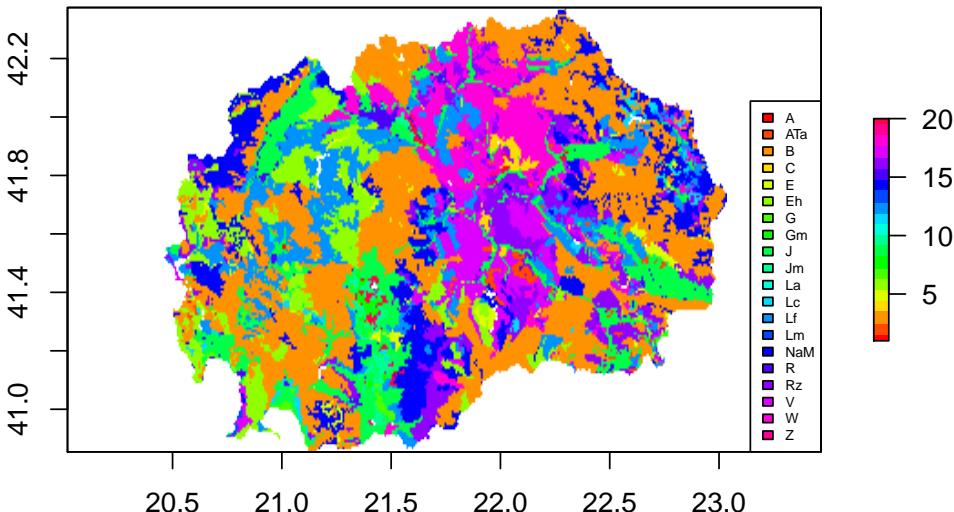
5.3.1 Technical Steps - Rasterizing a Vector Layer in R

```
# the "Symbol" attribute from the vector layer will be used for the
# rasterization process. It has to be a factor
soilmap@data$Symbol <- as.factor(soilmap@data$Symbol)

# save the levels names in a character vector
Symbol.levels <- levels(soilmap$Symbol)

# The rasterization process needs a layer with the target grid
# system: spatial extent and cell size.
soilmap.r <- rasterize(x = soilmap, y = DEM, field = "Symbol")
# The DEM raster layer could be used for this.

plot(soilmap.r, col=rainbow(21))
legend("bottomright", legend = Symbol.levels, fill=rainbow(21),
       cex=0.5)
```



5.4 Land Cover and Land use

Besides soil, geology, and climate, land use and/or land cover data are unarguably vital data for any statistical effort to map soil properties. There are many of various sources of data on the land cover including global and continental products, such as GlobCover, GeoCover, Globeland30, CORINE Land Cover.

```
landcover <- raster("cvs/LCEE10.tif")

# Land cover is a categorical covariate, this has to be made
```

```
# explicit using function as.factor()
landcover <- as.factor(landcover)
```

5.4.1 GlobCover (Global)

GlobCover is a European Space Agency (ESA) initiative which began in 2005 in partnership with JRC, EEA, FAO, UNEP, GOFC-GOLD, and IGBP. The aim of the project was to develop a service capable of delivering global composites and land cover maps using as input observations from the 300 m MERIS sensor onboard the ENVISAT satellite mission. ESA makes available the land cover maps, which cover 2 periods: December 2004 - June 2006 and January - December 2009. The classification module of the GlobCover processing chain consists in transforming the MERIS-FR multispectral mosaics produced by the pre-processing modules into a meaningful global land cover map. The global land cover map has been produced in an automatic and global way and is associated with a legend defined and documented using the UN LCCS. The GlobCover 2009 land cover map is delivered as one global land cover map covering the entire Earth. Its legend, which counts 22 land cover classes, has been designed to be consistent at the global scale and therefore, it is determined by the level of information that is available and that makes sense at this scale (Bontemps et al., 2011). The GlobCover data can be downloaded at http://due.esrin.esa.int/page_globcover.php

5.4.2 Landsat GeoCover (Global)

The Landsat GeoCover collection of global imagery was merged into mosaics by the Earth Satellite Company (now MDA Federal). The result was a series of tiled imagery that is easier to wield than individual scenes, especially since they cover larger areas than the originals. The great detail in these mosaic scenes, however, makes them large in storage size, so the Mr.Sid file format, which includes compression operations, was chosen for output. While GeoCover itself is available in three epochs of 1975, 1990 and 2000, only the latter two epochs were made into mosaics. Coverage: The GeoCover Landsat mosaics are delivered in a Universal Transverse Mercator (UTM) / World Geodetic System 1984 (WGS84) projection. The mosaics extend north-south over 5 degrees of latitude and span east-west for the full width of the UTM zone. For mosaics below 60 degrees north latitude, the width of the mosaic is the standard UTM zone width of 6 degrees of longitude. For mosaics above 60 degrees of latitude, the UTM zone is widened to 12 degrees, centered on the standard even-numbered UTM meridians. To insure overlap between adjacent UTM zones, each mosaic extends for at least 50 kilometers to the east and west, and 1 kilometer to the north and south. Pixel size: 14.25 meters (V 2000) The data is available at ftp://ftp.glcf.umd.edu/glcf/Mosaic_Landsat/ (FTP Access)

5.4.3 Globeland30 (Global)

GlobeLand30, the world's first global land cover dataset at 30 m resolution for the years 2000 and 2010, was recently released and made publicly available by China. The National Geomatics Center of China under the "Global Land Cover Mapping at Finer Resolution" project has recently generated a global land cover map named GlobeLand30. The dataset covers two timestamps of 2000 and 2010, primarily acquired from Landsat TM and ETM+ sensors, which were then coupled/checked with some local products. The data is publicly available for non-commercial purposes at <http://www.globallandcover.com/GLC30Download/index.aspx>. Further reading and other global data sources: http://worldgrids.org/doku.php/wiki:land_cover_and_land_use

5.4.4 CORINE Land Cover (Europe Only)

The pan-European component is coordinated by the European Environment Agency (EEA) and produces satellite image mosaics, land cover/land use (LC/LU) information in the CORINE Land Cover data, and the High-Resolution Layers. The CORINE Land Cover is provided for 1990, 2000, 2006 and 2012. This vector-based dataset includes 44 land cover and land use classes. The time-series also includes a land-change layer, highlighting changes in land cover and land-use. The high-resolution layers (HRL) are raster-based datasets (100 m, 250 m) which provide information about different land cover characteristics and is complementary to land-cover mapping (e.g. CORINE) datasets. The CORINE Land Cover Data are available at <http://www.eea.europa.eu/data-and-maps/data>

5.5 Climate

5.5.1 WorldClim V1.4 and V2 (Global)

WorldClim is a set of global climate layers (gridded climate data) with a spatial resolution of about 1 km² (10 minutes, 5 minutes, 2.5 minutes are also available). These data can be used for mapping and spatial modeling. The current version is Version 1.4. and a preview of Version 2 is available for testing at worldclim.org. The data can be downloaded as generic grids or in ESRI Grid format.

The WorldClim data layers were generated by interpolation of average monthly climate data from weather stations on a 30 arc-second resolution grid. In V1.4, variables included are monthly total precipitation, and monthly mean, minimum and maximum temperatures, and 19 derived bioclimatic variables. The WorldClim precipitation data were obtained from a network of 1,473 stations, mean temperature from 24,542 stations, and minimum and maximum temperatures from 14,835 stations ([Hijmans et al., 2005](#)).

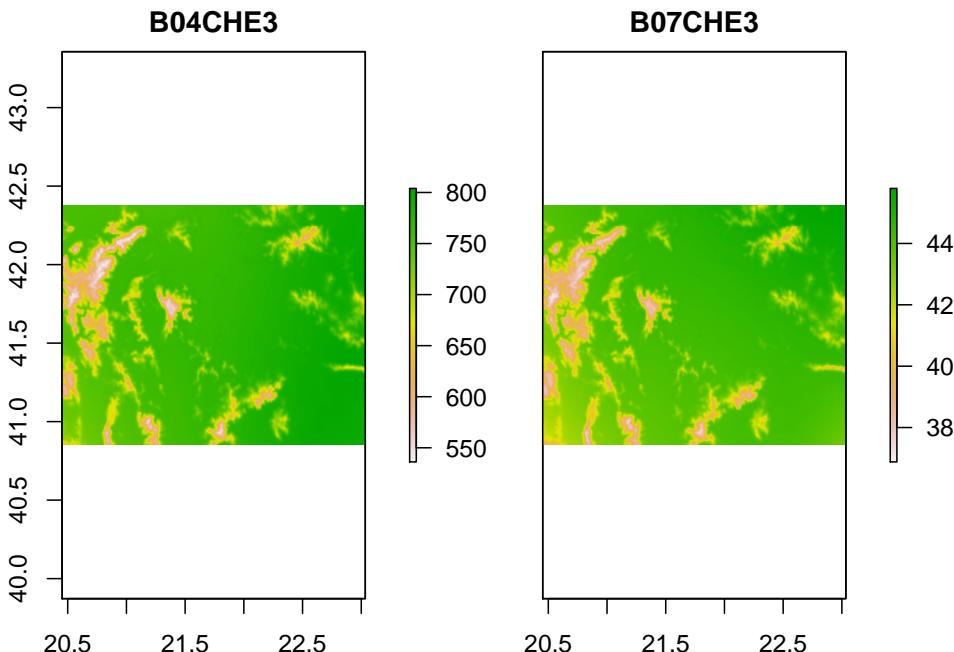


Figure 5.3: Two layers included in the climate covariates

The Bioclimatic parameters are: annual mean temperature, mean diurnal range, iso-thermality, temperature seasonality, max temperature of warmest month, minimum temperature of coldest month, temperature annual range , mean temperature of wettest quarter, mean temperature of driest quarter, mean temperature of warmest quarter, mean temperature of coldest quarter, annual precipitation, precipitation of wettest month, precipitation of driest month, precipitation seasonality (coefficient of variation), precipitation of wettest quarter, precipitation of driest quarter, precipitation of warmest quarter, precipitation of coldest quarter.

WorldClim Climate Data are available at: www.worldclim.org (WorldClim 1.4 (current conditions) by www.worldclim.org; [Hijmans et al. \(2005\)](#). Is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License).

```
# load the climate covariates from the raster tif files
files <- list.files(path = "coks/", pattern = "CHE3.tif",
                     full.names = TRUE)

# stack all the files in one RasterStack
climate <- stack(files)

# plot the first 2 layers
plot(climate[[1:2]])
```

5.5.2 Gridded Agro-Meteorological Data in Europe (Europe)

CGMS database contains meteorological parameters from weather stations interpolated on a 25×25 km grid. Meteorological data are available on a daily basis from 1975 to the last calendar year completed, covering the EU Member States, neighboring European countries.

The following parameters are available at 1-day time resolution:

- maximum air temperature ($^{\circ}\text{C}$)
- minimum air temperature ($^{\circ}\text{C}$)
- mean air temperature ($^{\circ}\text{C}$)
- mean daily wind speed at 10m (m/s)
- mean daily vapor pressure (hPa)
- sum of precipitation (mm/day)
- potential evaporation from a free water surface (mm/day)
- potential evapotranspiration from a crop canopy (mm/day)
- potential evaporation from a moist bare soil surface (mm/day)
- total global radiation (KJ/m²/day)
- Snow Depth

Data Access: <http://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx>

5.6 GSOCMap - Data Repository (ISRIC, 2017)

ISRIC World Soil Information has established a data repository which contains raster layers of various biophysical earth surface properties for each territory in the world. These layers can be used as covariates in a digital soil mapping exercise.

5.6.1 Covariates and Empty Mask

The territories and their boundaries are obtained from the Global Administrative Unit Layers (GAUL)dataset: each folder contains three subfolders; cova: GIS layers of various biophysical earth surface properties mask: an ‘empty’ grid file of the territory with territory boundary according to GAUL. This grid to be used for the final delivery. . soilgrids: all SoilGrids250m soil class and property layers as available through www.soilgrids.org. Layers are aggregated to 1 km.

5.6.2 Data Specifications

File format: GeoTiff Coordinate system: WGS84, latitude-longitude in decimal degrees Spatial resolution: 1km

5.6.3 Data Access

<ftp://gsp.isric2.org/> (username: gsp, password: gspisric) or <ftp://85.214.253.67/> (username: gsp, password: gspisric)

LICENCE and ACKNOWLEDGEMENT *The GIS layers can be freely used under the condition that proper credit should be given to the original data source in each publication or product derived from these layers. Licences, data sources, data citations are indicated the data description table.*

5.7 Extending the Soil Property Table for Spatial Statistics

The upscaling procedures (see chapter 6) depend on the rationale that the accumulation of local soil carbon stocks (and also other properties) depend on parameters for which spatial data are available, such as climate, soil type, parent material, slope, management. This information (Covariates) must be collected first. Details are provided above. The properties contained in the covariates can be extracted to each georeferenced sample site and added to the soil property table (Table 3.1). This table is used for training and validation of the statistical model for predicting the SOC stocks which subsequently can be applied to the full spatial extent.

5.8 Preparation of a Soil Property Table for Spatial Statistics

The upscaling procedures (see chapter 6) depend on the rationale, that the accumulation of local soil carbon concentrations and stocks (and also other properties) depends on influential parameters for which spatial data are available, such as climate, soil type, parent material, slope, management. Any parameter in the table of local soil properties, for which a spatial layer is available, may be included in the final table. Other covariates will be added in section 3. An example is the clay content, which may be derived from a soil type or parent rock map.

In case this table is prepared for different depths, 0-10 cm, 10-30 cm, and if the host institution intends to develop different spatial models for different depths (e.g. separate spatial prediction model for litter and mineral soil 0-30), then the separate grids have to be added.

5.9 Technical Steps - Overlay Covariates and Soil Points Data

5.9.1 Load soil sample data and covariates

```
# Load the processed data. This table was prepared in the previous
# chapter.
dat <- read.csv("data/dat_train.csv")

# read covariates from tif raster files
files <- list.files(path = "cobs", pattern = "tif$",
                     full.names = TRUE)

cobs <- stack(files)
```

5.9.2 Combine the covariates provided with the raster version of the soil map

```
# soilmap.r is the rasterization of the soil map and was obtained
# in a previous step
cobs <- stack(cobs, soilmap.r)

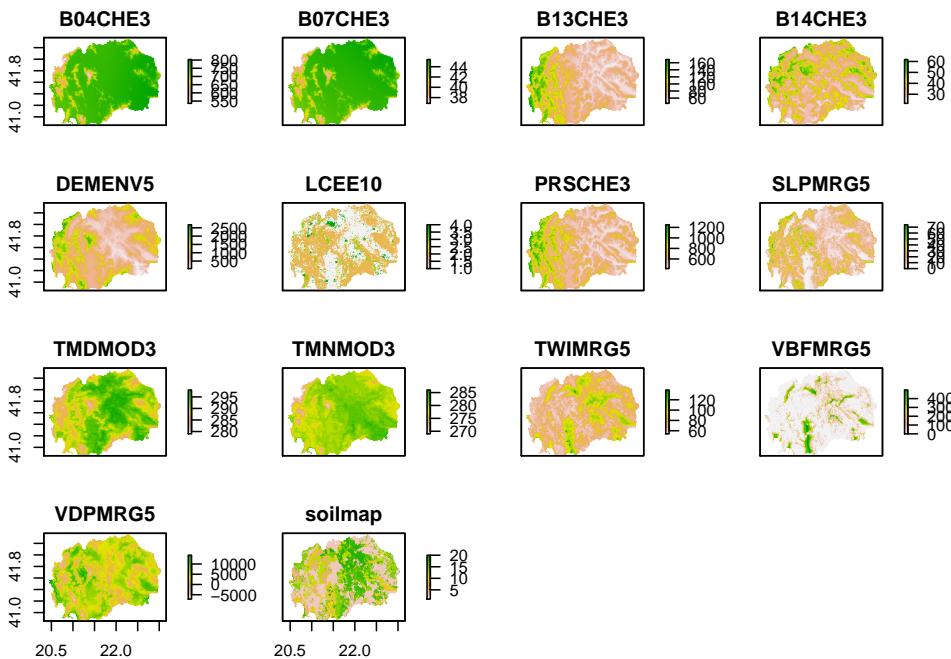
# correct the name for layer 14
names(cobs)[14] <- "soilmap"
```

Finally, we will mask the covariates with a mask developed using the country limits. Next, we will export all the covariates as 1 file. This will allow us to load this file in the following chapters of this book.

```
#mask the covariates with the country mask from the data repository
mask <- raster("data/mask.tif")
cobs <- mask(x = cobs, mask = mask)

# export all the covariates
save(cobs, file = "covariates.RData")

plot(cobs)
```



5.9.3 Overlay Covariates and Spatial Data

In order to carry out digital soil mapping in terms of examining the statistical significance of environmental predictors for explaining the spatial variation of SOC, we should link both sets of data together and extract the values of the covariates at the locations of the soil point data. Note that the stacking of rasters can only be possible if they are in the same resolution and extent. If they are not, **raster** package `resample` and `projectRaster()` functions are for harmonizing all your different raster layers. With the stacked rasters (Covstack), we can now perform the intersection and extraction.

```
#upgrade points data frame to SpatialPointsDataFrame
coordinates(dat) <- ~ X + Y

# extract values from covariates to the soil points
dat <- extract(x = covs, y = dat, sp = TRUE)

# LCEE10 and soilmap are categorical variables
dat@data$LCEE10 <- as.factor(dat@data$LCEE10)
dat@data$soilmap <- as.factor(dat@data$soilmap)

levels(soilmap) <- Symbol.levels

summary(dat@data)
```

```

##      id          SOC          BLD
## P0003 : 1   Min.   : 0.080   Min.   :0.05353
## P0007 : 1   1st Qu.: 1.772   1st Qu.:1.27881
## P0008 : 1   Median  : 2.620   Median  :1.39605
## P0009 : 1   Mean    : 3.579   Mean    :1.37990
## P0010 : 1   3rd Qu.: 4.090   3rd Qu.:1.47619
## P0011 : 1   Max.    :86.510   Max.    :2.89888
## (Other):2910
##      CRFVOL        OCSKGM       meaERROR
## Min.   : 0.00000   Min.   :0.03524   Min.   :0.172
## 1st Qu.: 0.01195   1st Qu.:0.70410   1st Qu.:3.160
## Median : 5.00000   Median :0.99674   Median :3.830
## Mean   :10.91665   Mean   :1.15062   Mean   :3.717
## 3rd Qu.:17.19974   3rd Qu.:1.40756   3rd Qu.:4.260
## Max.   :93.95013   Max.   :7.43023   Max.   :8.620
##
##      OCSKGMlog       B04CHE3       B07CHE3
## Min.   :-3.345652   Min.   :547.2   Min.   :37.60
## 1st Qu.:-0.350842   1st Qu.:759.8   1st Qu.:43.74
## Median : -0.003263  Median :763.9   Median :44.06
## Mean   : -0.008980  Mean   :759.3   Mean   :43.88
## 3rd Qu.: 0.341860   3rd Qu.:774.8   3rd Qu.:44.54
## Max.   : 2.005557   Max.   :802.9   Max.   :45.39
##
##      B13CHE3       B14CHE3       DEMENV5       LCEE10
## Min.   : 45.71   Min.   :22.26   Min.   : 45.0   1   :1967
## 1st Qu.: 60.01   1st Qu.:27.70   1st Qu.:395.5   2   : 698
## Median : 71.19   Median :30.11   Median :594.0   3   : 94
## Mean   : 74.26   Mean   :32.31   Mean   :655.8   4   :156
## 3rd Qu.: 78.79   3rd Qu.:35.61   3rd Qu.:814.2   NA's:  1
## Max.   :167.31   Max.   :60.32   Max.   :2375.0
##
##      PRSCHE3       SLPMRG5       TMDMOD3
## Min.   : 430.4   Min.   : 0.000   Min.   :280.0
## 1st Qu.: 529.9   1st Qu.: 0.000   1st Qu.:291.0
## Median : 565.4   Median : 4.000   Median :293.0
## Mean   : 604.6   Mean   : 8.553   Mean   :292.3
## 3rd Qu.: 651.3   3rd Qu.:13.000   3rd Qu.:294.0
## Max.   :1211.9   Max.   :61.000   Max.   :297.0
##
##      TMNMOD3       TWIMRG5       VBFMRG5
## Min.   :270.0   Min.   : 56.00   Min.   : 0.0
## 1st Qu.:279.0   1st Qu.: 79.00   1st Qu.: 0.0
## Median :280.0   Median : 94.00   Median : 70.5
## Mean   :279.7   Mean   : 91.12   Mean   :173.6
## 3rd Qu.:281.0   3rd Qu.:102.00   3rd Qu.:390.0
## Max.   :284.0   Max.   :139.00   Max.   :498.0

```

```
##          VDPMRG5      soilmap
##  Min.   : -5869    9   : 857
##  1st Qu.: 3571     3   : 425
##  Median : 5702     12  : 217
##  Mean   : 5370     10  : 211
##  3rd Qu.: 7024     14  : 205
##  Max.   : 14104    (Other): 982
##          NA's    : 19
```

After the extraction, it's useful to check if there are missing values (NA) both in the target variable and covariates. In these cases, these data should be excluded. A quick way to assess if there are missing or NA values in the data is to use the `complete.cases()` function.

After removing NAs, now there do not appear to be any missing data as indicated by the `integer(0)` output above. It means we have zero rows with missing information.

The last step involves exporting a table our regression matrix including the soil data and the values of the environmental covariates in the position of the point samples.

The summary of the `dat` `data.frame` shows 1 points with NA values for most of the covariates. And 22 points with NA values in the soilmap layer. The regression matrix should not contain NA values. There are two options to proceed:

- **Option 1:** In some cases, this NA values are from points with bad position data. Therefore, the points area outside the study area. In this case, the solution is to correct the coordinates or eliminate the points. This is the case for the two points with NA values for most of the covariates.
- **Option 2:** Another case is when a covariate is incomplete and does not cover all the area. This could produce many NA values. There are two different solutions, either to eliminate the covariate or to eliminate the point data. This is the case for the soilmap layer and the 30 points.

5.9.4 Convert result to `data.frame` and save as a csv table

```
dat <- as.data.frame(dat)

# The points with NA values has to be removed
dat <- dat[complete.cases(dat),]

# export as a csv table
write.csv(dat, "data/MKD_RegMatrix.csv", row.names = FALSE)
```

Chapter 6

Mapping Methods

R Baritz, M Guevara, VL Mulder, GF Olmedo, C Thine, RR Vargas, Y Yigini

In this chapter, we want to introduce 5 different approaches for obtaining the SOC map for FYROM. The first two methods presented are classified as conventional upscaling. The first one is class-matching. In this approach, we derive average SOC stocks per class: soil type for which a national map exists, or combination with other spatial covariates (e.g. land use category, climate type, biome, etc.). This approach is used in the absence of spatial coordinates of the source data. The second one is geo-matching, where upscaling is based on averaged SOC values per mapping unit. Then, we present 3 methods from digital soil mapping. Regression-Kriging is a hybrid model with both, a deterministic and a stochastic component (Hengl et al., 2007). Next method is called random forest. This one is an ensemble of regression trees based on bagging. This machine learning algorithm uses a different combination of prediction factors to train multiple regression trees (Breiman, 1996). The last method is called Support Vector Machines (SVM). This method applies a simple linear method to the data but in a high-dimensional feature space non-linearly related to the input space (Karatzoglou et al., 2006). We present this diversity of methods because there is no best mapping method for digital soil mapping, and testing and selection has to be done for every data scenario (Guevara et al., 2018).

6.1 Conventional Upscaling Using Soil Maps

R Baritz, VL Mulder

6.1.1 Overview

The two conventional upscaling methods, in the context of SOC mapping, are described by Lettens et al. (2004). Details about weighted averaging can be found

in Hiederer (2013). Different conventional upscaling approaches were applied in many countries (Baritz et al. 1999 (Germany), Krasilnikov et al. (2013) (Mexico), Greve et al. (2007) (Denmark), Koelli et al. 2009 (Estonia), Arrouays et al. (2001) (France), Bhatti et al. (2002) (Canada)). Because the structure of soil map databases differs between countries (definition of the soil mapping unit, stratification, soil associations, dominating and co-dominating soils, typical and estimate soil properties for different depths), it is difficult to define a generic methodology for the use of these maps for mapping soil property information.

However, the essential principle which is commonly used is to combine soil property data from local observations with soil maps via class- and geomatching.

Diversity of national soil legacy data sets in order to develop a representative and large national soil database, very often, data from different sources (e.g. soil surveys or projects in different parts of the country at different times) are combined. The following case of Belgium demonstrates how available legacy databases could be combined. Three different sources are used to compile an overview of national SOC stocks:

Data source 1: soil profile database with 13,000 points of genetic horizons; for each site, there is information about the soil series, map coordinates, and land use class; for each horizon, there is information about depth and thickness, textural fractions and class, volume percentage of rock fragments; analytically, there is the organic carbon content and inorganic carbon content.

Data source 2: forest soil data base which includes ectorganic horizons. According to their national definition, the term “ectorganic” designates the surface horizons with an organic matter content of at least 30%, thus, it includes both the litter layer and the organic soil layers. For the calculation of SOC stocks for the ectorganic layer, no fixed-depth was used, instead, the measured thickness of the organic layers and litter layers was applied.

Data source 3: 15,000 soil surface samples were used (upper 20 cm of mineral soil); carbon measurements are available per depth class.

From all data sources, SOC stocks for peat soils were calculated separately.

6.1.2 Technical Steps: Class-matching

6.1.2.1 Data Preparation

- Separate the database for forests, peat, and other land uses If only horizons are provided: derive or estimate average depth of horizons per soil type; add upper and lower depth.
- Check completeness of parameters per depth using the solum depth to code empty cells
- Correction of organic carbon in case total carbon was determined (total carbon minus inorganic carbon concentration)
- Correction of Walkley and Black method for incomplete oxidation (1.32)

- If BD measured is lacking, select proper pedotransfer functions (PTF) and estimate BD. There are many PTF. At best, publications about the choice of the best suited PTF for specific physio-geographic conditions are available.
- If the stone content is missing, investigate using other data sources or literature, to which a correction for stones should be applied
- if possible, derive the standard average stone content for different soils/horizons/depths, or used published soil profiles, as a simple correction factor.
- Calculate SOC stocks for all mineral and peat soils over 0-30 cm, and optionally for forest organic layers and, peat >30 <100 cm.

6.1.2.2 Preparatory GIS Operations

- Prepare Covariates
- Identify properties of covariates for each point observation using geo-matching
- Mapping using geo-matching of all points: Extract the covariate information to all georeferenced sample sites. The SOC values from all points within the unit are then averaged. It is assumed that the points represent the real variability of soil types within the units

6.1.2.3 Mapping

- Mapping using class-matching of points in agreement with classes

Through *class-matching*, only those points or profiles are attributed to a soil or landscape unit if both the soil and the land use class are the same. Class-matching thus can be performed regardless of the profile location. Before averaging, a weighing factor can be introduced according to the area proportions of dominant, co-dominant and associated soils. Each profile needs to be matched to its soil type/landscape type, and the SOC value averaged. 1. Determine a soil or landscape unit (e.g. national soil legend stratified by climate area and mainland cover type (forest, grassland, cropland) 2. Calculate average SOC stocks from all soils which match the soil/landscape unit 3. Present the Soil/landscape map with SOC stocks, do not classify SOC stocks into groups (e.g. < 50, 50-100, > 100).

Note: Pre-classified SOC maps cannot be integrated into a global GSOCmap legend.

- Mapping using geo-matching

Because of its importance, geo-matching is described in more detail.

6.1.3 Technical Steps: Geo-Matching

It is important to first prepare the working environment pre-processed all input data. The following section presents different Geo-matching procedures;

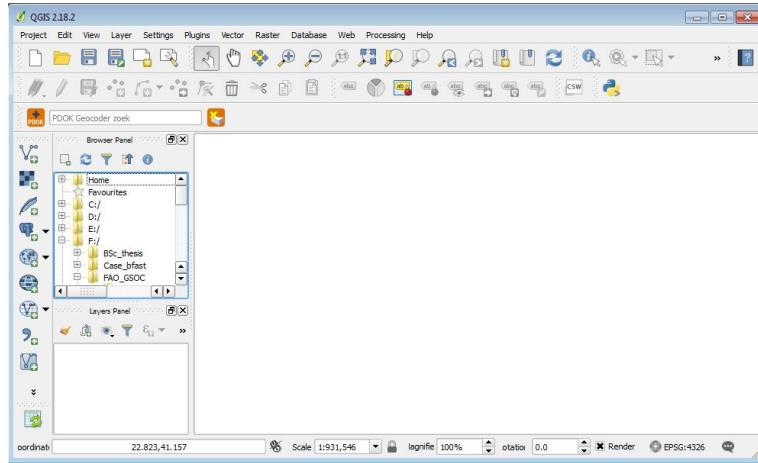


Figure 6.1: QGIS Desktop with the browser panel on the upper left, the layer information on the bottom left and the display of your layers on the right

1. Setting up software and working environment
2. Geo-matching SOC with WRB Soil map (step-by-step, using the Soil Map of FYROM and the demonstration data presented above)
3. Geo-matching SOC with other environmental variables: Land use
4. Finally, the development of Landscape Units (Lettens et al. 2004) is outlined.

This example was developed for QGIS and focusses on SOC mapping using vector data. QGIS 2.18 with GRASS 7.05 will be used. For more information, see also:

- <https://gis.stackexchange.com>
- <http://www.qgis.org/>
- <http://www.qgisforum.org/>

6.1.3.1 Setting Up a QGIS Project

1. Install QGIS and supporting software; download the software at <http://www.qgis.org/en/site/forusers/download.html> (select correct version for Windows, Mac or Linux, 32 or 64 bit).
2. Create a work folder, e.g. D:\GSOC\practical_matching. Copy the folder with the FYROM demonstration data into this folder.
3. Start 'QGIS desktop with GRASS': Fig. 6.1 shows the start screen of QGIS desktop. In the upper left panel, there is the browser panel, which lists the geodata used for this example. In the bottom left, the layer information is given for the layers displayed on the right.
4. Load the FYROM soil map. Right-click the file in the Browser panel and add the map to your project.
5. Display the soil classes. Right-click on the file in the Layers Panel, properties. Go to Style and change from 'Single symbol' to 'Categorized' (Fig. 6.2).

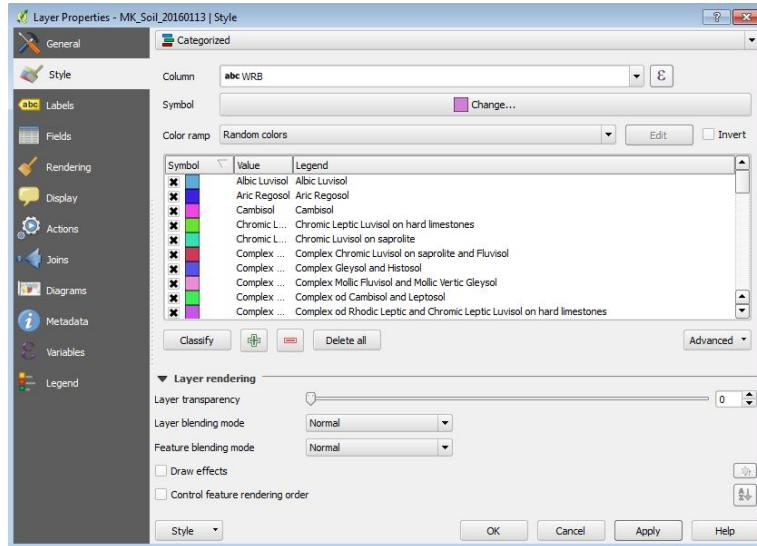


Figure 6.2: Changing layer properties for the FYROM Soil Map

Select the column ‘WRB’ and press the icon ‘Classify’ and change the colors if you want. Next, apply the change and finish by clicking the OK-button.

6. Ensure the correct projection for this project. Go to: Project -> Project properties -> CRS In this case, you automatically use the local projection for FYROM. The EPSG code is 3909 which corresponds to MG 1901/ Balkans zone 7 (Fig. 6.3).
7. Save the project in the created folder Load and display the pre-processed SOC point data. If a shapefile already exists, this is done the same way as described in Step 4. If you have the data as a text file, you need to create a vector layer out of that file. Go to Layer -> Add Layer -> Add Delimited Text layer. Select the correct file and proper CRS projection. The layer should be added to your Layers Panel and displayed on top of the Soil Map.

6.1.3.2 Geo-Matching SOC with WRB Soil Map

In this section you will make a SOC map, based on the FYROM Soil Map and the SOC values at the sampled points, following 3 steps: 1) Extract the soil map information for the point data, 2) obtain the mean and standard deviation of the SOC stocks per soil class, based on the point data and 3) assign these values to the corresponding soil map units. The steps are detailed below:

1. Extract the soil map information to the soil profile data by ‘Join Attributes by location’. Vector -> Data Management Tools -> Join Attributes by location. Here, the target vector layers are the soil point data, and the join vector layer is the FYROM Soil Map. The geometric predicate is ‘intersects’.

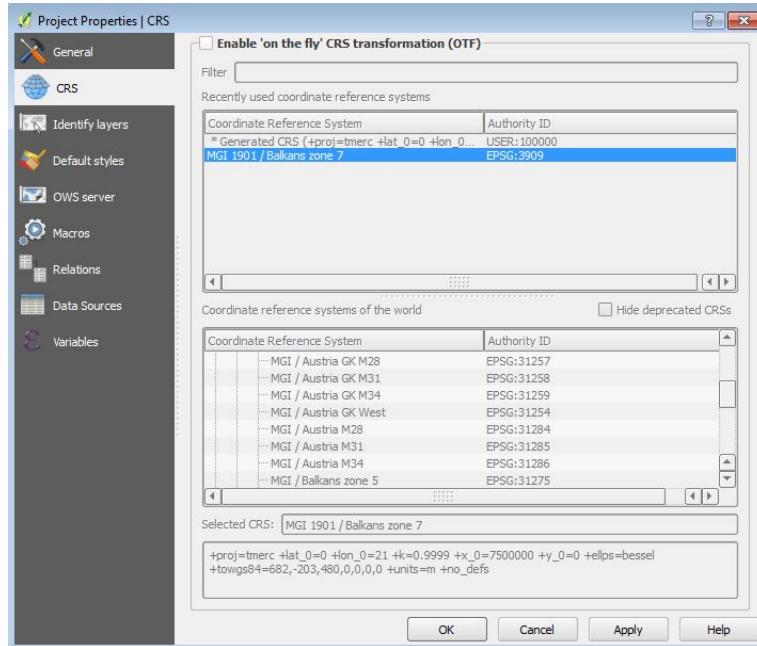


Figure 6.3: Project properties and projection settings

Specify at the ‘joined table’ to keep only matching records and save the ‘joined layer’ as a new file (Fig. 8.4).

2. Check the newly generated file, open the attribute table. The new file is added to the ‘Layers Panel’ . Right-click on the file and open the attribute table. The information from the FYROM Soil Map is now added to the soil point data.
3. Most likely, the SOC values in the table are not numeric and thus statistics cannot be calculated. Check the data format, right-click on the file in the ‘Layers Panel’ and check the Type name of the SOC field under the tab ‘Fields’. If they are not integer then change the format.
4. Change of the data format: Open the attribute table and start editing (the pencil symbol in the upper left corner of your table). Open the field calculator and follow these instructions (Fig. 8.5):
 - a. Checkbox: Create a new field
 - b. Output field name: Specify the name of your field
 - c. Output field type: Decimal Number (real)
 - d. Output field length: 10, precision: 3
 - i. Expression: `to_real('SOC')`, the `to_real` function can be found under ‘conversions’ and the ‘SOC’ field is found under ‘Fields and Values’
5. After calculating the field, save edits and leave the editing mode prior to closing the table. If changes are not saved, the added field will be lost.

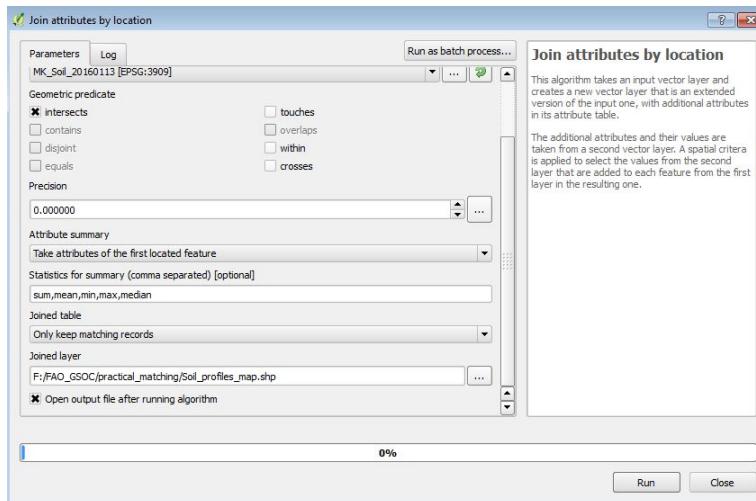


Figure 6.4: Join attributes by location

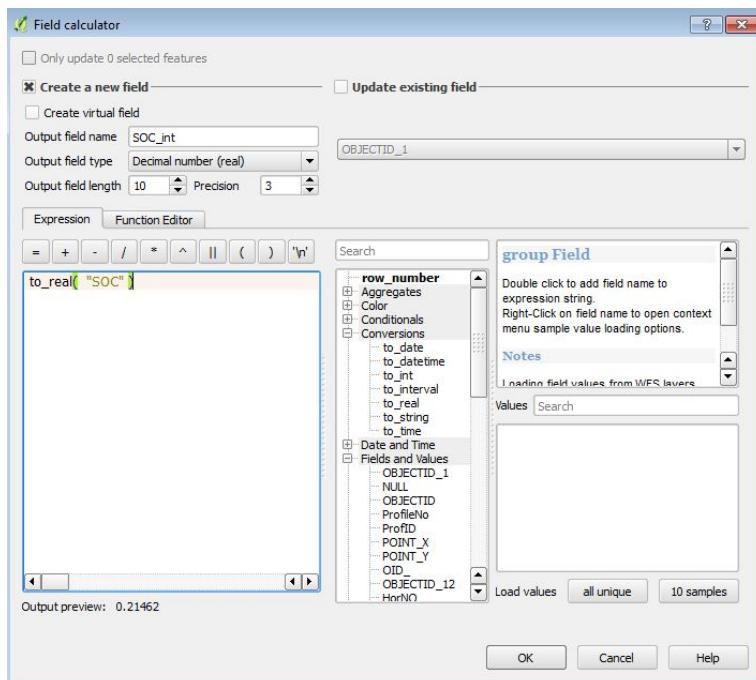


Figure 6.5: Example field calculator

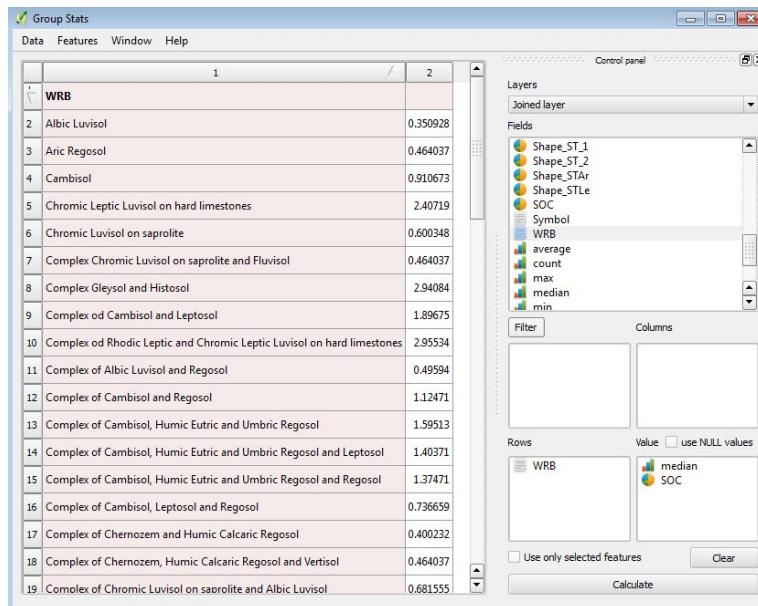


Figure 6.6: Calculate group statistics

6. Calculate the median SOC stock per soil type. Go to the tab ‘Vector’-> group stats. Select the layer from the spatial join you made in Step 2. Add the field ‘SOC’ and median to the box with ‘Values’ and the field ‘WRB’ to the ‘Rows’. Make sure the box with ‘use only selected features’ is not checked. Now calculate the statistics. A table will be given in the left pane (Figure 8.6). Save this file as .csv and repeat the same for the standard deviation.
7. Join the mean and standard deviation of SOC to the Soil Map. First, add the files generated during step 6 to the Layers Panels. In the Layers Panel, right-click on the FYROM Soil Map. Go to Properties -> Joins and add a new join for both the median and standard deviation of SOC. The Join and Target Field are both ‘WRB’.
8. Display the SOC maps. Go to the layer properties of the FYROM Soil Map. Go to Style and change the legend to a graduated legend. In the column, you indicate the assigned SOC values. Probably this is not a integer number and so you have to convert this number again to a numeric values. You can do this with the box next to the box (Fig. 8.7). Change the number of classes to e.g. 10 classes, change the mode of the legend and change the color scheme if you want and apply the settings. Now you have a map with the median SOC stocks per WRB soil class.
9. In order to generate a proper layout, go to Project -> New Print Composer
 - a. Add map using Layout -> Add Map. Define a square on the canvas and the selected map will be displayed.
 - b. Similarly, title, scale bar, legend and a north arrow can be added. Specific

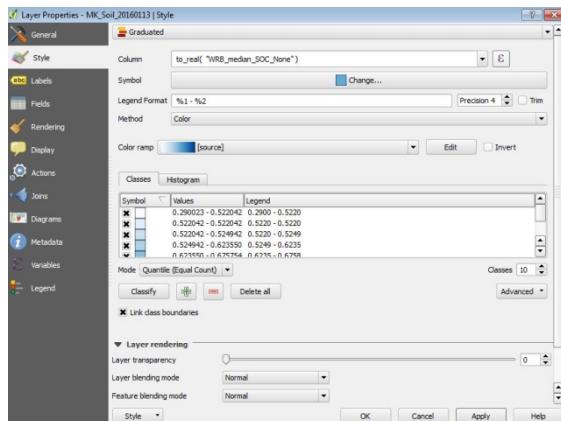


Figure 6.7: Change the legend style to display the SOC values

properties can be changed in the box ‘Item properties’.

- When the map is finished, it can be exported as an image or pdf.
- Repeat step 2-8 but now for the standard deviation of the SOC stocks.
- Save the file as a new shapefile: Go to ‘Layer Panels -> Save as -> ESRI ShapeFile and make sure that you define the symbology export: Feature Symbology. Now, a shapefile is generated, with both the median and standard deviation SOC stock per soil type. Redundant fields can be removed after the new file is created.

6.1.3.3 Geo-Matching SOC with Other Environmental Variables: Land Use

- Start a new project and add the soil point data and FYROM Soil Map layers from the Browser panel
- Add the Land Use raster file to the Layers Panels. This is a raster file with 1-kilometer resolution and projected in lat-long degrees (WGS84). For more information about this product see the online information from worldgrids: <http://worldgrids.org/doku.php/wiki:glcesa3>
- Change the projection to the MGI 1901/ Balkans region7. Go to Raster -> Projections -> Warp and select the proper projection and a suitable file name, e.g. LU_projected_1km. Tick the checkbox for the resampling method and choose Near. This is the nearest neighbor and most suitable for a transformation of categorical data, such as land use (Fig. 8.9).
- In order to geomatch the soil point data with Land Use, the raster file needs to be converted into a vector file. Go to Raster -> Conversions -> Polygonize. Set a proper output filename, e.g. LU_polygon_1km, and check the tickbox for Fieldname.
- Change the legend style into categories (Step 1-5): Now, the steps from the previous section need to be repeated, using the land use polygon map instead

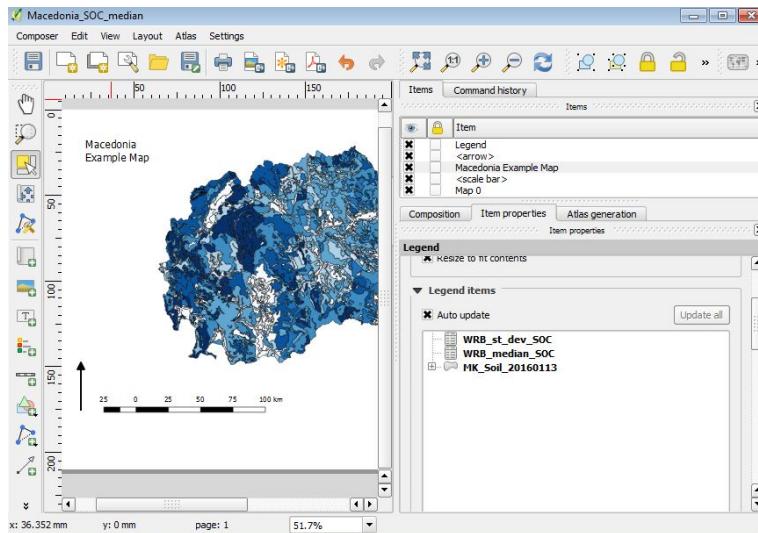


Figure 6.8: Example of the Map composer

of using the FYROM Soil Map.

6. Join attributes by location using the soil point data and the polygon land use map.
7. Calculate the median and standard deviation of SOC by using the Group Statistics for SOC and the Land Use classes and save the files as .csv.
8. Add the generated .csv files to the Layers Panel.
9. Join the files with the LU polygon map, generated at step 3-4.
10. Change the classes in the legend and inspect the histogram with the median SOC values. Try to find a proper definition of the class boundaries (Step 2-8).

6.1.3.4 Joining Landscape Units and Soil Mapping Units to Support Class-and Geo-Matching (Optional)

In this section, it is outlined how SOC stocks can be mapped following the method outlined by Lettens et al. (2004). The general idea is that the landscape is stratified into more or less homogenous units and subsequently, the SOC stocks are obtained following the procedure outlined earlier in this practical. Lettens et al. (2004) outlines a method to stratify the landscape into homogeneous strata with respect to Land Use and Soil Type, as was explained earlier. In order to obtain such strata, the Soil Map and the Land Use map need to be combined. This can be done using various types of software, e.g. ArcMap, GRASS, QGIS or R. When using the GIS software, the only thing that needs to be done is intersecting the vector files and dissolving the newly created polygon features. Depending on the software and the quality of your shapefile you may experience problems with the geometry of your shapefile. Generally, ArcMap and GRASS correct the geometry when the shapefile

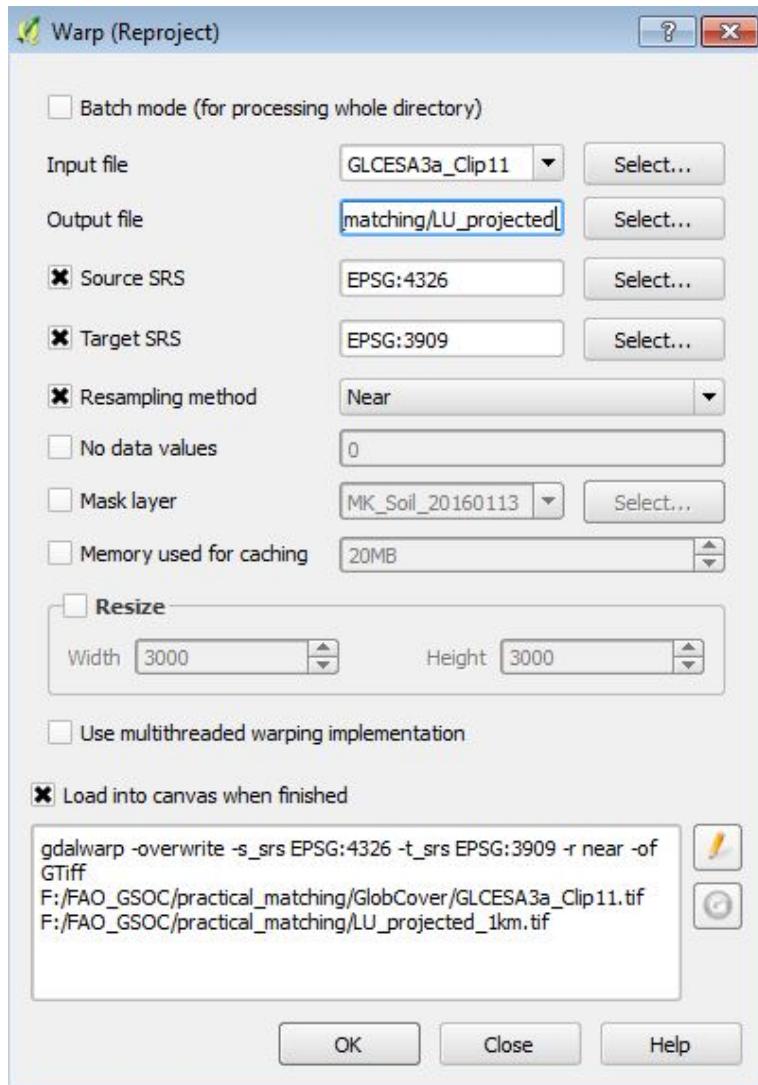


Figure 6.9: Change the projection of a raster file

is loaded, while QGIS does not do this automatically. There are various ways to correct the geometry, however, correcting the geometry falls outside the scope of this training. Therefore, we give some hints on how to correct your geometry prior to using the functions ‘Intersect’ and ‘Dissolve’.

1. Change the LU raster map to 5-kilometer resolution: Right-click the Lu_project_1km file and select Save as. Change the resolution to 5000 meters. Scroll down, check the Pyramids box, and change the resampling method to Nearest Neighbour.
2. Convert the raster map to a polygon map and add the file to the Layers Panel
3. Check the validity of the Soil Map and Land Use Map: Vector -> Geometry Tools -> Check Validity Below you find the instructions in case you have no problems with your geometry:
4. Intersect the Soil Map and the Land Use Map. In ArcGIS and QGIS you can use this function. Go to Vector -> Geoprocessing tools -> Intersection. (In GRASS you have to use the function ‘Overlay’ from the Vector menu)
5. Dissolve the newly generated polygons. Vector -> Geoprocessing tools -> Dissolve
6. Next, this layer can be used to continue with the class matching or geomatching procedures.

When encountering problems with the geometry there are at least three ways to correct your geometry:

- Run the v_clean tool from GRASS within QGIS. Open the Processing Tool-Box -> GRASS GIS 5 commands -> Vector -> v.clean
- Install the plugin ‘Processing LWGEOM Provider’. Go to the Plugins menu and search for the plugin and install. You can find the newly installed tool in the Processing Toolbox by typing the name in the search function
- Manually correct the error nodes of the vector features

6.2 Regression-Kriging

GF Olmedo & Y Yigini

6.2.1 Overview

Regression-kriging is a spatial interpolation technique that combines a regression of the dependent variable (target variable) on predictors (i.e. the environmental covariates) with kriging of the prediction residuals. In other words, Regression-Kriging is a hybrid method that combines either a simple or a multiple-linear regression model with ordinary kriging of the prediction residuals. The Multiple regression analysis models the relationship of multiple predictor variables and one dependent variable, i.e. it models the deterministic trend between the target variable and environmental covariates. The modeled relationship between predictors and target are summarized in the regression equation, which can then be applied to a different data set in which the target values are unknown but the predictor variables are known. The regression equation predicts the value of the dependent variable using a linear function of the independent variables. In this section, we review the regression kriging method. First, the deterministic part of the trend is modeled using a regression model. Next, the prediction residuals are kriged. In the regression phase of a regression-kriging technique, there is a continuous random variable called the dependent variable (target) Y (in our case SOC) and a number of independent variables which are selected covariates, x_1, x_2, \dots, x_p . Our purpose is to predict the value of the dependent variable using a linear function of the independent variables. The values of the independent variables (environmental covariates) are known quantities for purposes of prediction, the model is:

6.2.2 Assumptions

Standard linear regression models with standard estimation techniques make a number of assumptions about the predictor variables, the response variables, and their relationship. One must review the assumptions made when using the model.

Linearity: The mean value of Y for each specific combination of the X 's is a linear function of the X 's. In practice this assumption can virtually never be confirmed; fortunately, multiple regression procedures are not greatly affected by minor deviations from this assumption. If curvature in the relationships is evident, one may consider either transforming the variables or explicitly allowing for nonlinear components. *Normality Assumption:* It is assumed in multiple regression that the residuals (predicted minus observed values) are distributed normally (i.e., follow the normal distribution). Again, even though most tests (specifically the F-test) are quite robust with regard to violations of this assumption, it is always a good idea, before drawing final conclusions, to review the distributions of the major variables of interest. You can produce histograms of the residuals as well as normal probability plots, in order to inspect the distribution of the residual values.

Collinearity: There is not perfect collinearity in any combination of the X's. A higher degree of collinearity, or overlap, among independent variables, can cause problems in multiple linear regression models. Collinearity (also multicollinearity) is a phenomenon in which two or more predictors in a multiple regression models are highly correlated. Collinearity causes increase in variances and relatively increases inaccuracy. *Distribution of the Errors:* The error term is normally distributed with a mean of zero and constant variance. *Homoscedasticity:* The variance of the error term is constant for all combinations of X's. The term homoscedasticity means “same scatter.” Its antonym is heteroscedasticity (“different scatter”).

6.2.3 Pre-Processing of Covariates

Before using the selected predictors, multicollinearity assumption must be reviewed. As an assumption, there is not perfect collinearity in any combination of the X's. A higher degree of collinearity, or overlap, among independent variables, can cause problems in multiple linear regression models. The multicollinearity of a number of variables can be assessed using Variance Inflation Factor (VIF). In R, the function `vif()` from `caret` package can estimate the VIF. There are several rules of thumb to establish when there is a serious multi-collinearity (e.g. when the VIF square root is over 2). The Principal component analysis can be used to overcome multicollinearity issues. Principal components analysis can cope with data containing large numbers of covariates that are highly collinear which is the common case in environmental predictors. Often the principal components with higher variances are selected as regressors. However, for the purpose of predicting the outcome, the principal components with low variances may also be important, in some cases even more important. The PCA + Linear Regression (PCR) method may be coarsely divided into three main steps: 1. Run PCA on the data matrix for the predictors to obtain the principal components, and then select a subset of the principal components for further use. 2. Regress the dependent variable on the selected principal components as covariates, linear regression to get estimated regression coefficients. 3. Transforming the data back to the scale of the actual covariates, using the selected PCA loadings.

6.2.4 The Terminology

- **Dependent variable (Y):** What we are trying to predict (e.g. soil organic carbon content).
- **Independent variables (Predictors) (X):** Variables that we believe influence or explain the dependent variable (Covariates: environmental covariates - DEM derived covariates, soil maps, land cover maps, climate maps). The data sources for the environmental predictors are provided in chapter 5.
- **Coefficients ():** values, computed by the multiple regression tool, reflect the relationship and strength of each independent variable to the dependent variable.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n + \varepsilon$$

Y Dependent Variable
 β_n Coefficients
 X_n Predictors
 ε Residuals

Figure 6.10: Linear regression model

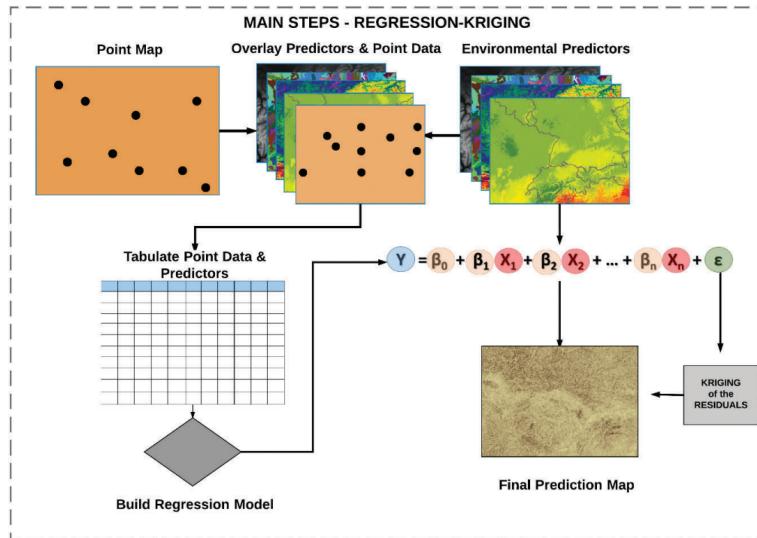


Figure 6.11: Workflow for Regression Kriging

- **Residuals ()**: the portion of the dependent variable that cannot be explained by the model; the model under/over predictions.

Before we proceed with the regression analysis, it is advisable to inspect the histogram of the dependent/target variable, in order to see if it needs to be transformed before fitting the regression model. The data for the selected soil property is normal when the frequency distribution of the values follow a bell-shaped curve (Gaussian distribution) which is symmetric around its mean. Normality tests may be used to assess normality. If a normality test indicates that data are not normally distributed, it may be necessary to transform the data to meet the normality assumption.

Both, the normality tests and the data transformation can be easily performed using any commercial or open source statistical tool (R, SPSS, MINITAB...)

The main steps for the multiple linear regression analysis are shown in the Figure 6.11.

1. The first step is to prepare a map showing the spatial distribution

- of the sample locations and the corresponding soil property information, e.g. soil organic matter and environmental properties. The first can be achieved as outlined in section [Overlay covariates and spatial data](#). The overlaying operation can be performed in R, ArcGIS, SAGA GIS or QGIS.
2. The essential part of multiple regression analysis is to build a regression model by using the environmental predictors. After extracting the values of explanatory maps and target variables into the single table, we can now start fitting multiple regression model using the table that contains data from dependent variable and predictors.
 3. In particular cases, stepwise multiple linear regression (SMLR) can be used to eliminate insignificant predictors. Stepwise multiple linear regression (SMLR) usually selects predictors that have the strongest linear correlations with the target variable, which reflect the highest predictive capacity.
 4. Kriging of the residuals (prediction errors): In the regression-kriging, the regression model detrends the data, produces the residuals which we need to krig and to be added to the regression model predictions.

6.2.5 Interpret the Key Results of Multiple Regression

Regression analysis generates an equation to describe the statistical relationship between one or more predictor variables and the response variable. The r-squared, p-values and coefficients that appear in the output for linear regression analysis must also be reviewed. Before accepting the result of a linear regression it is important to evaluate its suitability at explaining the data. One of the many ways to do this is to visually examine the residuals. If the model is appropriate, then the residual errors should be random and normally distributed.

R-sq

R² is the percentage of variation in the response that is explained by the model. The higher the R² Value, the better the model fits your data. R-squared is always between 0% and 100%. R² usually increases when additional predictors are added in the model.

P Values

To determine whether the association between the dependent and each predictor in the model is statistically significant, compare the p-value for the term to your significance level to assess the null hypothesis. Usually, a significance level of 0.05 works well. P-value > significance level: The relationship is statistically significant. If the p-value is less than or equal to the significance level, we can conclude that there is a statistically significant relationship between the dependent variable and the predictor. P-value < significance level: The relationship is not statistically significant, If the p-value is greater than the significance level, you cannot conclude

that there is a statistically significant relationship between the dependent variable and the predictor. You may want to refit the model without the predictor.

Residuals

We can plot the residuals which can help us determine whether the model is adequate and meets the assumptions of the analysis. If the model is appropriate, then the residual errors should be random and normally distributed. We can plot residuals versus fits to verify the assumption that the residuals are randomly distributed and have constant variance. Ideally, the points should fall randomly on both sides of “0”, with no recognizable patterns in the points.

The diagnostic plots for the model should be evaluated to confirm if all the assumptions of linear regression are met. After the abovementioned assumptions are validated, we can proceed with making the prediction map using the model with significant predictors.

6.2.6 Using the Results of a Regression Analysis to Make Predictions

The purpose of a regression analysis, of course, is to develop a model that can be used to make the prediction of a dependent variable. The derived regression equation is to be used to create the prediction map for the dependent variable.

Raster calculation can be easily performed using “raster” Package in R or ArcGIS using the ”Raster Calculator” tool (It’s called Map Algebra in the prior versions).

6.2.7 Technical Steps - Regression Kriging

Requirements The following are required to implement Regression Kriging in R

- Setting-up the Software Environment
- Obtaining and Installing R Studio
- R Packages
- Preparation of local soil property data
- Preparation of spatial covariates
- DEM-derived covariates
- Land cover/Land use
- Climate
- Parent material

6.2.7.1 Setting Working Space and Initial Steps

One of the first steps should be setting our working directory. If you read/write files from/ to disk, this takes place in the working directory. If we don't set the working directory we could easily write files to an undesirable file location. The following example shows how to set the working directory in R to our folder which contains data for the study area (point data, covariates).

Note that we must use the forward slash / or double backslash \\ in R! Single backslash \ will not work. Now we can check if the working directory has been correctly set by using the function:

```
getwd()
```

6.2.7.2 Data Preparation

Point Dataset

We previously applied spline function to produce continuous soil information to a given soil depth (0-30 cm) in section 3.4.1. Spline function basically imports soil profile data (including instances where layers are not contiguous), fits it to a mass-preserving spline and outputs attribute means for a given depth. The output file should contain profile id, upper (surface) and lower depth (30cm), the estimated value for the selected soil attribute (Value) and tmse (estimated mean squared error of the spline). If you used the Spline Tool V2, the coordinates were not kept in the output file. The coordinates should be added back in the data table. You can use Profile IDs to add the X, Y columns back. Once your point dataset is ready, copy this table into your working directory as a .csv file.

Environmental Predictors (Covariates)

In the Chapter 5, we presented and prepared several global and continental datasets. In addition to these datasets, numerous covariate layers have been prepared by ISRIC for the GSOC Map project. These are GIS raster layers of various biophysical earth surface properties for each country in the world. Some of these layers will be used as predictors in this section. Please download the covariates for your own study area from GSOCMap Data Repository as explained in section 5.6.

In section 5.9, a table with the points values after data preparation and the values of our spatial predictors was prepared. This step involves loading this table.

Now we will import our point dataset using `read.csv()` function. The easiest way to create a data frame is to read in data from a file—this is done using the function `read.csv`, which works with comma delimited files. Data can be read in from other file formats as well, using different functions, but `read.csv` is the most commonly used approach. R is very flexible in how it reads in data from text files (`read.table`, `read.csv`, `read.csv2`, `read.delim`, `read.delim2`). Please type `?read.table()` for help.

```
# load data
dat <- read.csv("data/MKD_RegMatrix.csv")

dat$LCEE10 <- as.factor(dat$LCEE10)
dat$soilmap <- as.factor(dat$soilmap)

# explore the data structure
str(dat)

## 'data.frame': 2897 obs. of 23 variables:
## $ id      : Factor w/ 2897 levels "P0003","P0007",...: 1 2 3 4...
## $ Y       : num 42 42 42.1 42 42 ...
## $ X       : num 20.8 20.8 20.8 20.9 20.9 ...
## $ SOC     : num 26.38 6.15 3.94 3.26 2.29 ...
## $ BLD     : num 0.73 1.17 1.3 1.34 1.41 ...
## $ CRFVOL  : num 8 18.6 31.9 21.7 14.5 ...
## $ OCSKGM  : num 5.32 1.75 1.04 1.03 0.83 ...
## $ meaERROR: num 2.16 2.85 2.65 3.16 3.63 2.83 2.94 2.49 2.77...
## $ OCSKGMlog: num 1.6712 0.5591 0.0429 0.0286 -0.1862 ...
## $ B04CHE3 : num 574 553 693 743 744 ...
## $ B07CHE3 : num 38.5 37.8 42.1 43.7 43.7 ...
## $ B13CHE3 : num 111.6 125 99.8 118.1 121 ...
## $ B14CHE3 : num 59.2 60.3 42.4 39.9 38.7 ...
## $ DEMENV5 : int 2327 2207 1243 1120 1098 1492 1413 1809 1731...
## $ LCEE10  : Factor w/ 4 levels "1","2","3","4": 1 3 2 1 2 2 2...
## $ PRSCHE3 : num 998 1053 780 839 844 ...
## $ SLPMRG5 : int 13 36 6 25 30 24 15 17 20 43 ...
## $ TMDMOD3 : int 282 280 285 288 289 287 286 286 287 286 ...
## $ TMNMOD3 : int 272 270 277 279 279 277 277 273 274 273 ...
## $ TWIMRG5 : int 61 62 81 66 65 72 68 67 65 59 ...
## $ VBFMRG5 : int 0 0 14 0 0 0 0 0 0 0 ...
## $ VDPMRG5 : int 311 823 10048 1963 -173 -400 -9 -692 -1139 2...
## $ soilmap  : Factor w/ 20 levels "1","2","3","4",...: 6 14 14 3...
```

Since we will be working with spatial data we need to define the coordinates for the imported data. Using the `coordinates()` function from the `sp` package we can define the columns in the data frame to refer to spatial coordinates—here the coordinates are listed in columns `X` and `Y`.

```
library(sp)

# Promote to SpatialPointsDataFrame
coordinates(dat) <- ~ X + Y

class(dat)

## [1] "SpatialPointsDataFrame"
## attr(,"package")
```

```
## [1] "sp"
```

SpatialPointsDataFrame structure is essentially the same data frame, except that additional “spatial” elements have been added or partitioned into slots. Some important ones being the bounding box (sort of like the spatial extent of the data), and the coordinate reference system proj4string(), which we need to define for the sample dataset. To define the CRS, we must know where our data are from, and what was the corresponding CRS used when recording the spatial information in the field. For this data set, the CRS used was: WGS84 (EPSG:4326).

To clearly tell R this information we define the CRS which describes a reference system in a way understood by the [PROJ.4 projection library](#). An interface to the PROJ.4 library is available in the rgdal package. As an alternative to using Proj4 character strings, we can use the corresponding yet simpler EPSG code (European Petroleum Survey Group). rgdal also recognizes these codes. If you are unsure of the Proj4 or EPSG code for the spatial data that you have but know the CRS, you should consult <http://spatialreference.org/> for assistance.

Please also note that, when working with spatial data, it’s very important that the CRS (coordinate reference system) of the point data and covariates are the same.

Now, we will define our CRS:

```
dat@proj4string <- CRS(projargs = "+init=epsg:4326")
```

```
dat@proj4string
```

```
## CRS arguments:  
## +init=epsg:4326 +proj=longlat +datum=WGS84 +no_defs  
## +ellps=WGS84 +towgs84=0,0,0
```

Now we will import the covariates. When the covariate layers are in common resolution and extent, rather than working with individual rasters it is better to stack them all into a single R object. In this example, we use 13 covariates from the GSOCMap Data Repository and a rasterized version of the soil type map. The rasterization of vectorial data was covered in [Technical Steps - Rasterizing a vector layer in R](#). The file containing all the covariates was prepared at the end of chapter 5.

```
load(file = "covariates.RData")  
  
names(covs)  
  
## [1] "B04CHE3" "B07CHE3" "B13CHE3" "B14CHE3" "DEMENV5" "LCEE10"  
## [7] "PRSCHE3" "SLPMRG5" "TMDMOD3" "TMNMOD3" "TWIMRG5" "VBFMRG5"  
## [13] "VDPMRG5" "soilmap"
```

6.2.7.3 Fitting the MLR Model

Fitting the MLR Model

It would be better to progress with a data frame of just the data and covariates required for the modeling. In this case, we will subset the columns SOC, the covariates and the spatial coordinates (X and Y).

```
datdf <- dat@data

datdf <- datdf[, c("OCSKGM", names(covs))]
```

Let's fit a linear model using with all available covariates.

```
# Fit a multiple linear regression model between the log transformed
# values of OCS and the top 20 covariates
model.MLR <- lm(log(OCSKGM) ~ ., data = datdf)
```

From the summary of our fitted model (model.MLR) above, it seems only a few of the covariates are significant in describing the spatial variation of the target variable. To determine the most predictive model we can run a stepwise regression using the `step()` function. With this function, we can also specify the mode of stepwise search, can be one of “both”, “backward”, or “forward”.

```
## stepwise variable selection
model.MLR.step <- step(model.MLR, direction="both")
```

Comparing the summary of both the full and stepwise linear models, there is very little difference between the models such as the R2. Both models explain about 23% of variation of the target variable. Obviously, the “full” model is more complex as it has more parameters than the “step” model.

```
# summary and anova of the new model using stepwise covariates
# selection
summary(model.MLR.step)
anova(model.MLR.step)

##
## Call:
## lm(formula = log(OCSKGM) ~ B04CHE3 + B07CHE3 + B13CHE3 + DEMENV5 +
##     LCEE10 + PRSCHE3 + SLPMRG5 + TMDMOD3 + TMNMOD3 + VBFMRG5 +
##     VDPMRG5 + soilmap, data = datdf)
##
## Residuals:
##      Min        1Q    Median        3Q       Max
## -3.3625 -0.2637  0.0368  0.3111  1.8859
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) 9.166e+00 4.343e+00  2.111  0.03489 *
## B04CHE3    -5.877e-03 1.099e-03 -5.347 9.64e-08 ***
## B07CHE3     1.110e-01 3.460e-02  3.209  0.00135 **
## B13CHE3    -4.361e-03 1.640e-03 -2.659  0.00788 **
## DEMENV5    -1.882e-04 8.926e-05 -2.108  0.03508 *
```

```

## LCEE102    9.745e-02  3.369e-02   2.893  0.00385  **
## LCEE103    1.399e-01  5.490e-02   2.548  0.01088  *
## LCEE104    -3.612e-02  4.360e-02  -0.829  0.40741
## PRSCHE3    9.174e-04  3.139e-04   2.923  0.00350  **
## SLPMRG5    -2.440e-03  1.508e-03  -1.619  0.10559
## TMDMOD3    -5.584e-02  7.612e-03  -7.336  2.86e-13 ***
## TMNMOD3    2.467e-02  1.291e-02   1.911  0.05611 .
## VBFMRG5    4.941e-04  9.867e-05   5.008  5.84e-07 ***
## VDPMRG5    -2.696e-05  4.360e-06  -6.185  7.11e-10 ***
## soilmap2    -3.848e-01  4.885e-01  -0.788  0.43090
## soilmap3    -2.094e-01  4.825e-01  -0.434  0.66429
## soilmap4    -1.955e-01  4.886e-01  -0.400  0.68919
## soilmap5    -6.323e-02  5.202e-01  -0.122  0.90327
## soilmap6    2.087e-01  4.841e-01   0.431  0.66649
## soilmap7    1.459e-01  4.857e-01   0.300  0.76398
## soilmap8    -1.875e-01  4.848e-01  -0.387  0.69904
## soilmap9    -3.278e-01  4.817e-01  -0.681  0.49617
## soilmap10   -1.001e-01  4.833e-01  -0.207  0.83590
## soilmap11   -3.587e-01  4.874e-01  -0.736  0.46188
## soilmap12   -2.135e-01  4.822e-01  -0.443  0.65797
## soilmap13   3.091e-01  5.563e-01   0.556  0.57855
## soilmap14   -2.224e-01  4.828e-01  -0.461  0.64506
## soilmap15   -1.905e-01  4.876e-01  -0.391  0.69600
## soilmap16   -3.482e-01  4.831e-01  -0.721  0.47112
## soilmap17   -1.478e-01  4.838e-01  -0.306  0.75996
## soilmap18   -8.714e-02  4.830e-01  -0.180  0.85684
## soilmap19   -5.491e-01  5.082e-01  -1.080  0.28002
## soilmap20   -3.123e-01  4.846e-01  -0.644  0.51934
##
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.4806 on 2864 degrees of freedom
## Multiple R-squared:  0.2472, Adjusted R-squared:  0.2388
## F-statistic: 29.38 on 32 and 2864 DF,  p-value: < 2.2e-16
##
## Analysis of Variance Table
##
## Response: log(OCSKGM)
##             Df Sum Sq Mean Sq  F value    Pr(>F)
## B04CHE3     1 111.35 111.347 482.0082 < 2.2e-16 ***
## B07CHE3     1   2.33   2.335  10.1060  0.001494 **
## B13CHE3     1   1.64   1.642   7.1059  0.007726 **
## DEMENV5     1   5.07   5.067  21.9339 2.953e-06 ***
## LCEE10      3  17.22   5.740  24.8497 7.201e-16 ***
## PRSCHE3     1   4.91   4.910  21.2530 4.201e-06 ***
## SLPMRG5     1   1.97   1.971   8.5305  0.003520 **
## TMDMOD3     1   3.75   3.749  16.2300 5.756e-05 ***

```

```

## TMNMOD3      1   0.60   0.602   2.6081  0.106428
## VBFMRG5     1  12.75  12.750  55.1943 1.433e-13 ***
## VDPMRG5     1  10.80  10.797  46.7375 9.880e-12 ***
## soilmap      19  44.83   2.359  10.2135 < 2.2e-16 ***
## Residuals  2864 661.60    0.231
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```

In those two models above, we used all available points. It is important to test the performance of a model based upon an external validation. Let's fit a new model using a random subset of the available data. We will sample 70% of the SOC data for the model calibration data set.

```

# graphical diagnosis of the regression analysis
par(mfrow=c(2,2))
plot(model.MLR.step)

```

```

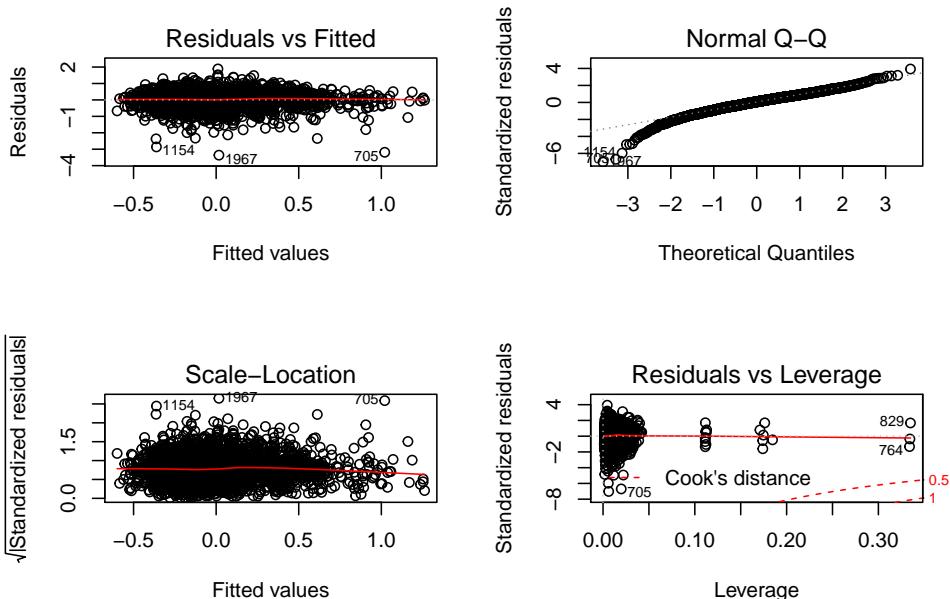
## Warning: not plotting observations with leverage one:
##       340

```

```

## Warning: not plotting observations with leverage one:
##       340

```



```
par(mfrow=c(1,1))
```

```

# collinearity test using variance inflation factors
library(car)
vif(model.MLR.step)

```

```

##          GVIF Df GVIF^(1/(2*Df))

```

```

## B04CHE3 17.352988 1      4.165692
## B07CHE3 17.580993 1      4.192969
## B13CHE3 14.463943 1      3.803149
## DEMENV5 14.325207 1      3.784866
## LCEE10   3.349841 3      1.223219
## PRSCHE3 20.323563 1      4.508166
## SLPMRG5  3.201225 1      1.789197
## TMDMOD3 6.724708 1      2.593204
## TMNMOD3 6.172634 1      2.484479
## VBFMRG5 4.182605 1      2.045142
## VDPMRG5 1.933334 1      1.390444
## soilmap 16.784795 19     1.077047

# problematic covariates should have sqrt(VIF) > 2
sqrt(vif(model.MLR.step))

```

```

##          GVIF      Df GVIF^(1/(2*Df))
## B04CHE3 4.165692 1.000000    2.041003
## B07CHE3 4.192969 1.000000    2.047674
## B13CHE3 3.803149 1.000000    1.950166
## DEMENV5 3.784866 1.000000    1.945473
## LCEE10   1.830257 1.732051    1.105992
## PRSCHE3 4.508166 1.000000    2.123244
## SLPMRG5 1.789197 1.000000    1.337609
## TMDMOD3 2.593204 1.000000    1.610343
## TMNMOD3 2.484479 1.000000    1.576223
## VBFMRG5 2.045142 1.000000    1.430085
## VDPMRG5 1.390444 1.000000    1.179171
## soilmap 4.096925 4.358899    1.037809

```

colinear: Temperature seasonality at 1 km (B04CHE3) and Temperature Annual Range [°C] at 1 km (B07CHE3)

```

# Removing B07CHE3 from the stepwise model:
model.MLR.step <- update(model.MLR.step, . ~ . - B07CHE3)

```

```

# Test the vif again:
sqrt(vif(model.MLR.step))

```

```

##          GVIF      Df GVIF^(1/(2*Df))
## B04CHE3 2.268418 1.000000    1.506127
## B13CHE3 3.624615 1.000000    1.903842
## DEMENV5 3.645817 1.000000    1.909402
## LCEE10   1.818077 1.732051    1.104762
## PRSCHE3 4.460815 1.000000    2.112064
## SLPMRG5 1.783090 1.000000    1.335324
## TMDMOD3 2.572322 1.000000    1.603846
## TMNMOD3 2.299838 1.000000    1.516522
## VBFMRG5 2.015123 1.000000    1.419550

```

```

## VDPMRG5 1.387165 1.000000          1.177780
## soilmap 3.840284 4.358899          1.036043

# summary of the new model using stepwise covariates selection
summary(model.MLR.step)

## 
## Call:
## lm(formula = log(OCSKGM) ~ B04CHE3 + B13CHE3 + DEMENV5 + LCEE10 +
##     PRSCHE3 + SLPMRG5 + TMMDMOD3 + TMNMOD3 + VBFMRG5 + VDPMRG5 +
##     soilmap, data = datdf)
## 
## Residuals:
##      Min    1Q Median    3Q   Max 
## -3.3857 -0.2662  0.0390  0.3096  1.9418 
## 
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)    
## (Intercept) 1.536e+01 3.896e+00 3.943 8.23e-05 ***
## B04CHE3    -2.919e-03 5.994e-04 -4.869 1.18e-06 ***
## B13CHE3    -5.955e-03 1.566e-03 -3.804 0.000146 *** 
## DEMENV5    -2.651e-04 8.612e-05 -3.079 0.002099 **  
## LCEE102    1.006e-01 3.373e-02 2.983 0.002879 **  
## LCEE103    1.250e-01 5.479e-02 2.281 0.022598 *   
## LCEE104    -2.756e-02 4.358e-02 -0.632 0.527224  
## PRSCHE3    1.063e-03 3.111e-04 3.417 0.000642 *** 
## SLPMRG5    -2.041e-03 1.505e-03 -1.356 0.175085  
## TMMDMOD3   -5.275e-02 7.563e-03 -6.974 3.80e-12 ***
## TMNMOD3    8.998e-03 1.197e-02 0.752 0.452305  
## VBFMRG5    4.401e-04 9.738e-05 4.519 6.47e-06 *** 
## VDPMRG5    -2.792e-05 4.357e-06 -6.410 1.70e-10 *** 
## soilmap2   -4.166e-01 4.892e-01 -0.852 0.394494  
## soilmap3   -1.925e-01 4.832e-01 -0.398 0.690372  
## soilmap4   -1.959e-01 4.894e-01 -0.400 0.688957  
## soilmap5   -6.440e-02 5.211e-01 -0.124 0.901641  
## soilmap6   2.098e-01 4.849e-01 0.433 0.665224  
## soilmap7   1.337e-01 4.865e-01 0.275 0.783490  
## soilmap8   -1.838e-01 4.856e-01 -0.379 0.705074  
## soilmap9   -3.376e-01 4.825e-01 -0.700 0.484097  
## soilmap10  -9.951e-02 4.841e-01 -0.206 0.837162  
## soilmap11  -3.570e-01 4.882e-01 -0.731 0.464661  
## soilmap12  -2.104e-01 4.830e-01 -0.436 0.663172  
## soilmap13  2.675e-01 5.570e-01 0.480 0.631148  
## soilmap14  -2.312e-01 4.836e-01 -0.478 0.632615  
## soilmap15  -1.733e-01 4.883e-01 -0.355 0.722668  
## soilmap16  -3.620e-01 4.839e-01 -0.748 0.454464  
## soilmap17  -1.564e-01 4.846e-01 -0.323 0.746854  
## soilmap18  -6.759e-02 4.837e-01 -0.140 0.888886

```

```

## soilmap19 -5.479e-01 5.090e-01 -1.076 0.281873
## soilmap20 -3.061e-01 4.853e-01 -0.631 0.528351
## ---
## Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.4814 on 2865 degrees of freedom
## Multiple R-squared: 0.2445, Adjusted R-squared: 0.2363
## F-statistic: 29.9 on 31 and 2865 DF, p-value: < 2.2e-16
# outlier test using the Bonferroni test
outlierTest(model.MLR.step)

##          rstudent unadjusted p-value Bonferonni p
## 1967      -7.114604     1.4122e-12   4.0897e-09
## 705       -6.795188     1.3108e-11   3.7959e-08
## 1154      -6.045856     1.6789e-09   4.8621e-06
## 1395      -5.112379     3.3907e-07   9.8194e-04
## 709       -5.078342     4.0515e-07   1.1733e-03
## 1229      -4.842237     1.3520e-06   3.9155e-03
## 1136      -4.468410     8.1860e-06   2.3707e-02

```

6.2.7.4 Prediction and Residual Kriging

Now we can make the predictions and plot the map. We can use either our DSM_data table for covariate values or `covs` object for making our prediction. Using `stack` avoids the step of arranging all covariates into a table format. If multiple rasters are being used, it is necessary to have them arranged as a `rasterStack` object. This is useful as it also ensures all the rasters are of the same extent and resolution. Here we can use the `raster predict` function such as below using the `covStack` raster stack as we created in the Step 3.

```

# Project point data.
dat <- spTransform(dat, CRS("+init=epsg:6204"))

# project covariates to VN-2000 UTM 48N
covs <- projectRaster(covs, crs = CRS("+init=epsg:6204"),
                       method='ngb')

covs$LCEE10 <- as.factor(covs$LCEE10)
covs$soilmap <- as.factor(covs$soilmap)

# Promote covariates to spatial grid dataframe. Takes some time and
# a lot of memory!
covs.sp <- as(covs, "SpatialGridDataFrame")
covs.sp$LCEE10 <- as.factor(covs.sp$LCEE10)
covs.sp$soilmap <- as.factor(covs.sp$soilmap)

## Checking if any bins have less than 5 points, merging bins when necessary...

```

```

## 
## Selected:
##   model      psill      range
## 1  Nug 0.16735323  0.000
## 2  Sph 0.06746394 6646.127
##
## Tested models, best first:
##   Tested.models kappa      SSerror
## 1          Sph    0 3.964233e-07
## 25         Ste   10 4.182590e-07
## 24         Ste    5 4.266696e-07
## 23         Ste    2 4.501717e-07
## 22         Ste   1.9 4.519816e-07
## 21         Ste   1.8 4.539405e-07
## 20         Ste   1.7 4.560649e-07
## 19         Ste   1.6 4.583753e-07
## 18         Ste   1.5 4.608930e-07
## 17         Ste   1.4 4.636455e-07
## 16         Ste   1.3 4.666616e-07
## 3          Gau    0 4.680499e-07
## 15         Ste   1.2 4.699776e-07
## 14         Ste   1.1 4.736337e-07
## 13         Ste    1 4.776785e-07
## 12         Ste   0.9 4.821684e-07
## 11         Ste   0.8 4.871689e-07
## 10         Ste   0.7 4.927610e-07
## 9          Ste   0.6 4.990387e-07
## 2          Exp    0 5.061150e-07
## 8          Ste   0.5 5.061153e-07
## 7          Ste   0.4 5.141265e-07
## 6          Ste   0.3 5.232363e-07
## 5          Ste   0.2 5.336428e-07
## 4          Ste   0.05 1.148336e-06
## [using universal kriging]

#### RK model
library(automap)

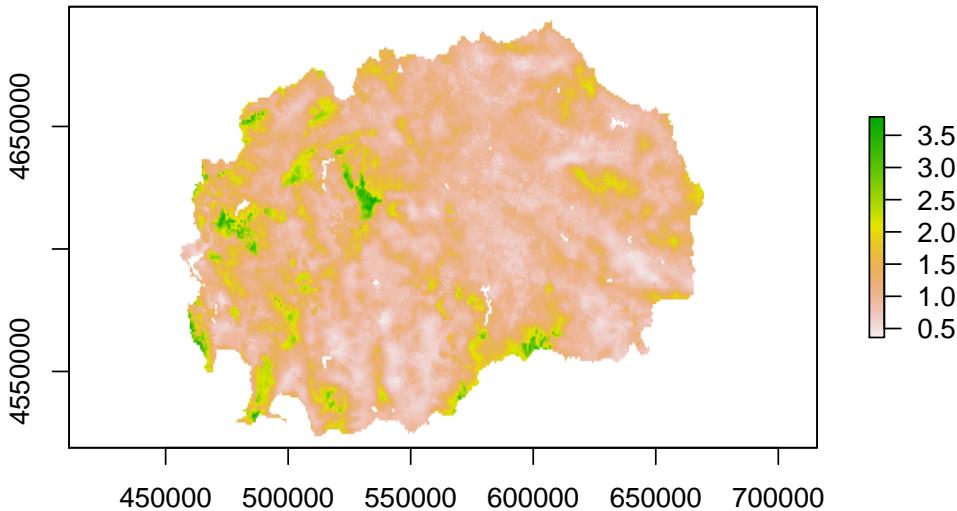
## Run regression kriging prediction. This step can take hours...!
OCS.krige <- autoKrigie(formula =
                           as.formula(model.MLR.step$call$formula),
                           input_data = dat,
                           new_data = covs.sp,
                           verbose = TRUE,
                           block = c(1000, 1000))

```

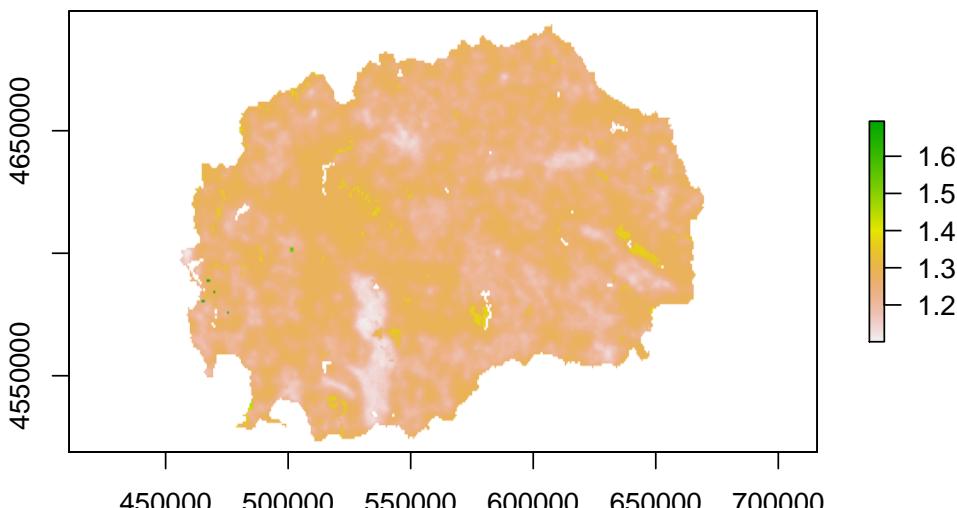
```
OCS.krige
```

```
## Convert prediction and standard deviation to rasters
## And back-transform the values
RKprediction <- exp(raster(OCS.krige$krige_output[1]))
RKpredsd <- exp(raster(OCS.krige$krige_output[3]))

plot(RKprediction)
```



```
plot(RKpredsd)
```



```
## Save results as tif files
writeRaster(RKprediction, filename = "results/MKD_OCSKGM_RK.tif",
            overwrite = TRUE)
```

```
writeRaster(RKpredsd, filename = "results/MKD_OCSKGM_RKpredsd.tif",
            overwrite = TRUE)

# save the model
saveRDS(model.MLR.step, file="results/RKmodel.Rds")
```

6.2.8 Technical Steps - Cross-validation of Regression Kriging models

Cross-validation is introduced in Section 7.4.3. In Regression-Kriging models, n-fold cross-validation and leave-one-out cross-validation can be run using the `krige.cv()` included in `gstat` R package. In this example, we will apply 10 fold cross-validation to our RK model.

```
OCS.krige.cv <- autoKrige.cv(formula =
                                as.formula(model.MLR.step$call$formula),
                                input_data = dat, nfold = 10)

summary(OCS.krige.cv)

##                [,1]
## mean_error  0.004726
## me_mean     -0.3918
## MAE         0.3402
## MSE         0.2692
## MSNE        0.9504
## cor_obsprd 0.4471
## cor_predres -0.3132
## RMSE        0.5188
## RMSE_sd     0.9418
## URMSE       0.5188
## iqr         0.5223
```

6.3 Data mining: Random Forest

M Guevara, C Thine, GF Olmedo & RR Vargas

6.3.1 Overview

Data mining uses different forms of statistics, such as machine learning, to explore data matrices for a particular situation, from specific information sources, and with a specific objective. Data mining is used in digital soil mapping frameworks to generate spatial and temporal predictions of soil properties or classes in places where no information is available. Under a data mining-based digital soil mapping framework, the exploration of statistical relationships (linear and non-linear) between soil observational data and soil environmental predictors is generally performed by the means of machine learning. Machine learning methods represent a branch of statistics that can be used to automatically extract information from available data, including the non-linear and hidden relationships of high dimensional spaces or hyper-volumes of information when high performance or distributed computing resources are available. Machine learning methods do not rely on statistical assumptions about the spatial structure of soil variability or the empirical relationship of soil available data and its environmental predictors. Therefore machine learning methods are also suitable for digital soil mapping under limited and sparse scenarios of data availability, although in practice the statistical performance of machine learning (or any statistical method) is reduced by a low representativeness of a soil property or class in the statistical space given available data. Machine learning methods can be used for (supervised and unsupervised) regression (e.g., predicting soil organic carbon) or classification (e.g., predicting soil type classes) on digital soil mapping. Machine learning methods can be roughly divided into four main groups: linear-based (e.g., multiple linear regression), kernel-based (e.g., kernel weighted nearest neighbors or support vector machines), probabilistic-based (e.g., Bayesian statistics) and tree-based (e.g., classification and regression trees). Random forest is a tree-based machine learning algorithm that is popular on digital soil mapping because it has proven to be efficient mapping soil properties across a wide range of data scenarios and scales of soil variability. Random forest can be implemented using open source platforms and this chapter is devoted to provide a reproducible example of this machine learning algorithm applied to soil organic carbon mapping across Macedonia.

6.3.2 Random forests

Random forest is a Decision-tree-based machine learning method used in digital soil mapping for uncovering the statistical relationship between a dependent variable (e.g., soil property) and its predictors. Decision-tree-based models (also known as classifiers) are literally like trees (e.g., with stem, many branches, and leaves). The leaves are the prediction outcomes (final decisions) that flow from higher levels based on decision rules through the stem and the branches (Breiman et al.,

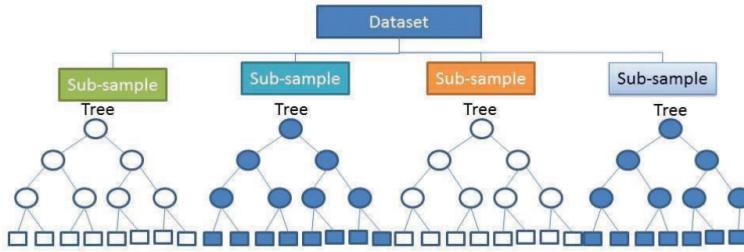


Figure 6.12: Schematic representation of data splitting data to generate the random subsets used to train regression trees within a Random forest model (ensemble of regression trees)

1984). The decision tree model recursively splits the data into final uniform groups (classes) or unique values based on a set of rules (e.g., based on probability values and hypothesis testing). In random forest, there are many decision trees and each tree recursively splits randomly selected sub-samples from the data (Figure 6.12). The name random forest originates from the fact that the original data is first randomly split into sub-samples, and many decision trees (or forest) are used to model the sub-samples.

Random forest has been tested by many researchers on digital soil mapping (see for example Poggio et al. (2013); Rad et al. (2014), and references therein). For soil carbon mapping (which for large areas usually rely on sparse datasets), it holds a lot of promises when compared to other prediction models, because it's practically free of assumptions. Random Forest has shown accuracy of spatial predictions and, given the random selection of subsets and prediction factors, reduce potential over-fitting and data noise (Wiesmeier et al., 2011). Over-fitting and data noise are important uncertainty sources across high dimensionally spaces used to represent the soil forming environment. Thus, the advent of open-source platforms and freely downloadable ancillary data (e.g., worldgrids.org) to represent the soil forming environment makes of random forest and other such models increasingly appealing on digital soil mapping.

To predict continuous data (such as carbon density) Random forest generates an averaged ensemble of regression trees based on bagging, which is the statistical term for the random selection of subsets and predictors to generate each regression tree. Bagging is a bootstrapping aggregation technique where each sample is different from the original data set but resembles it in distribution and variability (Breiman, 1996, 2001). Each tree contributes to weight the statistical relationship between a dependent variable (e.g. soil property) and its prediction factors (e.g., terrain attributes, remote sensing, climate layers and/or legacy maps). Each tree (generated using a different subset of available data and random combinations of the prediction factors) is internally evaluated by an out-of-bag cross validation form which allows assessing the relative importance of the available prediction factors. Thus, higher weight is given to the most accurate trees (which use the most informative prediction factors). The final prediction of new data is the weighted

average of all generated trees. This method has been used to generate accurate predictions of soil organic carbon from the plot to the global scale and also in a country-specific basis (Hengl et al., 2014; Bonfatti et al., 2016; Hengl et al., 2017; Guevara et al., 2018). Random forest can be implemented for digital soil mapping using open source code (e.g., the R package of random forest, see Breiman, 2017) and public sources of environmental information. The objective of this chapter is to demonstrate a reproducible framework for the implementation of the Random forest algorithm applied for soil organic carbon predictive mapping, including the uncertainty of model estimates and using open source platforms for statistical computing.

6.3.3 Conceptual model and data preparation

To use Random forest for digital soil organic carbon mapping the SCORPAN (Soils, Climate, Organisms, Relief, Parent material, Age and N space) conceptual model (McBratney et al., 2003; Florinsky, 2012) will have take the following form: $SOC_{x,y,t} \sim \text{randomForest}(E_{x,y,t})$ where soil organic carbon estimates (*SOC*) for a specific site (*x,y*) and for a specific period of time (~*t*) can be modeled as a Random forest (*randomForest*) function of the soil forming environment (*E* *x,y,t*), which is represented by the *SOC* prediction factors (e.g., terrain attributes, remote sensing, climate layers and/or legacy maps). To feed the right side of the equation, $SOC_{x,y,t}$ is usually represented in a tabular form or a geospatial object (e.g., shapefile) with three fundamental columns. Two columns represent the spatial coordinates x and y (e.g., latitude and longitude) that are used to extract the values of the prediction factors for the representative locations of the *SOC* estimates. *SOC* estimates are represented in a third column (see previous chapters of this book dealing with the transformation of soil carbon density to mass units). The left side of the equation is generally represented by gridded (raster) files, so all available sources of information should be first harmonized into a common pixel size and coordinate reference system.

6.3.4 Software

For the Random Forest implementation, we will use the platform for statistical computing R (R Core Team, 2016). This is an open source object-oriented software that relies on specific-contributor libraries. There are several libraries for the implementation of the Random forest algorithm in R as well as several variants of the method that can be used to solve digital soil mapping problems. In this section, we will show the use of Random forest using the *randomForest*, the *quantregForest*, the *raster* and the *caret* R packages. The quantile regression forest (*quantregForest*; (Meinshausen, 2006)) has two main advantages. First, it can be used to extract the variance of all the trees generated by Random forest, not just the mean (as in the original *randomForest* package), and therefore we can calculate the dispersion of the full conditional distribution of SOC as a function of the prediction factors, which given available data, represent the Random forest

model uncertainty. Second, the quantile regression forest approach can also run in parallel using all available computational resources, in a way that we can predict and estimate the uncertainty of predictions at reasonable time frames with large datasets.

6.3.5 Tuning Random forest parameters

Two important parameters of Random forest are mtry and ntree. The mtry parameter controls the number of prediction factors that are randomly used on each tree, while the ntree parameter controls the number of trees generated by Random forest. These two parameters can be selected by the means of cross-validation to maximize the prediction capacity of Random forest. We will use the caret package to select the most appropriate values for these parameters using 10-fold cross-validation (Kuhn et al. 2017). Tuning the main parameters of Random forest (or any other model) can be time-consuming in computational terms because implies the need to run and internally validate an independent model for each possible combination of parameter values. Thus, tuning the Random forest parameters would be relevant, given available data, to achieve the best possible accuracy of predictions.

6.3.6 Technical steps - Random forest

We will use the Macedonia dataset for this exercise (see previous chapters of this book dealing with data preparation). The first dataset contains in a tabular form the *OCSKGM* values and the values of the prediction factors for the same locations (e.g., x, y, *OCSKGM*, covariate1, covariate2...) while the second database is represented by a stack of raster files containing prediction factors across all the area of interest at the spatial resolution of 0.0083° (approx. 1km). Import the datasets and load in R all our libraries of interest.

6.3.6.1 Data Preparation

Point Dataset

We previously applied spline function to produce continuous soil information to a given soil depth (0-30 cm) in section 3.4.1. Spline function basically imports soil profile data (including instances where layers are not contiguous), fits it to a mass-preserving spline and outputs attribute means for a given depth. The output file should contain profile id, upper (surface) and lower depth (30cm), the estimated value for the selected soil attribute (Value) and tmse (estimated mean squared error of the spline). If you used the Spline Tool V2, the coordinates were not kept in the output file. The coordinates should be added back in the data table. You can use Profile IDs to add the X, Y columns back. Once your point dataset is ready, copy this table into your working directory as a .csv file.

Environmental Predictors (Covariates)

In the Chapter 5, we presented and prepared several global and continental data sets. In addition to these datasets, numerous covariate layers have been prepared by ISRIC for the GSOC Map project. These are GIS raster layers of various biophysical earth surface properties for each country in the world. Some of these layers will be used as predictors in this section. Please download the covariates for your own study area from GSOCMap Data Repository as explained in Section 5.6.

In section 5.9, a table with the points values after data preparation and the values of our spatial predictors was prepared. This step involves loading this table.

Now we will import our point dataset using `read.csv()` function. The easiest way to create a data frame is to read in data from a file—this is done using the function `read.csv`, which works with comma delimited files. Data can be read in from other file formats as well, using different functions, but `read.csv` is the most commonly used approach. R is very flexible in how it reads in data from text files (`read.table`, `read.csv`, `read.csv2`, `read.delim`, `read.delim2`). Please type `?read.table()` for help.

```
# load data
dat <- read.csv("data/MKD_RegMatrix.csv")

dat$LCEE10 <- as.factor(dat$LCEE10)
dat$soilmap <- as.factor(dat$soilmap)

# explore the data structure
str(dat)

## 'data.frame': 2897 obs. of 23 variables:
## $ id      : Factor w/ 2897 levels "P0003","P0007",...: 1 2 3 4...
## $ Y       : num  42 42 42.1 42 42 ...
## $ X       : num  20.8 20.8 20.8 20.9 20.9 ...
## $ SOC     : num  26.38 6.15 3.94 3.26 2.29 ...
## $ BLD     : num  0.73 1.17 1.3 1.34 1.41 ...
## $ CRFVOL  : num  8 18.6 31.9 21.7 14.5 ...
## $ OCSKGM  : num  5.32 1.75 1.04 1.03 0.83 ...
## $ meaERROR : num  2.16 2.85 2.65 3.16 3.63 2.83 2.94 2.49 2.77...
## $ OCSKGMlog: num  1.6712 0.5591 0.0429 0.0286 -0.1862 ...
## $ B04CHE3 : num  574 553 693 743 744 ...
## $ B07CHE3 : num  38.5 37.8 42.1 43.7 43.7 ...
## $ B13CHE3 : num  111.6 125 99.8 118.1 121 ...
## $ B14CHE3 : num  59.2 60.3 42.4 39.9 38.7 ...
## $ DEMENV5 : int  2327 2207 1243 1120 1098 1492 1413 1809 1731...
## $ LCEE10  : Factor w/ 4 levels "1","2","3","4": 1 3 2 1 2 2 2...
## $ PRSCHE3 : num  998 1053 780 839 844 ...
## $ SLPMRG5 : int  13 36 6 25 30 24 15 17 20 43 ...
## $ TMDMOD3 : int  282 280 285 288 289 287 286 286 287 286 ...
## $ TMNMOD3 : int  272 270 277 279 279 277 277 273 274 273 ...
## $ TWIMRG5 : int  61 62 81 66 65 72 68 67 65 59 ...
```

```
## $ VBFMRG5 : int 0 0 14 0 0 0 0 0 0 0 ...
## $ VDPMRG5 : int 311 823 10048 1963 -173 -400 -9 -692 -1139 2 ...
## $ soilmap : Factor w/ 20 levels "1","2","3","4",...: 6 14 14 3 ...
```

Since we will be working with spatial data we need to define the coordinates for the imported data. Using the `coordinates()` function from the `sp` package we can define the columns in the data frame to refer to spatial coordinates—here the coordinates are listed in columns X and Y.

```
library(sp)

# Promote to SpatialPointsDataFrame
coordinates(dat) <- ~ X + Y

class(dat)

## [1] "SpatialPointsDataFrame"
## attr(,"package")
## [1] "sp"
```

`SpatialPointsDataFrame` structure is essentially the same data frame, except that additional “spatial” elements have been added or partitioned into slots. Some important ones being the bounding box (sort of like the spatial extent of the data), and the coordinate reference system `proj4string()`, which we need to define for the sample dataset. To define the CRS, we must know where our data are from, and what was the corresponding CRS used when recording the spatial information in the field. For this data set, the CRS used was: WGS84 (EPSG:4326).

To clearly tell R this information we define the CRS which describes a reference system in a way understood by the [PROJ.4 projection library](#). An interface to the PROJ.4 library is available in the `rgdal` package. As an alternative to using Proj4 character strings, we can use the corresponding yet simpler EPSG code (European Petroleum Survey Group). `rgdal` also recognizes these codes. If you are unsure of the Proj4 or EPSG code for the spatial data that you have but know the CRS, you should consult <http://spatialreference.org/> for assistance.

Please also note that, when working with spatial data, it’s very important that the CRS (coordinate reference system) of the point data and covariates are the same.

Now, we will define our CRS:

```
dat@proj4string <- CRS(projargs = "+init=epsg:4326")

dat@proj4string

## CRS arguments:
## +init=epsg:4326 +proj=longlat +datum=WGS84 +no_defs
## +ellps=WGS84 +towgs84=0,0,0
```

Now we will import the covariates. When the covariate layers are in common resolution and extent, rather than working with individual rasters it is better to

stack them all into a single R object. In this example, we use 13 covariates from the GSOCMap Data Repository and a rasterized version of the soil type map. The rasterization of vectorial data was covered in [Technical Steps - Rasterizing a vector layer in R](#). The file containing all the covariates was prepared at the end of chapter 5.

```
load(file = "covariates.RData")
names(covs)

## [1] "B04CHE3" "B07CHE3" "B13CHE3" "B14CHE3" "DEMENV5" "LCEE10"
## [7] "PRSCHE3" "SLPMRG5" "TMDMOD3" "TMNMOD3" "TWIMRG5" "VBFMRG5"
## [13] "VDPMRG5" "soilmap"
```

Random forest does not have assumptions about the statistical distribution of the response variable, but it is a good practice prior to model building to analyze the statistical distribution of the response variable (e.g., if is normal or not) and its relationships with the prediction factors. Soil organic carbon tends to have a log-normal distribution with a right-skew, and transforming the original values to its natural logarithm would generate a normal distribution of soil organic carbon values. For further analysis, we will use the dataset transformed to its natural logarithm (*OCSKGMlog*) because this transformation, given this dataset, increases the correlation of the response variable and the covariate space.

Keep in mind that selecting the most appropriate prediction factors is required to generate an interpretable model and high accuracy of prediction in places where no information is available. Variable selection ideally should incorporate expert soil knowledge about the study area and statistical criteria (e.g., just to use the best-correlated predictors). Multivariate analysis (e.g., principal component analysis) is a widely used approach to identify informative predictors. Here we use this combination of prediction factors to be consistent with other book chapters and because they were previously selected for this exercise using expert knowledge about the spatial variability of soil organic carbon. Now, we will build a working hypothesis from our conceptual model, using all the continuous prediction factors for *OCSKGMlog*:

OCSKGMlog ~ randomForest *B04CHE3 + B07CHE3 + B13CHE3 + B14CHE3 + DEMENV5 + LCEE10 + PRSCHE3 + SLPMRG5 + TMDMOD3 + TMNMOD3 + TWIMRG5 + VBFMRG5 + VDPMRG5*

```
# For its use on R we need to define a model formula
fm = as.formula(paste("log(OCSKGM) ~", paste0(names(covs)[[-14]], collapse = "+")))
```

This is the R syntax to define a model formula required for the model structure, where soil organic carbon transformed to its natural logarithm (*OCSKGMlog*) can be predicted as a function of the available prediction factors (each explained in previous chapters of this book, e.g., *B04CHE3*, *B07CHE3*, *B13CHE3*, *B14CHE3*, *DEMENV5*, *LCEE10*, *PRSCHE3*, *SLPMRG5*, *TMDMOD3*, *TMN-*

MOD3, TWIMRG5, VBFMRG5, VDPMRG5).

Note that the variable soilmap is categorical, so is not included in the correlation analysis. In fact, although soil type polygon maps are in theory powerful predictors for *OCSKGM* we will not use this map for this exercise, because not all categories in the map are represented by available *OCSKGM* estimates, therefore this map requires a generalization of soil type units in function of the classes represented by the sites of *OCSKGM* estimates, which is beyond the scope of this chapter. Ideally, the number of observations across all the categories of soil type or any other factorial variable should be balanced. Another alternative to using an unbalanced categorical map is by generating dummy variables, where each category in the map becomes an independent binomial predictor variable (e.g., only 0 and 1 values) as is explained in the following chapter. The risk of doing so rely upon the potential underestimation of the spatial variability of the target variable under each category with a low density of available data.

6.3.6.2 Tuning parameters

Now we will use the cross-validation strategy implemented in the train function of the caret package (Kuhn et al. 2017), which default is 10-fold. The result of this function includes information to select the best mtry parameter and to decide the appropriate number of trees. The out-of-bag root mean squared error (rmse) will be used to select the optimal mtry model. To analyze the ntree parameter we will plot the number of trees against the out-of-bag rmse, an optimal ntree can be selected with the number of trees when these relationships stabilizes at the minimum possible rmse (in the y axis). Reducing the number of trees will reduce the computational demand, which is specially important when dealing with large databases. In the presence of multidimensional and highly correlated prediction factors, avoiding an excessive number of trees will also reduce the risk of model overfitting.

```
library(randomForest)
library(caret)

# Default 10-fold cross-validation
ctrl <- trainControl(method = "cv", savePred=T)
# Search for the best mtry parameter
rfmodel <- train(fm, data=dat@data, method = "rf", trControl = ctrl,
                  importance=TRUE)
# This is a very useful function to compare and test different
# prediction algorithms. Type names(getModelInfo()) to see all the
# possibilities implemented on this function
```

The object derived from the train function can be used to generate predictions of OCSKGMlog at the spatial resolution of the prediction factors. Before generating predictions, we will plot the most important predictors sorted in decreasing order of importance. From the variable importance plot, %IncMSE represent an infor-

`rfmodel[11][[1]]`

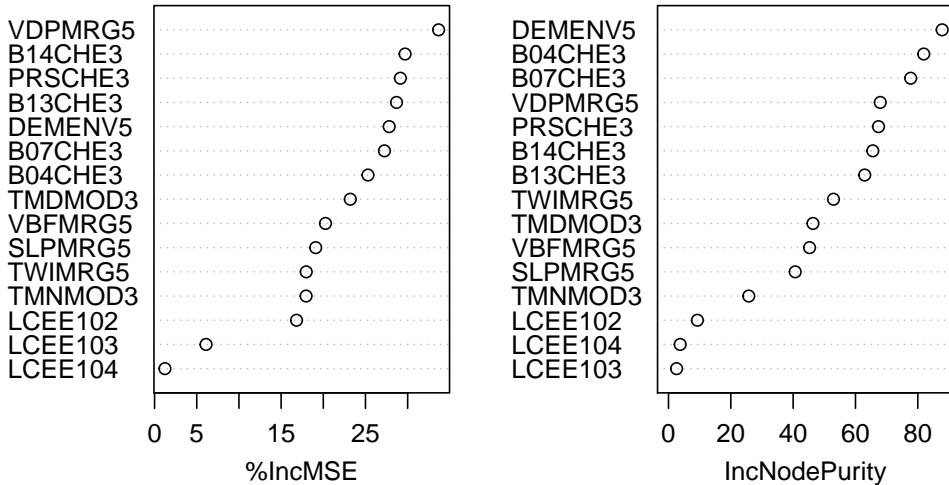


Figure 6.13: Model Decreasing Error and Node Purity

mative measure for variable selection. It is the increase in error (mean squared error, MSE) of predictions which was estimated with out-of-bag-cross validation as a result of prediction factor being permuted with values randomly shuffled. This is one of the strategies that Random forest uses to reduce overfitting.

```
# Variable importance plot, compare with the correlation matrix
# Select the best prediction factors and repeat
varImpPlot(rfmodel[11][[1]])

# Check if the error stabilizes
plot(rfmodel[11][[1]])
```

Random forest users are encouraged to compare and test the prediction capacity of different combinations of prediction factors in order to reduce the complexity of the model and the statistical redundancy of environmental information on further applications of predicted OCSKGM maps (e.g., quantifying the carbon dynamics). The resulting map of our Random forest model needs to be validated using the independent dataset to complement the results of the cross-validation (e.g., rmse and explained variance) derived using the train function and to have a more comprehensive interpretation of accuracy and bias. Note how the rmse and the explained variance derived from the independent validations are slightly lower than the values obtained using cross-validation.

rfmodel[11][[1]]

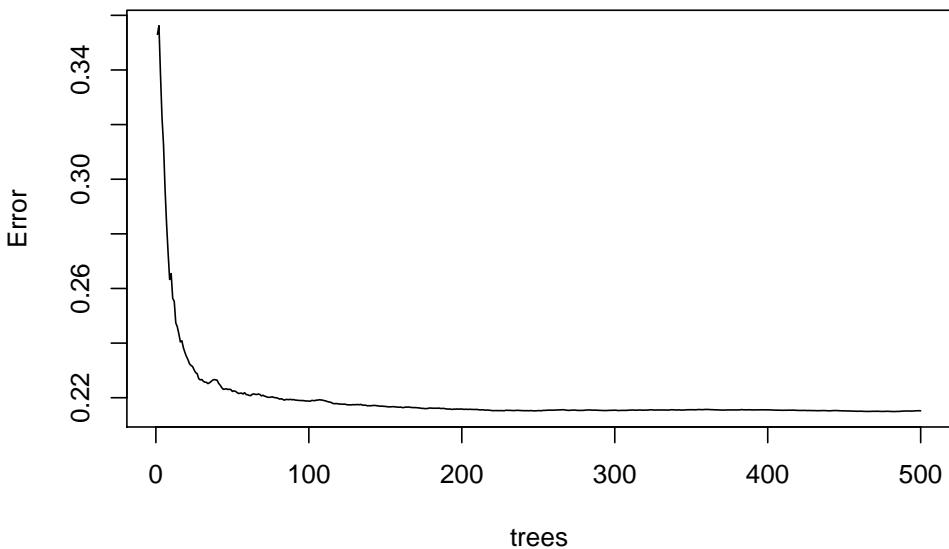


Figure 6.14: select ntree

```
#Make a prediction across all Macedonia
#Note that the units are still in log
pred <- predict(covs, rfmodel)

## Warning in .local(object, ...): not sure if the correct factor
## levels are used here

# Back transform predictions log transformed
pred <- exp(pred)

# Save the result as a tiff file
writeRaster(pred, filename = "results/MKD_OCSKGM_rf.tif",
            overwrite=TRUE)

plot(pred)
```

6.3.7 Modelling Uncertainty Using Random Forest

Ideally, a digital soil map should include a spatial explicit metric of uncertainty. The uncertainty can be roughly divided into four main components, uncertainty in soil data, uncertainty in soil covariates, uncertainty in the model and uncertainty in

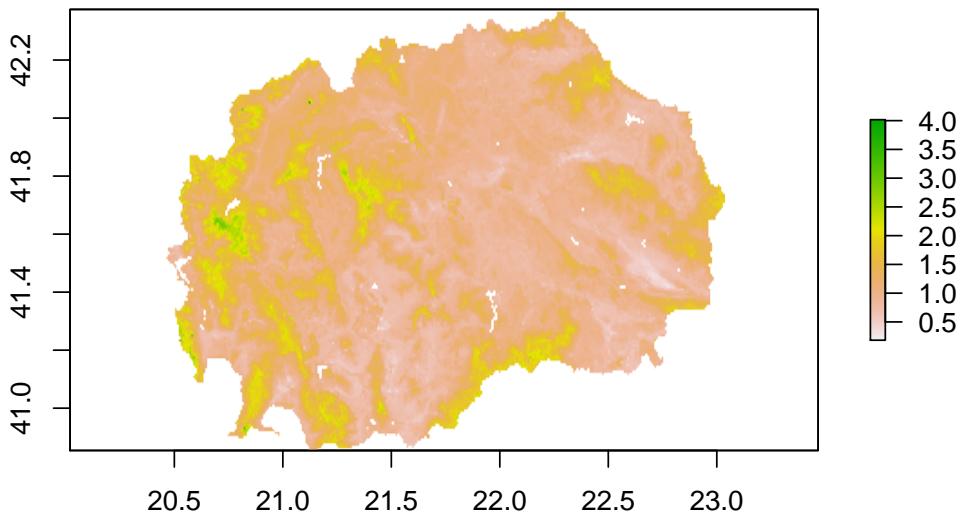


Figure 6.15: SOC prediction using a randomForest model

variations of available data. Here, we show an approach to estimate the sensitivity of the model to available data and the uncertainty of the model. The first two are beyond of the aim of this chapter. For the third and fourth we will generate a reproducible example.

6.3.7.1 Technical steps - Using Quantile Regression Forest to estimate uncertainty

To analyze the sensitivity of the model to available data we need to randomly split the data several times (e.g., 10 or more, is possible until the variance stabilizes) in training and testing subsets. A model generation and prediction are made on each split, in a way that the dispersion of the predicted values at the pixel level will represent the uncertainty and the sensitivity of the model to variations in available data. This process increases computational demand and memory since it will repeat n times (10 in this example) the model and the prediction using each time a different random combination of data for training and testing the models. As larger the sample and the number of realizations the more robust our validation strategy. For this example, we will use only 10 realizations and random splits of 25% of available data. The validation plot shows the regression line between observed and predicted of a model that uses 75% (black line) and the regression lines of 10 model realizations, each with a different random combination of data for training and validating the models. The rmse and the explained variance of the models is stored in the object validation (type `summary(validation)`). The standard deviation of all the ten predictions allows generating a map of model sensitivity to available data.

```

#Generate an empty dataframe
validation <- data.frame(rmse=numeric(), r2=numeric())
#Sensitivity to the dataset
#Start a loop with 10 model realizations
for (i in 1:10){
  # We will build 10 models using random samples of 25%
  smp_size <- floor(0.25 * nrow(dat))
  train_ind <- sample(seq_len(nrow(dat)), size = smp_size)
  train <- dat[train_ind, ]
  test <- dat[-train_ind, ]
  modn <- train(fm, data=train, method = "rf", trControl = ctrl)
  pred <- stack(pred, predict(covariates, modn))
  test$pred <- predict(modn[11][[1]], test)
  # Store the results in a dataframe
  validation[i, 1] <- rmse(test$OCSKGMlog, test$pred)
  validation[i, 2] <- cor(test$OCSKGMlog, test$pred)^2
}

#The sensitivity map is the dispersion of all individual models
sensitivity <- calc(pred[[-1]], sd)

plot(sensitivity, col=rev(topo.colors(10)),
      main='Sensitivity based on 10 realizations using 25% samples')

#Sensitivity of validation metrics
summary(validation)

# Plot of the map based on 75% of data and the sensitivity to data
# variations
prediction75 <- exp(pred[[1]])

plot(prediction75, main='OCSKGM prediction based on 75% of data',
      col=rev(topo.colors(10)))

```

Finally, we will estimate the model uncertainty, represented by the full conditional distribution of the response variable (OCSKGMlog) as a function of the selected prediction factors using the quantile regression forest package of R. This approach has proven to be efficient for digital soil mapping across large areas (Vaysse and Lagacherie, 2017).

```

# Use quantile regression forest to estimate the full conditional
# distribution of OCSKGMlog, note that we are using the mtry
# parameter that was selected by the train function of the caret
# package, assuming that the 75% of data previously used well
# resembles the statistical distribution of the entire data
# population. Otherwise, repeat the train function with all available
# data (using the object dat that instead of train) to select mtry.

```

```
model <- quantregForest(y=dat$OCSKGMlog, x=dat[,1:13], ntree=500,
                         keep.inbag=TRUE, mtry = as.numeric(mod$bestTune))
```

This method will calculate a probability distribution function for each pixel and therefore can be time-consuming. Therefore we will run it using parallel computing. Note that the code to run in parallel this analysis can also be passed to the previous predictions (predict function). The result will be a map of the standard deviation of the distribution calculated for each pixel, which represents the extreme values that a prediction can take for a specific site (e.g., pixel) given available data and predictors. Note that this analysis is performed using all available data and a second map of OCSKGM is created. Our final prediction uses all available data, while the total uncertainty (in percent) is represented by the sum of the quantile regression forest standard deviation and the sensitivity map from the previous section. The total uncertainty is then divided by the prediction to obtain a percent map, which is easier to interpret.

```
library(snow)
# Estimate model uncertainty at the pixel level using parallel
# computing
beginCluster() #define number of cores to use
# Estimate model uncertainty
unc <- clusterR(covariates, predict, args=list(model=model,what=sd))
# OCSKGMlog prediction based in all available data
mean <- clusterR(covariates, predict,
                   args=list(model=model, what=mean))
# The total uncertainty is the sum of sensitivity and model
# uncertainty
unc <- unc + sensitivity
# Express the uncertainty in percent (divide by the mean)
Total_unc_Percent <- exp(unc)/exp(mean)
endCluster()

# Plot both maps (the predicted OCSKGM + its associated uncertainty)
plot(exp(mean), main='OCSKGM based in all data',
      col=rev(topo.colors(10)))

plot(Total_unc_Percent, col=rev(heat.colors(100)), zlim=c(0, 5),
      main='Total uncertainty')
```

Finally, the predicted OCSKGM and the total uncertainty can be saved in the working directory in a generic (*.tif) raster format.

```
#Save the resulting maps in separated *.tif files
writeRaster(exp(mean), file='rfOCSKGMprediction.tif',
            overwrite=TRUE)
writeRaster(Total_unc_Percent, file='rfOCSKGMtotalUncertPercent.tif',
            overwrite=TRUE)
```

We have created two maps in the working directory, one represents the predicted OCSKGM and the second one its uncertainty, which is the sum of the model sensitivity to data variations and the full conditional distribution of the response variable as a function of available prediction factors. The following chapters of this book will show you how to prepare a stock report based on this soil carbon digital soil maps.

6.4 Data mining: Support Vector Machines

GF Olmedo & M Guevara

6.4.1 Overview

Support vector machines (svm) is a kernel-based machine learning technique suitable for mapping SOC. svm use decision surfaces (defined by a kernel function) to map non-linear relationships across a high-dimension induced feature space (Cortes and Vapnik 1995, Machine Learning,20, 273-297). svm is widely used to perform classification and regression analysis on digital soil mapping. According to Pedregosa et al. (2011) the advantages of svm are:

- Effective in high dimensional spaces.
- Still effective in cases where the number of dimensions is greater than the number of samples.
- Uses a subset of training points in the decision function (called support vectors), so it is also memory efficient.
- Versatile: different Kernel functions can be specified for the decision function. Common kernels are provided, but it is also possible to specify custom kernels.

And the disadvantages of svm include:

- If the number of features is much greater than the number of samples, avoid over-fitting in choosing Kernel functions and regularization term is crucial.
- svm do not directly provide probability estimates, these are calculated using an expensive five-fold cross-validation.

In digital soil mapping, the problems usually involve working in high dimensional spaces (were the dimensions are the covariates) with a limited number of samples. svm is a technique mostly used in classification problems, but it can be used to solve regression problems, such as modeling the continuous variability of SOC using environmental covariates. When svm is used to solve regression problem is called support vector regression.

Support vector regression applies a simple linear method to the data but in a high-dimensional feature space non-linearly related to the input space. It creates n hyperplanes through the n-dimensional spectral-space and each hyperplanes separates numerical data based on a kernel function (e.g., Gaussian). svm uses parameters such as gamma, cost and epsilon. These parameters are used to define the shape of the hyperplane, including the margin from the closest point to the hyperplane that divides data with the largest possible margin and defines the tolerance to errors on each single training. Linear models are fitted to the support vectors and used for prediction purposes. The support vectors are the points which fall within each hyperplane (Guevara et al., 2018).

In the example below, we will use the implementation of svm in the R package e1071 (Meyer et al., 2017). The package e1071 offers an interface to the award-

winning C++ implementation by Chih-Chung Chang and Chih-Jen Lin, libsvm (current version: 2.6). For further implementation details on libsvm, see [Chang and Lin \(2001\)](#).

svm is a broad research area and for a better understanding of the mathematical background we can recommend the following books: [Vapnik \(2013\)](#), [Friedman et al. \(2001\)](#), and [James et al. \(2013\)](#).

6.4.2 Technical Steps - Fitting an SVM Model to Predict the SOC

6.4.2.1 Setting Working Space and Initial Steps

One of the first steps should be setting our working directory. If you read/write files from/ to disk, this takes place in the working directory. If we don't set the working directory we could easily write files to an undesirable file location. The following example shows how to set the working directory in R to our folder which contains data for the study area (point data, covariates).

Note that we must use the forward slash / or double backslash \\ in R! Single backslash \ will not work. Now we can check if the working directory has been correctly set by using the function:

```
getwd()
```

6.4.2.2 Data Preparation

Point Dataset

We previously applied spline function to produce continuous soil information to a given soil depth (0-30 cm) in the section [3.4.1](#). Spline function basically imports soil profile data (including instances where layers are not contiguous), fits it to a mass-preserving spline and outputs attribute means for a given depth. The output file should contain profile id, upper (surface) and lower depth (30cm), estimated value for the selected soil attribute (Value) and tmse (estimated mean squared error of the spline). If you used the Spline Tool V2, the coordinates were not kept in the output file. The coordinates should be added back in the data table. You can use Profile IDs to add the X, Y columns back. Once your point dataset is ready, copy this table into your working directory as a .csv file.

Environmental Predictors (Covariates)

In the Chapter [5](#), we presented and prepared several global and continental datasets. In addition to these datasets, numerous covariate layers have been prepared by ISRIC for the GSOC Map project. These are GIS raster layers of various biophysical earth surface properties for each country in the world. Some of these layers will be used as predictors in this section. Please download the

covariates for your own study area from GSOCMap Data Repository as explained in Section 5.6.

In section 5.9, a table with the points values after data preparation and the values of our spatial predictors was prepared. This step involves loading this table.

Now we will import our point dataset using `read.csv()` function. The easiest way to create a data frame is to read in data from a file—this is done using the function `read.csv`, which works with comma delimited files. Data can be read in from other file formats as well, using different functions, but `read.csv` is the most commonly used approach. R is very flexible in how it reads in data from text files (`read.table`, `read.csv`, `read.csv2`, `read.delim`, `read.delim2`). Please type `?read.table()` for help.

```
# load data
dat <- read.csv("data/MKD_RegMatrix.csv")

dat$LCEE10 <- as.factor(dat$LCEE10)
dat$soilmap <- as.factor(dat$soilmap)

# explore the data structure
str(dat)

## 'data.frame': 2897 obs. of 23 variables:
## $ id      : Factor w/ 2897 levels "P0003","P0007",...: 1 2 3 4 ...
## $ Y       : num 42 42 42.1 42 42 ...
## $ X       : num 20.8 20.8 20.8 20.9 20.9 ...
## $ SOC     : num 26.38 6.15 3.94 3.26 2.29 ...
## $ BLD     : num 0.73 1.17 1.3 1.34 1.41 ...
## $ CRFVOL  : num 8 18.6 31.9 21.7 14.5 ...
## $ OCSKGM  : num 5.32 1.75 1.04 1.03 0.83 ...
## $ meaERROR: num 2.16 2.85 2.65 3.16 3.63 2.83 2.94 2.49 2.77...
## $ OCSKGMlog: num 1.6712 0.5591 0.0429 0.0286 -0.1862 ...
## $ B04CHE3 : num 574 553 693 743 744 ...
## $ B07CHE3 : num 38.5 37.8 42.1 43.7 43.7 ...
## $ B13CHE3 : num 111.6 125 99.8 118.1 121 ...
## $ B14CHE3 : num 59.2 60.3 42.4 39.9 38.7 ...
## $ DEMENV5 : int 2327 2207 1243 1120 1098 1492 1413 1809 1731...
## $ LCEE10  : Factor w/ 4 levels "1","2","3","4": 1 3 2 1 2 2 2 ...
## $ PRSCHE3 : num 998 1053 780 839 844 ...
## $ SLPMRG5 : int 13 36 6 25 30 24 15 17 20 43 ...
## $ TMDMOD3 : int 282 280 285 288 289 287 286 287 286 ...
## $ TMNMOD3 : int 272 270 277 279 279 277 277 273 274 273 ...
## $ TWIMRG5 : int 61 62 81 66 65 72 68 67 65 59 ...
## $ VBFMRG5 : int 0 0 14 0 0 0 0 0 0 0 ...
## $ VDPMRG5 : int 311 823 10048 1963 -173 -400 -9 -692 -1139 2 ...
## $ soilmap  : Factor w/ 20 levels "1","2","3","4",...: 6 14 14 3 ...
```

Since we will be working with spatial data we need to define the coordinates for

the imported data. Using the `coordinates()` function from the `sp` package we can define the columns in the data frame to refer to spatial coordinates—here the coordinates are listed in columns X and Y.

```
library(sp)

# Promote to spatialPointsDataFrame
coordinates(dat) <- ~ X + Y

class(dat)

## [1] "SpatialPointsDataFrame"
## attr(,"package")
## [1] "sp"
```

`SpatialPointsDataFrame` structure is essentially the same data frame, except that additional “spatial” elements have been added or partitioned into slots. Some important ones being the bounding box (sort of like the spatial extent of the data), and the coordinate reference system `proj4string()`, which we need to define for the sample dataset. To define the CRS, we must know where our data are from, and what was the corresponding CRS used when recording the spatial information in the field. For this data set, the CRS used was: WGS84 (EPSG:4326).

To clearly tell R this information we define the CRS which describes a reference system in a way understood by the [PROJ.4 projection library](#). An interface to the PROJ.4 library is available in the `rgdal` package. As an alternative to using Proj4 character strings, we can use the corresponding yet simpler EPSG code (European Petroleum Survey Group). `rgdal` also recognizes these codes. If you are unsure of the Proj4 or EPSG code for the spatial data that you have but know the CRS, you should consult <http://spatialreference.org/> for assistance.

Please also note that, when working with spatial data, it’s very important that the CRS (coordinate reference system) of the point data and covariates are the same.

Now, we will define our CRS:

```
dat@proj4string <- CRS(projargs = "+init=epsg:4326")

dat@proj4string

## CRS arguments:
## +init=epsg:4326 +proj=longlat +datum=WGS84 +no_defs
## +ellps=WGS84 +towgs84=0,0,0
```

Now we will import the covariates. When the covariate layers are in common resolution and extent, rather than working with individual rasters it is better to stack them all into a single R object. In this example, we use 13 covariates from the GSOCMap Data Repository and a rasterized version of the soil type map. The rasterization of vectorial data was covered in [Technical Steps - Rasterizing a vector layer in R](#). The file containing all the covariates was prepared at the end of chapter 5.

```
load(file = "covariates.RData")
names(covs)

## [1] "B04CHE3" "B07CHE3" "B13CHE3" "B14CHE3" "DEMENV5" "LCEE10"
## [7] "PRSCHE3" "SLPMRG5" "TMDMOD3" "TMNMOD3" "TWIMRG5" "VBFMRG5"
## [13] "VDPMRG5" "soilmap"
```

6.4.2.3 Variable selection using correlation analysis

```
# plot the names of the covariates
names(dat@data)

## [1] "id"      "SOC"      "BLD"      "CRFVOL"   "OCSKGM"
## [6] "meaERROR" "OCSKGMlog" "B04CHE3"  "B07CHE3"  "B13CHE3"
## [11] "B14CHE3"  "DEMENV5"   "LCEE10"    "PRSCHE3"   "SLPMRG5"
## [16] "TMDMOD3"  "TMNMOD3"   "TWIMRG5"   "VBFMRG5"   "VDPMRG5"
## [21] "soilmap"
```

For the variable selection we will use `cor()` function. `x` must be a table including only the column with the response variable, and `y` must be a table including ONLY the covariates. Besides, remember `dat@data` in the `data.frame` included in the `spatialPointsDataFrame`. For `y`, columns 1 to 7 are out, because they are not covariates. At the same time, correlation analysis cannot be applied to categorical covariates, this means that columns 13 and 21 have to be removed too.

```
selectedCovs <- cor(x = as.matrix(dat@data[,5]),
y = as.matrix(dat@data[,-c(1:7,13,21)]))
```

```
# print correlation results
selectedCovs
```

```
##          B04CHE3    B07CHE3    B13CHE3    B14CHE3    DEMENV5
## [1,] -0.4199537 -0.3926615  0.330696  0.3481847  0.3926275
##          PRSCHE3    SLPMRG5    TMDMOD3    TMNMOD3    TWIMRG5
## [1,]  0.3948779  0.2593964 -0.4077552 -0.2963631 -0.2525764
##          VBFMRG5    VDPMRG5
## [1,] -0.1156285 -0.3001934
```

Now we used the correlation results to select the top five covariates.

```
library(reshape)
x <- subset(melt(selectedCovs), value != 1 | value != NA)
x <- x[with(x, order(-abs(x$value))),]

idx <- as.character(x$X2[1:5])

dat2 <- dat[c('OCSKGM', idx)]
```

```

names(dat2)

## [1] "OCSKGM"  "B04CHE3" "TMDMOD3" "PRSCHE3" "B07CHE3" "DEMENV5"
COV <- covs[[idx]]

# Selected covariates
names(COV)

## [1] "B04CHE3" "TMDMOD3" "PRSCHE3" "B07CHE3" "DEMENV5"

```

6.4.2.4 Categorical variables in svm models

According to Hsu et al. (2003), svm requires each variable to be represented by a vector of real numbers. This means that factor variables, like `covs$LCEE10` and `covs$soilmaphas` to be converted into numeric data. In statistics, this kind of variables are called boolean indicators or dummy variables. Dummy variables take a value of 0 or 1 indicating the presence or absence of a specific value/category in our factor covariate, i.e. if we have 5 categories like in `covs$LCEE10`, we will have 5 dummy variables indicating the presence/absence of every category. For converting our covariates to dummies we will have to create a new function that returns the dummy rasterStack from the factor version of the rasterLayer.

```

dummyRaster <- function(rast){
  rast <- as.factor(rast)
  result <- list()
  for(i in 1:length(levels(rast)[[1]][[1]])){
    result[[i]] <- rast == levels(rast)[[1]][[1]][i]
    names(result[[i]]) <- paste0(names(rast),
                                  levels(rast)[[1]][[1]][i])
  }
  return(stack(result))
}

```

We can use the function we just created to convert our categorical covariates to dummies and then stack all the layers together.

```

# convert soilmap from factor to dummy
soilmap_dummy <- dummyRaster(covs$soilmaphas)

# convert LCEE10 from factor to dummy
LCEE10_dummy <- dummyRaster(covs$LCEE10)

# Stack the 5 COV layers with the 2 dummies
COV <- stack(COV, soilmap_dummy, LCEE10_dummy)

# print the final layer names
names(COV)

```

```
## [1] "B04CHE3"    "TMDMOD3"     "PRSCHE3"     "B07CHE3"     "DEMENV5"
## [6] "soilmap1"   "soilmap2"   "soilmap3"   "soilmap4"   "soilmap5"
## [11] "soilmap6"   "soilmap7"   "soilmap8"   "soilmap9"   "soilmap10"
## [16] "soilmap11"  "soilmap12"  "soilmap13"  "soilmap14"  "soilmap15"
## [21] "soilmap16"  "soilmap17"  "soilmap18"  "soilmap19"  "soilmap20"
## [26] "LCEE101"    "LCEE102"    "LCEE103"    "LCEE104"
```

We have to convert the columns with categorical variables in the soil samples `data.frame` to dummies as well. For doing this we can use function `model.matrix()`. After this, we use `cbind()` to merge the resulting `data.frame`.

```
# convert soilmap column to dummy, the result is a matrix
# to have one column per category we had to add -1 to the formula
dat_soilmap_dummy <- model.matrix(~soilmap -1, data = dat@data)
# convert the matrix to a data.frame
dat_soilmap_dummy <- as.data.frame(dat_soilmap_dummy)
```

```
# convert LCEE10 column to dummy, the result is a matrix
# to have one column per category we had to add -1 to the formula
dat_LCEE10_dummy <- model.matrix(~LCEE10 -1, data = dat@data)
# convert the matrix to a data.frame
dat_LCEE10_dummy <- as.data.frame(dat_LCEE10_dummy)
```

```
dat@data <- cbind(dat@data, dat_LCEE10_dummy, dat_soilmap_dummy)
```

```
names(dat@data)
```

```
## [1] "id"          "SOC"         "BLD"         "CRFVOL"      "OCSKGM"
## [6] "meaERROR"   "OCSKGMlog"   "B04CHE3"    "B07CHE3"    "B13CHE3"
## [11] "B14CHE3"    "DEMENV5"     "LCEE10"      "PRSCHE3"    "SLPMRG5"
## [16] "TMDMOD3"    "TMNMOD3"     "TWIMRG5"    "VBFMRG5"    "VDPMRG5"
## [21] "soilmap"     "LCEE101"     "LCEE102"    "LCEE103"    "LCEE104"
## [26] "soilmap1"   "soilmap2"   "soilmap3"   "soilmap4"   "soilmap5"
## [31] "soilmap6"   "soilmap7"   "soilmap8"   "soilmap9"   "soilmap10"
## [36] "soilmap11"  "soilmap12"  "soilmap13"  "soilmap14"  "soilmap15"
## [41] "soilmap16"  "soilmap17"  "soilmap18"  "soilmap19"  "soilmap20"
```

6.4.2.5 Fitting a svm model

To improve the model performance the parameters of the svm can be tuned. In this example, we will show how to tune 2 parameters using a grid search for hyperparameter optimization using the function `tune()`. The first parameter is epsilon which is the insensitive-loss function (The larger epsilon is, the larger errors in the solution are not penalized). The default value for epsilon is 0.1, and we will try 11 different value from 0.05 to 0.12 in 0.1 increments. The second parameter is the cost which is the cost of constraints violation – it is the ‘C’-constant of the regularization term in the Lagrange formulation. The default value for this

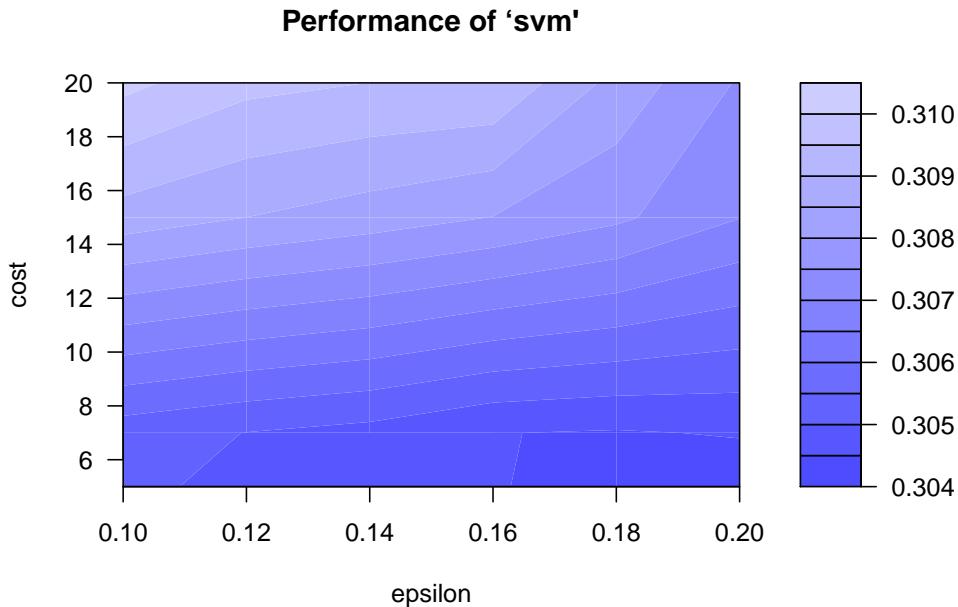


Figure 6.16: Performance of the different svm models in the parameter tuning procedure

parameter is 1, and we will try values from 1 to 20 in 5 increments. The value of cost helps us to avoid overfitting. This is a heavy and time consuming computational step since we will try a extensive number of different models in order to find the best parameters for our svm model.

```
library(e1071)
library(caret)

# Test different values of epsilon and cost
tuneResult <- tune(svm, OCSKGM ~., data = dat@data[,c("OCSKGM",
                                                       names(COV))],
                    ranges = list(epsilon = seq(0.1,0.2,0.02),
                                 cost = c(5,7,15,20)))
```

We can plot the performance of the different models. When the region is darker, the RMSE is closer to zero.

```
plot(tuneResult)
```

6.4.2.6 Select the model with the best combination of epsilon and cost

The best model is the one with the lowest mean squared error derived by cross-validation. The parameters for the cross-validation can be defined in the

`tune.control()` function. By default, it uses cross-validation using 10 folds.

```
# Choose the model with the best combination of epsilon and cost
tunedModel <- tuneResult$best.model

print(tunedModel)

##
## Call:
## best.tune(method = svm, train.x = OCSKGM ~ ., data = dat@data[,
##   c("OCSKGM", names(COV))], ranges = list(epsilon = seq(0.1,
##   0.2, 0.02), cost = c(5, 7, 15, 20)))
##
##
## Parameters:
##   SVM-Type:  eps-regression
##   SVM-Kernel: radial
##   cost: 5
##   gamma: 0.03448276
##   epsilon: 0.2
##
##
## Number of Support Vectors: 2193
```

6.4.2.7 Predict the OCS using the model

```
# Use the model to predict the SOC in the covariates space
OCSsvm <- predict(COV, tunedModel)

# Save the result
writeRaster(OCSsvm, filename = "results/MKD_OCSKGM_svm.tif",
            overwrite=TRUE)

plot(OCSsvm)
```

Finally, we can evaluate the contribution of each covariate to the model (Guyon and Elisseeff, 2003):

```
# Variable importance in svm. Code by:
# stackoverflow.com/questions/34781495

w <- t(tunedModel$coefs) %*% tunedModel$SV      # weight vectors
w <- apply(w, 2, function(v){sqrt(sum(v^2))})    # weight

w <- sort(w, decreasing = T)
print(w)

##      B04CHE3      soilmap6      TMDMOD3      soilmap7      soilmap1
```

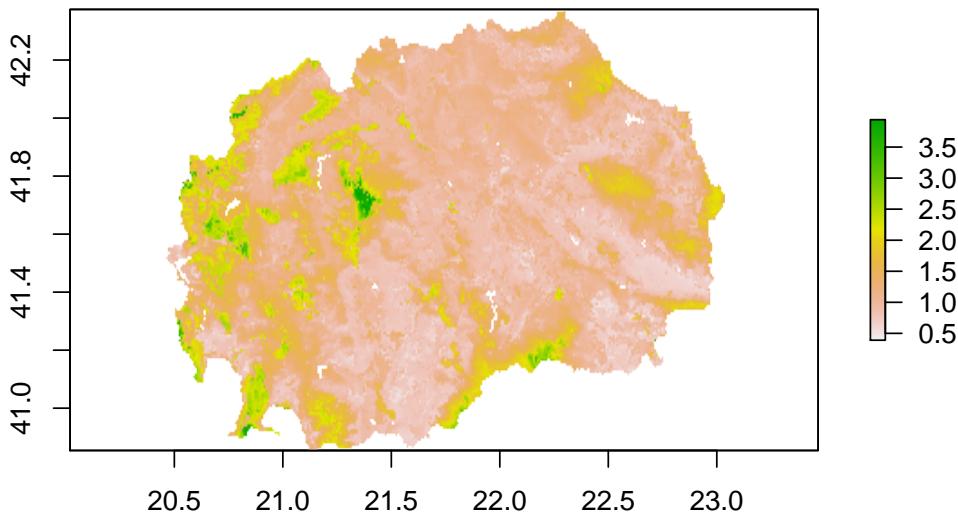


Figure 6.17: SOC prediction using a support vector machines model

```
## 6.712914e+01 4.443748e+01 4.010740e+01 3.928593e+01 3.882377e+01
##      DEMENV5      PRSCHE3      B07CHE3      LCEE103      soilmap2
## 3.824383e+01 3.350877e+01 3.107515e+01 2.646657e+01 2.478332e+01
##      soilmap19      LCEE104      soilmap16      LCEE101      soilmap5
## 2.441025e+01 1.529174e+01 1.448675e+01 1.324205e+01 1.309922e+01
##      soilmap15      LCEE102      soilmap4      soilmap20      soilmap9
## 1.295171e+01 1.175225e+01 8.849019e+00 8.166970e+00 6.701250e+00
##      soilmap10      soilmap3      soilmap17      soilmap12      soilmap8
## 6.046196e+00 5.059617e+00 4.705567e+00 3.552720e+00 2.691221e+00
##      soilmap18      soilmap14      soilmap11      soilmap13
## 5.275093e-01 1.498048e-01 7.365523e-02 1.110223e-15
```

svm is a powerful technique which represent another welcome possibility to generate reliable and interpretable SOC predictions across different scales of data availability, including country-specific SOC maps.

Chapter 7

Validation

B Kempen, DJ Brus & GBM Heuvelink

7.1 What is Validation?

No map is perfect. All maps, including soil maps, are representations of reality that are often based on an underlying model. This means that there will always be a deviation between the phenomenon depicted on the map and the phenomenon observed in the real world, i.e. each map will contain errors. The magnitude of the errors determines the quality of the map. If a map matches reality well (the error is small), the quality or accuracy of the map is high. On the other hand, if a map does not match reality well, map accuracy is low.

Soil maps are used for many purposes. For example to report on (changes in) soil organic carbon stocks, as input in agro-environmental models, to determine land use suitability or for decision- and policy-making. It is therefore, important that the quality of a map is determined and quantified. This is achieved through (statistical) validation.

Validation is defined here as an activity in which the soil map predictions are compared with observed values. From this comparison, the map quality can be quantified and summarized using map quality measures. These measures indicate how accurate the map is on average for the mapping area, i.e. what is the expected error at a randomly selected location in the mapping area. This means that map quality measures obtained through validation are global measures: each quality measure gives one value for the entire map. Note that this is different from results obtained through uncertainty assessment. Such assessment provides local, location-specific (i.e. for each individual grid cell) estimates of map quality as we saw in the previous sections. Another important difference between validation and uncertainty assessment is that validation can be done using a model-free approach. Uncertainty assessment takes a model-based approach by defining a geostatistical

model of the soil property of interest and deriving an interpolated map and the associated uncertainty from that, or by constructing a geostatistical model of the error in an existing map. The approach yields a complete probabilistic characterization of the map uncertainty, but such characterization is only valid under the assumptions made; for instance, the stationarity assumptions required for kriging. Validation, when done properly as explained hereafter, does not assume a geostatistical model of the error, and hence is model- or assumption-free. This is an important property of validation since we do not want to question the objectivity and validity of the validation results.

We distinguish internal and external map accuracy. Statistical methods typically produce direct estimates of map quality, for instance, the kriging variance or the coefficient of determination (R^2) of a linear regression model. These we refer to as internal accuracy measures since these rely on model assumptions and are computed from data that are used for model calibration. Preferably, validation is done with an independent dataset not used in map making. Using such dataset gives the external map accuracy. One will often see that the external accuracy is poorer than the internal accuracy.

In section 8.3.2 we will present the most common accuracy measures used to quantify map quality of quantitative (continuous) soil maps and qualitative (categorical) soil maps. In section 8.3.3 we will introduce three commonly used validation methods and show how to estimate the map quality measures from a sample. This chapter is largely based on Brus et al. (2011). For details, please refer to this paper.

7.2 Map Quality Measures

7.2.1 Quality Measures for Quantitative Soil Maps

All map quality measures considered here are computed from the prediction error. For quantitative soil maps of continuous soil properties (e.g. organic carbon content, pH, clay content) the prediction error is defined as the difference between the predicted value at a location and the true value at that location (which is the value that would be observed or measured by a preferably errorless measurement instrument) (Brus et al., 2011):

$$e(s) = \hat{Z}(s) - Z(s) \quad (7.1)$$

where $\hat{Z}(s)$ is the predicted soil property at validation location s , and $Z(s)$ is the true value of the soil property at that location. We consider six map quality measures that are computed from the prediction error here: the mean error, the mean absolute error, the mean squared error and root mean squared error, the model efficiency, and the mean squared deviation ratio.

Before we introduce the map quality measures and show how to estimate these, it is important to understand the difference between the population and a sample taken from the population. The population is the set of all locations in a mapping area. For digital soil maps, this is the set of all pixels or grid cells of a map. A sample is a subset of locations, selected in some way from the set of all locations in the mapping area. With validation we want to assess the map accuracy for the entire population, i.e. for the map as a whole; we are not interested in the accuracy at the sample of locations only. For instance, we would like to know the prediction error averaged over all locations of a map and not merely the average prediction error at a sample of locations. Map quality measures are, therefore, defined as population means. Because we cannot afford to determine the prediction error at each location (grid cell) of the mapping area to calculate the population means, we have to take a sample of a limited number of locations in the mapping area. This sample is then used to estimate the population means. It is important to realize that we are uncertain about the population means because we estimate it from a sample. Ideally, this uncertainty is quantified and reported together with the estimated map quality measures.

In this section, we will introduce the definitions of the map quality measures. In the next section, we show how we can estimate these measures from a sample.

Mean error

The mean error (ME) measures bias in the predictions. The ME is defined as the population mean (spatial mean) of the prediction errors:

$$ME = e = \frac{1}{N} \sum_{i=1}^N e(s_i) \quad (7.2)$$

where i indicates the location, $i = 1, 2, \dots, N$, and N is the total number of locations or grid cells/pixels in the mapping area. The mean error should be (close to) zero, which means that predictions are unbiased meaning that there is no systematic over- or under-prediction of the soil property of interest.

Mean absolute error and (root) mean squared error

The mean absolute error (MAE) and mean squared error (MSE) are measures of map accuracy and indicate the magnitude of error we make on average. The MAE is defined by the population mean of the absolute errors:

$$MAE = |\underline{e}| = \frac{1}{N} \sum_{i=1}^N \underline{e}(s_i) \quad (7.3)$$

and the MSE by the population mean of the squared errors:

$$MSE = \underline{e}^2 = \frac{1}{N} \sum_{i=1}^N \underline{e}^2(s_i) \quad (7.4)$$

Many authors report the root mean squared error (*RMSE*) instead of the *MSE*, which is computed by taking the square root of the *MSE*. The *RMSE* can be a more appealing quality measure since it has the same unit of measurement as the mapped property and can, therefore, more easily be compared to it. If the squared error distribution is strongly skewed, for instance when several very large errors are present, then this can severely inflate the (R)MSE. In such case, the (root) median squared error is a more robust statistic for the ‘average’ error (Kempen et al., 2012).

Brus et al. (2011) argue that instead of using a single summary statistic (the mean) to quantify map quality measures, one should preferably express quality measures for quantitative soil maps through cumulative distribution functions (CDFs). Such functions provide a full description of the quality measures from which various parameters can be reported, such as the mean, median or percentiles. Furthermore, they argue that it can be of interest to define CDFs or its parameters for sub-areas, for instance, geomorphic units, soil or land cover classes. Brus et al. (2011) give examples of estimating CDFs for validation of digital soil maps.

Amount of variance explained

The model efficiency, or Amount of Variance Explained (*AVE*) (Angelini et al., 2016, Samuel-Rosa et al. (2015)), quantifies the fraction of the variation in the data that is explained by the prediction model. It measures the improvement of the model prediction over using the mean of the data set as predictor and is defined as follows (Krause et al., 2005):

$$AVE = 1 - \frac{\sum_{i=1}^N (\hat{Z}(s_i) - Z(s_i))^2}{\sum_{i=1}^N (Z(s_i) - \bar{Z})^2} \quad (7.5)$$

where \bar{Z} is the population mean of soil property Z . The quantity in the numerator is the sum of the squared prediction errors (for each location the prediction error is computed and squared; the squared prediction errors are summed over all locations in the area). In linear regression, this quantity is known as the residual sum of squares (*RSS*). The quantity in the denominator is also a sum of squared prediction errors, but here the mean of the area is used as a predictor. In linear regression, this quantity is known as the total sum of squares (*TSS*). Note that if we would divide the quantity in the denominator by the number of locations in the mapping area N we would obtain the population variance (spatial variance) of the soil property Z .

If the numerator and denominator are equal, meaning the *AVE* is zero, then the model predictions are no improvement over using the mean of the data set as a predictor for any location in the mapping area. An *AVE* value larger than zero (*RSS* smaller than *TSS*) means that the model predictions are an improvement over using the mean as a predictor (this is what we hope for). In case the *AVE* is negative, then the mean of the data set is a better predictor than the prediction model.

Mean squared deviation ratio

Finally, we introduce the mean squared deviation ratio (*MSDR*) as a map quality measure (Kempen et al., 2010, Lark (2000), Voltz and Webster (1990), Webster and Oliver (2007)). Contrary to the quality measures discussed so far, the *MSDR* assesses how well the prediction model estimates the prediction uncertainty (expressed as the prediction error variance). The *MSDR* is defined as:

$$MSDR = \frac{1}{N} \sum_{i=1}^N \frac{(\hat{Z}(s_i) - Z(s_i))^2}{\sigma^2(s_i)} \quad (7.6)$$

where $\sigma^2(s_i)$ is the prediction error variance at location $s_i, i = 1, 2, \dots, N$. The numerator is the squared error at location s_i . The fraction represents the squared Z_{score} . In case of kriging, the prediction error variance is the kriging variance. In case of linear regression, the prediction error variance is the prediction variance of the linear regression predictions that can be obtained by the statistical software R by running the predict function with argument `se.fit = TRUE`. This function returns for each prediction location the standard error of the predicted value as well as the residual standard deviation (the `residual.scale` value). By squaring both values and then summing these, the prediction error variance is obtained. If the prediction model estimates the error variance well, then the *MSDR* should be close to one. A value smaller than one suggests that the prediction error variance overestimates the variance; a value larger than one suggests that the prediction error variance underestimates the variance.

Lark (2000) notes that outliers in the prediction data will influence the squared Z_{score} and suggests to use the median squared Z_{score} instead of the mean since it is a more robust estimator. A median squared Z_{score} equal to 0.455 suggests that the prediction model estimates the prediction uncertainty well.

7.2.2 Quality Measures for Qualitative Soil Maps

Like the quality measures for quantitative soil maps, the quality measures for qualitative or categorical soil maps (e.g. soil classes) are defined for the population, i.e. all locations in the mapping area. The basis for map quality assessment of qualitative maps is the error matrix (Brus et al., 2011, Lark (1995)). This matrix is constructed by tabulating the observed and predicted class for all locations in the mapping area in a two-way contingency table. The population error matrix is a square matrix of order U , with U being the number of soil classes observed and mapped. The columns of the matrix correspond to observed soil classes and the rows of predicted soil classes (the map units). N is the total number of locations of the mapping area. Elements N_{ij} are the number of locations mapped as class i with observed class j . The row margins N_{i+} are the locations mapped as class i , and column margins N_{+j} the locations for which the observed soil class is j . Note that the elements of the population error matrix can also be interpreted as surface areas. In that case element N_{ij} is the surface area mapped as class i with observed class j .

From the population error matrix, several quality measures can be summarized, though it is strongly recommended that the error matrix is included in a validation assessment. Brus et al. (2011) follow the suggestion by Stehman (1997) that quality measures for categorical maps should be directly interpretable in terms of the probability of a misclassification and therefore recommend the use of three map quality measures: the overall purity, the map unit purity, and class representation. We follow this recommendation here. Note that the map unit purity often is referred to as user's accuracy, and class representation as producer's accuracy (Stehman, 1997, Adhikari et al. (2014)). Lark (1995) however, questions the appropriateness of these terms since both quality measures can be important for users as well as producers. He proposes to use map unit purity and class representation instead, which is adopted by Brus et al. (2011) and followed here.

A fourth frequently used group of quality measures are Kappa indices, which adjust the overall purity measure for hypothetical chance agreement (Stehman, 1997). How this chance agreement is defined differs between the various indices. Some authors, however, conclude that Kappa indices are difficult to interpret, not informative, misleading and/or flawed and suggest to abandon their use (Pontius Jr and Millones, 2011). These authors argue that Kappa indices attempt to compare accuracy to a baseline of randomness, but randomness is not a reasonable alternative for map construction. We, therefore, do not consider kappa here.

The overall purity is the fraction of locations for which the mapped soil class equals the observed soil class and is defined as (Brus et al., 2011):

$$\rho = \sum_{i=1}^U N_{uu}/N \quad (7.7)$$

which is the sum of the principal diagonal of the error matrix divided by the total number of locations in the mapping area. The overall purity can be interpreted as the areal proportion of the mapping area that is correctly classified.

Alternatively, an indicator approach can be used to compute the overall purity. A validation site gets a '1' if the observed soil class is correctly predicted and a '0' otherwise. The overall purity is then computed by taking the average of the indicators.

Map unit purity

The map unit purity is calculated from the row marginals of the error matrix. It is the fraction of validation locations with mapped class u for which the observed class is also u . The map unit purity for class u is defined as (Brus et al., 2011):

$$\rho_u = \frac{N_{uu}}{N_{u+}} \quad (7.8)$$

The map unit purity can be interpreted as the proportion of the area of the map unit that is correctly classified. The complement of ρ_u , $1 - \rho_u$, is referred to as the error of commission for mapped class u .

Class representation

The class representation is calculated from the column marginals of the error matrix. It is the fraction of validation locations with observed class u for which the mapped class is u . The class representation for class u is defined as (Brus et al., 2011):

$$r_u = \frac{N_{uu}}{N_{+u}} \quad (7.9)$$

The class representation can be interpreted as the proportion of the area where in reality class u occurs that is also mapped as class u . The complement of r_u , $1 - r_u$, is referred to as the error of omission for mapped class u .

7.2.3 Estimating the Map Quality Measures and Associated Uncertainty

In validation, we estimate the population means of the map quality measures from a sample taken from a limited number of locations in the mapping area. After all, we cannot afford to sample all locations, i.e. each grid cell of our soil map. Because the map quality measures are estimates, we are uncertain about these: we infer the quality measures from only a limited number of observations taken from the population. We do not know the true population means. The estimation uncertainty can be quantified with the sampling variance. From the variance, the lower and upper boundary of a confidence interval, typically the 95%, can be computed using basic statistical theory:

$$CI = (\hat{x} - 1.96x\frac{\sigma}{\sqrt{n}}; \hat{x} + 1.96x\frac{\sigma}{\sqrt{n}}) \quad (7.10)$$

where x is the estimated map quality measure, for instance, the ME , MSE or overall purity, σ is the estimated standard deviation of the map quality measure and n is the validation sample size.

Quantified information about the uncertainty associated to map quality measures is useful and required for statistical testing. For instance, if one wants to test if one mapping method performs better than the other method one needs quantified information about uncertainty. Because we are uncertain about the estimated quality measures, an observed difference in map quality between two methods does not necessarily mean that one method is better than the others, even when there is a substantial difference. The difference might be attributed to chance because we infer the quality measures from a limited sample from the population. With statistical hypothesis testing, we can calculate how large the probability is that observed difference is caused by chance. Based on the outcome we can accept or reject the hypothesis that there is no difference between the performance of two mapping methods (this would be the null hypothesis for statistical testing) for a given significance level, usually 0.05.

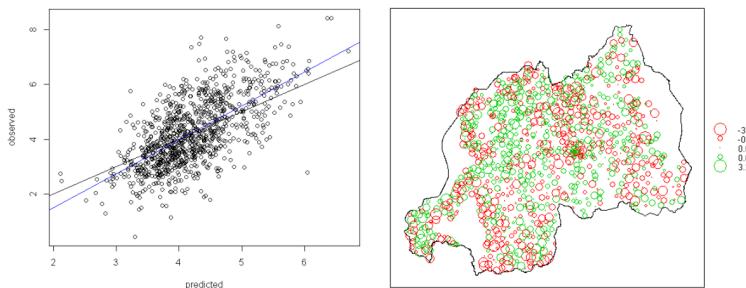


Figure 7.1: Scatterplot of predicted versus observed soil organic matter content for Rwanda (left) and spatial bubble plot of cross-validation error for soil organic matter (right) (Kempen et al., 2015). The black line in the scatter plot represents the 1:1 line of prediction versus observed, the blue line represents the regression between observed and predicted values

7.3 Graphical Map Quality Measures

In addition to quantifying map accuracy statistically, one can also present validation results obtained from a sample graphically. This can be done by creating scatter plots of predicted against observed values and spatial bubble plots of validation errors. Figure 7.1 shows an example of a scatterplot and bubble plot. Both plots can be easily made with R ([R Core Team, 2017](#)). Use the function `plot(x,y)` to generate a scatter plot. The 1:1 line (black line in Figure 7.1) can be added to the plot with the command `abline(0,1)`. The spatial bubble plot can be generated with the `bubble` function of the `sp` package ([Pebesma and Bivand, 2005](#)).

7.4 Validation Methods and Statistical Inference

Following [Brus et al. \(2011\)](#), we introduce and discuss three common validation methods: additional probability sampling, data-splitting and cross-validation, and show how to estimate the map quality measures introduced in the previous section from a sample.

With additional probability sampling, an independent dataset is collected from the sampling population (all grid cells of a digital soil map) for the purpose of validation. This dataset is used in addition to a dataset that is used to calibrate a prediction model. Such dataset is often a legacy dataset collected with a purposive sampling design.

Data-splitting and cross-validation are applied in situations where one has only one data set available for prediction model calibration and validation. This can be a dataset collected with probability sampling, but in practice this typically is a legacy dataset collected with some purposive sampling design.

We warn here that if one uses data-splitting or cross-validation with a dataset collected with purposive sampling, then this has severe implications on the validity and interpretation of the estimated map quality measures as we will explain below.

7.4.1 Additional Probability Sampling

The most appropriate approach for validation is by additional probability sampling. This means that an independent validation dataset is collected in the field on basis of a probability sampling design. Validation based on probability sampling ensures one obtains unbiased and valid estimates of the map quality measures (Brus et al., 2011, Stehman (1999)). Additional probability sampling has several advantages compared to data-splitting and cross-validation using non-probability sample data. These are:

- no model is needed for estimating map quality estimates. We can apply design-based estimation, meaning that model-free unbiased and valid estimates of the map quality measures can be obtained;
- discussions on the validity of the estimated map quality are avoided;
- model-free, valid estimates of the variance of the map quality measures can be obtained that allows for hypothesis testing, e.g. for comparison of model performance.

Disadvantages can be extra costs involved in collecting an additional sample or terrain conditions that make it difficult to access all locations in the mapping area. Probability sampling is random sampling such that:

- all locations in the mapping area have a probability larger than 0 of being selected
- the inclusion probabilities are known but need not be equal.

It should be noted that random sampling is often used for arbitrary or haphazard sampling. Such sampling is not probability sampling because the inclusion probabilities are not known. Design-based, model-free estimation of map quality measures is not possible in this case. All probability samples are random samples but not all random samples are probability samples. The term probability sampling should therefore only be used for random sampling with known inclusion probabilities.

There are many different probability sampling designs: simple, stratified, systematic, two-stage, clustered random sampling. We will not give an exhaustive overview here of all these designs. A good resource is De Gruijter et al. (2006). For reasons of simplicity, we focus here on simple random sampling.

In simple random sampling, no restrictions are imposed on the random selection of sampling sites except that the sample size is fixed and chosen prior to sampling (De Gruijter et al., 2006). All sampling locations are selected with equal probability and independently from each other. This can, for instance, be done as follows (De Gruijter et al., 2006):

1. Determine the minimum and maximum X and Y coordinates of the mapping area (the bounding box).
2. Generate two independent random coordinates X and Y from a uniform probability distribution on the interval (x_{min}, x_{max}) and (y_{min}, y_{max})
3. Check if the selected sampling site falls within the mapping area. Accept the sampling site if it does; discard the sampling site if it does not.
4. Repeat steps 2 and 3 until the n locations have been selected.

If a sampling location cannot be visited because of inaccessibility for instance, then this location should be discarded and be replaced by a location chosen from a reserve list. Always the location at the top of the list should be selected for this purpose; not an arbitrarily chosen location from the list such as the closest one. It is not allowed to shift an inaccessible sampling location to a location nearby that can be accessed. Irregularity, clustering and open spaces characterize the simple random sampling design (De Gruijter et al., 2006).

Estimation of quantitative map quality measures: For each validation location we compute the error, $e(s_i)$, the absolute error, $|e|(s_i)$, or squared error, $e^2(s_i)$. The spatial mean of the mapping area for map quality measure x is then estimated by:

$$e(s_i) = \hat{Z}(s_i) - Z(s_i) \quad (7.11)$$

$$|e|(s_i) = |\hat{Z}(s_i) - Z(s_i)| \quad (7.12)$$

$$e^2(s_i) = (\hat{Z}(s_i) - Z(s_i))^2 \quad (7.13)$$

$$\hat{x} = \frac{1}{N} \sum_{i=1}^N x(s_i) \quad (7.14)$$

where i indicates the validation location, $i = 1, 2, \dots, n$, n the validation sample size, and x_{si} the estimated population mean of map quality measure x at location s_i . x is the prediction error in case of the ME , absolute error in case of the MAE , squared prediction error in case of the MSE . Note that the estimator is the unweighted sample mean. This unweighted mean is an unbiased estimator because all sampling locations were selected with equal probability.

The $MSDR$ is estimated by:

$$\widehat{MSDR} = \frac{1}{N} \sum_{i=1}^n \frac{(\hat{Z}(s_i) - Z(s_i))^2}{\sigma^2(s_i)} \quad (7.15)$$

and the AVE by:

$$\widehat{AVE} = 1 - \frac{\sum_{i=1}^n (\hat{Z}(s_i) - Z(s_i))^2}{\sum_{i=1}^n (Z(s_i) - \underline{\hat{Z}})^2} \quad (7.16)$$

where $\underline{\hat{Z}}$ is the mean of the target soil property estimated from the validation sample.

One should be careful when assessing the proportion of variance explained by computing the R^2 from a linear regression of the predicted value on the observed value (Krause et al., 2005), as is often done in practice. The R^2 quantifies the dispersion around the regression line; not around the 1:1 line in which we are interested in validation. So it does not directly compare the predicted with observed value as does the AVE ; i.e. it is not based on the prediction error. A high R^2 -value, therefore, does not automatically mean a high AVE . For instance, in case of strongly biased predictions the R^2 can be high but the AVE will be low. The blue line in Figure 7.1 is the regression line that one obtains when regressing the observed value of the predicted value. This line slightly differs from the 1:1 line. In this example, the R^2 of the regression is 0.42 while the AVE is 0.40. The uncertainty associated to the estimated map quality measures is quantified with the sampling variance, which for the ME , MAE and MSE is estimated by:

$$Var(\hat{x}) = \frac{1}{n(n-1)} \sum_{i=1}^n (x(s_i) - \hat{x})^2 \quad (7.17)$$

and the 95% confidence interval (CI) of x is given by:

$$CI_{95} = \hat{x} \pm 1.96 \sqrt{Var(\hat{x})} \quad (7.18)$$

We should warn here that the calculation of the CI is based on the assumption that the estimated map quality measure means have a normal distribution (the central limit theorem). For the squared errors this assumption can be unrealistic, especially for small sample sizes.

Estimation of qualitative map quality measures: For validation of qualitative soil maps, a sample error matrix is constructed from the validation data (Figure 7.2). n is the total number of validation locations in the sample. Element n_{ij} of the matrix corresponds to the number of validation locations that have been predicted as class i , $i = 1, 2, \dots, U$ and belong to class j , $j = 1, 2, \dots, U$ (Lark, 1995). The matrix summarizes correct predictions and incorrect predictions within the validation data.

From the sample error matrix the overall purity, map unit purity and class representation are estimated by:

$$\hat{p} = \sum_{i=1}^U n_{uu}/n \quad (7.19)$$

		Observed			U	Σ	
		1	2	.	.	.	
Mapped	1	n_{11}	n_{12}	.	.	n_{1U}	n_{1+}
	2	n_{21}	n_{22}	.	.	n_{2U}	n_{2+}

	U	n_{U1}	n_{U2}	.	.	n_{UU}	n_{U+}
	Σ	n_{+1}	n_{+2}	0	0	n_{+U}	n

Figure 7.2: Sample error matrix

$$\hat{\rho}_u = \frac{n_{uu}}{n_{u+}} \quad (7.20)$$

$$\hat{r}_u = \frac{n_{uu}}{n_{+u}} \quad (7.21)$$

Alternatively, the overall purity can be estimated by defining a purity indicator variable for each validation location that takes value 1 if the mapped soil class equals the observed soil class at that location, and 0 else. The overall purity is then estimated by:

$$\hat{\rho} = \frac{1}{n} \sum_{i=1}^n \delta(s_i) \quad (7.22)$$

where $\delta(s_i)$ is the indicator variable at validation location s_i . The variance of the estimated overall purity is estimated by:

$$Var(\hat{\rho}) = \frac{1}{n(n-1)} \sum_{i=1}^n (\delta(s_i) - \hat{\rho})^2 \quad (7.23)$$

Alternatively, the variance is estimated by:

$$Var(\hat{\rho}) = \frac{\hat{\rho}(1-\hat{\rho})}{n-1} \quad (7.24)$$

which is the variance of a binomial probability distribution. The 95% confidence interval of $\hat{\rho}$ is given by:

$$CI_{95} = \hat{\rho} \pm 1.96 \sqrt{Var(\hat{\rho})} \quad (7.25)$$

We warn that the CI as calculated here is a rough approximation which only holds when $n \times \hat{\rho}$ and $n \times (1-\hat{\rho})$ are large (5 as a rule of thumb). Otherwise, the binomial distribution should be used to compute the CI . Figure 7.3 shows a hypothetical

		Observed					
		Anthrosol	Cambisol	Gleysol	Luvisol	Podzol	Σ
Mapped	Anthrosol	19	5	3	0	1	28
	Cambisol	5	33	9	13	5	65
	Gleysol	2	8	25	3	5	43
	Luvisol	3	15	9	42	2	71
	Podzol	1	3	8	2	19	33
	Σ	30	64	54	60	32	240

Figure 7.3: Sample error matrix for a hypothetical soil class map

Table 7.1: Map unit purity and class representation statistics for an hypothetical example.

unit	map.unit.purity	class.representation
Anthrosol	0.679	0.633
Cambisol	0.508	0.516
Gleysol	0.508	0.463
Luvisol	0.592	0.700
Podzol	0.576	0.594

example of a sample error matrix for soil class map. For this example, the overall purity is estimated by:

$$\hat{p} = \frac{(19 + 33 + 25 + 42 + 19)}{240} = 0.575 \quad (7.26)$$

meaning that for an estimated 57.5% of the mapping area the mapped soil class is equal to the true soil class.

Table 7.1 gives the map unit purities and class representations for this example. The map unit purity of the Gleysol is 0.581, meaning that at 58.1% of the validation locations for which a Gleysol is predicted, a Gleysol is observed. Assuming the validation data were collected by simple random sampling, we could conclude that for 58.1% of the area mapped as Gleysol we would find a Gleysol in the field. The class representation of the Gleysol is 0.463, meaning that for 46.3% of the validation locations classified as Gleysol, we map a Gleysol. The majority of the Gleysol locations is thus mapped as a different soil class. Again, assuming the validation data were collected by probability sampling, we would estimate that 22.5% ($\frac{54}{240} \times 100\%$) of our mapping area is covered by Gleysols. We map Gleysols for 17.9% of the area ($\frac{43}{240} \times 100\%$). It can happen that a soil class has a high map unit purity and a low-class representation. This means that if we map a Gleysol we will likely find a Gleysol there, but that a large extent of the true Gleysol area is not mapped as such.

7.4.2 Data-Splitting

In data-splitting, the sample data set is split into two subsets. One subset is used to calibrate the prediction model. The other subset is used for validation. A frequently used splitting criterion is 70-30, where 70% of the sample data are used for calibration and 30% for validation. The choice of a splitting criterion, however, is arbitrary and it is not evident how to split a data set in such a way that unbiased and valid estimates of the map accuracy can be obtained. For sparse data sets, data-splitting can be inefficient since the information in the data set is not fully exploited for both calibration and validation.

It is important to note here that a random subsample of (legacy) data that are collected with a purposive (non-probability) design, is not a probability sample of the study area. This means that design-based estimation of map quality measures is not possible.

Thus, we will not obtain model-free, unbiased and valid estimates of the quality measures from non-probability sample validation data. In a case study, [Knotters and Brus \(2013\)](#) showed that model-based predictions of producer's accuracies from two models differed strongly, indicating that with the model-based approach the validation results strongly depend on model assumptions.

In most studies, however, spatial correlation is not accounted for when estimating map quality measures using the estimators presented above under 'Simple random sampling' from non-probability sample data. In such case, the quality measures cannot be considered unbiased and valid estimates of the population means of the map quality measures. In addition, the estimated variance of the map quality measures is not valid and statistical testing of mapping methods to assess which method gives the most accurate predictions cannot be done.

In other words, if the simple random sampling estimators are used to estimate map quality measures then these are only valid for the validation data points. The map quality measures do not give a valid estimate of the quality of the map as a whole (the population). For instance, the overall purity cannot be interpreted as an areal proportion of correctly mapped soil classes, only as the proportion of the validation data points for which the soil class is correctly predicted. 70-30, where 70% of the sample data are used for calibration and 30% for validation. The choice of a splitting criterion, however, is arbitrary and it is not evident how to split a data set in such a way that unbiased and valid estimates of the map accuracy can be obtained. For sparse data sets, data-splitting can be inefficient since the information in the data set is not fully exploited for both calibration and validation.

It is important to note here that a random subsample of (legacy) data that are collected with a purposive (non-probability) design, is not a probability sample of the study area. This means that design-based estimation of map quality measures is not possible.

If a validation (sub)sample is a non-probability sample of the mapping area, then we must account for possible spatial autocorrelation of the prediction errors when

estimating the map quality measures. One can imagine that when two validation locations are close together and the prediction errors are correlated that there is less information in these two locations (there is information redundancy because of autocorrelation) than in two isolated locations. This information redundancy has to be accounted for when estimating map quality measures and implies that we have to rely on model-based estimation: a model for the spatially autocorrelated prediction error has to be assumed. Thus, we will not obtain model-free, unbiased and valid estimates of the quality measures from non-probability sample validation data. In a case study, Knotters and Brus (2013) showed that model-based predictions of producer's accuracies from two models differed strongly, indicating that with the model-based approach the validation results strongly depend on model assumptions.

In most studies, however, spatial correlation is not accounted for when estimating map quality measures using the estimators presented above under 'Simple random sampling' from non-probability sample data. In such case, the quality measures cannot be considered unbiased and valid estimates of the population means of the map quality measures. In addition, the estimated variance of the map quality measures is not valid and statistical testing of mapping methods to assess which method gives the most accurate predictions cannot be done.

In other words, if the simple random sampling estimators are used to estimate map quality measures then these are only valid for the validation data points. The map quality measures do not give a valid estimate of the quality of the map as a whole (the population). For instance, the overall purity cannot be interpreted as an areal proportion of correctly mapped soil classes, only as the proportion of the validation data points for which the soil class is correctly predicted.

7.4.3 Cross-Validation

In K -fold cross-validation (CV), the dataset is split into K roughly equal sets. One of these sets is set aside for validation. The model is then calibrated using the data from the $K-1$ sets and used to predict the target variable for the data points set aside. From this prediction, the prediction error is calculated. This procedure is repeated K times, each time setting a different set aside for validation. In this way, we obtain K estimates of the prediction error: one for each validation sample site. In this way, all data are used for validation and model calibration. It is thus much more efficient than data-splitting.

K is typically chosen as 5 or 10 or as N the number of data points. The latter is referred to as leave-one-out cross-validation (LOOCV) in which only one validation site is set aside in each iteration. The model is then calibrated with $N-1$ observations. Some repeat K -fold cross-validation a number of times and average the results to obtain a more robust estimate of the map quality measures.

Note that the problem of spatially correlated errors remains when data are non-probability sample data. Cross-validation using a non-probability sampling dataset suffers from the same drawbacks with respect to unbiasedness and validity of the

estimates of the map quality measures as data-splitting. The estimates cannot be interpreted as being valid for the mapping area, but only for the validation locations.

In R, the caret package (Kuhn, 2016) offers functionality for data-splitting and cross-validation.

7.5 Technical steps - Validation

GF Olmedo

7.5.1 Prediction error

First, we will load the validation dataset. This dataset was measured at the same time as the modeling dataset. After data preparation in chapter 3, we used the code in section 7.5.4 to split the database: 75% of the points were used in the models from chapter 6 and now we will use the remaining 25% of the points to test those results.

```
dat <- read.csv("data/dat_test.csv")

# Promote to spatialPointsDataFrame
library(sp)
coordinates(dat) <- ~ X + Y

dat@proj4string <- CRS(projargs = "+init=epsg:4326")
```

Now, we will load the predicted layers from chapter 6, extract the predicted value for every point and then, estimate the prediction error.

```
library(raster)

OCSKGM_RK <- raster("results/MKD_OCSKGM_RK.tif")
OCSKGM_rf <- raster("results/MKD_OCSKGM_rf.tif")
OCSKGM_svm <- raster("results/MKD_OCSKGM_svm.tif")

dat <- extract(x = OCSKGM_RK, y = dat, sp = TRUE)
dat <- extract(x = OCSKGM_rf, y = dat, sp = TRUE)
dat <- extract(x = OCSKGM_svm, y = dat, sp = TRUE)

dat$PE_RK <- dat$MKD_OCSKGM_RK - dat$OCSKGM
dat$PE_rf <- dat$MKD_OCSKGM_rf - dat$OCSKGM
dat$PE_svm <- dat$MKD_OCSKGM_svm - dat$OCSKGM

# Save the validation results
write.csv(dat, "results/validation.csv", row.names = F)
```

Table 7.2: Summary of prediction errors for 3 different mapping methods

	RK	randomForest	svm
Min.	-4.09	-4.25	-4.78
1st Qu.	-0.31	-0.30	-0.25
Median	0.00	0.01	0.04
Mean	-0.08	-0.08	-0.03
3rd Qu.	0.23	0.24	0.32
Max.	2.01	2.24	1.78
NA's	10.00	12.00	12.00

7.5.2 Estimating the Map Quality Measures

In this section, we present the code needed to estimate the map quality measures for quantitative soil maps.

```
# Mean Error
ME_RK <- mean(dat$PE_RK, na.rm=TRUE)
ME_rf <- mean(dat$PE_rf, na.rm=TRUE)
ME_svm <- mean(dat$PE_svm, na.rm=TRUE)

# Mean Absolute Error (MAE)
MAE_RK <- mean(abs(dat$PE_RK), na.rm=TRUE)
MAE_rf <- mean(abs(dat$PE_rf), na.rm=TRUE)
MAE_svm <- mean(abs(dat$PE_svm), na.rm=TRUE)

# Mean Squared Error (MSE)
MSE_RK <- mean(dat$PE_RK^2, na.rm=TRUE)
MSE_rf <- mean(dat$PE_rf^2, na.rm=TRUE)
MSE_svm <- mean(dat$PE_svm^2, na.rm=TRUE)

# Root Mean Squared Error (RMSE)
RMSE_RK <- sqrt(sum(dat$PE_RK^2, na.rm=TRUE) / length(dat$PE_RK))
RMSE_rf <- sqrt(sum(dat$PE_rf^2, na.rm=TRUE) / length(dat$PE_rf))
RMSE_svm <- sqrt(sum(dat$PE_svm^2, na.rm=TRUE) / length(dat$PE_svm))

# Amount of Variance Explained (AVE)
AVE_RK <- 1 - sum(dat$PE_RK^2, na.rm=TRUE) /
  sum( (dat$MKD_OCSKGM_RK - mean(dat$OCSKGM, na.rm = TRUE))^2,
       na.rm = TRUE)

AVE_rf <- 1 - sum(dat$PE_rf^2, na.rm=TRUE) /
  sum( (dat$MKD_OCSKGM_rf - mean(dat$OCSKGM, na.rm = TRUE))^2,
       na.rm = TRUE)
```

Table 7.3: Summary of map quality measures for 3 different mapping methods

	RK	randomForest	svm
ME	-0.077	-0.081	-0.026
MAE	0.359	0.369	0.392
MSE	0.293	0.314	0.333
RMSE	0.538	0.557	0.574
AVE	-1.054	-1.627	-1.426
MSDR	1.000	1.000	1.000

```

AVE_svm <- 1 - sum(dat$PE_svm^2, na.rm=TRUE) /
  sum( (dat$MKD_OCSKGM_svm - mean(dat$OCSKGM, na.rm = TRUE))^2,
       na.rm = TRUE)

# Mean Squared Deviation Ratio (MSDR)
MSDR_RK <- 1 # filler
MSDR_rf <- 1
MSDR_svm <- 1

```

7.5.3 Graphical Map Quality Measures

In this section, we will apply the proposed graphical quality measures to the results of chapter 6.

```

par(mfrow=c(3,1)) # Two plots in one plot

# scatter plot
plot(dat$MKD_OCSKGM_RK, dat$OCSKGM, main="RK", xlab="predicted",
      ylab='observed')
# 1:1 line in black
abline(0,1, lty=2, col='black')
# regression line between predicted and observed in blue
abline(lm(dat$OCSKGM ~ dat$MKD_OCSKGM_RK), col = 'blue', lty=2)

# scatter plot
plot(dat$MKD_OCSKGM_rf, dat$OCSKGM, main="rf", xlab="predicted",
      ylab='observed')
# 1:1 line in black
abline(0,1, lty=2, col='black')
# regression line between predicted and observed in blue
abline(lm(dat$OCSKGM ~ dat$MKD_OCSKGM_rf), col = 'blue', lty=2)

# scatter plot
plot(dat$MKD_OCSKGM_svm, dat$OCSKGM, main="svm", xlab="predicted",
      ylab='observed')

```

```

    ylab='observed')
# 1:1 line in black
abline(0,1, lty=2, col='black')
# regression line between predicted and observed in blue
abline(lm(dat$OCSKGM ~ dat$MKD_OCSKGM_svm), col = 'blue', lty=2)

par(mfrow=c(1,1))

# spatial bubbles for prediction errors
bubble(dat[!is.na(dat$PE_RK),], "PE_RK", pch = 21,
       col=c('red', 'green'))

# spatial bubbles for prediction errors
bubble(dat[!is.na(dat$PE_rf),], "PE_rf", pch = 21,
       col=c('red', 'green'))

# spatial bubbles for prediction errors
bubble(dat[!is.na(dat$PE_svm),], "PE_svm", pch = 21,
       col=c('red', 'green'))

```

7.5.4 Data-Splitting

As explained before, many times for running validation analysis, we split the data before fitting the models. In this section, we present the code needed to achieve this using **caret** package.

```

library(caret)

dat <- read.csv("data/dataproc.csv")

train.ind <- createDataPartition(1:nrow(dat), p = .75, list = FALSE)
train <- dat[train.ind,]
test <- dat[-train.ind,]

plot(density(log(train$OCSKGM)), col='red')
lines(density(log(test$OCSKGM)), col='blue')
legend('topright', legend=c("train", "test"),
       col=c("red", "blue"), lty=1, cex=1.5)

write.csv(train, file="data/dat_train.csv", row.names = FALSE)
write.csv(test, file="data/dat_test.csv", row.names = FALSE)

```

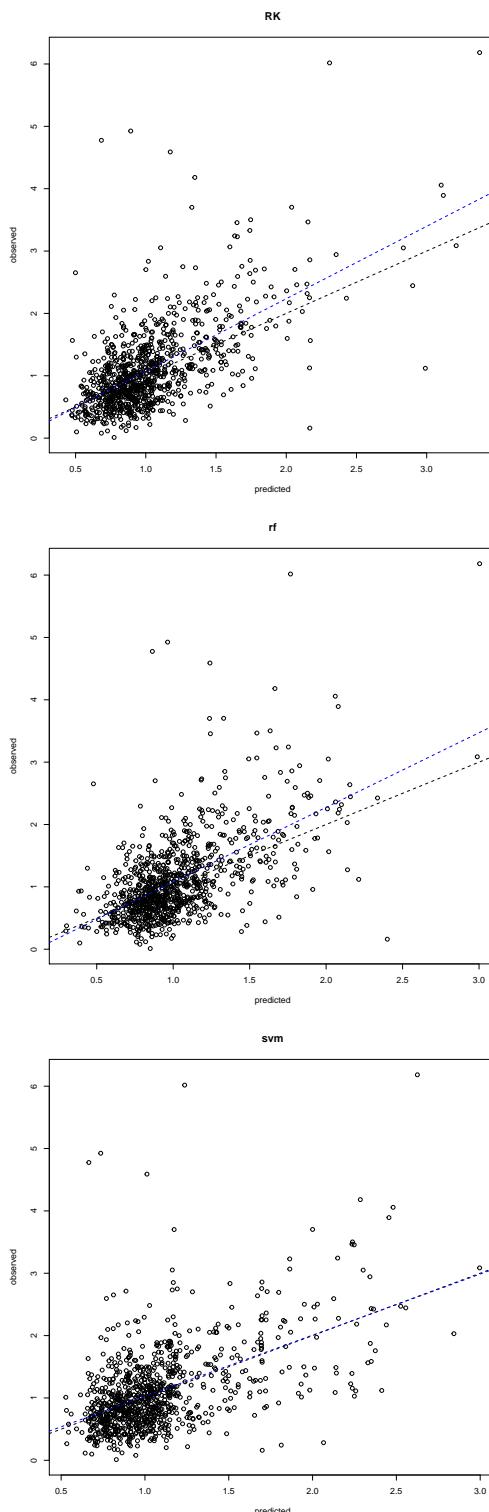


Figure 7.4: Scatter plots of predicted against observed values

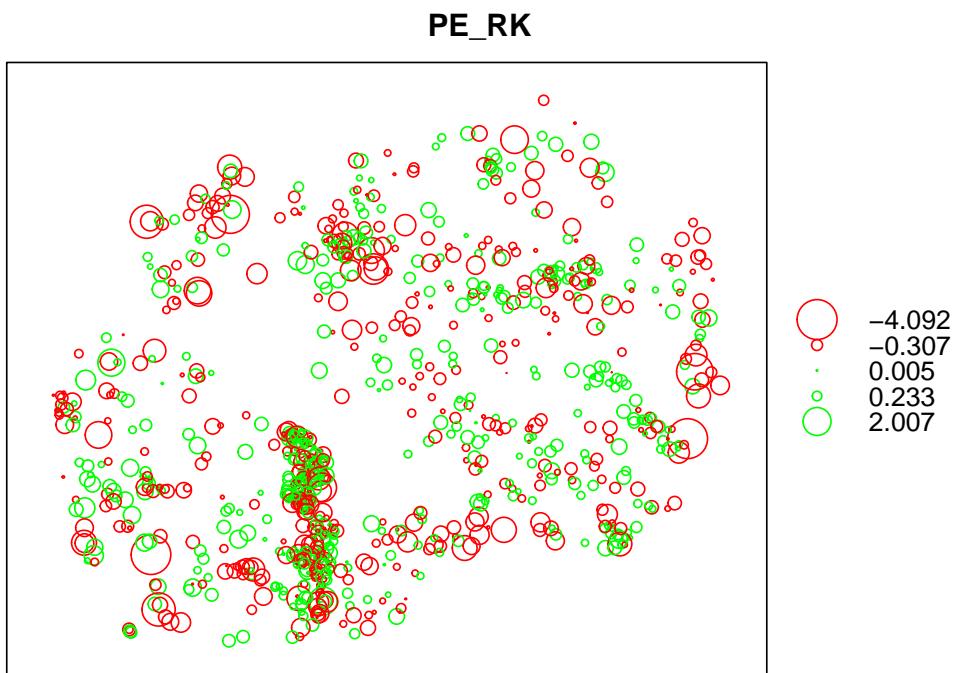


Figure 7.5: Spatial bubble of the prediction errors for RK

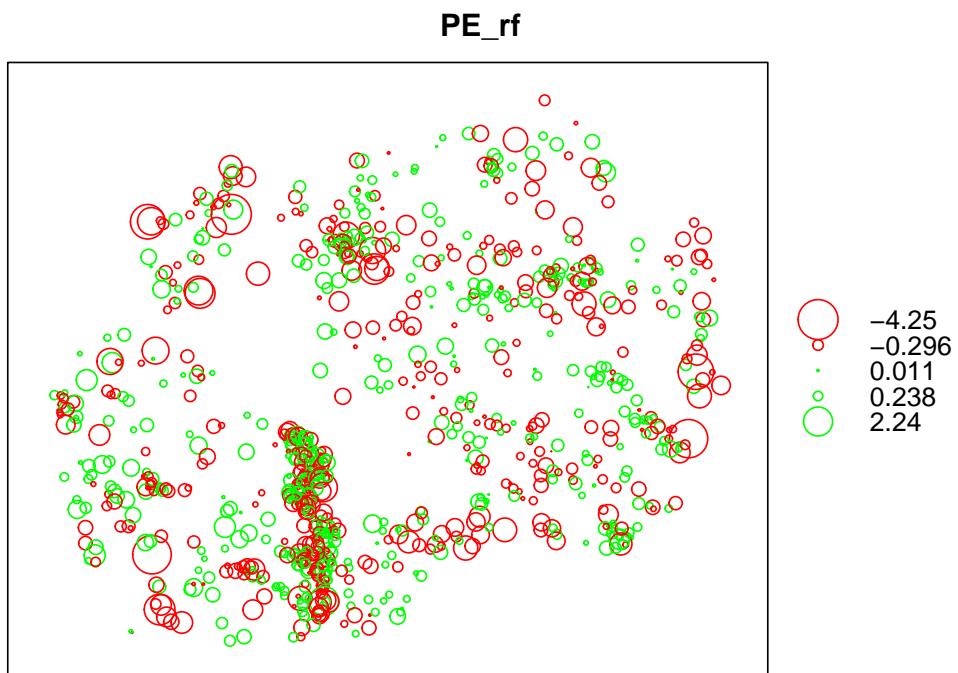


Figure 7.6: Spatial bubble of the prediction errors for rf

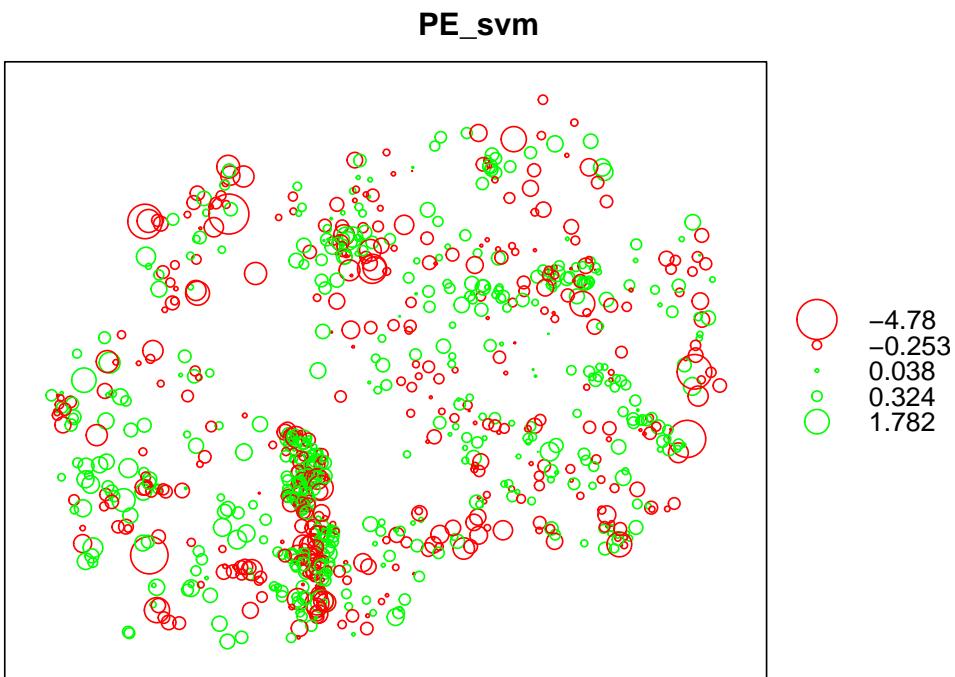


Figure 7.7: Spatial bubble of the prediction errors for svm

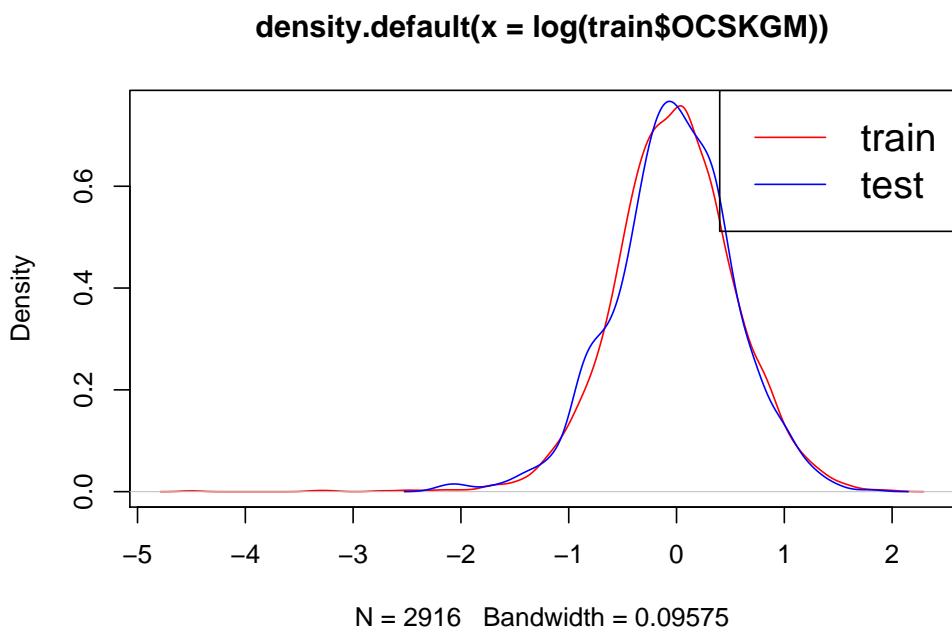


Figure 7.8: Statistical distribution of train and test datasets

Chapter 8

Model Evaluation in Digital Soil Mapping

M Guevara & GF Olmedo

There are no best methods for statistical modeling and different evaluation strategies should be considered in order to identify, realistically, the overall modeling accuracy (Ho and Pepyne (2002); Qiao et al. (2015); Guevara et al. (2018); Nussbaum et al. (2018)). This section is devoted to describe quantitative methods for model evaluation applied to SOC mapping across FYROM. Our objective is to provide a model evaluation example based on a vector of observed SOC and a vector of modeled SOC estimates derived from three different statistical methods (multiple linear regression-kriging RK (Sect.6.2) random forests RF (Sect.6.3), and support vector machines SVM (Sect.6.4)). The model evaluation methods presented here were adapted from the original work of Carslaw & Ropkins for air quality assessments and its R package openair (Carslaw and Ropkins, 2012).

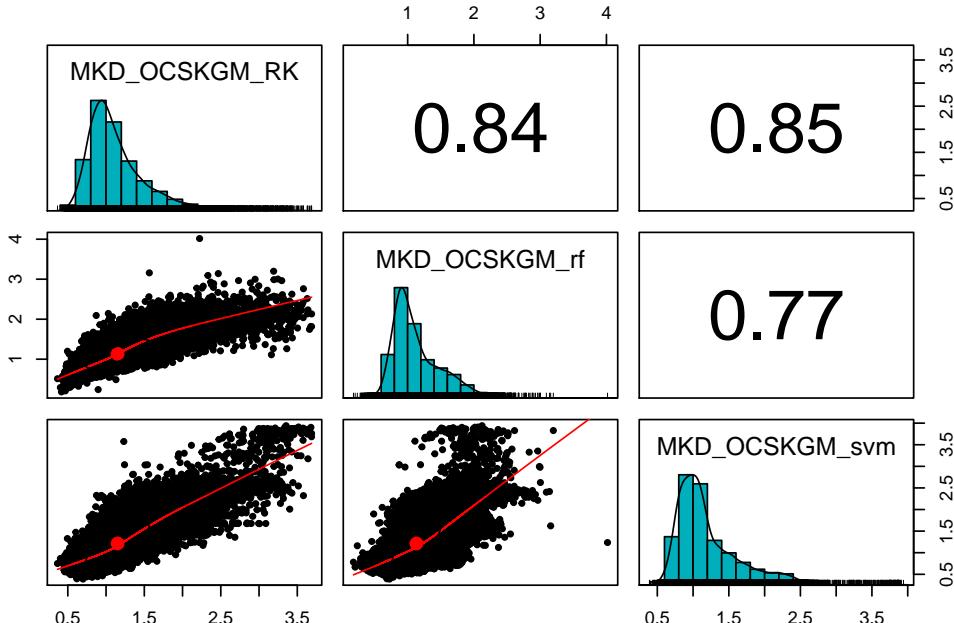
We found in this package a very useful set of functions for model evaluation metrics that are suitable (and we highly recommend) for comparing digital soil maps derived from different prediction algorithms. We will first analyze the simple correlation and major differences of generated SOC maps by the three different methods. Then for further analysis we will prepare a data frame containing the observed and modeled vectors as well as the method column. Ideally the observed vector should be derived from a completely independent SOC dataset, as explained in the previous chapter. The cross validation strategy and the repeated random split for training and testing the models are other two alternatives when no independent dataset is available for validation purposes. However, we do not recommend to use the same training dataset for performing the following analysis, since the resulting ‘best method’ could be the one that overfits the most.

8.1 Technical steps - Model correlations and spatial differences

We will import the predicted maps and harmonize them in to the same regular grid (~1x1km of spatial resolution). Then we will plot the statistical distribution and the correlation between the three different methods (RK, RF, SVM).

```
library(raster)
RF<-raster('results/MKD_OCSKGM_rf.tif')
RK<-raster('results/MKD_OCSKGM_RK.tif')
SVM<-raster('results/MKD_OCSKGM_svm.tif')
#Note that RK has a different reference system
RK <- projectRaster(RK, SVM)
models <- stack(RK, RF, SVM)

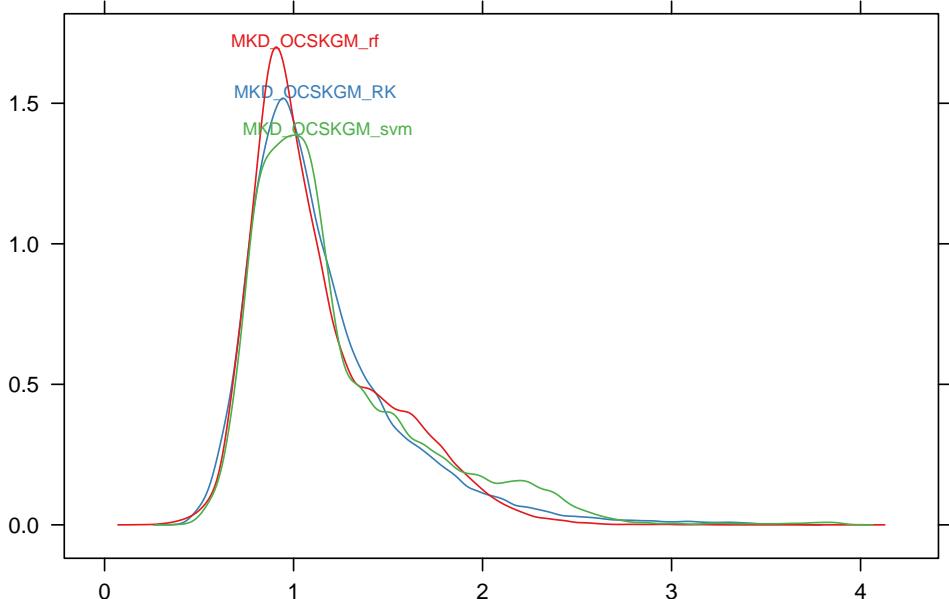
library(psych)
pairs.panels(na.omit(as.data.frame(models)),
            method = "pearson", # correlation method
            hist.col = "#00AFBB",
            density = TRUE, # show density plots
            ellipses = TRUE # show correlation ellipses
            )
```



Here we found that the higher correlation between predicted values was between RK and SVM (0.86). We also found that the statistical distribution of predicted values is quite similar between the three methods and that the lowest correlation of predictions was found between the two machine learning approaches (0.79, RF

and SVM). We can in addition overlap the probability distribution functions for the three different methods to verify that their predictions are similar across the full data distribution of values.

```
library(rasterVis)
densityplot(models)
```

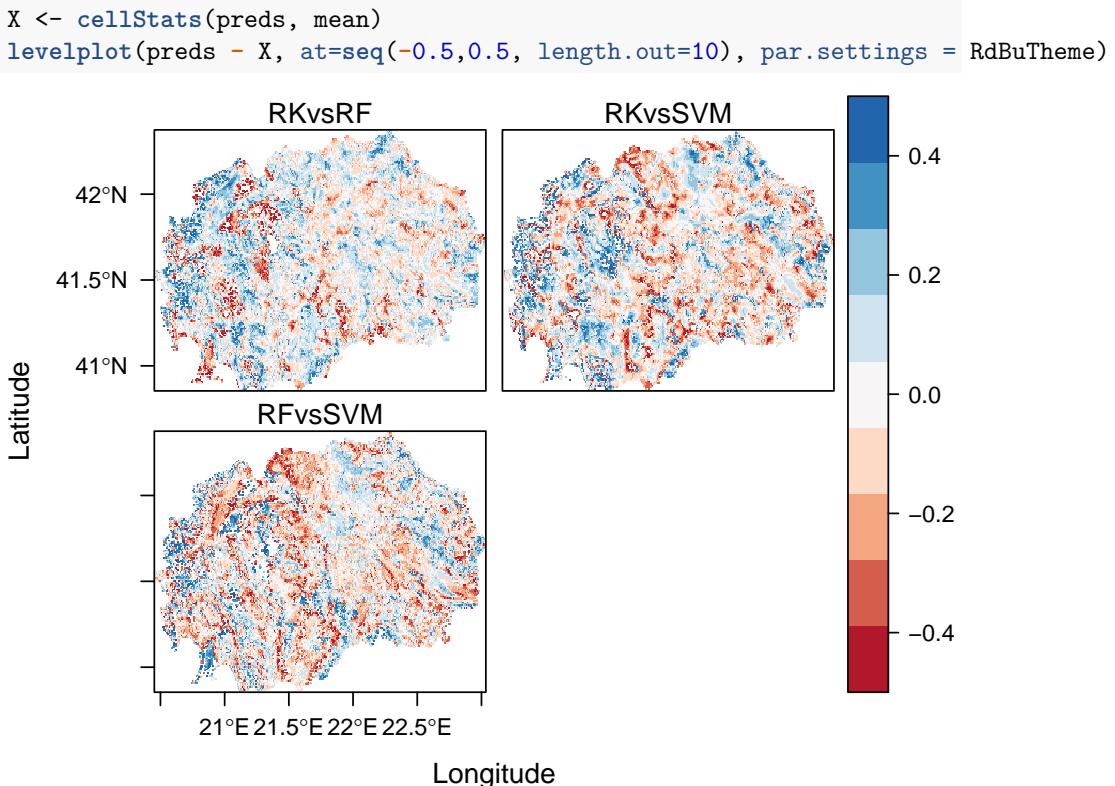


Lets now take a look at the spatial differences. This step will allow to identify the geographical areas within the prediction domain where model predictions more agree and disagree. To spatially compare model predictions we will estimate the standard deviation and the differences between the three SOC maps.

```
SD <- calc(models , sd)
library(mapview)
mapview(SD)
```

The mapview command will plot the standard deviation map in a *.html* file. Note roughly how the hotspots (yellow to red colors) of higher variance of predictions tend to be higher towards the west of the country, whereas models tend to agree in their predictions across the east side of the country. Note also that the variability although noisy, it shows a general pattern, (e.g., from east to west), suggesting that model agreement could be associated with specific land surface characteristics. Now we will analyze specific differences between the three models (RK vs RF, RK vs SVM, RF vs SVM).

```
RKRF <- calc(models[[c(1,2)]], diff)
RKSVM <- calc(models[[c(1,3)]], diff)
RFSVM <- calc(models[[c(2,3)]], diff)
preds <- stack(RKRF, RKSVM, RFSVM)
names(preds) <- c('RKvsRF', 'RKvsSVM', 'RFvsSVM')
```



Note how the spatial differences of the predicted SOC values have similar patterns, but the difference between RK and RF seems to be less sharp than the differences of SVM with the other two methods. Note that we use the `levelplot` function to generate a better visualization (from red-to-white-to-blue) of the main effects of differences (e.g., if they are positive or negative), but we could also use the `mapview` function to analyze these maps in a more interactive fashion. The variance of predictions derived from different models can be used as a proxy of model uncertainty and provides valuable information to consider in further applications of SOC maps (e.g., modeling crop production or quantifying SOC stocks).

8.2 Technical steps - Model evaluation

To compare the performance of the three models, we will compare the observed values used and the predicted values for the validation points. We have to load the validation dataset and the prediction result of the 3 models. The table containing these values was prepared in Section 7.5.

```
dat <- read.csv("results/validation.csv")
```

We will prepare a new table from this data that we are going to use for model

evaluation purposes. The new table should have the observed value, the predicted value and the model.

```
# prepare 3 new data.frame with the observed, predicted and the model
modRK <- data.frame(obs = dat$OCSKGM, mod = dat$MKD_OCSKGM_RK,
                      model = "RK")

modRF <- data.frame(obs = dat$OCSKGM, mod = dat$MKD_OCSKGM_rf,
                      model = "RF")

modSVM <- data.frame(obs = dat$OCSKGM, mod = dat$MKD_OCSKGM_svm,
                      model = "SVM")

# merge the 3 data.frames into one
modData <- rbind(modRK, modRF, modSVM)

summary(modData)
```

	obs	mod	model
## Min.	:0.0111	Min. :0.2980	RK :970
## 1st Qu.	:0.6681	1st Qu.:0.8196	RF :970
## Median	:0.9518	Median :0.9589	SVM:970
## Mean	:1.1076	Mean :1.0422	
## 3rd Qu.	:1.3744	3rd Qu.:1.1507	
## Max.	:6.1827	Max. :3.3768	
## NA's			:34

Now we will use the `modStats` function to calculate common numerical model evaluation statistics which are described and mathematically defined in the openair manual ([Carslaw \(2015\)](#), Ch. 27, pp 231-233). These include:

- n , the number of complete pairs of data.
- $FAC2$, fraction of predictions within a factor of two.
- MB , the mean bias.
- MGE , the mean gross error.
- NMB , the normalized mean bias.
- $NMGE$, the normalized mean gross error.
- $RMSE$, the root mean squared error.
- r , the Pearson correlation coefficient.
- COE , the Coefficient of Efficiency based on [Legates and McCabe \(1999\)](#), [Legates and McCabe \(2013\)](#). A perfect model has a $COE = 1$. A value of $COE = 0.0$ or negative implies no prediction capacity.
- IOA , the Index of Agreement based on [Willmott et al. \(2012\)](#), which spans between -1 and 1 with values approaching +1 representing better model performance.

A perfect model would have a $FAC24$, r , COE and $IOA \sim 1.0$, while all the others ~ 0 . However, digital soil mappers should have in mind that there is no such thing as a perfect model on digital SOC mapping for large areas, especially if we deal

Table 8.1: Summary of Different Model Evaluation Statistics for the 3 Models Compared

model	FAC2	MB	MGE	NMB	NMGE	RMSE	r	COE	IOA
RK	0.89	-0.08	0.36	-0.07	0.32	0.54	0.63	0.25	0.63
RF	0.88	-0.08	0.37	-0.07	0.33	0.56	0.59	0.23	0.62
SVM	0.86	-0.03	0.39	-0.02	0.36	0.58	0.53	0.18	0.59

with sparse data from legacy soil profile or pit observations usually collected over long periods of time. Depending on the situation, some performance measures might be more appropriate than others. Hence, there is not a single best measure, and it is necessary to use a combination of the performance measures (Chang and Hanna, 2004).

```
#Load the openair library
library(openair)

modsts <- modStats(modData,obs = "obs", mod = "mod", type = "model")
```

From our SOC mapping example across FYROM, the three models generate similar results. The FAC2 is close to 0.8 in all cases, being RK the one closer to 1. MB and NMB suggest that all the model's tend to underestimate SOC because they are negative. SVM tend to underestimate less than RK and RF. The MGE, NMGE, and RMSE suggest however that SVM is generating the larger error rate and by the values of r COE and IOA, we could say that given available SOC data across FYROM, the RK method improves the predictive capacity of RF and SVM.

The aforementioned conclusion can be verified by plotting a Taylor Diagram (Fig. 8.1), which summarizes multiple aspects of model performance, such as the agreement and variance between observed and predicted values (Taylor, 2001). Recent reports show that the integration of simple validation metrics (e.g., the rmse correlation ratio) allows to extract information about modeling performance that could not be obtained by analyzing the validation metrics independently, such as the agreement between explained variance and bias (Guevara et al. (2018); Nussbaum et al. (2018)). Taylor Diagrams interpretation rely on the relationships between explained variance and bias (from observed and modeled data). Note from our Taylor Diagram that the RK method is closer to the observed value, followed by RF. Although, no significant difference was evident between the model of the three implemented algorithms.

```
TaylorDiagram(modData, obs = "obs", mod = "mod", group = "model",
cols = c("orange", "red","blue"), cor.col='brown',rms.col='black')
```

However, we need to check that the effectiveness of RK remains across all the full distribution of SOC observed values. For doing this, we can plot the conditional quantiles to verify the higher prediction capacity of RK (Fig. 8.2).

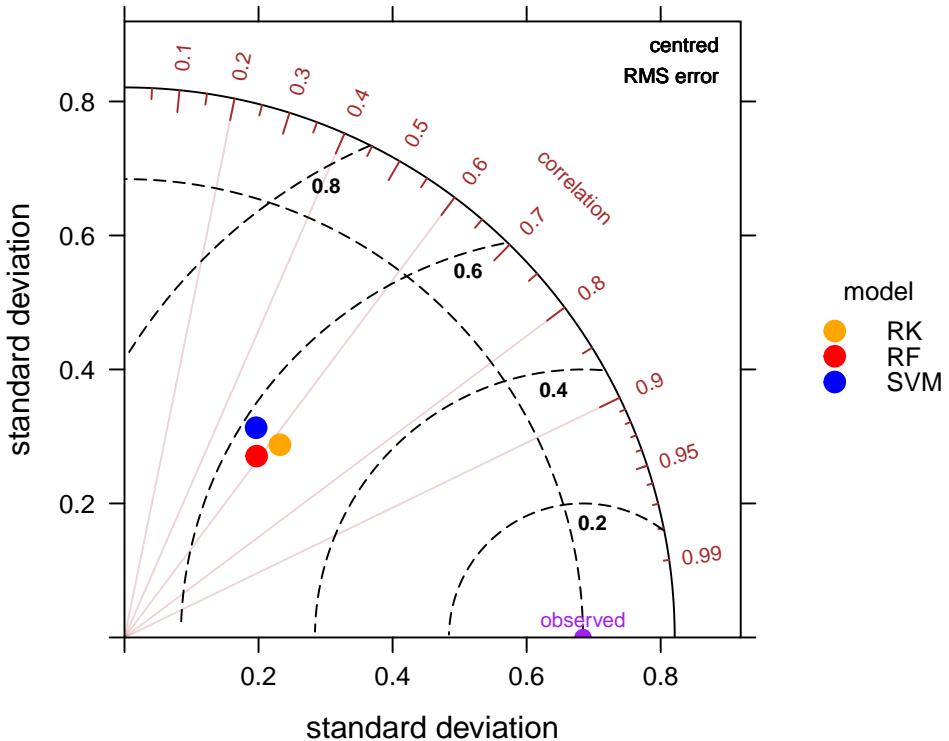


Figure 8.1: Taylor diagram used in the evaluation of the 3 digital soil mapping models

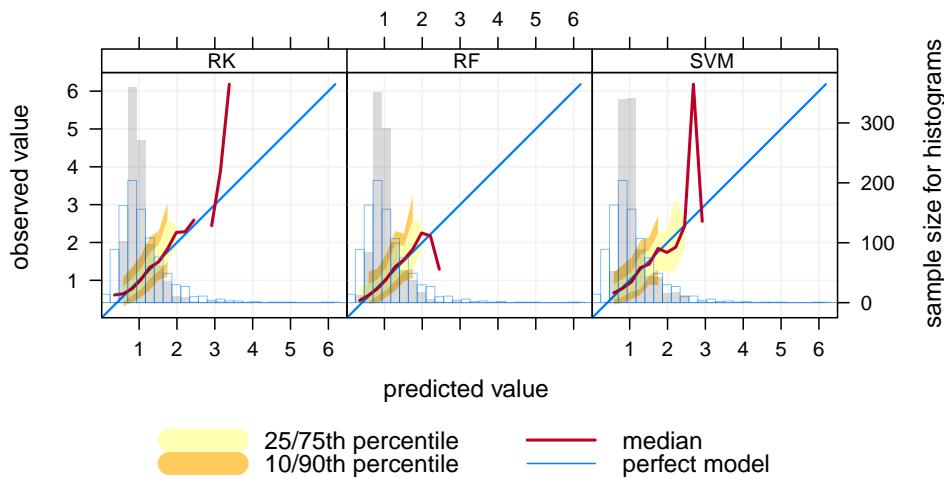


Figure 8.2: Effectiveness of the different digital soil mapping models across the full distribution of SOC observed values

```
conditionalQuantile(modData, obs = "obs", mod = "mod", type = "model")
```

The blue line shows the results for a perfect model. In this case, the observations cover a range from 0 to 6 kg.m⁻². Interestingly, the maximum predicted value is in all cases less than 3 kg.m⁻², which is consistent with the MB and NMB previous results. Note that the median of predictions across the larger SOC values seems to have more variability across SVM and RK compared with RF, which could generate less biased predictions across SOC values >2.0 kg.m⁻². The red line shows the median value of the predictions. The shading shows the predicted quantile intervals (i.e. the 25/75th and the 10/90th). A perfect model would lie on the blue line and have a very narrow spread and the histograms show the counts of observed (gray) and predicted values (blue).

We conclude, for this specific example, that RK showed the best performance based on the implemented evaluation metrics. Therefore RK is a suitable method predicting SOC values across Macedonia, although our results show a large scattered variance of higher SOC predicted values (after the third quantile quantile of the data range) compared with the observed vector. While RF shows more conservative results across the higher SOC values (e.g., fourth quantile), SVM had the lowest model performance based these metrics. SVM was also the method showing higher spatial differences compared with RF and RK.

Finally, we want to highlight that Integrating different statistical methods and visualization tools, such as those provided by the openair package of R (Carslaw and Ropkins, 2012) will enhance our capacity to identify the best modeling approaches and a combination of SOC prediction factors given a specific dataset. Model evaluation benefits our understanding of the circumstances why each modeling approach

will generate different results, which is a first step towards reducing the uncertainty of model performance while increasing the spatial resolution of predictions, the eternal digital soil mapping problem.

Chapter 9

Uncertainty

GBM Heuvelink

Soil mapping involves making predictions at locations where no soil measurements were taken. This inevitably leads to prediction errors because soil spatial variation is complex and cannot be modeled perfectly. It also implies that we are uncertain about the true soil class or true soil property at prediction locations. We only have the predictions, which differ from the true values in an unpredictable way, and hence we are uncertain about the true value. In fact, we may even be uncertain about the soil at the measurement locations because no measurement method is perfect and uncertainty also arises from measurement errors.

This chapter describes how uncertainty may be characterized by probability distributions. It also explains how the parameters of these distributions may be derived, leading to quantification of uncertainty. We will see that this can become quite complex, because soil properties vary in space and are often cross-correlated, which the uncertainty model must take into account. A further complication is that there are many different sources of uncertainty. In some cases, it may be too difficult to arrive at a spatially explicit characterization of uncertainty, and in such case, statistical validation may be used to derive summary measures of the accuracy of soil maps. We begin this chapter with a description of uncertainty sources.

9.1 Sources of Uncertainty

Consider a case in which soil samples were taken from a large number of measurement locations in a study area, taken to the laboratory and analyzed for various soil properties. Let us further assume that the measurement locations were indicated on a topographic map and that the soil was also classified at each measurement location. Next, the soil property and soil type observations were used to create maps of soil properties and soil type using digital soil mapping techniques. These techniques not only make use of the soil observations but also benefit from maps of

environmental variables that are correlated with the soil, and hence help explain the soil spatial variation. Which sources of uncertainty contribute to uncertainty about the final soil maps? We distinguish four main categories.

9.1.1 Attribute Uncertainty of Soil Measurements

Soil measurements suffer from measurement errors in the field and laboratory. Perhaps the soil was not sampled at the right depth, perhaps the organic layer was not removed completely before collecting soil material, or perhaps by accident bags were interchanged or numbered wrongly. Field estimates of soil type and soil properties are also not error-free, especially when estimation is difficult, such as estimation of SOC content or texture. Field estimates may also be subjective because soil scientists may be trained differently and so there may be systematic differences between their field estimates of soil properties. Similarly, it is also not uncommon for soil scientists to disagree about the soil type when classifying a soil in the field.

Laboratory analysis adds error too. Soil samples may not be perfectly mixed prior to taking a much smaller subsample that is actually measured; instruments have limited precision and may have systematic errors, climate conditions in the lab vary, and there can be differences between procedures used by laboratory personnel. Differences between laboratories are even bigger and may be of the same order of magnitude as the soil variation itself. It is strongly advised to always take sufficient duplicates and randomize the order in which soil samples are analyzed in the laboratory. This allows quantifying the combined field and laboratory measurement errors.

9.1.2 Positional Uncertainty of Soil Measurements

When collecting soil data in the field we would generally note the geographic coordinates of the measurement locations. Nowadays this is easy with GPS instruments and depending on the device, modest to high positional accuracy can be achieved. But it may still be too large to be negligible. For instance, consider the case where the soil data are used to train a digital soil mapping model that predicts soil properties from covariates. Let these covariates be available at high spatial resolution and have substantial fine-scale spatial variation. Then it is clear that positional uncertainty in the soil measurements may link these measurements to the wrong covariates, which will weaken the strength of the relationship between the soil variable and covariates and deteriorate the quality of the final soil map.

Many soil legacy data suffer from large positional uncertainty. Locations may only be traced from vague descriptions such as “near village A” or “east of the road from B to C”. In such case, researchers should consider whether using such data for calibration of a DSM model and for spatial prediction using the calibrated DSM model is wise. It may do more harm than good. This depends on the specific DSM model used and the degree of spatial variation of the covariates. It also depends

on the degree of spatial variation of the soil property itself. If it has negligible fine-scale spatial variation and hence has similar values at the registered and actual geographic location, then little harm is done. For instance, in the Sahara desert many soil properties will show little spatial variation over distances of hundreds or perhaps thousands of meters, so in such case, poor geographic positional accuracy will not seriously affect DSM predictions.

9.1.3 Uncertainty in Covariates

Maps of covariates that are used in DSM can also suffer from errors and uncertainties. For instance, a Digital Elevation Model (DEM) is a major source of geomorphological covariates but DEMs are only approximations of the real elevation. DEM errors will propagate and cause uncertainty in geomorphological properties such as slope, aspect and topographic wetness index. As a result, the DSM model must be trained on covariate data that are merely approximations of the intended covariates, which will generally lead to weakened relationships and larger DSM prediction errors. Land cover is another example; soil properties may be strongly influenced by land cover, but such relationship may come out quite weak if the DSM model is trained with a land cover map that represents land cover wrongly for a large part of the study area.

Covariates also come in a specific spatial resolution which may be quite coarse in specific cases. In order to use the covariate in a fine-scale DSM model, the coarse-scale grid cell value will be copied to all fine-scale grid cells contained in it, but clearly, fine-scale spatial variation implies that uncertainties will be introduced. A possible solution might be to smooth the coarse-scale covariate prior to entering it to DSM calibration but clearly, this will not remedy all problems.

Uncertainty in covariates leads to weaker DSM models, but this weakening is not hidden to the developer because the deterioration of predictive power is implicitly included in the DSM model. For instance, the amount of variance explained by a DSM model that uses the true land cover as measured on sampling sites may be much higher than that of a model that uses a land cover map. Users may then be tempted to calibrate the DSM model with the true land cover data, but if they next apply that model using the land cover map to predict the soil at non-measurement locations they would systematically underestimate the uncertainty of the resulting map.

9.1.4 Uncertainty in Models Predicting Soil Properties From Covariates and Soil Point Data

Even if the soil point data and covariate data were error-free, the resulting DSM predictions would still deviate from the true soil properties. This is because the DSM model itself also introduces uncertainties. Models are merely simplified representations of the real world. The real world is too complex and approximations

are needed. For instance, even though we know that physical, chemical and biological processes determine the soil as given by the state equation of soil formation $soil = f(cl, o, r, p, t)$, the function f is too complex to be fully understood and implemented in a computer model. Instead, we use crude approximations such as multiple linear regression and machine-learning algorithms. These empirical models have the additional burden that extrapolation beyond conditions represented by the calibration data is difficult and risky. For extrapolation purposes, it is advised to use DSM models that better represent the mechanisms behind soil formation, but again it is practically impossible to build mechanistic models that represent the real world perfectly. This is not only because we may not understand all processes and their interactions well, but also because dynamic mechanistic models need much information, such as the initial state, boundary conditions, and driving forces. Such detailed information is generally lacking.

Model uncertainty is generally subdivided into model parameter uncertainty and model structural uncertainty. The first can be reduced by using models with fewer parameters or by using a larger calibration data set. The latter can be reduced by using a more complex model, but this will only work if there are enough data to calibrate such model. Thus, in general, a compromise has to be sought by choosing a level of model complexity that matches the amount of information available.

9.2 Uncertainty and Spatial Data Quality

Research into spatial accuracy in Geographic Information Science has listed five main elements of spatial data quality: * lineage * positional accuracy * attribute accuracy * logical consistency * completeness

We have already discussed positional and attribute accuracy. Lineage refers to documenting the original sources for the data and the processing steps. This is strongly related to the principle of reproducible research. Logical consistency addresses whether there are any contradictory relationships in the database. For instance, it checks whether all data have the same geographic projection and that measurement units are consistent. Completeness refers to whether there are any missing data. For instance, covariate maps must cover the entire study area if they are to be used as explanatory variables in a DSM model. Soil profile data need not capture all relevant soil properties and tend to have fewer soil measurements at greater depths.

In summary, there are many sources of uncertainty that affect the quality of DSM products. This section has reviewed these sources but was purposely descriptive. The next section selects a few major uncertainty sources and works out quantitatively how these cause uncertainty in the resulting soil map. Perhaps it is useful to mention that focussing attention on errors and uncertainties may give the wrong impression that soil maps are generally inaccurate and of poor quality. This is not the message that we wish to convey here. But producers and users of soil maps should be aware of the sources of uncertainty and should ideally identify how these uncertainties affect the final product. Thus, quantification of the uncer-

tainty in DSM maps, be it through explicit modeling or independent validation is important.

9.3 Quantifying Prediction Uncertainty

Uncertainties in soil measurements, covariates and DSM models propagate to resulting soil maps. The uncertainty propagation can fairly easily be traced provided that the uncertainty sources are characterized adequately. The most appropriate way of doing that is by making use of statistics and probability distributions. This section also takes that approach and starts by providing a brief overview of probability distributions and how these may be used to represent uncertainty. Next, it analyses how the four sources of uncertainty distinguished in Section 5.1 lead to uncertainty in soil maps produced using DSM.

9.3.1 Uncertainty Characterised by Probability Distributions

If we are uncertain about the value of a soil property at some location and depth this means that we cannot identify one single, true value for that soil property (Goovaerts (2001); Heuvelink (2014)). Instead, we may be able to provide a list of all possible values for it and attach a probability to each. In other words, we represent the true but unknown soil property by a probability distribution. For instance, suppose that we estimate the sand content of a soil sample in the field as 35%, while recognizing that a field estimate is quite crude and that the true sand content may very well be less or more than the estimated 35%. We might be confident that the estimation error is unlikely to be greater than 8%, and hence it would be reasonable to represent the sand content by a normal distribution with a mean of 35% and a standard deviation of 4%. For the normal distribution, 95% of the probability mass lies within two standard deviations from the mean, so we would claim that there is a 5% probability that the sand content is smaller than 27% or greater than 43%.

In the example above we had chosen the normal distribution because it is the most common probability distribution but we might as well have used a different distribution, such as the uniform or lognormal distribution. Indeed many soil properties, such as soil nutrient concentrations are better described by lognormal distributions, because values below zero cannot occur and because very high positive values (i.e. outliers) are not unlikely. For instance, we may estimate the organic carbon concentration (OC) of a soil sample as 1.2% and identify with it an asymmetric 95% credibility interval ranging from 0.8% to 2.5%. In general, statistical modeling is easier if the variables under study can be described by normal distributions. This explains why we usually apply a transformation to skewed variables prior to statistical modeling. For instance, when building a DSM model of OC, it may be wise to develop such model for the logarithm of OC and do a back-transform on the DSM predictions.

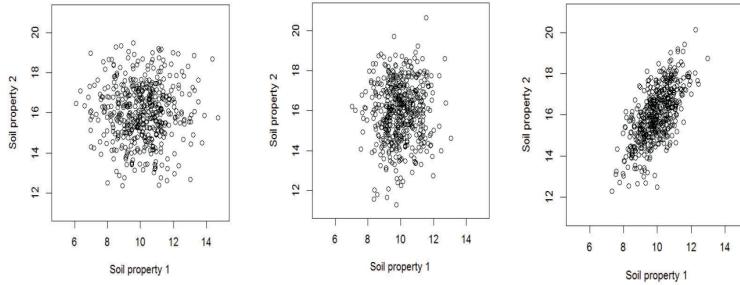


Figure 9.1: Scatter plots of 500 paired soil property values drawn from a two-dimensional normal distribution

There are many different soil properties that in addition vary in space and possibly time. Thus, the characterization of uncertainty about soil properties needs to be extended and include cross- and space-time correlations. It is beyond the scope of this chapter to explain this in detail, for this we refer to standard textbooks such as Goovaerts (1997) and Webster and Oliver (2007). If we assume a joint normal distribution, then a vector of soil properties (be it different soil properties or the same soil property at multiple locations, depths or times) Z is fully characterized by the vector of means m and variance-covariance matrix C . Figure 9.1 shows three examples of 500 paired soil property values that were simulated from different bivariate normal distributions. The left panel shows an uncorrelated case with equal standard deviations for both properties. The centre and right panels show a case where soil property 2 has a greater standard deviation than soil property 1. The difference between these two cases is that the centre panel has a zero correlation between the two soil properties while it is positive in the right panel.

9.3.2 Propagation of Model Uncertainty

Now that we have clarified how uncertainty in soil properties may be characterized by probability distributions, let us consider what these distributions look like in DSM and how these are influenced by the uncertainty sources described in Section 9.1. We begin with uncertainty source 4, uncertainty in DSM models. We noted before that uncertainty in DSM models may be separated in model parameter and model structural uncertainty. A typical example of this is a multiple linear regression model:

$$Z(s) = \beta_0 + \beta_1 \cdot X_1(s) + \beta_2 \cdot X_2(s) + \varepsilon(s) \quad (9.1)$$

Note that here for simplicity we assumed two environmental covariates X_1 and X_2 while in practice we are likely to use many more. Parameter uncertainty of this model occurs because the parameters β_0 , β_1 and β_2 are merely estimated using calibration data. Under the assumptions made by the linear regression model, these estimation errors are normally distributed and have zero mean, while their

standard deviations and cross-correlations can also be computed (e.g. Snedecor and Cochran 1989, Section 17.5). The standard deviations become smaller as the size of the calibration dataset increases. Both the standard deviations and cross-correlations are standard output of statistical software packages. Thus, we could sample from the joint distribution of the parameter estimation errors in a similar way as displayed in Figure 9.1.

The model structural uncertainty associated with the multiple linear regression model Eq. 9.1 is represented by the stochastic residual ε . It too is normally distributed and has zero mean, while its standard deviation depends on the (spatial) variation of the soil property Z and the strength of the relationship between Z and the covariates X_1 and X_2 . If the covariates explain a great deal of the variation of the soil property then the standard deviation of the residual will be much smaller than that of the soil property, as expressed by the goodness-of-fit characteristic R^2 , also termed ‘amount of variance explained’. It will be close to 1 in case of a strong linear relationship between soil property and covariates. In that case, the standard deviation of the stochastic residual will be much smaller than that of the soil property, because a large part of the variation is explained by the model. If the covariates bear no linear relationship with the soil property (i.e., $R^2 = 0$), the stochastic residual will have the same standard deviation as the soil property.

Since the joint probability distributions of the parameter estimation errors and the stochastic residual can analytically be computed and are routinely provided by statistical software, it is not difficult to analyse how these uncertainties propagate through the DSM model Eq. 9.1. This can be done analytically, because Eq. 9.1 is linear in the stochastic arguments (note that the covariates are treated known and deterministic). If we predict the soil property Z at a prediction location s_0 using the calibrated regression model as:

$$\hat{Z}(s_0) = \hat{\beta}_0 + \hat{\beta}_1 \cdot X_1(s_0) + \hat{\beta}_2 \cdot X_2(s_0) \quad (9.2)$$

then the prediction error will be normally distributed with zero mean and variance (i.e., the square of the standard deviation) given by:

$$\begin{aligned} Var(\hat{Z}(s_0) - Z(s_0)) &= Var(\hat{\beta}_0) + Var(\hat{\beta}_1) \cdot X_1(s_0)^2 + Var(\hat{\beta}_2) \cdot X_2(s_0)^2 + \\ &\quad 2Cov(\hat{\beta}_0, \hat{\beta}_1) \cdot X_1(s_0) + 2Cov(\hat{\beta}_0, \hat{\beta}_2) \cdot X_2(s_0) + \\ &\quad 2Cov(\hat{\beta}_1, \hat{\beta}_2) \cdot X_1(s_0) \cdot X_2(s_0) + Var(\varepsilon(s_0)) \end{aligned} \quad (9.3)$$

This is a complicated expression but all entries are known and hence it can be easily calculated.

In many DSM applications, an additional step will be included that makes use of the fact that the stochastic residual ε in Eq. 9.1 is spatially autocorrelated, as characterized by a semivariogram. If this is the case the residual spatial correlation can be exploited by incorporating a kriging step (Hengl et al., 2004). Kriging has been explained in Chapter 6, where it was also explained that the uncertainty in

the predictions is quantified by the kriging variance. We will not repeat the theory here, but simply note that the kriging variance computes the prediction error variance just as was done in Eq. 9.3, but that in case of kriging the $Var(\varepsilon(s_0))$) term in Eq. 9.3 is replaced by a smaller term, because kriging benefits from residual spatial correlation. In fact, in case of a pure nugget variogram, the kriging variance would be identical to Eq. 9.3, because in such case there is no spatial autocorrelation that one can benefit from. Note also that here we refer to Kriging with External Drift because we included a non-constant mean (i.e., covariates X_1 and X_2). If no covariates were included Eq. 9.3 would simplify dramatically leaving only uncertainty in the estimated (constant) mean and the stochastic residual. This might then be compared with the ordinary kriging variance.

So far we considered uncertainty in DSM models that are linear in the covariates and that represent the model structural uncertainty by an additive stochastic term. This was relatively easy because tracing how uncertainty in model parameters and model structure propagate to the model output could be done analytically. However, using linear models also poses serious restrictions. The relationship between soil properties and covariates are typically not linear but much more complex. This has led to the development and use of complex non-linear DSM models, such as regression trees, artificial neural networks, support vector machines and random forests approaches, all summarised under the term ‘machine learning’ (e.g. [Hengl et al. \(2015a\)](#)). These more complex models typically yield more accurate soil predictions but quantification of the associated uncertainty is more difficult. In most cases, one resorts to validation and cross-validation statistics that summarise the prediction accuracy over the entire study area. How this is done will be explained in detail in 7.3. Such summary validation measures are very valuable but are no substitute for spatially explicit uncertainties such as the kriging variance and the prediction error variance presented in Eq. 9.3. Research into quantification of location-specific uncertainties when using machine learning algorithms is therefore important. However, it is beyond the scope of this chapter to review this area of ongoing research. One particular approach makes use of quantile regression forests. We refer to [Meinshausen \(2006\)](#) for a general text and to [Vaysse and Lagacherie \(2017\)](#) for a DSM application of this promising, albeit computationally challenging approach.

9.3.3 Propagation of Attribute, Positional and Covariate Uncertainty

In Section 7.1 we noted that next to uncertainties in model parameters and model structure there may also be uncertainties in the attribute values and positions of the soil point data and in the covariates. These sources of uncertainty will also affect the outcome of DSM model predictions.

Uncertainties in soil attribute values effectively mean that the DSM model is calibrated with error-contaminated observations of the dependent variable. Let us consider the multiple linear regression model Eq. 9.1 again. True values of the dependent variable Z (i.e., the target soil property, such as pH, clay content or

total nitrogen concentration) are no longer for calibration of this model. Instead, we must make do with measurements Y of Z :

$$Y(s_i) = Z(s_i) + \delta(s_i), \quad i = 1 \dots n \quad (9.4)$$

where n is the number of measurement locations and $\delta(s_i)$ is a random variable representing measurement error. It is custom to assume that all $\delta(s_i)$ are normally distributed, have zero mean and are mutually independent, although these assumptions are not strictly necessary. Their standard deviations may vary between cases and depend on the accuracy and precision of the measurement method. For instance, field estimates tend to be more uncertain than laboratory measurements and so the corresponding measurement errors will have a larger standard deviation. The consequence of the presence of measurement errors is that the estimates of the model parameters will be more uncertain. This is no surprise because the calibration data are of poorer quality. The prediction error variance will be greater too, for the same reason. If spatial correlation of the model residual ε is included and an extension to Kriging with External Drift is made, uncertainty due to measurement errors is further increased because the conditioning of predictions to observations cannot benefit as much as when the observations were error-free. For mathematical details we refer to Cressie (1993). Finally, we should also note that if different observations have different degrees of measurement error, then this will influence the weights that each measurement gets in calibration and prediction. Measurements with larger measurement errors get smaller weights. This is automatically incorporated in multiple linear regression and Kriging with External Drift, but how this can be incorporated in machine-learning approaches is less clear.

Positional uncertainty of soil point observations will also deteriorate the quality of the predictions of calibrated DSM models. However, it is difficult to predict how much the prediction accuracy is affected. It largely depends on the degree of fine-scale spatial variation of the soil property and covariates. For instance, if both the soil property of interest and the covariates are spatially smooth and hardly change over distances within the range of spatial displacement due to positional uncertainty, then little damage is afflicted by positional uncertainty. But otherwise much harm can be done because the soil observations will be paired with covariate values from displaced locations that can be very different. So far, this interesting and important topic has received only little attention in the DSM literature. Grimm and Behrens (2010) and Nelson et al. (2011) are two examples of studies that assessed the effect of positional error on the accuracy of digital soil maps.

Finally, there are also uncertainties in covariates that affect the accuracy of DSM predictions. In fact, these uncertainties are already incorporated in the model structural uncertainty discussed before, because offering covariates that are poor approximations of the true soil forming factors will explain little of the spatial variation and lead to low goodness-of-fit statistics. From a statistical point of view, the covariates used in Eq. 9.1 need not be the ‘true’ soil forming factors but could as well be proxies of those. This does not harm the theory and quantification of the prediction error variance such as through Eq. 9.3 in the multiple linear regression

case or using the kriging variance in a KED approach remain perfectly valid. This does not mean that digital soil mappers should not look for the most accurate and informative covariates because clearly weak covariates lead to poor predictions of the soil (e.g. Samuel Rosa et al. 2015).

Chapter 10

Data Sharing

T Hengl, L Poggio, E Ribeiro & B Kempen

This chapter reviews possibilities and “good practices” of exchanging produced soil data. Once the analysis, spatial prediction and quality control have been all completed, it is useful to follow some minimum steps and export and prepare the data for distribution so that its potential users can easily access it, use it, and make a correct interpretation of data. We consider geo-publishing options for soil data either based on using third-party web services or by using one’s own installation of the software. We put a clear focus on using the Open Source software solutions: GDAL, R, GeoServer, OpenLayers and Leaflet, and public domain data and metadata standards.

The authors have 15+ years of experience in producing, publishing and sharing soil maps and have been involved in large soil mapping projects where data volumes often exceed standard desktop GIS capacities. For information on specific software please refer to the provided links. Even more information on using GDAL and similar GIS tools through a command line can be found via the Global Soil Information Facilities tutorials of ISRIC at <http://gsif.isric.org>. The text is illustrated with example scripts of the statistical software R in combination with GDAL.

10.1 Export Formats

10.1.1 Type of Soil Data and Their Formatting

Before we start reviewing soil data formats, it is useful to understand which types of soil variables, soil maps, and soil DBs are most commonly generated and used, and what are their specific advantages and limitations. Soil science works with many variables common to ecology and/or physical geography (e.g. soil temperature), but it also works with several variables specific to soil science only. Some soil factor-type variables specific to soil science only are for example:

- Soil taxa or soil classes (this includes taxonomic systems and connected diagnostic soil properties and horizons).
- Soil texture-class systems.
- Soil color classification systems e.g. Munsell color codes.
- Soil drainage classes (hydrological classifications).
- Soil diagnostic horizons.

Consider for example the following soil texture data:

```
library(soiltexture)
tex <- data.frame(
  CLAY = c(05,60,15,05,25,05,25,45,65,75,13,47),
  SILT = c(05,08,15,25,55,85,65,45,15,15,17,43),
  SAND = c(90,32,70,70,20,10,10,10,20,10,70,10)
)

TT.plot(class.sys = "USDA.TT", tri.data = tex, main = "",
        cex.axis=.7, cex.lab=.7)
```

The way soil texture data is displayed and texture classes (SaLo, Lo, Sa etc.) used in a texture triangle is specific to soil science. The way this data is formatted and presented can be, likewise, specific to soil science only.

Most of the soil data is in fact spatial. “**Spatial**” implies that spatial (and temporal) reference is attached to each measured/estimated value, i.e. it is location specific. Spatio-temporal references typically include for example:

- Geographic location in local or geographic coordinates (ideally longitude and latitude in the WGS84 coordinate system);
- Depth interval expressed in cm from land surface (upper and lower depth);
- Support size or referent soil volume (or voxel) i.e. the horizontal sampling area multiplied by the thickness of the sampling block;
- Temporal reference i.e. begin and end date/time of the period of measurements/estimations.

Spatial data formats are used to represent spatial objects. This can be (Bivand et al., 2013, neteler2013open):

- Points (2D or 3D): used to represent sampling locations, soil horizons, soil profiles etc.
- Lines (2D): used to represent soil transects, streams, administrative boundaries etc.
- Polygons (2D): used to represent soil mapping units and/or geomorphological units, landforms, administrative areas, farms, plot trials etc.
- Grids or rasters (2D or 2.5D): used to represent soil spatial predictions (spatially complete) of soil properties and classes etc.
- 3D grids or Voxels: used to represent soil spatial predictions (spatially complete) of soil properties in 3D.

It is also important to be able to distinguish between sampled or predicted soil data:

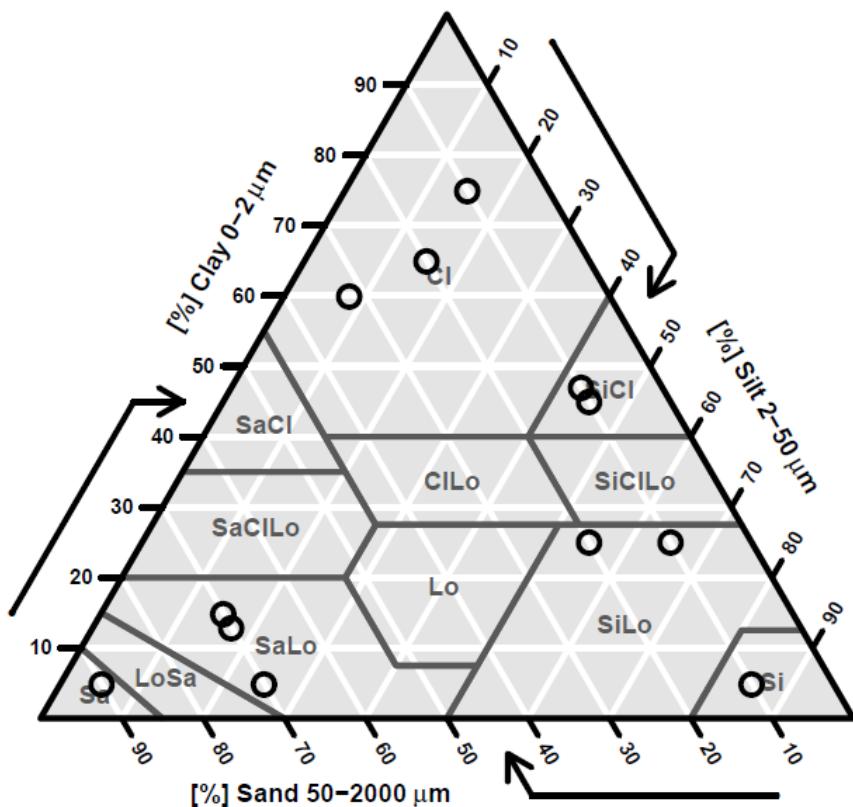


Figure 10.1: Soil texture triangle plot. An example of soil science specific data.

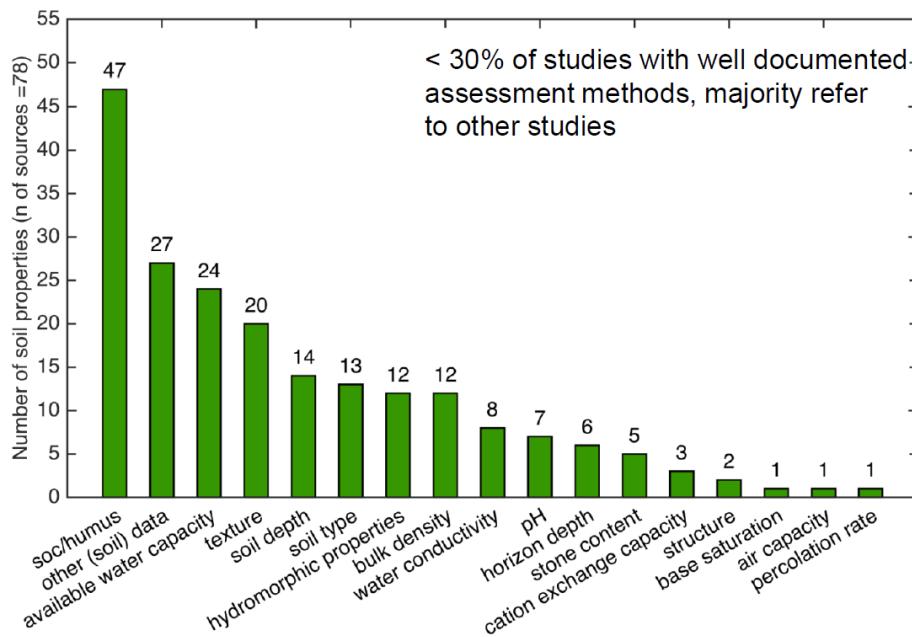


Figure 10.2: Some frequently required soil variables (sorted by number of studies) based on the study by Keller et al. (2014). This list is probably country/project specific but illustrates the differences considering the interest in soil data.

1. Soil samples (usually points or transects) are spatially incomplete. They are used to generate spatial predictions.
2. Spatial predictions of soil variables (soil maps) are spatially complete. They are used for decision making and further modeling i.e. they are used to construct a Soil Information System.

A collection of spatially exhaustive soil grids of various soil properties (physical and chemical soil properties, soil water, soil classification etc) make a **Soil Information System** (SIS). SIS are often complemented with soil sample data and serve both data formats. A Soil Information System should preferably be a **Database** (DB), so that users can access and query data using some standard DB languages (for example SQL). Steps to export soil data into a DB format are explained in later sections.

10.1.2 General GIS Data Formats: Vector, Raster, Table

All soil data we produce through soil mapping can be in principle distributed using one of the two basic GIS formats of data:

- Vector format: this format is often more suitable for exporting point, line,

- and polygon (areal) data,
- Raster or gridded format: this format is often more suitable for exporting spatial predictions of soil variables.

Data in vector format can be converted to raster (see e.g. `rasterize` function in the `raster` R package) and vice versa — raster data can be converted to vector formats. For example, rasters can be converted to polygons (see e.g. `rast2vect` function in the `plotKML` package). If the conversion is done carefully and if all the relations between scale and pixel size have been considered (see Hengl (2006) for more details), then information loss due to conversion from raster to vector and vice versa should be minimal.

Both vector and raster GIS data can also be converted to tabular data format. By converting a GIS layer to a table, spatial geometry and spatial relations will be ‘stripped off’, so that only limited spatial analysis operations can be applied. To convert raster layers to tabular data, consider using the **SpatialPixelsDataFrame-class** in the `sp` package and/or the **RasterLayer-class** from the `raster` package in combination with the `rgdal` package (Bivand et al., 2013):

```
library(rgdal)
library(plotKML)
?readGDAL
spnad83 <- readGDAL(system.file("pictures/erdas_spnad83.tif",
                                   package = "rgdal")[1])
spnad83.tbl <- as.data.frame(spnad83)
str(spnad83.tbl)
```

where `as.data.frame` is a function converting a raster object to a table. Note that the output table now contains coordinates for each cell (center of the grid node), which is in fact memory inefficient as coordinates are provided for each row in the table.

Likewise, to convert a vector layer to tabular formats one can use the Simple Features functionality of the `sf` package . The SF standard is widely implemented in spatial databases (PostGIS, ESRI ArcGIS) and forms the vector data basis for libraries such as GDAL and web standards such as GeoJSON (<http://geojson.org/>). To convert for example spatial polygons layer to a tabular format we would use:

```
library(sf); library(plotKML)
data(eberg_zones)
class(eberg_zones)
eberg_zones.tbl <- as(eberg_zones, "sf")
str(eberg_zones.tbl)
```

Note that using spatial layers in simple tabular formats can be cumbersome because many spatial relationships and properties are likely lost (although these can be assigned reversibly). In addition, the size of tabular objects is much bigger than if we use data in the original GIS data formats, especially if those formats support compression. On the other hand, having data in tabular format can be

often the only way to exchange the data from spatial to non-spatial databases or from software without any data communication bridge. Also, tabular data is human-readable which means that it can be opened in text editors, spreadsheet programs or similar.

10.1.3 Recommended GIS Data Exchange Formats

As a general recommendation producers of soil data should primarily look at using the following data formats for exchanging soil data (points, polygons, and rasters):

- GPKG (an Open Format for Geospatial Information): platform-independent, portable, self-describing, compact format for transferring geospatial information.
- GeoTIFF (for rasters): a TIFF (image) file that allows embedding spatial reference information, metadata and color legends. It also supports internal compression algorithms and hierarchical indexing.

Both formats can be read easily in R or similar data processing software. Vectors are also commonly exported and shared in ESRI Shapefile (SHP) format. The advantage of GPKG format versus somewhat more common ESRI SHP format is that GPKG files are basically a portable database (SQLite container) so that the user does not have to import the whole data into a program but also fetch parts of data by using SQL queries and it can handle vector and raster data in it. The following example demonstrates how to create a GPKG file and how to query it:

```
library(RSQLite)
data(eberg)
coordinates(eberg) <- ~X+Y
proj4string(eberg) <- CRS("+init=epsg:31467")
writeOGR(eberg, "eberg.gpkg", "eberg", "GPKG")
con <- dbConnect(RSQLite::SQLite(), dbname = "eberg.gpkg")
df <- dbGetQuery(con, 'select "soiltype" from eberg')
summary(as.factor(df$soiltype))
dbGetQuery(con,
           'select * from gpkg_spatial_ref_sys')[3,"description"]
```

Note that the RSQLite package is a generic package for connecting to SQLite DBs. This means that GPKG files can be accessed and updated in its native storage format without intermediate format translations. Just putting a GPKG file on a server with read and execute access allows users to connect and fetch data.

Alternatively, it is also a good idea to store point data in a non-spatial format such as simple tables. For example, in comma-separated file format (.csv). A fast way to publish and share tabular data is to use Google Fusion Tables™. Google Fusion Tables have an API that allows accessing and using tabular data through various programming platforms. The limitation of using Google Fusion tables is, however, data size (currently about 1GB per user) and similar data volume limits, so this platform should be only used as an intermediate solution for smaller data

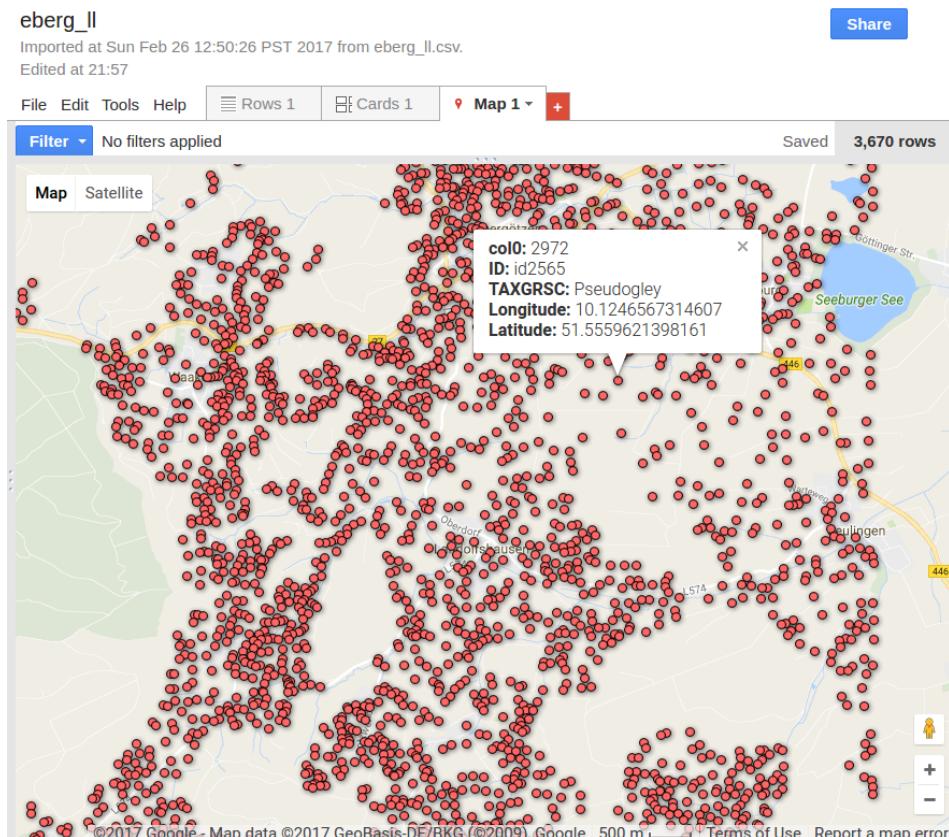


Figure 10.3: Displaying point dataset `eberg` (used in the previous example) in Google Fusion Tables.

sets.

GeoTIFF format is highly recommended for sharing raster data for the following reasons:

1. It is GDAL's default data format and much functionality for subsetting, reprojecting, reading and writing GeoTIFFs already exists (see GDAL utils).
2. It supports internal compression via creation options (e.g. “COMPRESS=DEFLATE”).
3. Extensive overlay, subset, index, translate functionality is available via GDAL and other Open Source software. Basically, GeoTiff functions as a raster DB.

Consider for, example the **gdallocationinfo** function which allows spatial queries following some indexing system such as row and column number:

```
spnad83.file = system.file("pictures/erdas_spnad83.tif",
                           package = "rgdal")[1]
system(paste0('gdallocationinfo ', spnad83.file, ' 100 100'))
```

Such type of overlay operations, thanks to GDAL (Warmerdam, 2008), are extremely fast and efficient. Likewise, **gdalwarp** function can be used subset rasters based on spatial extent or grid index. Rasters imported to GeoServer and shared through Web Coverage Service (see next section) or similar likewise function as a spatial raster DB.

As a general recommendation, and to avoid large file sizes, we recommend, however, that you always use integers inside GeoTiffs because floating point formats can lead to up to 4+ times larger sizes (without any gains in accuracy). This might mean you have to multiply the values of the soil property of interest by 10 or 100, in order not to lose accuracy (e.g. multiply pH values by 10 before exporting your raster as a GeoTiff).

10.2 Web Services - Serving Soil Data Using Web Technology

10.2.1 Third-Party Services

If you are a data producer but with limited technical capacity and/or financial resources, then publishing geo-data through a third-party service could be very well that the easiest and most professional solution for you. Some commonly used commercial web-services to share geo-data are:

- Google MyMaps (<https://www.google.com/mymaps>)
- ArcGIS Online (<https://www.arcgis.com/home/>)
- MapBox (<https://www.mapbox.com/>)
- CARTO (<https://carto.com/>)

All these have limitations and primarily suitable for sharing vector type data only. Their free functionality is very limited so before you start uploading any larger data sets, please check the size limits based on your account. Upgrading your license will allow you to increase storage and functionality so that even with few hundred dollars per year you could have a robust solution for sharing your data with thousands of users.

Soil data producers can also contact ISRIC, as World Data Centre for Soils, to request support for hosting and/or distributing their soil data in case they lack the technical capacity to do so themselves while adhering to the data sharing agreement and license set by the data producer.

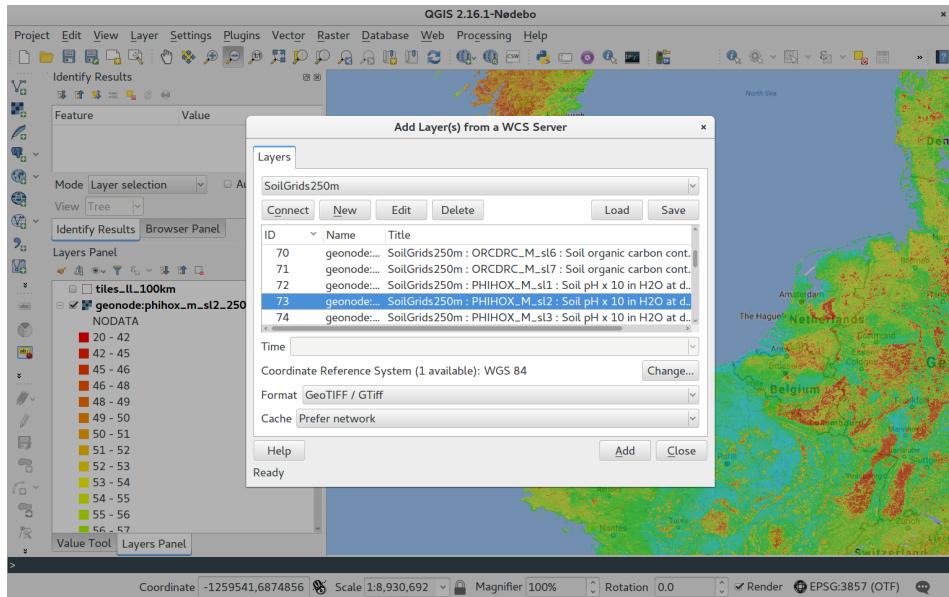


Figure 10.4: SoilGrids (Hengl et al. 2017) WCS opened in QGIS.

10.2.2 GeoServer (Web Serving and Web Processing)

GeoServer (<http://geoserver.org/>) is Open Source software solution for serving raster or vector data. It includes the majority of the Open Geospatial Consortium Service standards: the Web Map Service, Web Coverage Service and Web Processing Service (Youngblood, 2013). Installation and maintenance of GeoServer is however not trivial and requires specialized technical staff. Web services can also entail significant costs depending on the amount of web-processing and web-traffic. For every medium to large size organization, it is probably a better idea to use the out-of-box solution for GeoServer which is the GeoNode (<http://geonode.org/>). GeoNode also includes a web-interface and user-management system so that new layers can be uploaded to GeoServer through a web-form type interface.

The very important functionality of GeoServer are the OGC standard services such as the **Web Coverage Service** (WCS) and the **Web Feature Service** (WFS). WCS means that not only data views are available to users, but WCS can also do data translation, aggregation or resampling, overlay etc. Consider for example the SoilGrids WCS (which can also be opened in QGIS or similar software supporting WCS). Users can direct this WCS and request only a subset of data for some area, aggregated to some preferred resolution/pixel size by using gdal_translate or similar. This means that, in few steps, users can download a subset of data on GeoServer in a preferred format without a need to download the whole dataset.

10.2.3 Visualizing Data Using Leaflet and/or Google Earth

A quick way to visualize produced soil maps and then share them to users without GIS capacities is to use Leaflet package . Leaflet is basically a stand-alone web-page that contains all information (including some popular Web Mapping Services) so that users can visually explore patterns without having to install and use any desktop GIS. Consider the following example:

```
library(leaflet)
library(htmlwidgets)
library(GSIF)
library(raster)
demo(meuse, echo=FALSE)
omm <- autopredict(meuse["om"], meuse.grid[c("dist", "soil", "ffreq")],
                    method="ranger", auto.plot=FALSE, rvgm=NULL)
meuse.ll <- reproject(meuse["om"])
#Reprojecting to +proj=longlat +datum=WGS84 ...
m = leaflet() %>% addTiles() %>% addRasterImage(raster(omm$predicted["om"]),
  colors = SAGA_pal[[1]][4:20]) %>% addCircles(lng = meuse.ll@coords[,1],
  lat = meuse.ll@coords[,2], color = c('black'), radius=meuse.ll$om)
saveWidget(m, file="organicmater_predicted.html")
```

Note that the whole data set including styling and legends is basically available through a single HTML file (organicmater_predicted.html). Anyone opening that HTML in their browsers will get an interactive web-map that contains both samples and spatial predictions.

An alternative to using Leaflet is to put all data, including documents and multi-media, about your project in a KML (Keyhole Markup Language) file, so the data is available for viewing in Google Earth (Hengl et al., 2015b). KML is very rich in what it can incorporate: textual data, photographs, documents, animations, videos etc. In fact, probably whole projects can be put into a single KML file so that the users only need to open it in Google Earth and then explore interactively. Note that KML files with ground overlays will be generated by GeoServer by default, although further customization is up to the data producer.

10.3 Preparing Soil Data for Distribution

10.3.1 Metadata

One important thing to consider prior to data distribution is construction of metadata (explanation of data, how was it produced and what are the exact technical specifications). There are several metadata standards that can be used to prepare metadata. More recently, complete and consistent metadata is a requirement by many government agencies and organizations. There are now several public metadata validators that run all possible consistency and completeness checks before

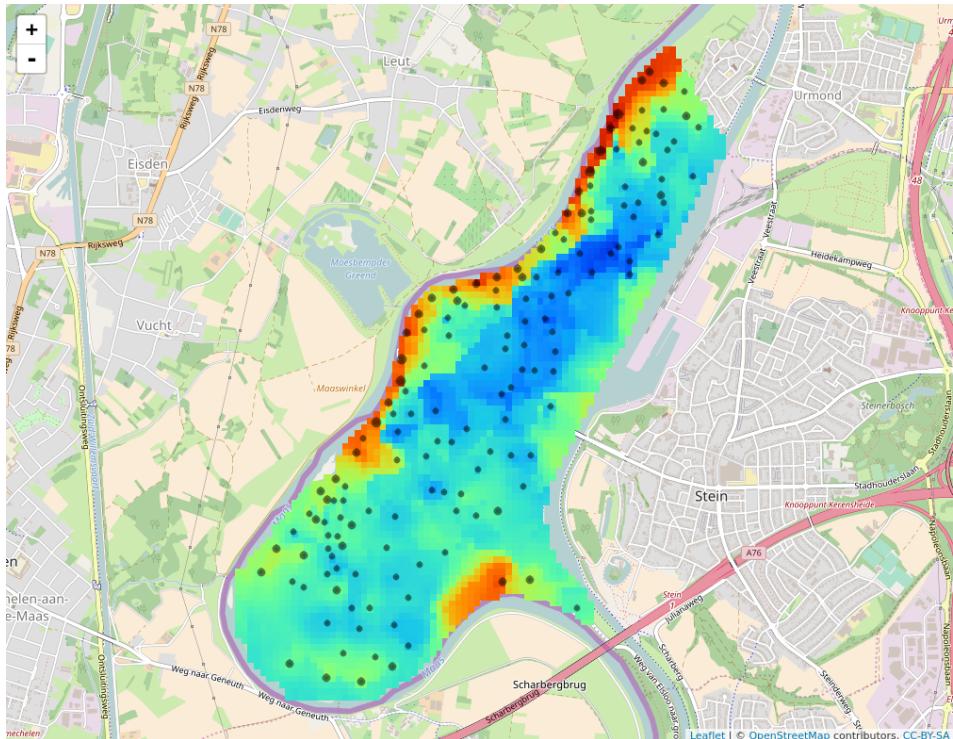


Figure 10.5: Sampled locations and produced predictions visualized using Leaflet package.

the metadata (and data) can be accepted.

Typical metadata should (at least) contain:

- Detailed description of the variables available in the data.
- Data license and terms of use (URL).
- Explanation of measurement methods and units used.
- Mention of the reference support size including referent depth intervals to which the soil data refers to (e.g. 0–30 cm depth interval).
- Mention of the referent time period in which the calibration data was collected.
- Link to literature (report, book or scientific article) where the data production is explained in detail. Using a published and peer-reviewed scientific article as the main reference for data is a good practice since it also shows that the data production process has been evaluated by independent researchers.
- Project homepage i.e. URL containing more information and especially up-to-date contacts where users can find original data producers and request support.

Metadata (including color legends) can be also directly embedded into the GeoTiff file by using the `gdal_edit` command available in GDAL. The following example shows how to add a simple explanation of the data and a URL to find more info about the GeoTiff:

```
data("eberg_grid")
gridded(eberg_grid) = ~ x+y
proj4string(eberg_grid) <- CRS("+init=epsg:31467")
writeGDAL(eberg_grid["DEMSRT6"], "eberg_DEM.tif",
          options="COMPRESS=DEFLATE")
?eberg
system(paste0('gdal_edit.py
-mo \"DESCRIPTION=elevation values from the SRTM DEM\
-mo \"DOWNLOAD_URL=http://geomorphometry.org/content/ebergotzen\
eberg_DEM.tif'))
system('gdalinfo eberg_DEM.tif')
```

Similarly, all necessary metadata can be added into GeoTiff so that future users have all information at one place i.e. inside the data file.

10.3.2 Exporting Data — Final Tips

As we have shown previously, if you export soil data into either GPKG and/or GeoTiff, these data can be accessed using DB operations. In fact, by exporting the data to GPKG and GeoTiffs, you have created a soil spatial DB or a soil information system. This does not necessarily mean that its targeted users will be able to find all information without problems and/or questions. How usable and how popular a data set is, is a function of many aspects, not only data quality. You could create maps of perfect quality but have no users at all. Some things

you should definitively consider, as a way to boost the usability of your data are:

1. Make a landing page for your data that includes: (1) simple access/download instructions, (2) screenshots of your data in action (people prefer visual explanations with examples), (3) links to key documents explaining how the data was produced, and (4) workflows explaining how to request support (who to contact and how).
2. Make data accessible from multiple systems e.g. both via WCS, FTP and through a mirror site. This might be inefficient considering there will be multiple copies of the same data, but sometimes it quadruples data usage.
3. Explain the data formats used to share data, and point to tutorials that explain how to access and use data to both beginners and advanced users.
4. Consider installing and using a version control system (or simply use GitHub or similar repository) so that the users can track back versions of data.
5. Consider closely following principles of reproducible research (all processing steps, inputs, and outputs accessible). This tutorial comes with R code that is available via GitHub so that everyone should be able to reproduce the examples shown in the text.

10.4 Export Formats

The produced results need to be exported in formats that can be easily read by a variety of GIS software. Two widely used formats for raster data are GeoTIFF and KML.

GeoTIFF is a public domain metadata standard which allows georeferencing information to be embedded within a TIFF file. The potential additional information includes map projection, coordinate systems, ellipsoids, datums, and everything else necessary to establish the exact spatial reference for the file. Keyhole Markup Language (KML) is an XML notation for expressing geographic annotation and visualization within Internet-based, two-dimensional maps and three-dimensional Earth browsers. KML became an international standard of the Open Geospatial Consortium in 2008.

Raster data in GeoTIFF format need a defined geographic projection. Each country has its own national system (or systems). In order to construct a mosaic of national datasets, a common projection has to be defined and national data need to be re-projected in the common projection. Data projections can be managed using open source tools such as GIS software, GDAL tools suite (<http://www.gdal.org/>) and various packages of the R software (<https://www.r-project.org/>). Projections can be defined according to different standards. A common way is the EPSG database. EPSG Geodetic Parameter Dataset is a collection of definitions of coordinate reference systems and coordinate transformations which may be global, regional, national or local application. A numeric code is assigned to each of the most common projections, making easier to refer to them and to switch between them. One of the most common global projections is WGS84 (EPSG 4336), used for maps and by the GPS satellite navigation system.

Each file should be accompanied by a set list of metadata. Geospatial metadata is a type of metadata that is applicable to objects that have an explicit or implicit geographic extent. While using GeoTIFF files it is possible to define a metadata field in which information can be recorded. Metadata can be edited with most GIS software and directly with GDAL tools (http://www.gdal.org/gdal_edit.html).

GDAL: gdalwarp -t_srs ‘xxx’ input.tif output.tif where t_srs is the target spatial reference set, i.e. the coordinate systems that can be passed are anything supported by the GRSpatialReference.SetFromUserInput() call, which includes EPSG PCS and GCSes (i.e. EPSG:4326), PROJ.4 declarations or the name of a .prj file containing well known text. For further information see <http://www.gdal.org/gdalwarp.html>

Chapter 11

Technical Overview and the Checklist

VL Mulder

11.1 Point Dataset

- Did you remove non-georeferenced observations from your dataset?
- Did you check for outliers or any unusual values for the measured SOC, pH, BD, stoniness/gravel content, and min/max definitions of your soil horizons?
- Is there spatial correlation in your SOC values, as observed from the variogram?
- Did you check the probability distribution and applied a transformation in case the samples were not normally distributed?
- Be aware whether you are going to predict SOC or SOM values!

11.2 Covariates

- Did you choose and apply the proper projection, one that is suitable for your country and is suitable for spatial statistics?
- Do all the covariates have a resolution of 1 km and did you use either nearest neighbor resampling for the categorical variables and IDW/cubic spline for continuous data?
- Did you correctly set the NoData values as NoData, i.e. not a standard assigned values such as -9999, 256 etc.
- Did you check for outliers or any unusual values, especially in your DEM Layer(s)?

- Did you set any categorical dataset as ‘factor’ instead of being ‘numeric’ or ‘integer’?

11.3 Statistical Inference

- Did you choose a proper model which is capable to model the variability in your SOC point data best? (multiple regression or data mining with or without interpolation of the residuals using kriging)?
- Did you make sure that the Random Forest did not over fit your data?
- Did you apply a validation scheme, e.g. k-fold cross-validation or an independent validation if so report the R² and RMSE as accuracy measures
- Do the model summaries make sense? i.e. most important predictor variables and model fit?
- Is there spatial structure left in your residuals, if so make sure you interpolate the model residuals using kriging?

11.4 Spatial Interpolation

- Did you obtain an exhaustive map or are there still gaps? If so, check if your raster has the correct ‘factor’ values, if the model was calibrated on fewer classes than the extrapolation may not work for those pixels?
- Do the patterns make sense or is there a covariate that causes an unrealistic pattern, based on expert judgment. If so, consider removing this covariate?
- In case you did kriging, don’t forget to look at the kriging variance. This is a very important indicator of the accuracy. Otherwise, consider modeling the 90% confidence intervals of the predictions!
- Don’t forget to back-transform your predicted values!

11.5 Calculation of Stocks

You might want to calculate stocks per LU type, management type or by municipality. If you do that make sure you give an informed number, i.e. an estimate plus an estimate of the uncertainty

11.6 Evaluation of Output and Quality Assessment

- Report the model calibration and validation statistics!
- Report some map quality measures!
- Evaluate to which extent the model and map is either underestimating or overestimating SOC/SOM!

- Describe the spatial patterns and relate them to the landscape characteristics!

Chapter 12

Deliverables

Y Yigini

Data shared by countries will be collected by the GSP Secretariat. The GSP data policy (see GSP GSOC Guidelines, Chapter 8.5) will ensure that the national terms of condition are fully respected. Data will be shared using common GIS formats, and metadata should be compiled into an excel file. The Soil Organic Carbon Map will be delivered as grid using the 30 arc-seconds grid.

The following data will be delivered:

- The Soil Organic Carbon Map: will be digitally delivered in grid with 30 arc-second resolution. An empty grid is provided by the GSP Secretariat (<ftp://gsp.isric2.org//mask/mask.tif>). The SOC values should be transferred to this empty grid from the produced SOC data. To transfer values to the empty grid, QGis (Raster Calculator), ArcGIS (Mosaicing tool, Raster Calculator) can be used.
- Uncertainty Layers and prediction quality figures: a) Qualitative assessment (Conventional Upscaling) b) Quantitative assessment for DSM Methods. The uncertainty associated with the estimated map quality measures will be provided (Mean Error (ME), Mean Absolute Error (MAE), and MSE (Mean Squared Error)).
- Metadata: Metadata is data describing data sets. It provides standardized information about a data set, for example, the maintaining institution through which the data can be accessed. It thus helps a user to find spatial data sets and services and to indicate for which purpose it can be used. In the case of the GSOC maps, a project-specific metadata template has been prepared. It deviates from the metadata elements listed in common standards such as ISO 19115. Following the guideline for SOC mapping, the importance of soil-specific methodical elements is given. This includes metadata describing the data sources used for SOC mapping and the upscaling method.

Chapter 13

Compendium of the code examples included in the cookbook

GF Olmedo

13.1 Overview

In this chapter, we present a compendium of the technical steps presented in the previous chapters of the cookbook. With the help of these examples, the user should be able to produce a soil property prediction map starting from the soil samples, covariates preparation, modeling and ending with the validation. However, we present different alternatives for the different steps. This proposed framework to prepare a soil property prediction map includes soil data preparation, covariates preparation, overlaying soil data and covariates, fitting a model for the spatial interpolation and validation:

1. Soil data preparation
 - **Option A:** Data Preparation - Soil Profiles (Code 13.2)
 - **Option B:** Data Preparation - Top Soil or Auger Samples (Code 13.3)
 - *[optional]:* Data Preparation - Merging Top Soil/Auger Samples and Soil Profiles (Code 13.4)
 - *[optional]:* Split the soil data in test and validations datasets (Code 13.5)
2. Covariates preparation
 - *[optional]* Rasterizing a Vector Layer in R (Code 13.6)
 - Overlay Covariates and Soil Points Data (Code 13.7)
3. Spatial interpolation model

- **Option A:** Fitting a Regression-Kriging model to predict the OCS (Code 13.8)
- **Option B:** Fitting a Random Forest model to predict the SOC (Code 13.9)
- **Option C:** Fitting a Support Vector Machines model to predict the SOC (Code 13.11)

4. Validation

- Quality measures for quantitative data (Code 13.12)
- *[optional]* Graphical quality measures for quantitative data (Code 13.13)
- *[optional]* Cross-validation for Regression-Kriging Models (Code 13.8.1)
- *[optional]* Validation of Random Forest using Quantile Regression Trees (Code 13.10)

13.2 Data Preparation for Soil Profiles

The extended and discussed version of the following code is presented in Chapter 3, by GF Olmedo & R Baritz.

```
dat <- read.csv(file = "data/horizons.csv")

# Explore the data
str(dat)
summary(dat)

dat_sites <- read.csv(file = "data/site-level.csv")

# Explore the data
str(dat_sites)

# summary of column CRF (Coarse Fragments) in the example data base
summary(dat$CRF)

# Convert NA's to 0
dat$CRF[is.na(dat$CRF)] <- 0

hist(dat$CRF)

# Creating a function in R to estimate BLD using the SOC
# SOC is the soil organic carbon content in %
estimateBD <- function(SOC, method="Saini1996"){
  OM <- SOC * 1.724
  if(method=="Saini1996"){BD <- 1.62 - 0.06 * OM}
  if(method=="Drew1973"){BD <- 1 / (0.6268 + 0.0361 * OM)}
  if(method=="Jeffrey1979"){BD <- 1.482 - 0.6786 * (log(OM))}
  if(method=="Grigal1989"){BD <- 0.669 + 0.941 * exp(1)^(-0.06 * OM)}
  if(method=="Adams1973"){BD <- 100 / (OM / 0.244 + (100 - OM) / 2.65)}
  if(method=="Honeyset_Ratkowsky1989"){BD <- 1 / (0.564 + 0.0556 * OM)}
  return(BD)
}

# summary of BLD (bulk density) in the example data base
summary(dat$BLD)

# See the summary of values produced using the pedo-transfer
# function with one of the proposed methods.
summary(estimateBD(dat$SOC[is.na(dat$BLD)], m
                   ethod="Honeyset_Ratkowsky1989"))

# Fill NA's using the pedotransfer function:
dat$BLD[is.na(dat$BLD)] <- estimateBD(dat$SOC[is.na(dat$BLD)],
```

```
method="Grigal1989")  
  
# explore the results  
boxplot(dat$BLD)  
  
# Load aqp package  
library(aqp)  
  
# Promote to SoilProfileCollection  
# The SoilProfileCollection is a object class in R designed to  
# handle soil profiles  
depths(dat) <- ProfID ~ top + bottom  
  
# Merge the soil horizons information with the site-level  
# information from dat_sites  
site(dat) <- dat_sites  
  
# Set spatial coordinates  
coordinates(dat) <- ~ X + Y  
  
# A summary of our SoilProfileCollection  
dat  
  
library(GSIF)  
  
## Estimate 0-30 standard horizon usin mass preserving splines  
try(SOC <- mpspline(dat, 'SOC', d = t(c(0,30))))  
try(BLD <- mpspline(dat, 'BLD', d = t(c(0,30))))  
try(CRFVOL <- mpspline(dat, 'CRF', d = t(c(0,30))))  
  
## Prepare final data frame  
dat <- data.frame(id = dat@site$ProfID,  
                   Y = dat@sp@coords[,2],  
                   X = dat@sp@coords[,1],  
                   SOC = SOC$var.std[,1],  
                   BLD = BLD$var.std[,1],  
                   CRFVOL = CRFVOL$var.std[,1])  
  
dat <- dat[complete.cases(dat),]  
  
## Take a look to the results  
head(dat)  
  
# Estimate Organic Carbon Stock  
# SOC must be in g/kg  
# BLD in kg/m3
```

```
# CRF in percentage
OCSKGM <- OCSKGM(ORCDRC = dat$SOC, BLD = dat$BLD*1000,
                    CRFVOL = dat$CRFVOL, HSIZE = 30)

dat$OCSKGM <- OCSKGM
dat$meaERROR <- attr(OCSKGM, "measurementError")
dat <- dat[dat$OCSKGM>0,]
summary(dat)

## We can save our processed data as a table
write.csv(dat, "data/dataproc.csv")
```

13.3 Data Preparation for Top Soil or Auger Samples

The extended and discussed version of the following code is presented in Chapter 3, by GF Olmedo & R Baritz.

```
dat <- read.csv(file = "data/auger.csv")

# Explore the data
str(dat)
summary(dat)

# Creating a function in R to estimate BLD using the SOC
# SOC is the soil organic carbon content in %
estimateBD <- function(SOC, method="Saini1996"){
  OM <- SOC * 1.724
  if(method=="Saini1996"){BD <- 1.62 - 0.06 * OM}
  if(method=="Drew1973"){BD <- 1 / (0.6268 + 0.0361 * OM)}
  if(method=="Jeffrey1979"){BD <- 1.482 - 0.6786 * (log(OM))}
  if(method=="Grigal1989"){BD <- 0.669 + 0.941 * exp(1)^(-0.06 * OM)}
  if(method=="Adams1973"){BD <- 100 / (OM / 0.244 + (100 - OM) / 2.65)}
  if(method=="Honeyset_Ratkowsky1989"){BD <- 1 / (0.564 + 0.0556 * OM)}
  return(BD)
}

# See the summary of values produced using the pedo-transfer
# function with one of the proposed methods.
summary(estimateBD(dat$SOC, method="Honeyset_Ratkowsky1989"))

# Estimate BLD using the pedotransfer function:
dat$BLD <- estimateBD(dat$SOC, method="Grigal1989")

# explore the results
boxplot(dat$BLD)

# Remove points with NA's values
dat <- dat[complete.cases(dat),]

## Take a look to the results
head(dat)

# Estimate Organic Carbon Stock
# SOC must be in g/kg
# BLD in kg/m3
# CRF in percentage
OCSKGM <- OCSKGM(ORCDRC = dat$SOC, BLD = dat$BLD*1000, CRFVOL = 0,
                  HSIZE = 30)
```

```
dat$OCSKGM <- OCSKGM
dat$meaERROR <- attr(OCSKGM, "measurementError")
dat <- dat[dat$OCSKGM>0,]
summary(dat)

## We can save our processed data as a table
write.csv(dat, "data/dataproc.csv")
```

13.4 Merging Top Soil and Soil Profiles Databases

13.5 Data-Splitting

The extended and discussed version of the following code is presented in Chapter 7, by B Kempen, DJ Brus & GBM Heuvelink, with code contributions from GF Olmedo.

```
library(caret)

dat <- read.csv("data/dataproc.csv")

train.ind <- createDataPartition(1:nrow(dat), p = .75, list = FALSE)
train <- dat[ train.ind,]
test  <- dat[-train.ind,]

plot(density (log(train$OCSKGM)), col='red',
      main='Statistical distribution of train and test datasets')
lines(density(log(test$OCSKGM)), col='blue')
legend('topright', legend=c("train", "test"),
       col=c("red", "blue"), lty=1, cex=1.5)

write.csv(train, file="data/dat_train.csv", row.names = FALSE)
write.csv(test, file="data/dat_test.csv", row.names = FALSE)
```

13.6 Rasterizing a Vector Layer in R

The extended and discussed version of the following code is presented in Chapter 5, by R Baritz & Y Yigini.

```
# the "Symbol" attribute from the vector layer will be used for the
# rasterization process. It has to be a factor
soilmap@data$Symbol <- as.factor(soilmap@data$Symbol)

# save the levels names in a character vector
Symbol.levels <- levels(soilmap$Symbol)

# The rasterization process needs a layer with the target grd
# system: spatial extent and cell size.
soilmap.r <- rasterize(x = soilmap, y = DEM, field = "Symbol")
# The DEM raster layer could be used for this.

plot(soilmap.r, col=rainbow(21))
legend("bottomright", legend = Symbol.levels, fill=rainbow(21),
       cex=0.5)
```

13.7 Overlay Covariates and Soil Points Data

The extended and discussed version of the following code is presented in Chapter 5, by R Baritz & Y Yigini.

```
# Load the processed data. This table was prepared in the previous
# chapter.
dat <- read.csv("data/dataproc.csv")

files <- list.files(path = "cobs", pattern = "tif$",
                     full.names = TRUE)

cobs <- stack(files)

cobs <- stack(cobs, soilmap.r)

# correct the name for layer 14
names(cobs)[14] <- "soilmap"

# mask the covariates with the country mask from the data repository
mask <- raster("data/mask.tif")

cobs <- mask(x = cobs, mask = mask)

plot(cobs)

#upgrade points data frame to SpatialPointsDataFrame
coordinates(dat) <- ~ X + Y

# extract values from covariates to the soil points
dat <- extract(x = cobs, y = dat, sp = TRUE)

# LCEE10 and soilmap are categorical variables
dat@data$LCEE10 <- as.factor(dat@data$LCEE10)
dat@data$soilmap <- as.factor(dat@data$soilmap)

#levels(soilmap) <- Symbol.levels

summary(dat@data)

dat <- as.data.frame(dat)

# The points with NA values has to be removed
dat <- dat[complete.cases(dat),]

# export as a csv table
write.csv(dat, "data/MKD_RegMatrix.csv", row.names = FALSE)
```

13.8 Fitting a Regression-Kriging model to predict the OCS

The extended and discussed version of the following code is presented in Section 6.2, by GF Olmedo & Y Yigini.

```
# load data
dat <- read.csv("data/MKD_RegMatrix.csv")

dat$LCEE10 <- as.factor(dat$LCEE10)
dat$soilmap <- as.factor(dat$soilmap)

# explore the data structure
str(dat)

library(sp)

# Promote to spatialPointsDataFrame
coordinates(dat) <- ~ X + Y

class(dat)

dat@proj4string <- CRS(projargs = "+init=epsg:4326")

dat@proj4string

library(raster)

# list all the itf files in the folder covs/
files <- list.files(path = "covs", pattern = "tif$",
                     full.names = TRUE)

# load all the tif files in one rasterStack object
covs <- stack(files)

# load the vectorial version of the soil map
soilmap <- shapefile("MK_soilmap_simple.shp")

# rasterize using the Symbol layer
soilmap@data$Symbol <- as.factor(soilmap@data$Symbol)
soilmap.r <- rasterize(x = soilmap, y = covs[[1]], field = "Symbol")

# stack the soil map and the other covariates
covs <- stack(covs, soilmap.r)

# correct the name for layer 14
names(covs)[14] <- "soilmap"
```

```

# print the names of the 14 layers:
names(covs)

datdf <- dat@data

datdf <- datdf[, c("OCSKGM", names(covs))]

# Fit a multiple linear regression model between the log transformed
# values of OCS and the top 20 covariates
model.MLR <- lm(log(OCSKGM) ~ ., data = datdf)

# stepwise variable selection
model.MLR.step <- step(model.MLR, direction="both")

# summary and anova of the new model using stepwise covariates
# selection
summary(model.MLR.step)
anova(model.MLR.step)

# graphical diagnosis of the regression analysis
par(mfrow=c(2,2))
plot(model.MLR.step)
par(mfrow=c(1,1))

# collinearity test using variance inflation factors
library(car)
vif(model.MLR.step)

# problematic covariates should have sqrt(VIF) > 2
sqrt(vif(model.MLR.step))

# Removing B07CHE3 from the stepwise model:
model.MLR.step <- update(model.MLR.step, . ~ . - B07CHE3)

# Test the vif again:
sqrt(vif(model.MLR.step))

## summary of the new model using stepwise covariates selection
summary(model.MLR.step)

# outlier test using the Bonferroni test
outlierTest(model.MLR.step)

# Project point data.
dat <- spTransform(dat, CRS("+init=epsg:6204"))

```

```

# project covariates to VN-2000 UTM 48N
covs <- projectRaster(covs, crs = CRS("+init=epsg:6204"),
                       method='ngb')

covs$LCEE10 <- as.factor(covs$LCEE10)
covs$soilmap <- as.factor(covs$soilmap)

# Promote covariates to spatial grid dataframe. Takes some time and
# a lot of memory!
covs.sp <- as(covs, "SpatialGridDataFrame")
covs.sp$LCEE10 <- as.factor(covs.sp$LCEE10)
covs.sp$soilmap <- as.factor(covs.sp$soilmap)

# RK model
library(automap)

# Run regression kriging prediction. This step can take hours...!
OCS.krige <- autoKrigie(formula =
                           as.formula(model.MLR.step$call$formula),
                           input_data = dat,
                           new_data = covs.sp,
                           verbose = TRUE,
                           block = c(1000, 1000))

OCS.krige

# Convert prediction and standard deviation to rasters
# And back-transform the values
RKprediction <- exp(raster(OCS.krige$krige_output[1]))
RKpredsd <- exp(raster(OCS.krige$krige_output[3]))

plot(RKprediction)

## Save results as tif files
writeRaster(RKprediction, filename = "results/MKD_OCSKGM_RK.tif",
            overwrite = TRUE)

writeRaster(RKpredsd, filename = "results/MKD_OCSKGM_RKpredsd.tif",
            overwrite = TRUE)

# save the model
saveRDS(model.MLR.step, file="results/RKmodel.Rds")

```

13.8.1 Cross-validation of Regression Kriging models

The extended and discussed version of the following code is presented in Section 6.2, by GF Olmedo & Y Yigini.

```
OCS.krige.cv <- autoKriging.cv(formula =
  as.formula(model.MLR.step$call$formula),
  input_data = dat, nfold = 10)

summary(OCS.krige.cv)
```

13.9 Fitting a random forest model to predict the SOC

The extended and discussed version of the following code is presented in Section 6.3, by M Guevara, C Thine, GF Olmedo & RR Vargas.

```
# load data
dat <- read.csv("data/MKD_RegMatrix.csv")

dat$LCEE10 <- as.factor(dat$LCEE10)
dat$soilmap <- as.factor(dat$soilmap)

# explore the data structure
str(dat)

library(sp)

# Promote to spatialPointsDataFrame
coordinates(dat) <- ~ X + Y

class(dat)

dat@proj4string <- CRS(projargs = "+init=epsg:4326")

dat@proj4string

load(file = "covariates.RData")

names(covs)

# For its use on R we need to define a model formula

fm = as.formula(paste("log(OCSKGM) ~", paste0(names(covs)[[-14]], collapse = "+")))

library(randomForest)
library(caret)

# Default 10-fold cross-validation
ctrl <- trainControl(method = "cv", savePred=T)
# Search for the best mtry parameter
rfmodel <- train(fm, data=dat@data, method = "rf", trControl = ctrl,
                  importance=TRUE)
# This is a very useful function to compare and test different
# prediction algorithms type names(getModelInfo()) to see all the
# possibilities implemented on this function
```

```
# Variable importance plot, compare with the correlation matrix
# Select the best prediction factors and repeat
varImpPlot(rfmodel[11][[1]])

# Check if the error stabilizes
plot(rfmodel[11][[1]])

# Make a prediction across all Macedonia
# Note that the units are still in log
pred <- predict(covs, rfmodel)

# Back transform predictions log transformed
pred <- exp(pred)

# Save the result as a tiff file
writeRaster(pred, filename = "results/MKD_OCSKGM_rf.tif",
            overwrite=TRUE)

plot(pred)
```

13.10 Using Quantile Regression Forest to estimate uncertainty

The extended and discussed version of the following code is presented in Section 6.3, by M Guevara, C Thine, GF Olmedo & RR Vargas.

```
#Generate an empty dataframe
validation <- data.frame(rmse=numeric(), r2=numeric())
#Sensitivity to the dataset
#Start a loop with 10 model realizations
for (i in 1:10){
  # We will build 10 models using random samples of 25%
  smp_size <- floor(0.25 * nrow(dat))
  train_ind <- sample(seq_len(nrow(dat)), size = smp_size)
  train <- dat[train_ind, ]
  test <- dat[-train_ind, ]
  modn <- train(fm, data=train, method = "rf", trControl = ctrl)
  pred <- stack(pred, predict(covariates, modn))
  test$pred <- predict(modn[11][[1]], test)
  # Store the results in a dataframe
  validation[i, 1] <- rmse(test$OCSKGMlog, test$pred)
  validation[i, 2] <- cor(test$OCSKGMlog, test$pred)^2
}
#The sensitivity map is the dispersion of all individual models
sensitivity <- calc(pred[[-1]], sd)

plot(sensitivity, col=rev(topo.colors(10)),
      main='Sensitivity based on 10 realizations using 25% samples')

#Sensitivity of validation metrics
summary(validation)

# Plot of the map based on 75% of data and the sensitivity to data
# variations
prediction75 <- exp(pred[[1]])

plot(prediction75, main='OCSKGM prediction based on 75% of data',
      col=rev(topo.colors(10)))

# Use quantile regression forest to estimate the full conditional
# distribution of OCSKGMlog, note that we are using the mtry
# parameter that was selected by the train function of the caret
# package, assuming that the 75% of data previously used well
# resembles the statistical distribution of the entire data
# population. Otherwise repeat the train function with all available
# data (using the object dat that instead of train) to select mtry.
```

```
model <- quantregForest(y=dat$OCSKGMlog, x=dat[,1:13], ntree=500,
                         keep.inbag=TRUE, mtry = as.numeric(mod$bestTune))

library(snow)
# Estimate model uncertainty at the pixel level using parallel
# computing
beginCluster() #define number of cores to use
# Estimate model uncertainty
unc <- clusterR(covariates, predict, args=list(model=model,what=sd))
# OCSKGMlog prediction based in all available data
mean <- clusterR(covariates, predict,
                   args=list(model=model, what=mean))
# The total uncertainty is the sum of sensitivity and model
# uncertainty
unc <- unc + sensitivity
# Express the uncertainty in percent (divide by the mean)
Total_unc_Percent <- exp(unc)/exp(mean)
endCluster()

# Plot both maps (the predicted OCSKGM + its associated uncertainty)
plot(exp(mean), main='OCSKGM based in all data',
     col=rev(topo.colors(10)))

plot(Total_unc_Percent, col=rev(heat.colors(100)), zlim=c(0, 5),
     main='Total uncertainty')

#Save the resulting maps in separated *.tif files
writeRaster(exp(mean), file='rfOCSKGMprediction.tif',
            overwrite=TRUE)
writeRaster(Total_unc_Percent, file='rfOCSKGMtotalUncertPercent.tif',
            overwrite=TRUE)
```

13.11 Fitting a svm model to predict the SOC

The extended and discussed version of the following code is presented in Section 6.4, by GF Olmedo & M Guevara.

```
# load data
dat <- read.csv("data/MKD_RegMatrix.csv")

dat$LCEE10 <- as.factor(dat$LCEE10)
dat$soilmap <- as.factor(dat$soilmap)

# explore the data structure
str(dat)

library(sp)

# Promote to spatialPointsDataFrame
coordinates(dat) <- ~ X + Y

class(dat)

dat@proj4string <- CRS(projargs = "+init=epsg:4326")

dat@proj4string

load(file = "covariates.RData")

names(covs)

# plot the names of the covariates
names(dat@data)

# variable selection using correlation analysis
selectedCovs <- cor(x = as.matrix(dat@data[,5]),
                      y = as.matrix(dat@data[,-c(1:7,13,21)]))

# print correlation results
selectedCovs

library(reshape)
x <- subset(melt(selectedCovs), value != 1 | value != NA)
x <- x[with(x, order(-abs(x$value))),]

idx <- as.character(x$X2[1:5])

dat2 <- dat[c('OCSKGM', idx)]
names(dat2)
```

```

COV <- covs[[idx]]

# Selected covariates
names(COV)

# Categorical variables in sum models
dummyRaster <- function(rast){
  rast <- as.factor(rast)
  result <- list()
  for(i in 1:length(levels(rast)[[1]][[1]])){
    result[[i]] <- rast == levels(rast)[[1]][[1]][i]
    names(result[[i]]) <- paste0(names(rast),
                                  levels(rast)[[1]][[1]][i])
  }
  return(stack(result))
}

# convert soilmap from factor to dummy
soilmap_dummy <- dummyRaster(covs$soilmap)

# convert LCEE10 from factor to dummy
LCEE10_dummy <- dummyRaster(covs$LCEE10)

# Stack the 5 COV layers with the 2 dummies
COV <- stack(COV, soilmap_dummy, LCEE10_dummy)

# print the final layer names
names(COV)

# convert soilmap column to dummy, the result is a matrix
# to have one column per category we had to add -1 to the formula
dat_soilmap_dummy <- model.matrix(~soilmap -1, data = dat@data)
# convert the matrix to a data.frame
dat_soilmap_dummy <- as.data.frame(dat_soilmap_dummy)

# convert LCEE10 column to dummy, the result is a matrix
# to have one column per category we had to add -1 to the formula
dat_LCEE10_dummy <- model.matrix(~LCEE10 -1, data = dat@data)
# convert the matrix to a data.frame
dat_LCEE10_dummy <- as.data.frame(dat_LCEE10_dummy)

dat@data <- cbind(dat@data, dat_LCEE10_dummy, dat_soilmap_dummy)

names(dat@data)

```

```
# Fitting a svm model and parameter tuning
library(e1071)
library(caret)

# Test different values of epsilon and cost
tuneResult <- tune(svm, OCSKGM ~., data = dat@data[,c("OCSKGM",
                                                       names(COV))],
                     ranges = list(epsilon = seq(0.1,0.2,0.02),
                                   cost = c(5,7,15,20)))

plot(tuneResult)

# Choose the model with the best combination of epsilon and cost
tunedModel <- tuneResult$best.model

print(tunedModel)

# Use the model to predict the SOC in the covariates space
OCSsvm <- predict(COV, tunedModel)

# Save the result
writeRaster(OCSsvm, filename = "results/MKD_OCSKGM_svm.tif",
            overwrite=TRUE)

plot(OCSsvm)

# Variable importance in svm. Code by:
# stackoverflow.com/questions/34781495

w <- t(tunedModel$coefs) %*% tunedModel$SV      # weight vectors
w <- apply(w, 2, function(v){sqrt(sum(v^2))})    # weight

w <- sort(w, decreasing = T)
print(w)
```

13.12 Validation

The extended and discussed version of the following code is presented in Chapter 7, by B Kempen, DJ Brus & GBM Heuvelink, with code contributions from GF Olmedo.

```
dat <- read.csv("data/dat_test.csv")

# Promote to spatialPointsDataFrame
coordinates(dat) <- ~ X + Y

dat@proj4string <- CRS(projargs = "+init=epsg:4326")

library(raster)

OCSKGM_rf <- raster("results/MKD_OCSKGM_rf.tif")

dat <- extract(x = OCSKGM_rf, y = dat, sp = TRUE)

# prediction error
dat$PE_rf <- dat$MKD_OCSKGM_rf - dat$OCSKGM

# Mean Error
ME_rf <- mean(dat$PE_rf, na.rm=TRUE)

# Mean Absolute Error (MAE)
MAE_rf <- mean(abs(dat$PE_rf), na.rm=TRUE)

# Mean Squared Error (MSE)
MSE_rf <- mean(dat$PE_rf^2, na.rm=TRUE)

# Root Mean Squared Error (RMSE)
RMSE_rf <- sqrt(sum(dat$PE_rf^2, na.rm=TRUE) / length(dat$PE_rf))

# Amount of Variance Explained (AVE)
AVE_rf <- 1 - sum(dat$PE_rf^2, na.rm=TRUE) /
  sum( (dat$MKD_OCSKGM_rf - mean(dat$OCSKGM, na.rm = TRUE))^2,
       na.rm = TRUE)
```

13.13 Graphical Map Quality Measures

The extended and discussed version of the following code is presented in Chapter 7, by B Kempen, DJ Brus & GBM Heuvelink, with code contributions from GF Olmedo.

```
# scatter plot
plot(dat$MKD_OCSKGM_rf, dat$OCSKGM, main="rf", xlab="predicted",
      ylab='observed')
# 1:1 line in black
abline(0,1, lty=2, col='black')
# regression line between predicted and observed in blue
abline(lm(dat$OCSKGM ~ dat$MKD_OCSKGM_rf), col = 'blue', lty=2)

# spatial bubbles for prediction errors
bubble(dat[!is.na(dat$PE_rf),], "PE_rf", pch = 21,
       col=c('red', 'green'))
```

Bibliography

- Adams, W. (1973). The effect of organic matter on the bulk and true densities of some uncultivated podzolic soils. *European Journal of Soil Science*, 24(1):10–17.
- Adhikari, K., Minasny, B., Greve, M. B., and Greve, M. H. (2014). Constructing a soil class map of denmark based on the fao legend using digital techniques. *Geoderma*, 214:101–113.
- Agus, F., Hairiah, K., and Mulyani, A. (2011). Measuring carbon stock in peat soils: practical guidelines | world agroforestry centre.
- Angelini, M. E., Heuvelink, G. B., Kempen, B., and Morrás, H. J. (2016). Mapping the soils of an argentine pampas region using structural equation modelling. *Geoderma*, 281:102–118.
- Arrouays, D., Deslais, W., and Badeau, V. (2001). The carbon content of topsoil and its geographical distribution in france. *Soil use and Management*, 17(1):7–11.
- Baritz, R., Eberhardt, E., Van Liedekerke, M., and Panagos, P. (2008). Environmental assessment of soil for monitoring: Volume iii database design and selection. *EUR*, 23490:125.
- Barney, R. J., Bevins, C. D., Bradshaw, L. S., Forestry Sciences Laboratory (Missoula, M. ., United States. Forest Service, and Intermountain Forest and Range Experiment Station (Ogden, U. (1981). *Forest floor fuel loads, depths and bulk densities in four interior Alaskan cover types*. Ogden, Utah : U.S. Dept. of Agriculture, Intermountain Forest and Range Experiment Station.
- Bernoux, M., Arrouays, D., Cerri, C. C., and Bourennane, H. (1998). Modeling vertical distribution of carbon in oxisols of the western brazilian amazon (rondonia). *Soil Science*, 163(12):941–951.
- Bhatti, J. S., Apps, M. J., and Tarnocai, C. (2002). Estimates of soil organic carbon stocks in central canada using three different approaches. *Canadian Journal of Forest Research*, 32(5):805–812.
- Bishop, T., McBratney, A., and Laslett, G. (1999). Modelling soil attribute depth functions with equal-area quadratic smoothing splines. *Geoderma*, 91(1):27–45.

- Bivand, R. S., Pebesma, E., and Gómez-Rubio, V. (2013). Classes for spatial data in r. In *Applied Spatial Data Analysis with R*, pages 21–57. Springer.
- Bontemps, S., Defourny, P., Bogaert, E. V., Arino, O., Kalogirou, V., and Perez, J. R. (2011). Globcover 2009-products description and validation report.
- Breiman, L. (1996). Bagging predictors. *Machine Learning*, 24(2):123–140.
- Breiman, L. (2017). Cutler’s random forests for classification and regression. 2015. r package version 4.6. 12.
- Breiman, L., Friedman, J., Stone, C. J., and Olshen, R. A. (1984). *Classification and regression trees*. CRC press.
- Brus, D., Kempen, B., and Heuvelink, G. (2011). Sampling for validation of digital soil maps. *European Journal of Soil Science*, 62(3):394–407.
- Carslaw, D. (2015). The openair manual—open-source tools for analysing air pollution data. manual for version 1.1–4, king’s college london.
- Carslaw, D. C. and Ropkins, K. (2012). openair — an r package for air quality data analysis. *Environmental Modelling & Software*, 27–28(0):52–61.
- Chang, C.-C. and Lin, C.-J. (2001). Libsvm: A library for support vector machines [eb/ol].
- Chang, J. and Hanna, S. (2004). Air quality model performance evaluation. *Meteorology and Atmospheric Physics*, 87(1-3):167–196.
- Cressie, N. A. (1993). Statistics for spatial data: Wiley series in probability and mathematical statistics. *Find this article online*.
- De Gruijter, J., Brus, D. J., Bierkens, M. F., and Knotters, M. (2006). *Sampling for natural resource monitoring*. Springer Science & Business Media.
- Dobos, E. (2006). *Digital Soil Mapping: As a Support to Production of Functional Maps*. Office for Official Publication of the European Communities.
- Drew, L. A. (1973). Bulk density estimation based on organic matter content of some minnesota soils.
- Friedman, J., Hastie, T., and Tibshirani, R. (2001). *The elements of statistical learning*, volume 1. Springer series in statistics New York.
- Goovaerts, P. (1997). *Geostatistics for natural resources evaluation*. Oxford University Press on Demand.
- Goovaerts, P. (2001). Geostatistical modelling of uncertainty in soil science. *Geoderma*, 103(1):3–26.
- Greve, M. H., Greve, M. B., Bøcher, P. K., Balstrøm, T., Breuning-Madsen, H., and Krogh, L. (2007). Generating a danish raster-based topsoil property map combining choropleth maps and point information. *Geografisk Tidsskrift-Danish Journal of Geography*, 107(2):1–12.

- Grigal, D., Brovold, S., Nord, W., and Ohmann, L. (1989). Bulk density of surface soils and peat in the north central united states. *Canadian Journal of Soil Science*, 69(4):895–900.
- Grimm, R. and Behrens, T. (2010). Uncertainty analysis of sample locations within digital soil mapping approaches. *Geoderma*, 155(3):154–163.
- Guevara, M., Olmedo, G. F., Stell, E., Yigini, Y., Aguilar Duarte, Y., Arellano Hernández, C., Arévalo, G. E., Arroyo-Cruz, C. E., Bolívar, A., Bunning, S., Bustamante Cañas, N., Cruz-Gaistardo, C. O., Davila, F., Dell Acqua, M., Encina, A., Figueredo Tacona, H., Fontes, F., Hernández Herrera, J. A., Ibelles Navarro, A. R., Loayza, V., Manueles, A. M., Mendoza Jara, F., Olivera, C., Osorio Hermosilla, R., Pereira, G., Prieto, P., Alexis Ramos, I., Rey Brina, J. C., Rivera, R., Rodríguez-Rodríguez, J., Roopnarine, R., Rosales Ibarra, A., Rosales Riveiro, K. A., Schulz, G. A., Spence, A., Vasques, G. M., Vargas, R. R., and Vargas, R. (2018). No silver bullet for digital soil mapping: Country-specific soil organic carbon estimates across latin america. *SOIL Discussions*, 2018:1–20.
- Guyon, I. and Elisseeff, A. (2003). An introduction to variable and feature selection. *Journal of machine learning research*, 3(Mar):1157–1182.
- Hartmann, J. and Moosdorf, N. (2012). The new global lithological map database glim: A representation of rock properties at the earth surface. *Geochemistry, Geophysics, Geosystems*, 13(12).
- Hengl, T. (2006). Finding the right pixel size. *Computers & Geosciences*, 32(9):1283–1298.
- Hengl, T. (2016). Gsif: Global soil information facilities. r package version 0.5-3.
- Hengl, T., Heuvelink, G. B., Kempen, B., Leenaars, J. G., Walsh, M. G., Shepherd, K. D., Sila, A., MacMillan, R. A., de Jesus, J. M., Tamene, L., et al. (2015a). Mapping soil properties of africa at 250 m resolution: random forests significantly improve current predictions. *PloS one*, 10(6):e0125814.
- Hengl, T., Heuvelink, G. B., and Rossiter, D. G. (2007). About regression-kriging: from equations to case studies. *Computers & geosciences*, 33(10):1301–1315.
- Hengl, T., Heuvelink, G. B., and Stein, A. (2004). A generic framework for spatial prediction of soil variables based on regression-kriging. *Geoderma*, 120(1):75–93.
- Hengl, T., Roudier, P., Beaudette, D., Pebesma, E., et al. (2015b). plotkml: scientific visualization of spatio-temporal data. *Journal of Statistical Software*, 63(5):1–25.
- Heuvelink, G. (2014). Uncertainty quantification of globalsoilmap products. in ‘globalsoilmap, basis of the global spatial soil information system’.(eds d arrouays, nj mckenzie, jw hempel, ar de forges, ab mcbratney) pp. 327–332.
- Hiederer, R. (2013). Mapping soil properties for europe—spatial representation of soil database attributes. *Publications Office of the European Union, EUR26082EN Scientific and Technical Research series. Luxembourg*.

- Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., and Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International journal of climatology*, 25(15):1965–1978.
- Ho, Y.-C. and Pepyne, D. L. (2002). Simple explanation of the no-free-lunch theorem and its implications. *Journal of optimization theory and applications*, 115(3):549–570.
- Honeysett, J. and Ratkowsky, D. (1989). The use of ignition loss to estimate bulk density of forest soils. *European Journal of Soil Science*, 40(2):299–308.
- Hsu, C.-W., Chang, C.-C., Lin, C.-J., et al. (2003). A practical guide to support vector classification.
- Jackson, I. (2007). Onegeology: Making geological map data for the earth accessible. *Episodes*, 30(1):60–61.
- James, G., Witten, D., Hastie, T., and Tibshirani, R. (2013). *An introduction to statistical learning*, volume 112. Springer.
- Jeffrey, D. (1970). A note on the use of ignition loss as a means for the approximate estimation of soil bulk density. *The Journal of Ecology*, pages 297–299.
- Karatzoglou, A., Meyer, D., and Hornik, K. (2006). Support Vector Algorithm in R. *Journal of Statistical Software*, 15(9):1–28.
- Kempen, B., Brus, D. J., Stoorvogel, J. J., Heuvelink, G., and de Vries, F. (2012). Efficiency comparison of conventional and digital soil mapping for updating soil maps. *Soil Science Society of America Journal*, 76(6):2097–2115.
- Kempen, B., Heuvelink, G., Brus, D., and Stoorvogel, J. (2010). Pedometric mapping of soil organic matter using a soil map with quantified uncertainty. *European journal of soil science*, 61(3):333–347.
- Knotters, M. and Brus, D. (2013). Purposive versus random sampling for map validation: a case study on ecotope maps of floodplains in the netherlands. *Eco-hydrology*, 6(3):425–434.
- Krasilnikov, P., del Carmen Gutiérrez-Castorena, M., Ahrens, R. J., Cruz-Gaistardo, C. O., Sedov, S., and Solleiro-Rebolledo, E. (2013). *The soils of Mexico*. Springer Science & Business Media.
- Krause, P., Boyle, D., and Bäse, F. (2005). Comparison of different efficiency criteria for hydrological model assessment. *Advances in geosciences*, 5:89–97.
- Kuhn, M. (2016). A short introduction to the caret package. URL: <https://cran.r-project.org/web/packages/caret/vignettes/caret.pdf>.
- Lark, R. (1995). Components of accuracy of maps with special reference to discriminant analysis on remote sensor data. *International Journal of Remote Sensing*, 16(8):1461–1480.

- Lark, R. (2000). A comparison of some robust estimators of the variogram for use in soil survey. *European Journal of Soil Science*, 51(1):137–157.
- Legates, D. R. and McCabe, G. J. (1999). Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation. *Water resources research*, 35(1):233–241.
- Legates, D. R. and McCabe, G. J. (2013). A refined index of model performance: a rejoinder. *International Journal of Climatology*, 33(4):1053–1056.
- Lettens, S., Orshoven, J., Wesemael, B., Muys, B., and Perrin, D. (2005). Soil organic carbon changes in landscape units of belgium between 1960 and 2000 with reference to 1990. *Global Change Biology*, 11(12):2128–2140.
- Lettens, S., Orshoven, J. v., Wesemael, B., , and Muys, B. (2004). Soil organic and inorganic carbon contents of landscape units in belgium derived using data from 1950 to 1970. *Soil Use and Management*, 20(1):40–47.
- Meinshausen, N. (2006). Quantile regression forests. *Journal of Machine Learning Research*, 7(Jun):983–999.
- Meyer, D., Dimitriadou, E., Hornik, K., Weingessel, A., and Leisch, F. (2017). *e1071: Misc Functions of the Department of Statistics, Probability Theory Group (Formerly: E1071)*, TU Wien. R package version 1.6-8.
- Nelson, D. and Sommers, L. (1982). Total carbon, organic carbon, and organic matter. In *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*, pages 539–579. American Society of Agronomy, Soil Science Society of America.
- Nelson, M., Bishop, T., Triantafilis, J., and Odeh, I. (2011). An error budget for different sources of error in digital soil mapping. *European Journal of Soil Science*, 62(3):417–430.
- Nussbaum, M., Spiess, K., Baltensweiler, A., Grob, U., Keller, A., Greiner, L., Schaeppman, M. E., and Papritz, A. (2018). Evaluation of digital soil mapping approaches with large sets of environmental covariates. *Soil*, 4(1):1.
- Ottmar, R. and Andreu, A. (2007). Litter and duff bulk densities in the southern united states: final report for joint fire sciences program, project 04-2-1-49.
- Pebesma, E. J. and Bivand, R. S. (2005). Classes and methods for spatial data in r. *R news*, 5(2):9–13.
- Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot, M., and Duchesnay, E. (2011). Scikit-learn: Machine learning in Python. *Journal of Machine Learning Research*, 12:2825–2830.
- Poggio, L., Gimona, A., and Brewer, M. J. (2013). Regional scale mapping of soil properties and their uncertainty with a large number of satellite-derived covariates. *Geoderma*, 209:1–14.

- Ponce Hernandes, R., Marriott, F., and Beckett, P. (1986). An improved method for reconstructing a soil profile from analyses of a small number of samples. *European Journal of Soil Science*, 37(3):455–467.
- Pontius Jr, R. G. and Millones, M. (2011). Death to kappa: birth of quantity disagreement and allocation disagreement for accuracy assessment. *International Journal of Remote Sensing*, 32(15):4407–4429.
- Qiao, H., Soberón, J., and Peterson, A. T. (2015). No silver bullets in correlative ecological niche modelling: insights from testing among many potential algorithms for niche estimation. *Methods in Ecology and Evolution*, 6(10):1126–1136.
- R Core Team (2017). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.
- Rad, M. R. P., Toomanian, N., Khormali, F., Brungard, C. W., Komaki, C. B., and Bogaert, P. (2014). Updating soil survey maps using random forest and conditioned latin hypercube sampling in the loess derived soils of northern iran. *Geoderma*, 232:97–106.
- Rosell, R., Gasparoni, J., and Galantini, J. (2001). Soil organic matter evaluation. In *Assessment methods for soil carbon*, pages 311–322. Lewis Publishers Boca Raton.
- Saini, G. (1966). Organic matter as a measure of bulk density of soil. *Nature*, 210(5042):1295–1296.
- Samuel-Rosa, A., Heuvelink, G., Vasques, G., and Anjos, L. (2015). Do more detailed environmental covariates deliver more accurate soil maps? *Geoderma*, 243:214–227.
- Stehman, S. V. (1997). Selecting and interpreting measures of thematic classification accuracy. *Remote sensing of Environment*, 62(1):77–89.
- Stehman, S. V. (1999). Basic probability sampling designs for thematic map accuracy assessment. *International Journal of remote sensing*, 20(12):2423–2441.
- Taylor, K. E. (2001). Summarizing multiple aspects of model performance in a single diagram. *Journal of Geophysical Research: Atmospheres*, 106(D7):7183–7192.
- Vapnik, V. (2013). *The nature of statistical learning theory*. Springer science & business media.
- Vaysse, K. and Lagacherie, P. (2017). Using quantile regression forest to estimate uncertainty of digital soil mapping products. *Geoderma*, 291:55–64.
- Voltz, M. and Webster, R. (1990). A comparison of kriging, cubic splines and classification for predicting soil properties from sample information. *European Journal of Soil Science*, 41(3):473–490.

- Warmerdam, F. (2008). The geospatial data abstraction library. In Hall, G. B. and Leahy, M. G., editors, *Open Source Approaches in Spatial Data Handling*, pages 87–104. Springer Berlin Heidelberg. DOI: 10.1007/978-3-540-74831-1_5.
- Webster, R. and Oliver, M. A. (2007). *Geostatistics for environmental scientists. Statistics in practice. 2nd Edition.* John Wiley & Sons,.
- Wiesmeier, M., Barthold, F., Blank, B., and Kögel-Knabner, I. (2011). Digital mapping of soil organic matter stocks using random forest modeling in a semi-arid steppe ecosystem. *Plant and soil*, 340(1-2):7–24.
- Willmott, C. J., Robeson, S. M., and Matsuura, K. (2012). A refined index of model performance. *International Journal of Climatology*, 32(13):2088–2094.
- Wong, W. V. C., Tsuyuki, S., Ioki, K., and Phua, M.-H. (2014). Accuracy Assessment of Global Topographic Data (SRTM & ASTER GDEM) in Comparison With LIDAR for Tropical Montane Forest.
- Youngblood, B. (2013). *GeoServer Beginner's Guide.* Packt Publishing Ltd.

This cookbook was prepared thanks to the financial support of
The Kingdom of the Netherlands and the Swiss Confederation



Ministry of Foreign Affairs of the
Netherlands



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation