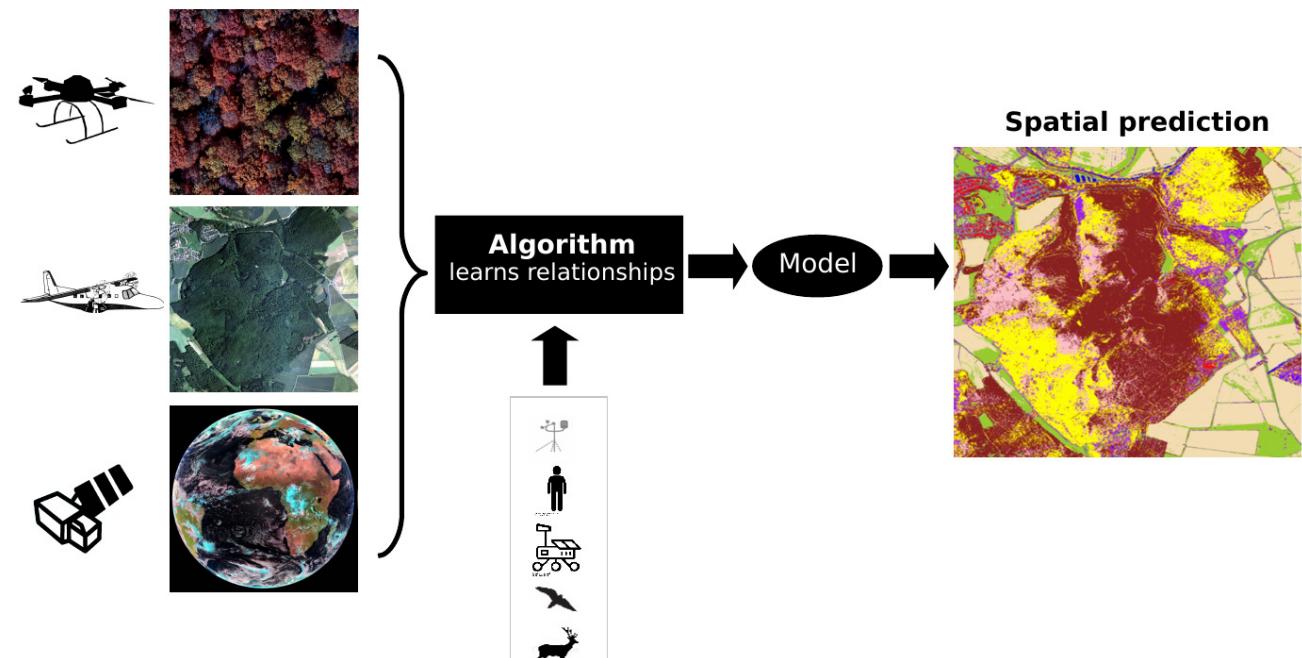


Practice: Machine learning for earth observation & Mapping the „Area of Applicability“ of spatial prediction models

Hanna Meyer

Remote Sensing & Spatial Modelling,
Institute of Landscape Ecology, WWU Münster



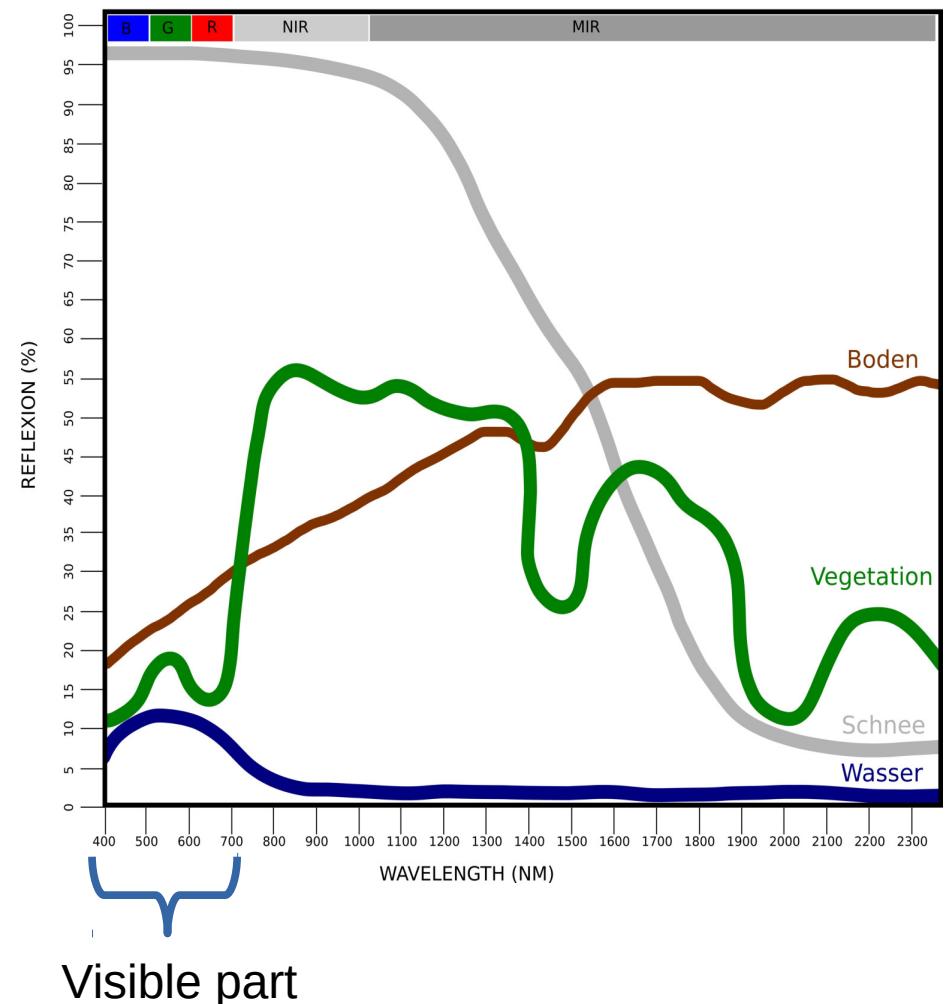
Aim of the workshop

- Getting to know the basic workflow: Machine learning for remote sensing applications
- Example: land cover classification
- Analysing the area of applicability of a prediction model
- Assessing the transferability of a prediction model

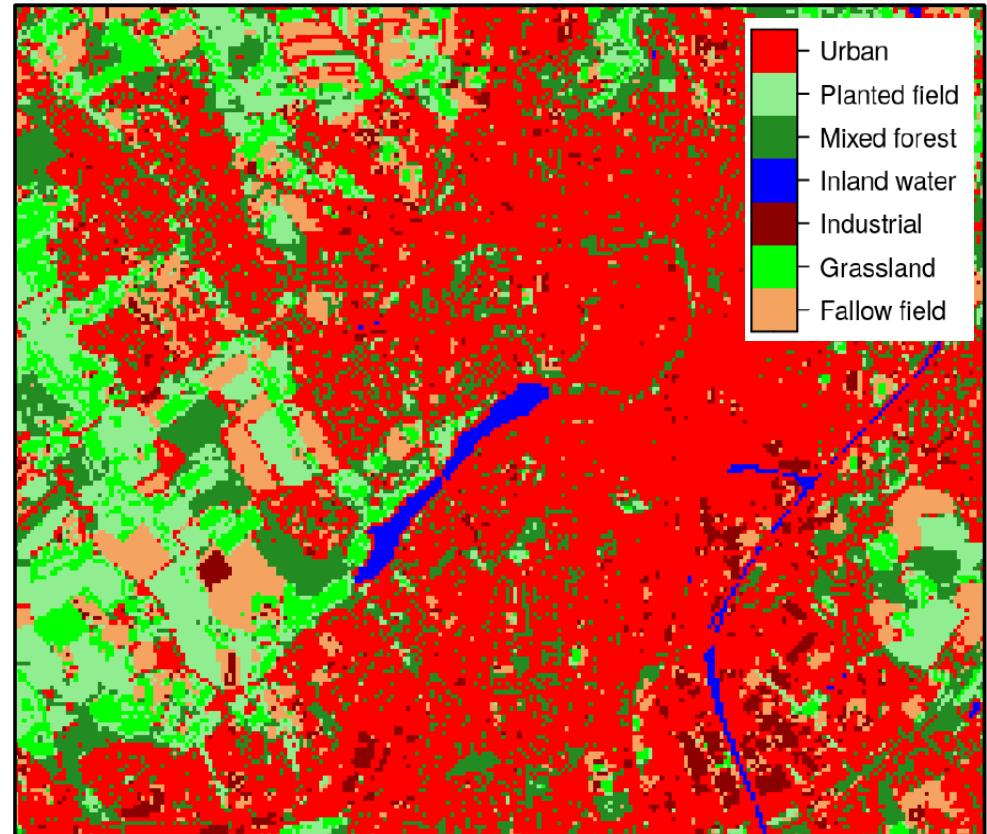
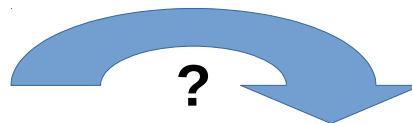
Next ~45min: Introduction, then guided hands-on

Idea of a land cover classification

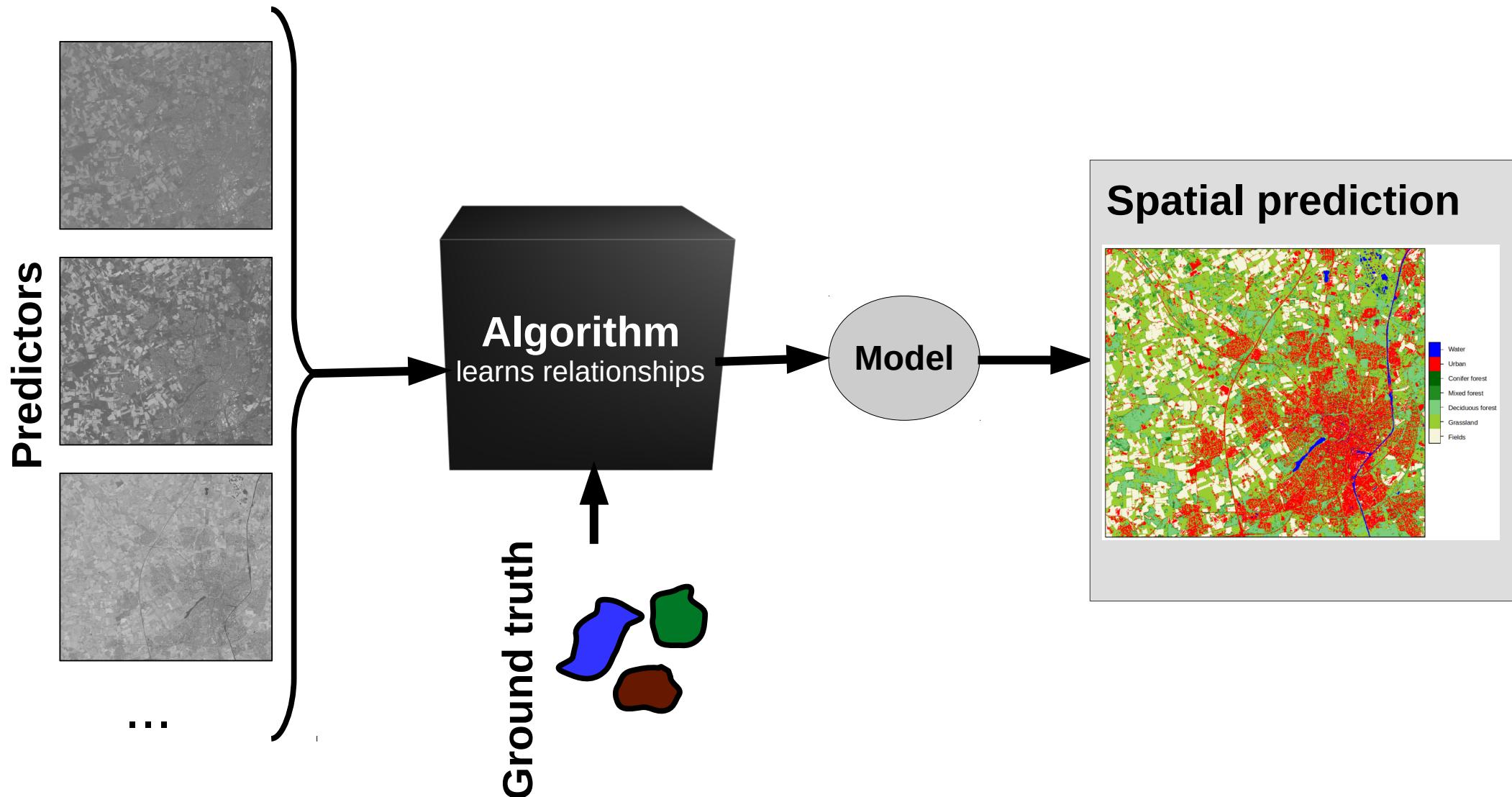
- Land cover types differ in their reflection properties
- Apply Statistical methods to infer land use classes from reflection properties
- Idea: Learning from known data and applying the model to the entire landscape



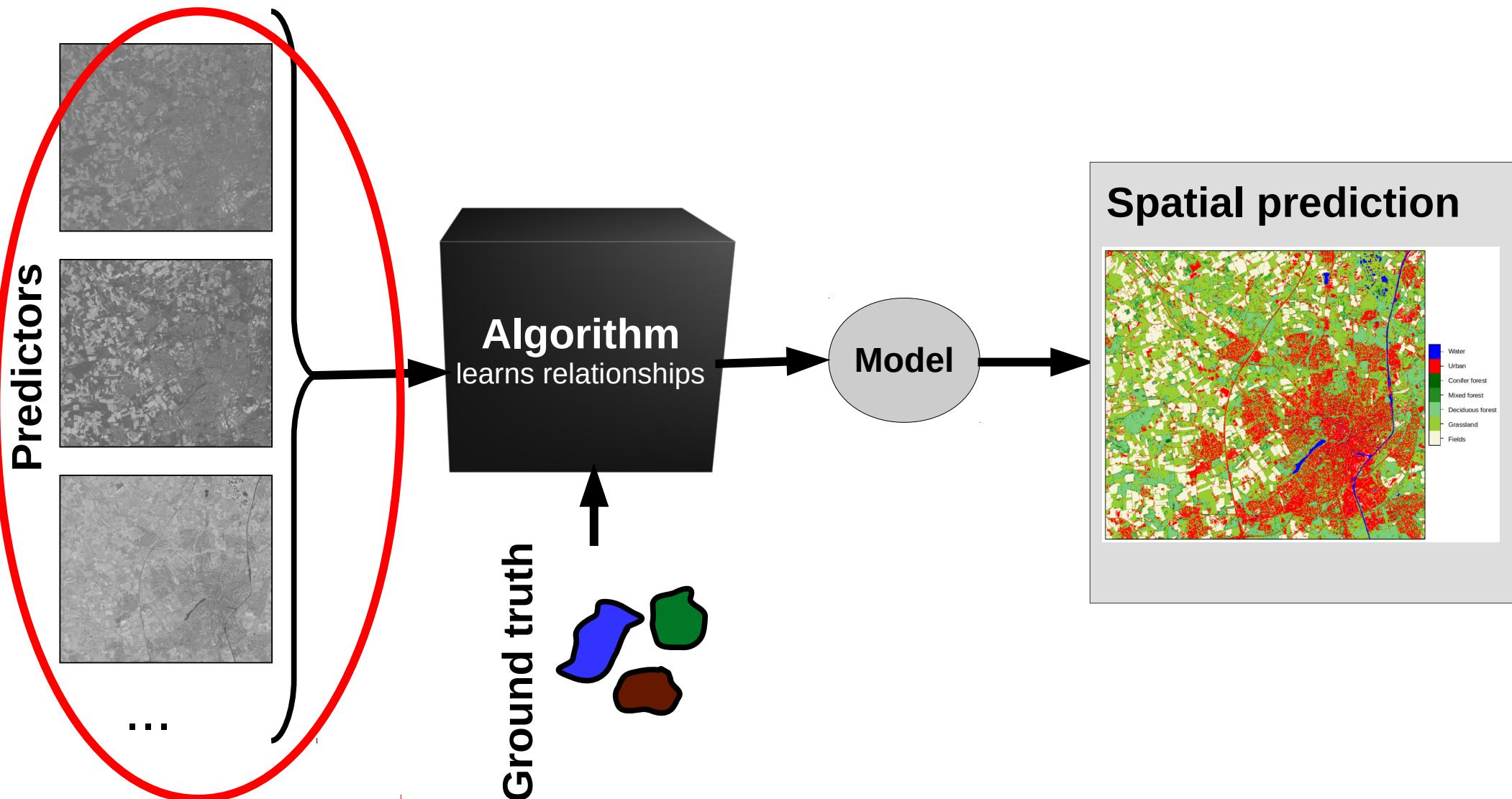
Case Study for the tutorial



How to use the spectral properties to classify land cover?



How to use the spectral properties to classify land cover?



Satellite data (selection)

Platform/Sensor	Spatial resolution (m)	Temporal resolution	Availability
Landsat MSS	79	16 days	since 1972
Landsat TM	30	16 days	since 1982
Landsat ETM+	30	16 days	since 1999
Landsat 8 (OLI)	30	16 days	since 2013
Sentinel-2	10	5/10 days	since 2014
MODIS Terra/Aqua	250-1000	4 per day	since 2000
Meteosat Second Generation	3000	15 minutes	since 2002

Sentinel-2 data

Spectral bands for the Sentinel-2 sensors^[10]

Sentinel-2 bands	Sentinel-2A		Sentinel-2B		Spatial resolution (m)
	Central wavelength (nm)	Bandwidth (nm)	Central wavelength (nm)	Bandwidth (nm)	
Band 1 - Coastal aerosol	442.7	21	442.2	21	60
Band 2 - Blue	492.4	66	492.1	66	10
Band 3 - Green	559.8	36	559.0	36	10
Band 4 - Red	664.6	31	664.9	31	10
Band 5 - Vegetation red edge	704.1	15	703.8	16	20
Band 6 - Vegetation red edge	740.5	15	739.1	15	20
Band 7 - Vegetation red edge	782.8	20	779.7	20	20
Band 8 - NIR	832.8	106	832.9	106	10
Band 8A - Narrow NIR	864.7	21	864.0	22	20
Band 9 - Water vapour	945.1	20	943.2	21	60
Band 10 - SWIR - Cirrus	1373.5	31	1376.9	30	60
Band 11 - SWIR	1613.7	91	1610.4	94	20
Band 12 - SWIR	2202.4	175	2185.7	185	20

<https://en.wikipedia.org/wiki/Sentinel-2>

Getting satellite data

- E.g. using the Earth Explorer
- Or automatic download via getSpatialData package

The screenshot shows the USGS Earth Explorer interface. At the top, there's a navigation bar with the USGS logo and links for Home, New System Message, Save Criteria, Load Favorite, Manage Criteria, Item Basket (0), HannaM, RSS, Feedback, and Help. The main area has tabs for Search Criteria, Data Sets, Additional Criteria, and Results. The Results tab is active, displaying a list of 4 search results for Sentinel-2 data. The results are as follows:

- ID: L1C_T32UMC_2007427_20180000T103440
Acquisition Date: 2018/08/08
Platform: SENTINEL-2B
Tile Number: T32UMC
- ID: L1C_T32UMC_A016307_20180806T104340
Acquisition Date: 2018/08/06
Platform: SENTINEL-2A
Tile Number: T32UMC
- ID: L1C_T32ULC_A016307_20180806T104340
Acquisition Date: 2018/08/06
Platform: SENTINEL-2A
Tile Number: T32ULC
- ID: L1C_T32ULC_A007370_20180804T105022
Acquisition Date: 2018/08/04
Platform: SENTINEL-2B
Tile Number: T32ULC
- ID: L1C_T32ULC_A016264_20180803T103239
Acquisition Date: 2018/08/03
Platform: SENTINEL-2A

Below the results is a large map of a rural area in Germany, specifically the region around Arnhem and Nijmegen. The map shows agricultural fields, roads, and towns. A red location marker is placed near the center of the map. The map includes a legend and various controls for zooming and panning. The bottom of the map displays copyright information from Google and TerraMetrics.

→ <https://earthexplorer.usgs.gov/>

Load satellite data in R

- Packages for raster data: raster, stars, terra
- Here we will use the raster package but stars version available (see Edzer's PR)

Load satellite data in R

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How to import satellite data into R

```
library(raster)
sen <- stack("blue.tif", "green.tif",
            "red.tif", "NIR.tif")
plot(sen)          And more channels!
```

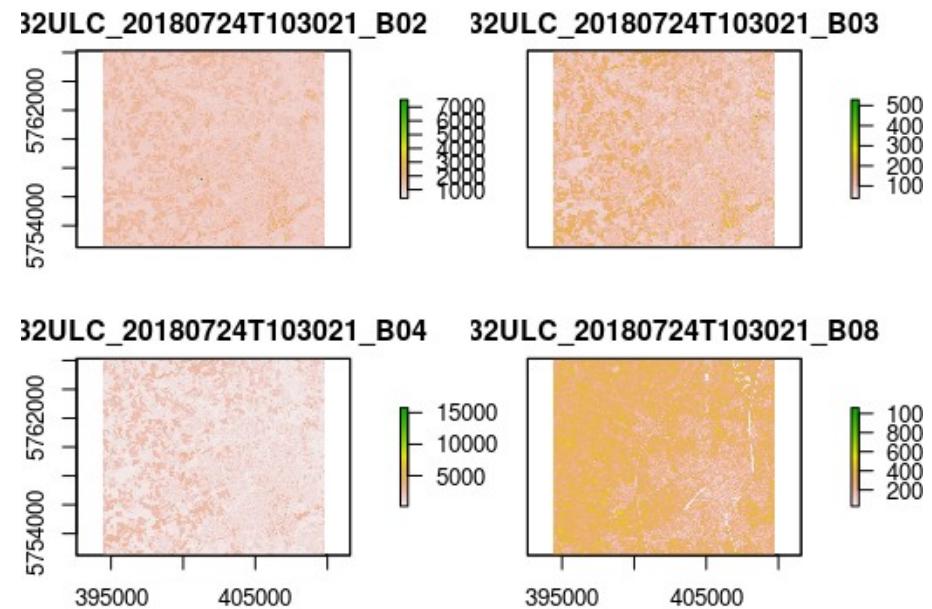
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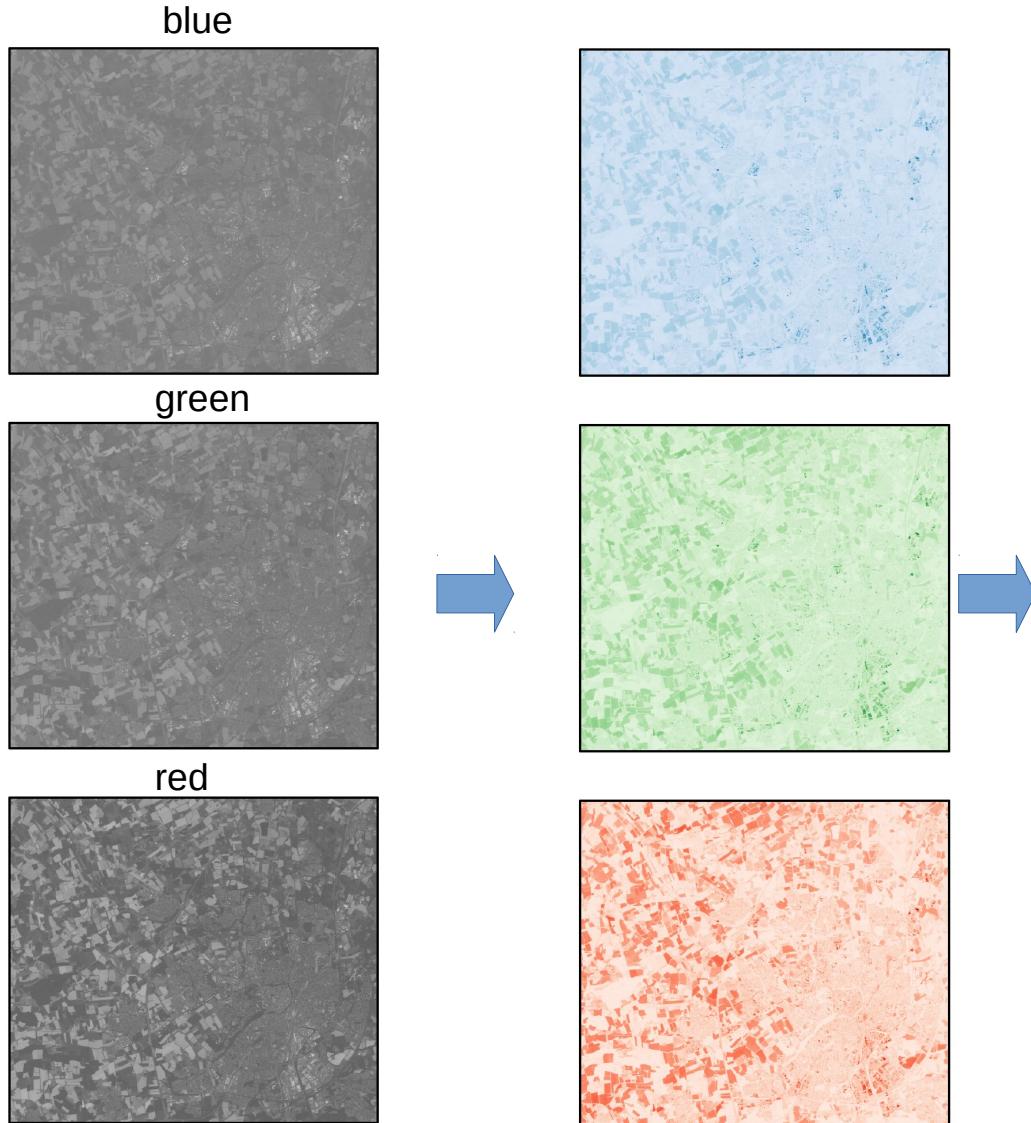
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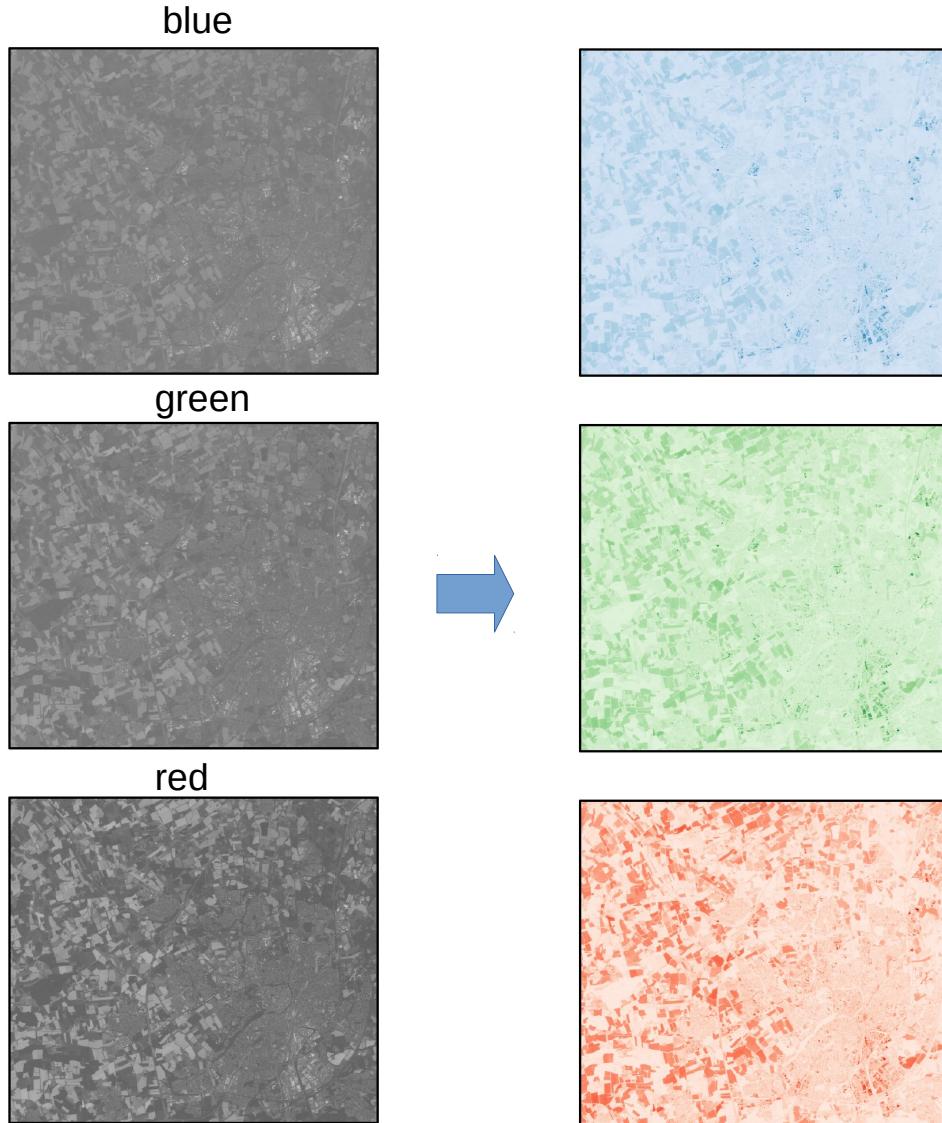
And more channels!



Excursus: how do we get the “color” in the satellite data?



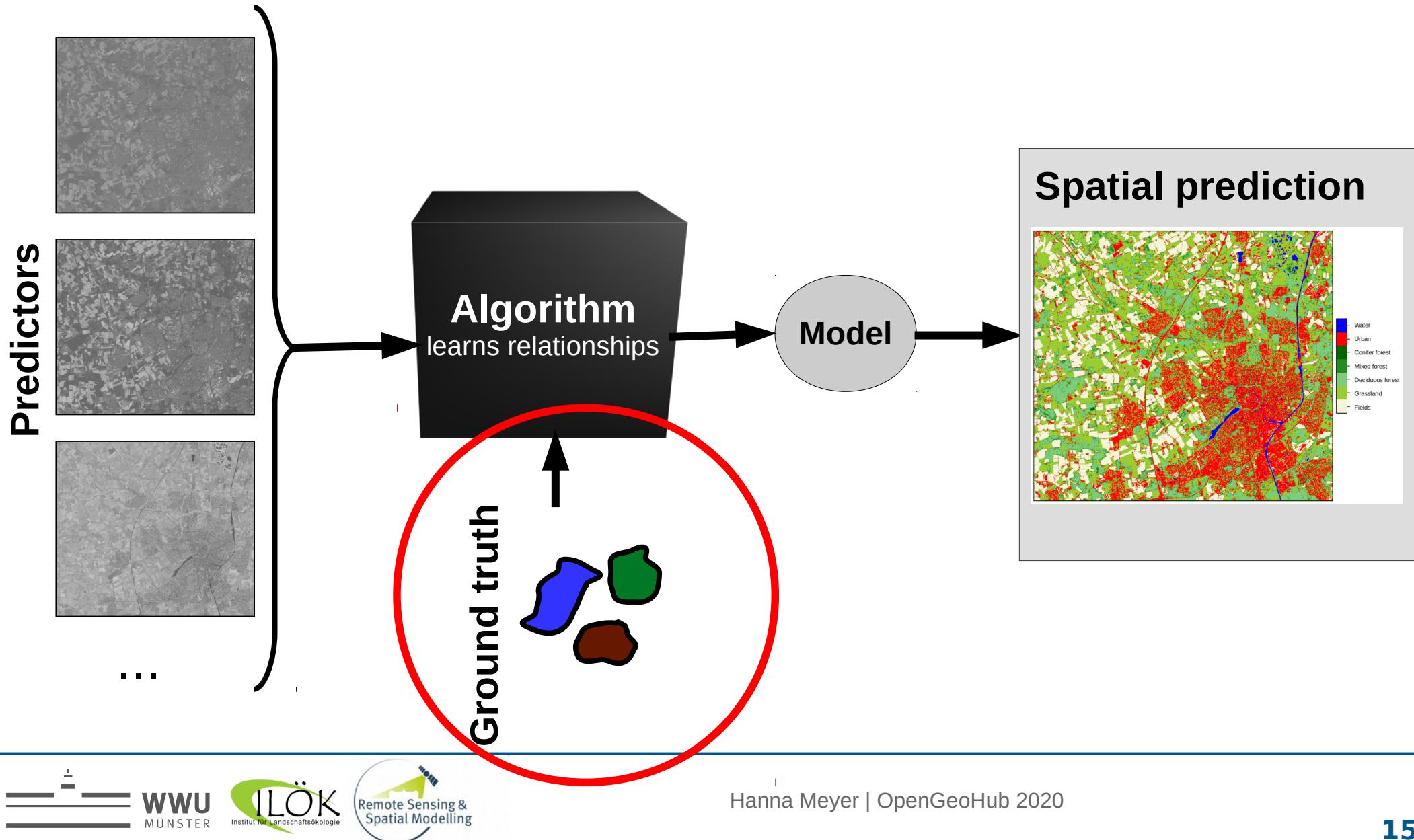
Excursus: how do we get the “color” in the satellite data?



How to do a color composite in R

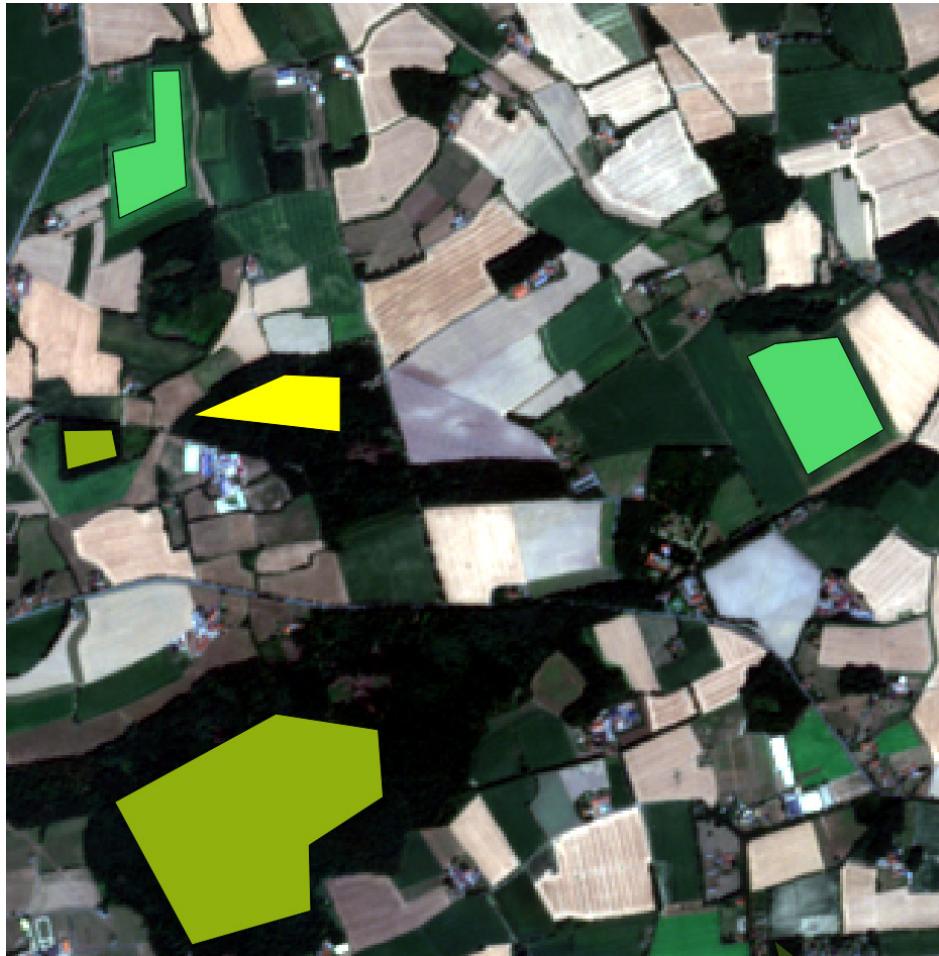
```
sen <- stack("blue.tif", "green.tif",
            "red.tif", "NIR.tif")
plotRGB(sen, r=3, g=2, b=1, stretch="lin")
```

How to use the spectral properties to classify land cover?



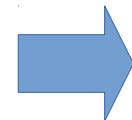
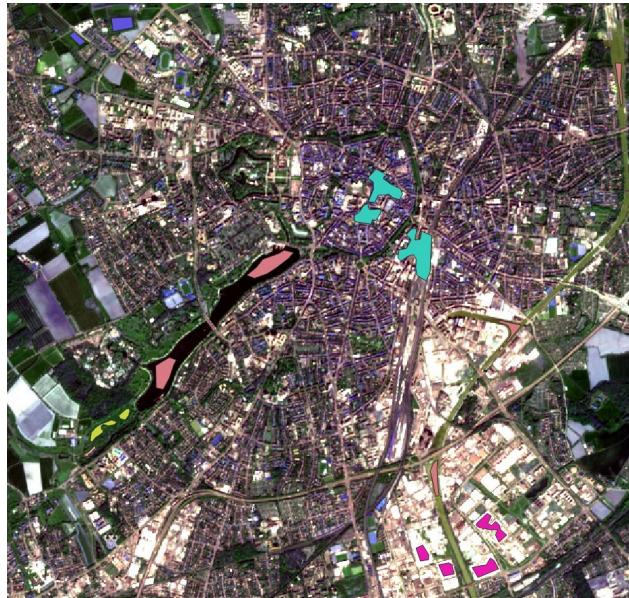
How to use the spectral properties to classify land cover?

Reference data are required



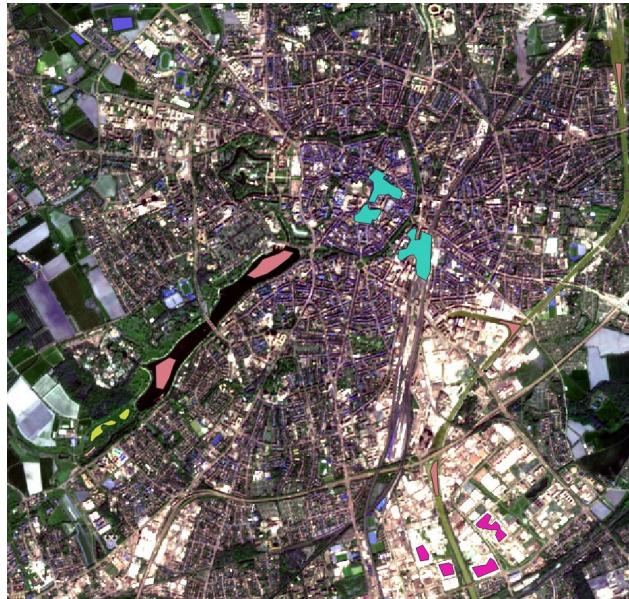
- Training data from field work, expert knowledge, existing databases,...
- Usually polygons that are taken using a GPS or manually digitized
- In this case study: digitized (in QGIS)

Combine predictors and response



	B02	B03	B04	B08	... Class
1	857	632	387	308	Water
2	848	633	389	312	Water
3	843	624	357	343	Water
4	854	630	360	333	Water
5	854	628	376	302	Water
6	859	615	364	350	Water

Combine predictors and response

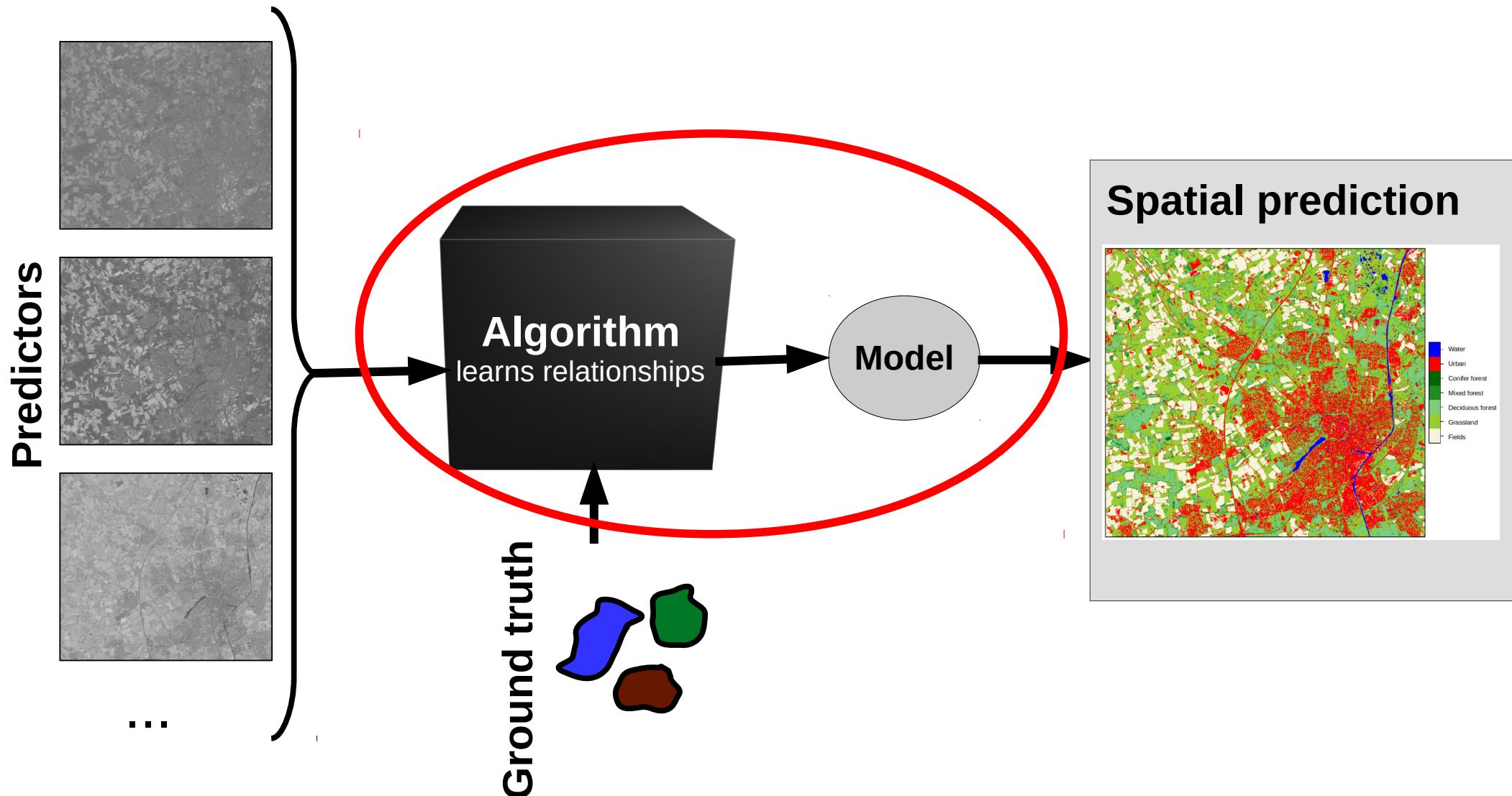


	B02	B03	B04	B08	... Class
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3	843	624	357	343	Water
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5	854	628	376	302	Water
6	859	615	364	350	Water

How to do it in R

```
extr <- extract(sen, trainSites, df=TRUE)
extr <- merge(extr, trainSites, by.x="ID", by.y="PolygonID")
```

Model training



Model training in R

- Many packages for different ML algorithms (e.g. Random Forests, Neural Networks, Support Vector Machines, ...)
- For classification and regression problems

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 - Caret (Classification And REgression Training)
 - Mlr (Machine Learning in R)
 - Tidymodels

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 - Mlr (Machine Learning in R) For today's session
 - Tidymodels



Step 1: Model training in R

"Default model"

Predictors					Response	
	B02	B03	B04	B08	...	class
1	857	632	387	308		Water
2	848	633	389	312		Water
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Step 1: Model training in R

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4	854	630	360	333	Water
5	854	628	376	302	Water
6	859	615	364	350	Water

How to do it in R

```
library(caret)
model <- train(predictors,
                 response,
                 method="rf")
```

Random Forest used here as
Machine learning algorithm



Step 1: Model training in R

"Default model": Example of results

Variables	Validation	Accuracy	Kappa
all	random	>0.99	>0.99

Perfect prediction?

Step 1: Model training in R

...however spatial dependencies need to be taken into account

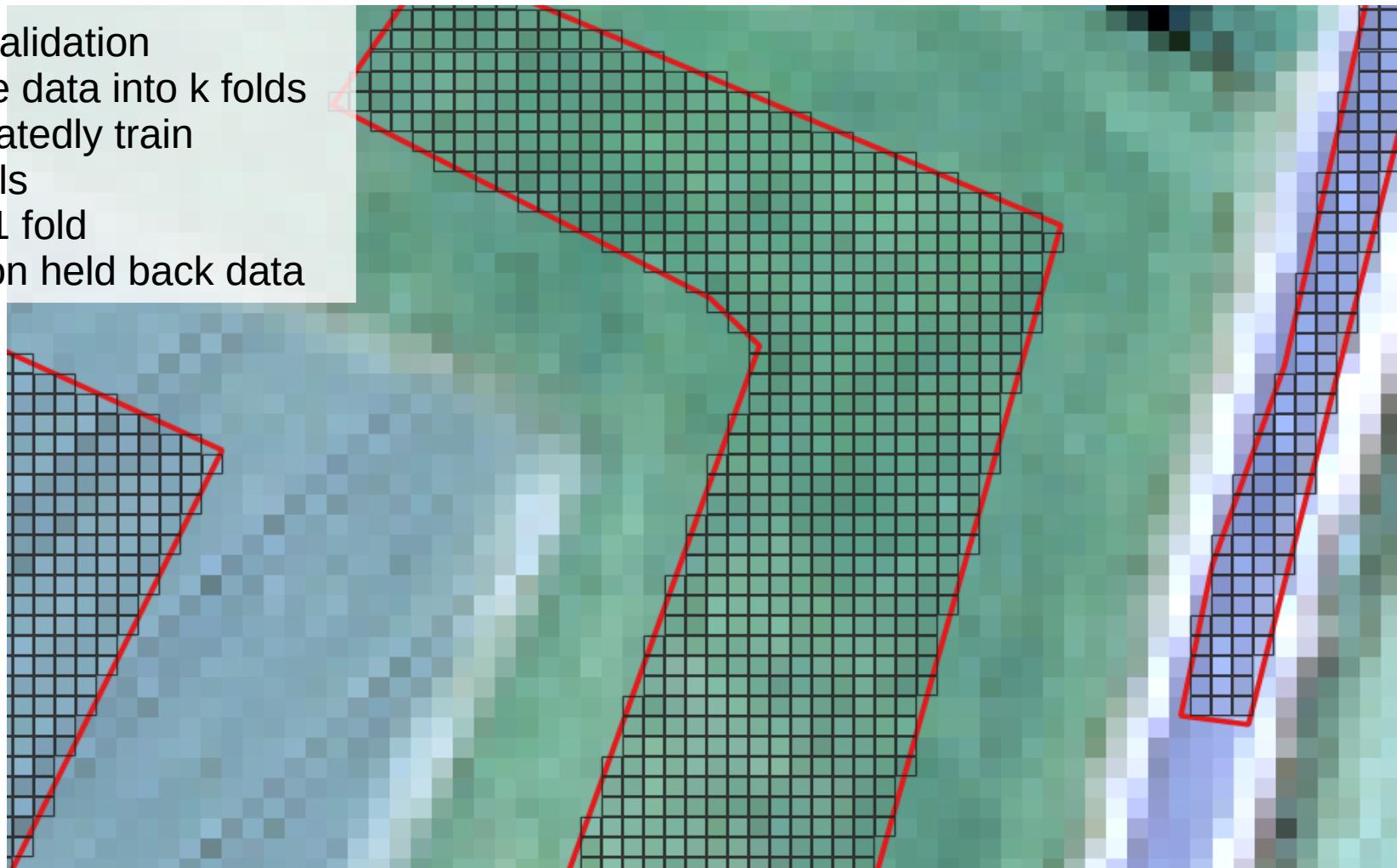


Step 1: Model training in R

...however spatial dependencies need to be taken into account

Cross-validation

- Divide data into k folds
- Repeatedly train models on $k-1$ fold
- Test on held back data

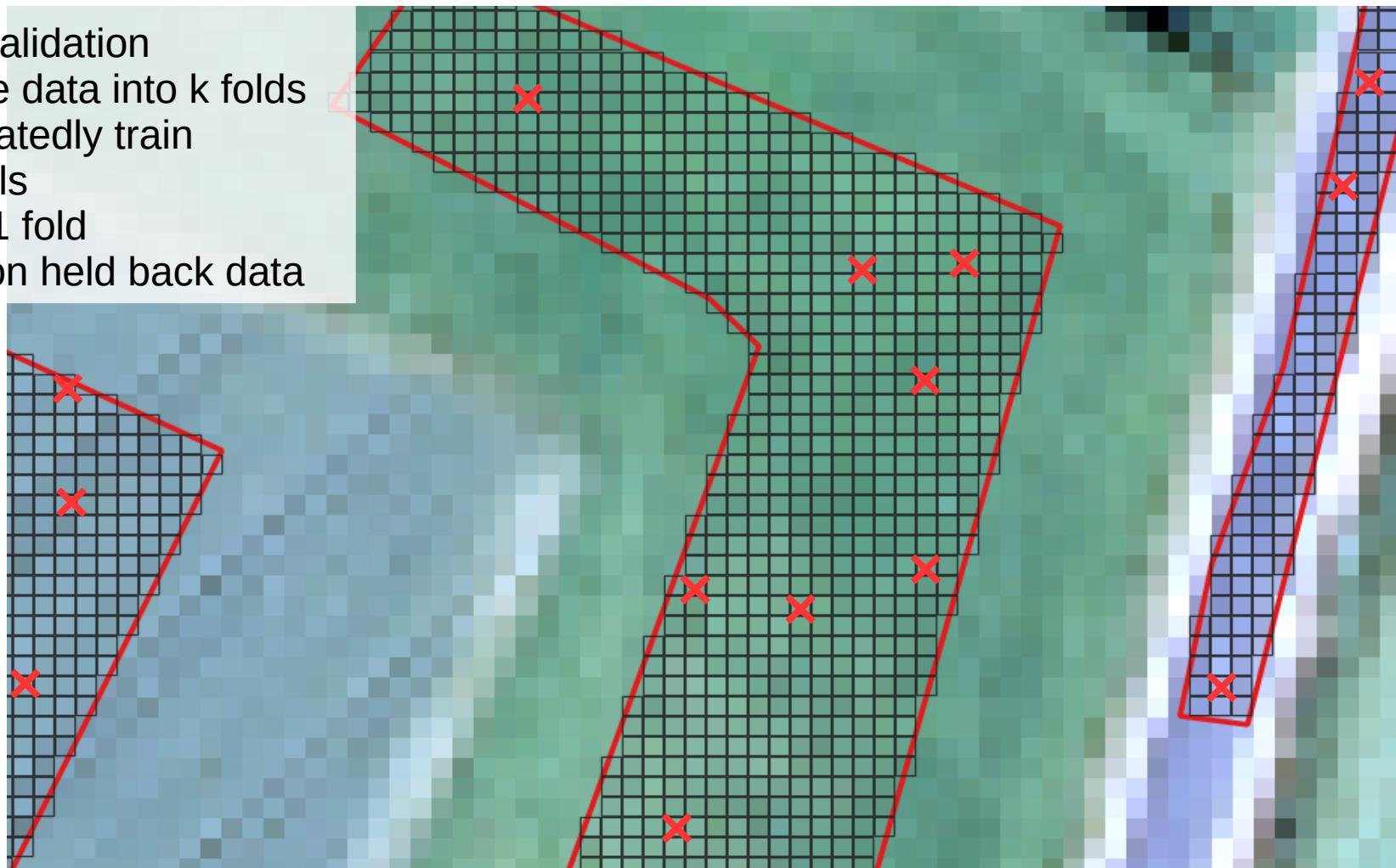


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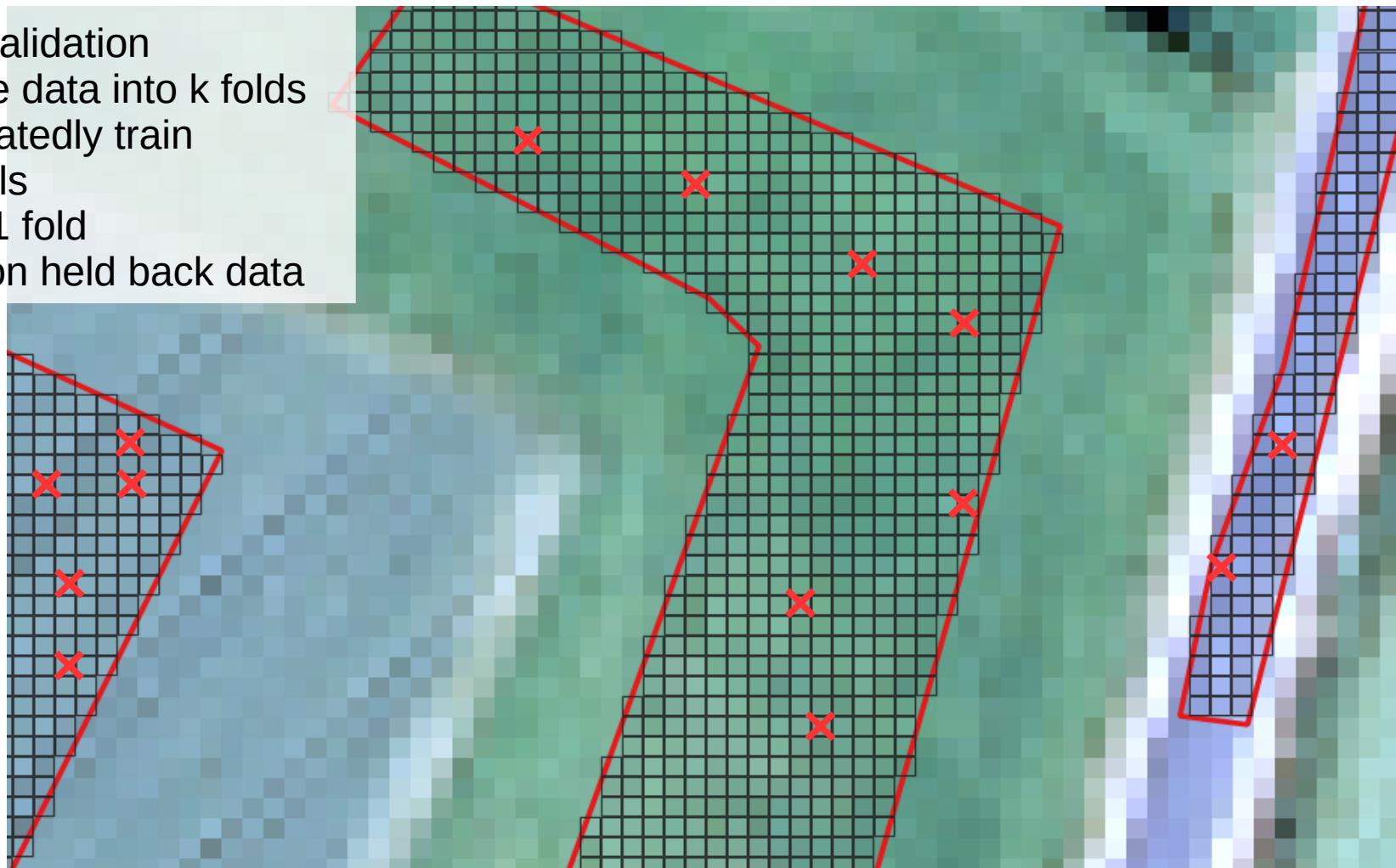


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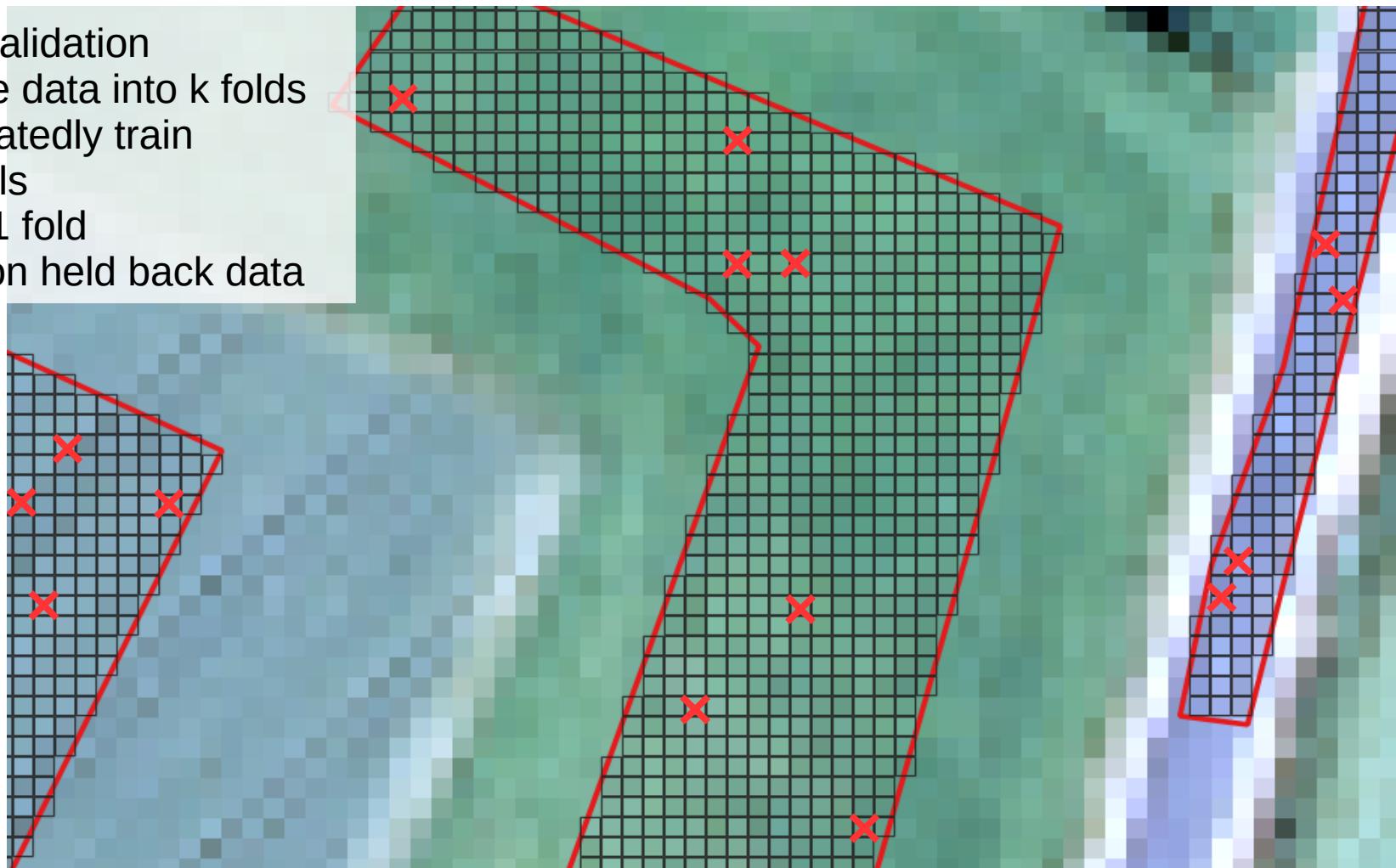


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Step 1: Model training in R

...however spatial dependencies need to be taken into account

Cross-validation

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- Test on held back data



Random Cross-validation answers question how well model performs on very similar locations

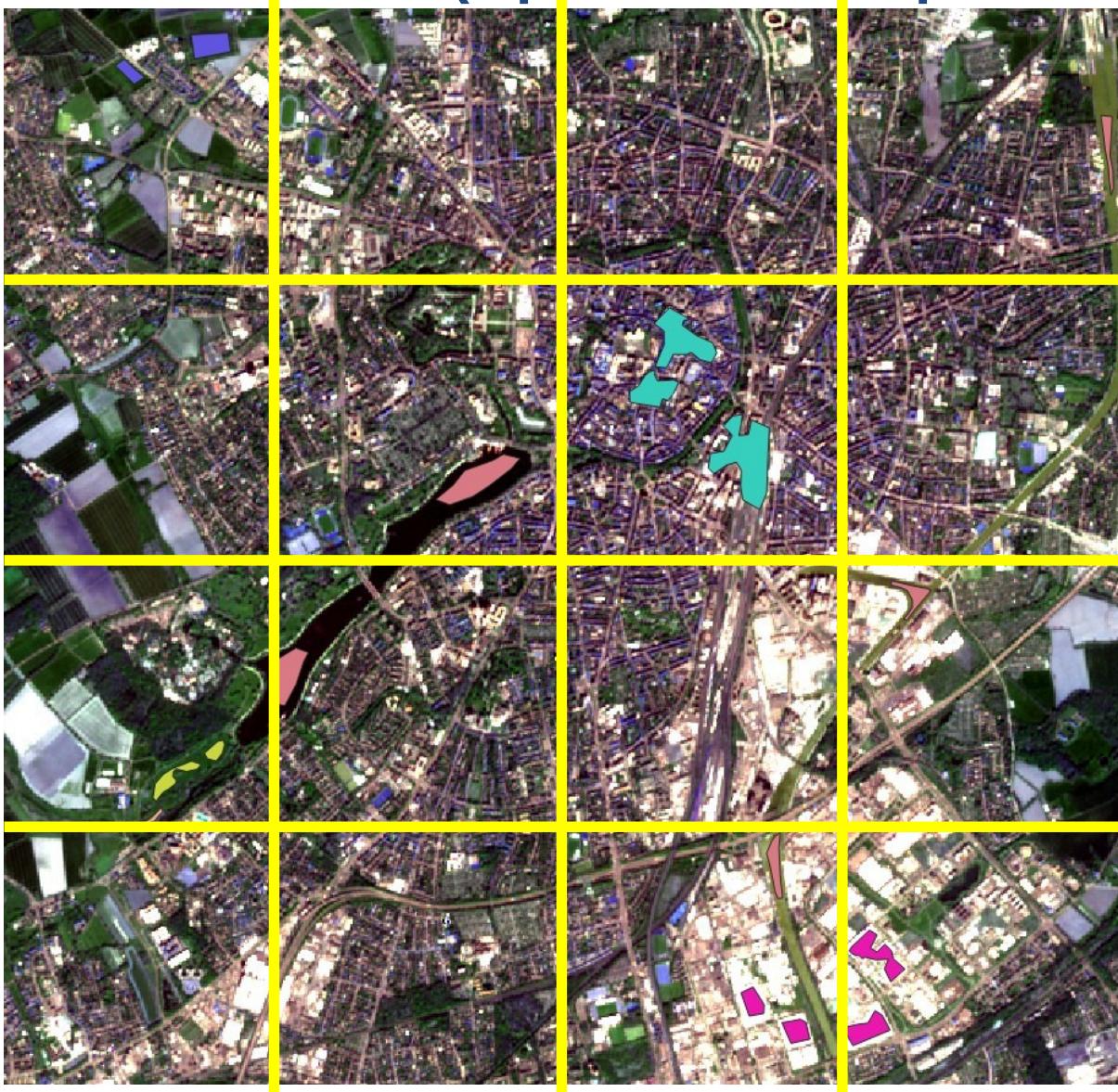
Step 1: Model training in R

Spatial cross-validation (Option: Leave spatial block out)



Step 1: Model training in R

Spatial cross-validation (Option: Leave spatial block out)



Step 1: Model training in R

Spatial cross-validation (Option: Leave spatial block out)



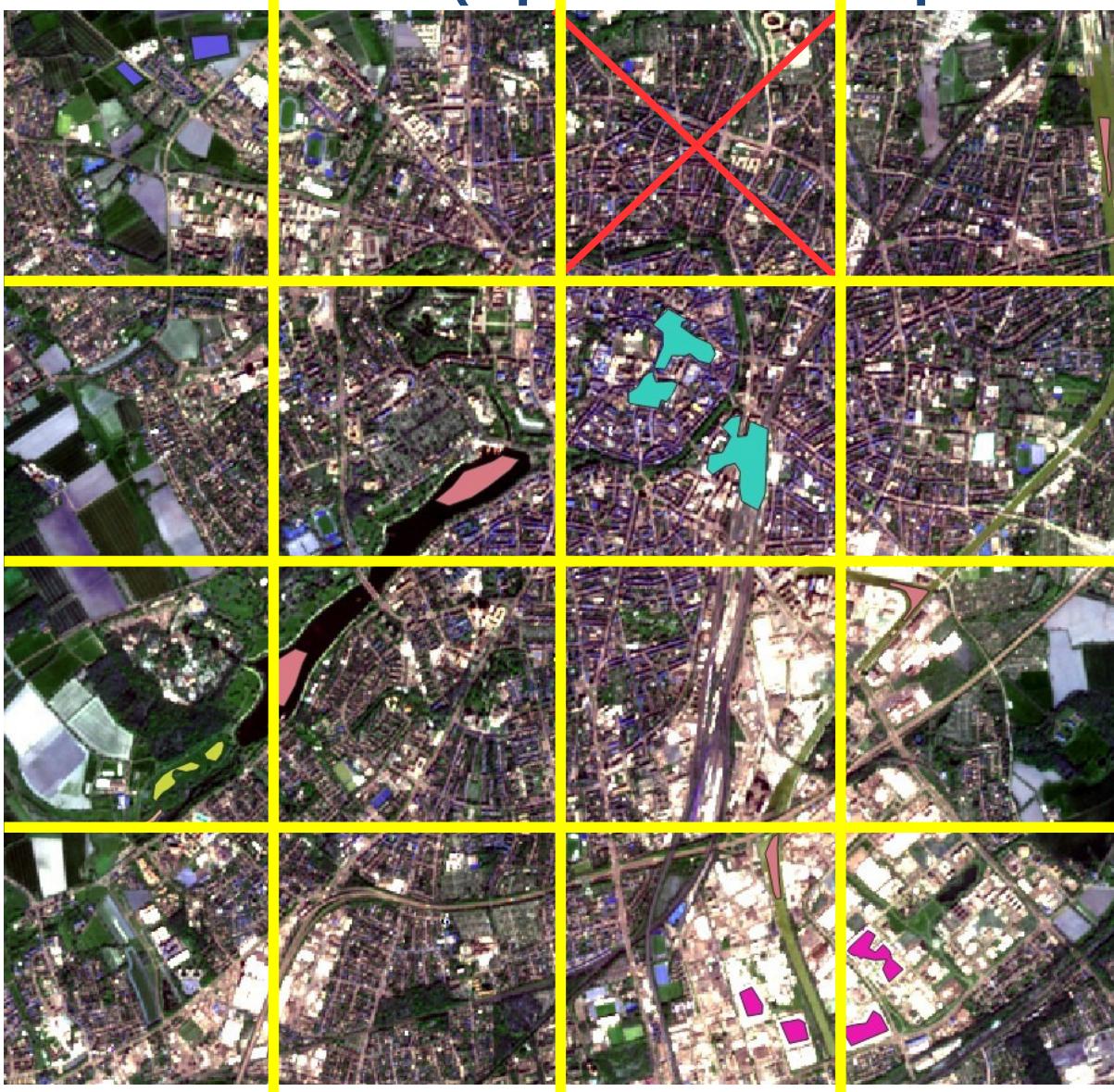
Step 1: Model training in R

Spatial cross-validation (Option: Leave spatial block out)



Step 1: Model training in R

Spatial cross-validation (Option: Leave spatial block out)



Step 1: Model training in R

Spatial cross-validation (Option: Leave group of polygons out)



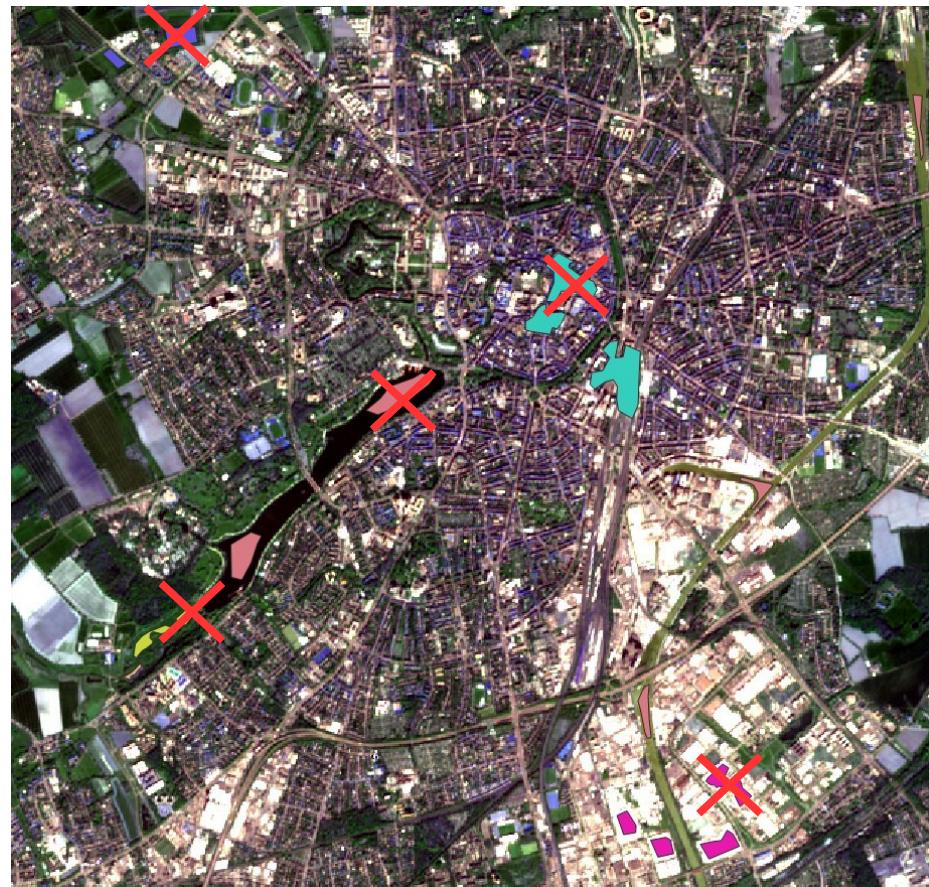
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Spatial cross-validation (Option: Leave group of polygons out)



Step 1: Model training in R

Spatial cross-validation (Option: Leave group of polygons out)



How to do it in R

```
library(CAST) "Caret Applications for Statio-temporal  
models"  
  
indices <- CreateSpacetimeFolds(trainDat,  
spacevar = "PolygonID",  
k=3,  
class="Label")  
  
ctrl <- trainControl(method="cv",  
index = indices$index)  
  
model <- train(predictors,  
response,  
method="rf",  
trControl=ctrl)
```

Step 1: Model training in R

Spatial cross-validation: Example of results

Variables	Validation	Accuracy	Kappa
all	random	>0.99	>0.99
all	spatial	0.68	0.61

- Random cross-validation performance tells how well we can reproduce training data
- Spatial cross-validation tells us how well we can make predictions
- The spatial performance is usually lower, but this no reason to use the random performance!!!

Step 1: Model training in R

Use spatial cross-validation for the entire modelling process

Spatial cross-validation should be used for the entire modelling process

- For variable selection
- Hyperparameter tuning
- Error assessment

Usually improves spatial performance!

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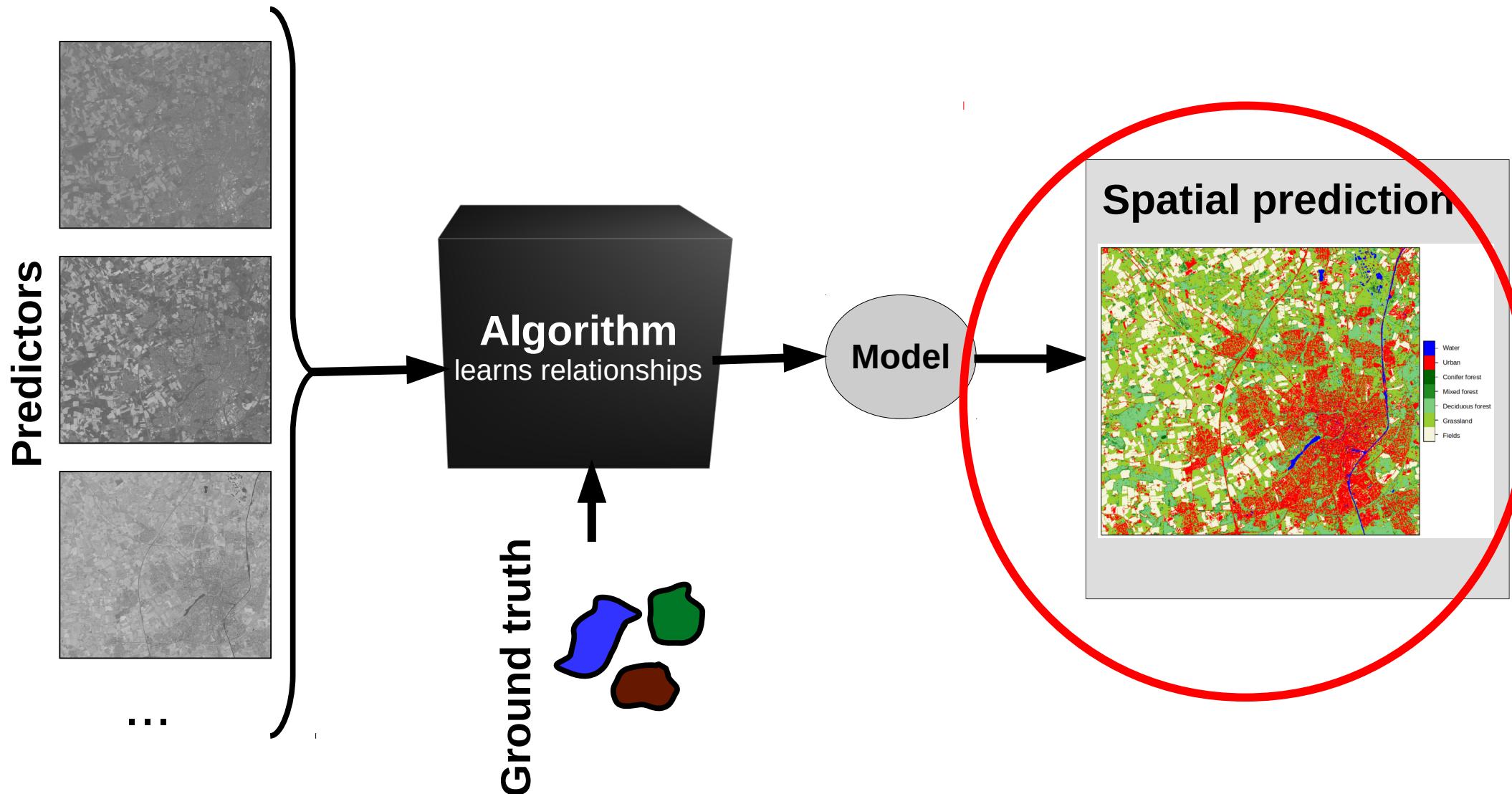
How to do it in R

```
model <- ffs(predictors,  
               response,  
               method="rf",  
               tuneLength=5,  
               trControl=ctrl)
```

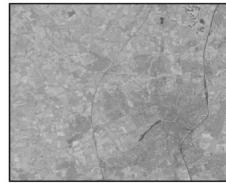
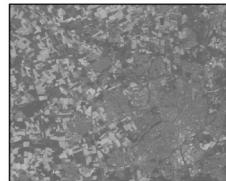
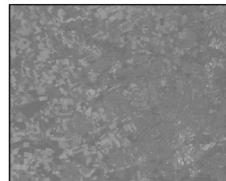
Important!!!
Use spatial folds here!!!



Step 2: Model prediction in R

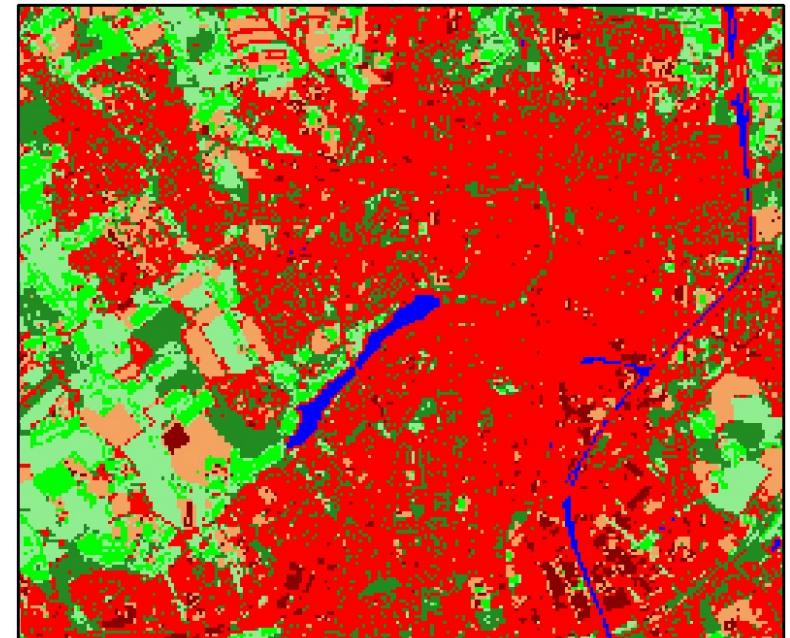


Step 2: Model prediction in R

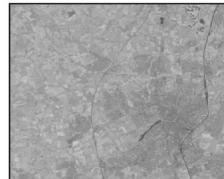
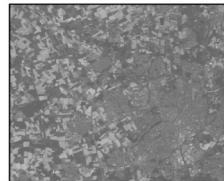
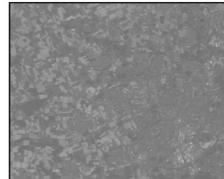


+ trained model =

...

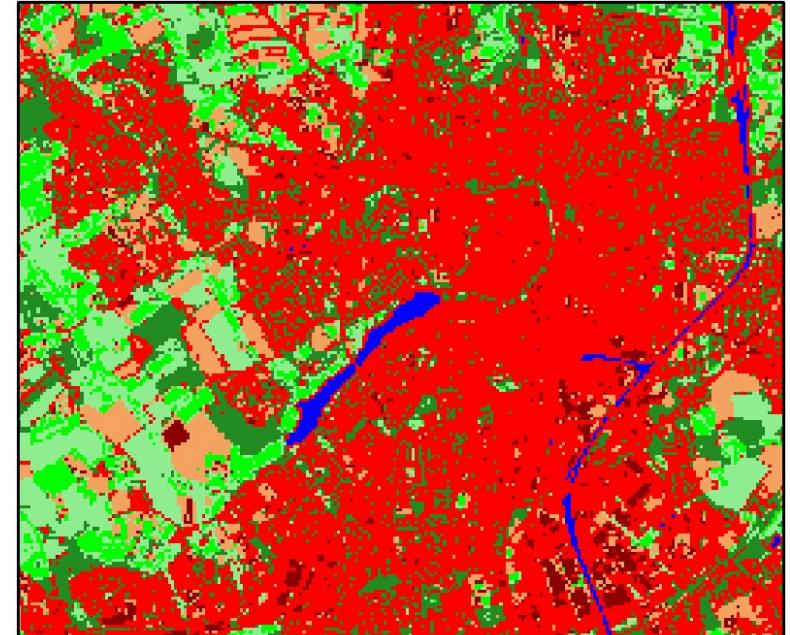


Step 2: Model prediction in R



+ trained model =

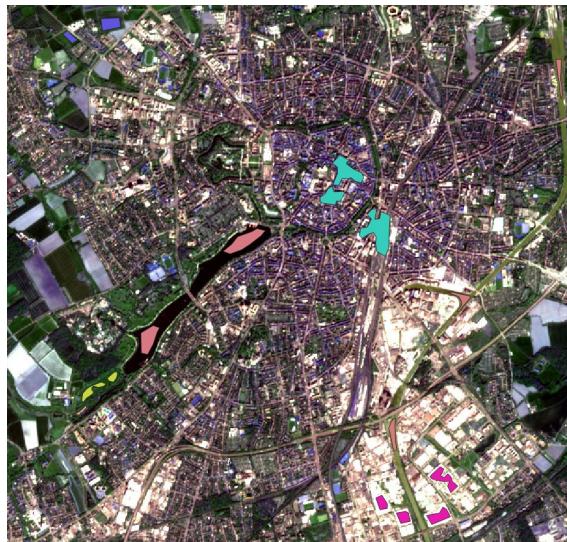
...



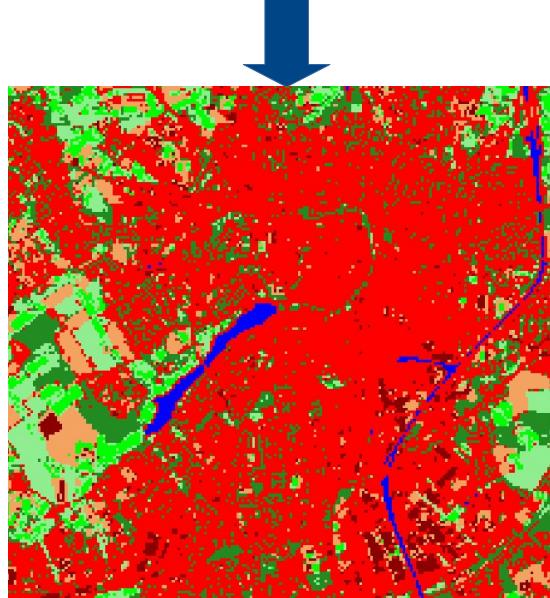
How to do it in R

```
library(raster)
pred_sp <- stack(predictors)
prediction <- predict(pred_sp,model)
```

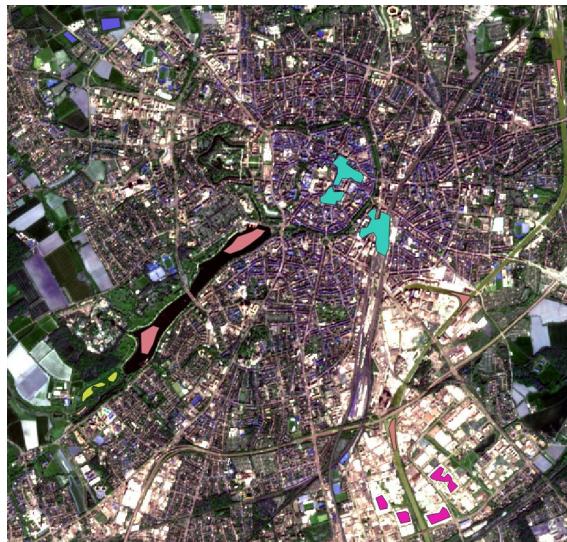
Step 3: Estimating the area of applicability



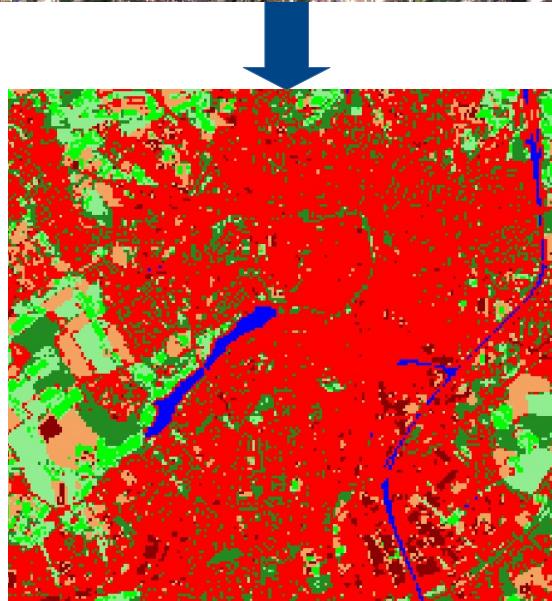
Can we really apply the model to the entire area?



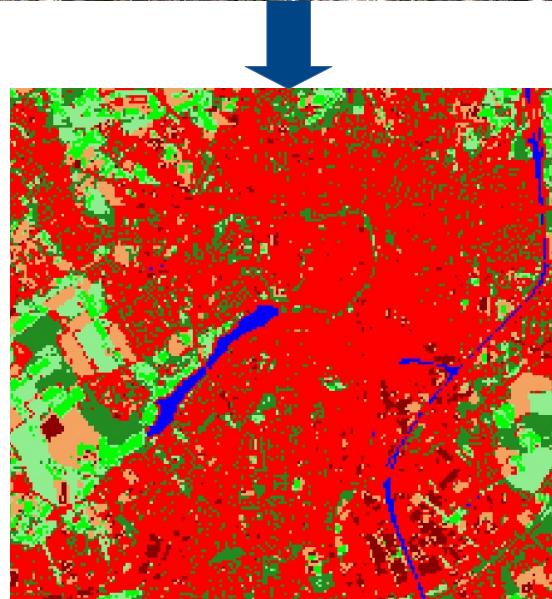
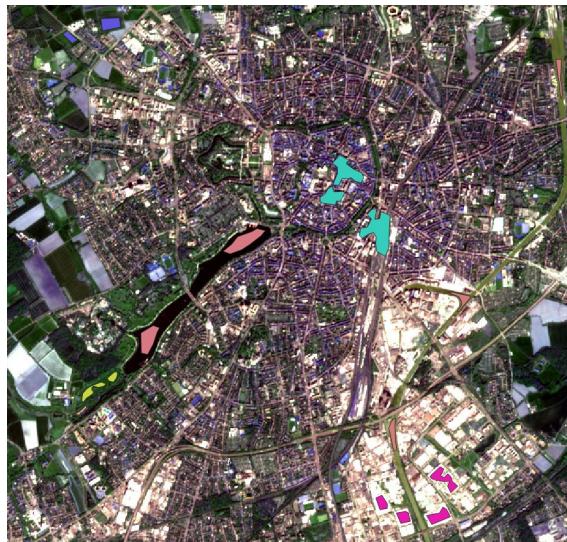
Step 3: Estimating the area of applicability



Can we really apply the model to the entire area?



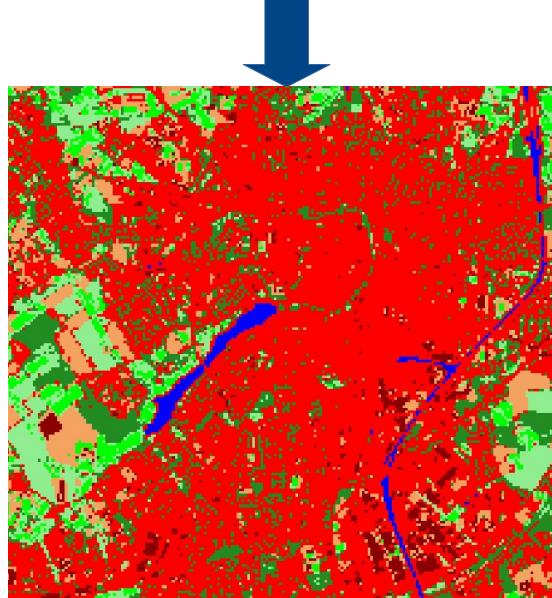
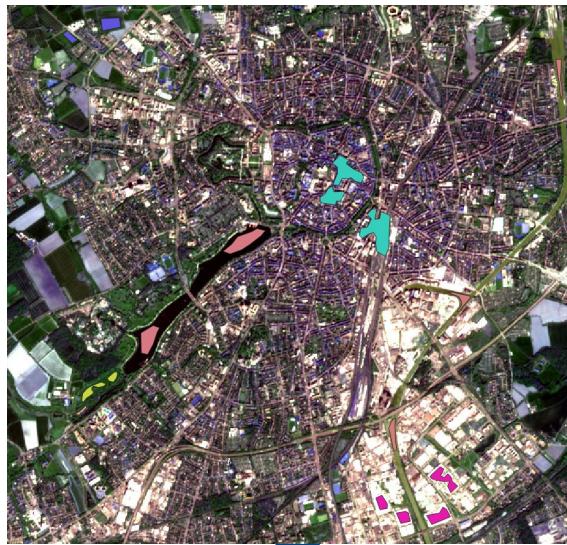
Step 3: Estimating the area of applicability



Can we really apply the model to the entire area?

- Transfer to new space required

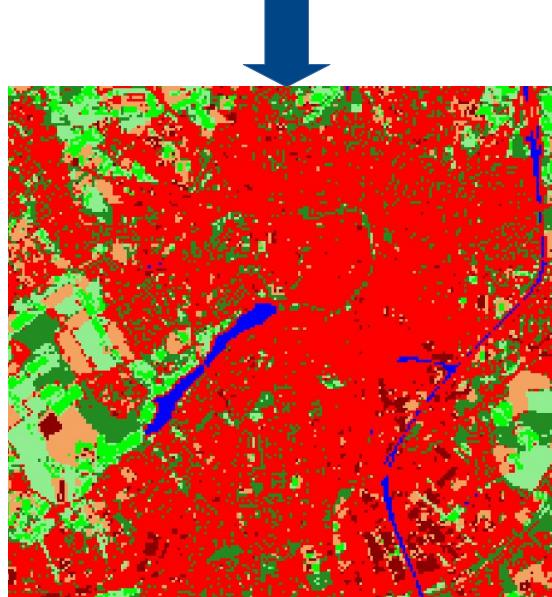
Step 3: Estimating the area of applicability



Can we really apply the model to the entire area?

- Transfer to new space required
- New space might differ in environmental properties

Step 3: Estimating the area of applicability

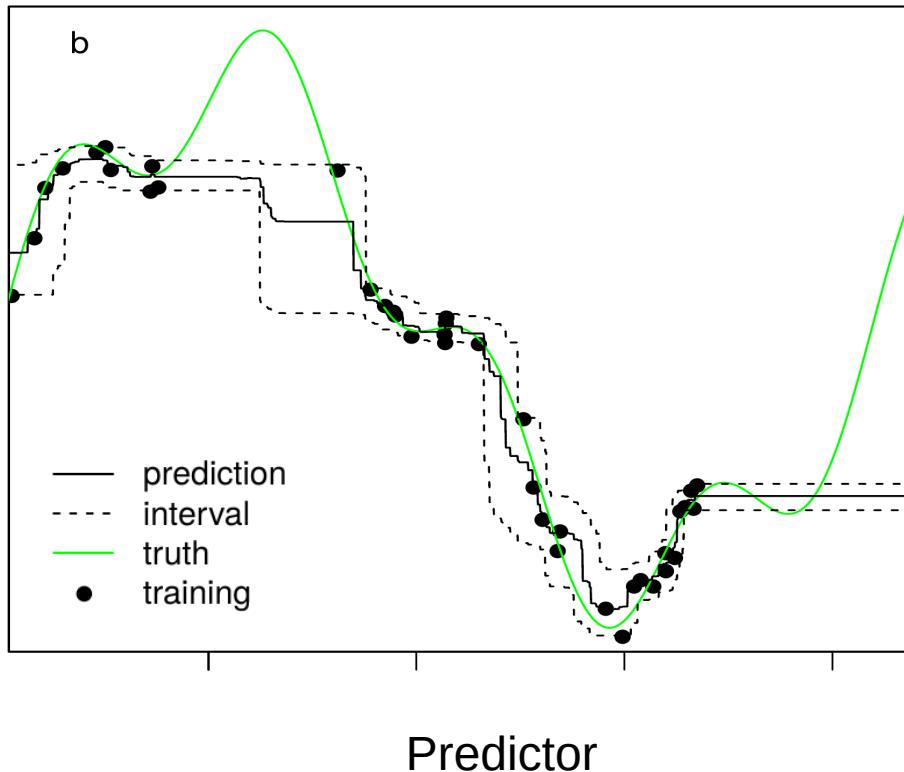


Can we really apply the model to the entire area?

- Transfer to new space required
- New space might differ in environmental properties
- But what if the algorithm has never seen such properties?

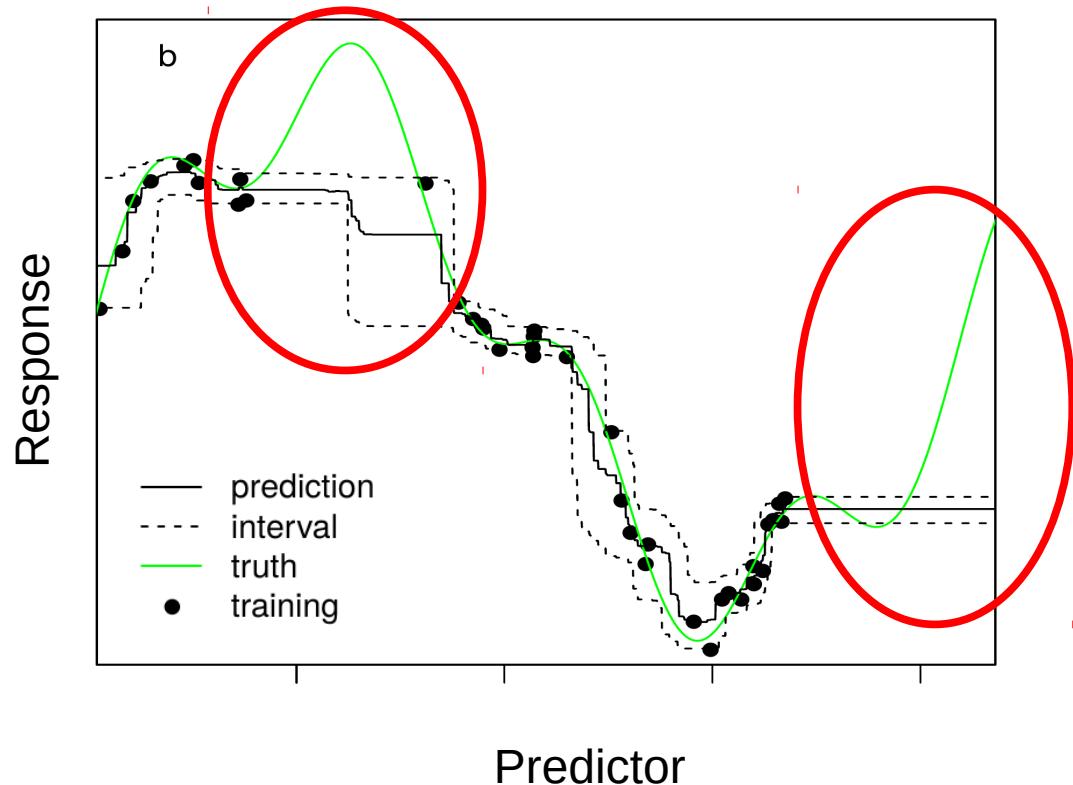
Step 3: Estimating the area of applicability

Response



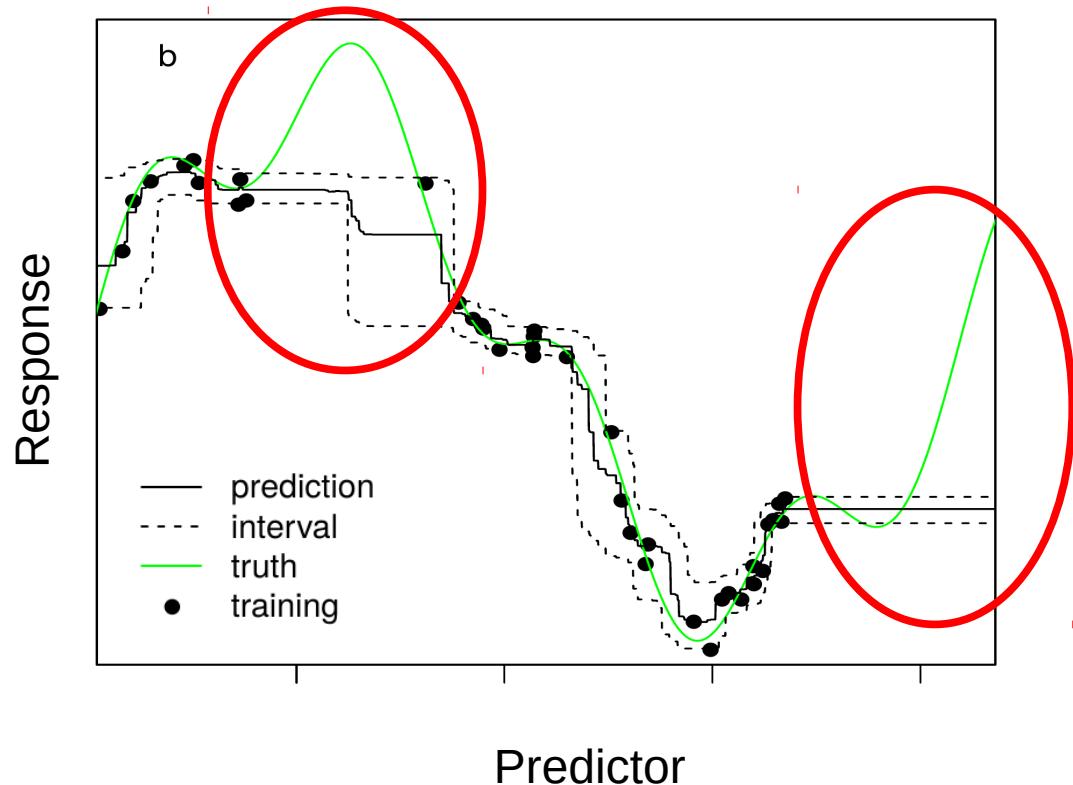
- Machine learning can fit very complex relationships.

Step 3: Estimating the area of applicability



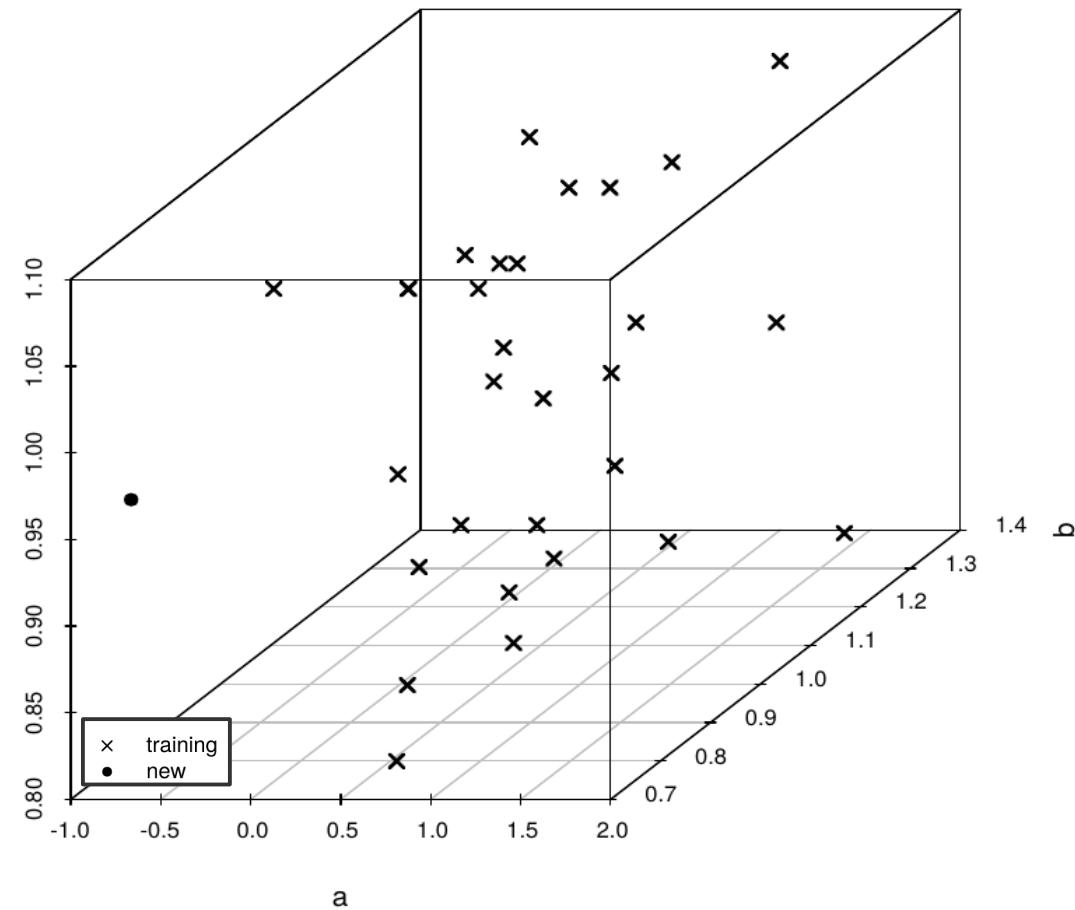
- Machine learning can fit very complex relationships.
- But gaps in predictor space are problematic (the model has no knowledge about these areas!)

Step 3: Estimating the area of applicability



- Machine learning can fit very complex relationships.
- But gaps in predictor space are problematic (the model has no knowledge about these areas!)
- A measure for “unknown space” is needed to estimate the area of applicability of a model!

Step 3: Estimating the area of applicability

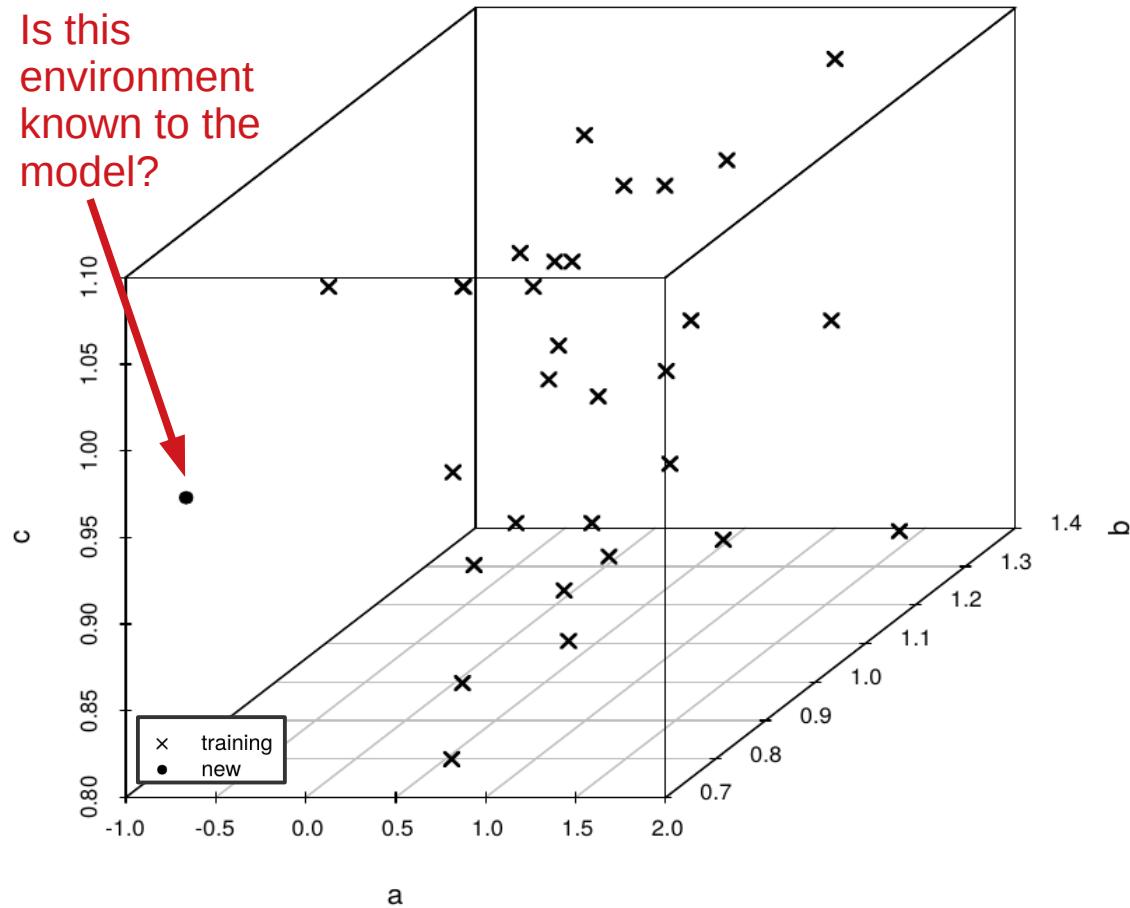


Meyer&Pebesma (under review)

- Unknown space: Environmental conditions that are very different from the training locations

Step 3: Estimating the area of applicability

Is this environment known to the model?

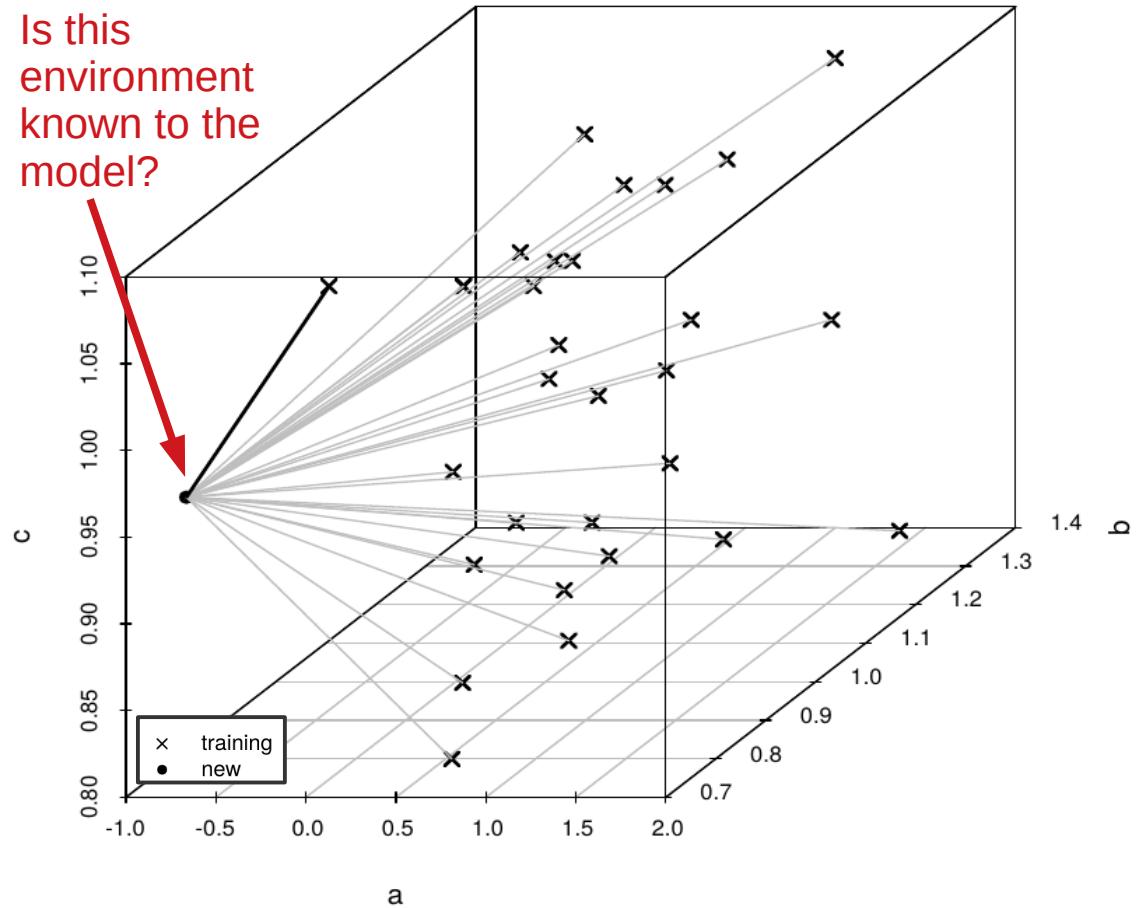


Meyer&Pebesma (under review)

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Step 3: Estimating the area of applicability

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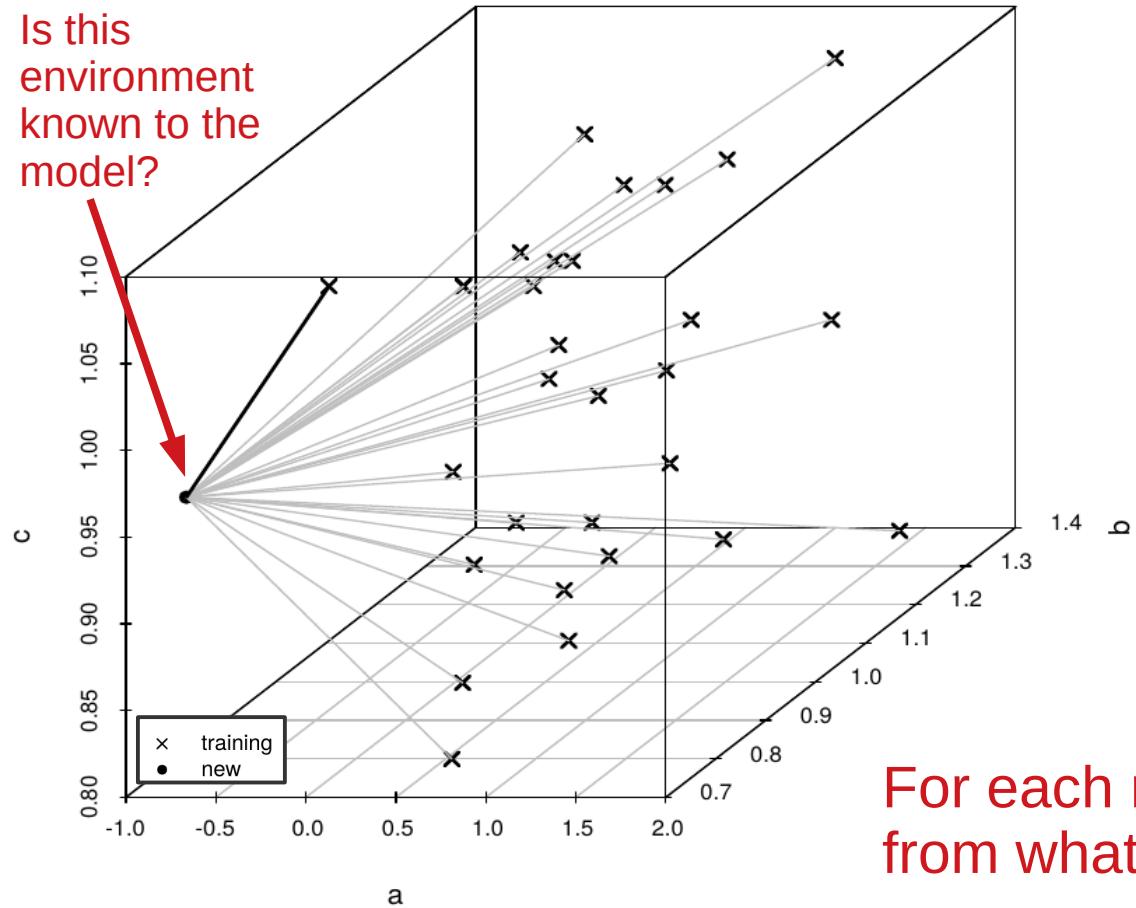


Meyer&Pebesma (under review)

- Unknown space: Environmental conditions that are very different from the training locations
- Suggestion: Distance in (weighted) predictor space as measure for unknown space (Dissimilarity Index)

Step 3: Estimating the area of applicability

Is this environment known to the model?



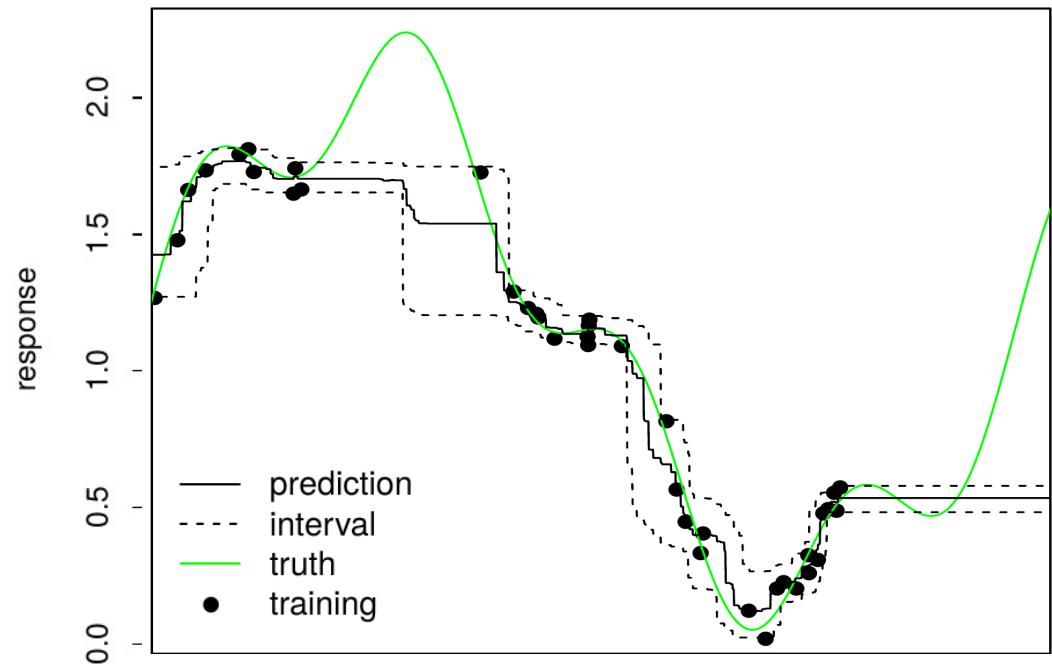
Meyer&Pebesma (under review)

- Unknown space: Environmental conditions that are very different from the training locations
- Suggestion: Distance in (weighted) predictor space as measure for unknown space (Dissimilarity Index)

For each new location/pixel: how distant is it from what the algorithms has seen?

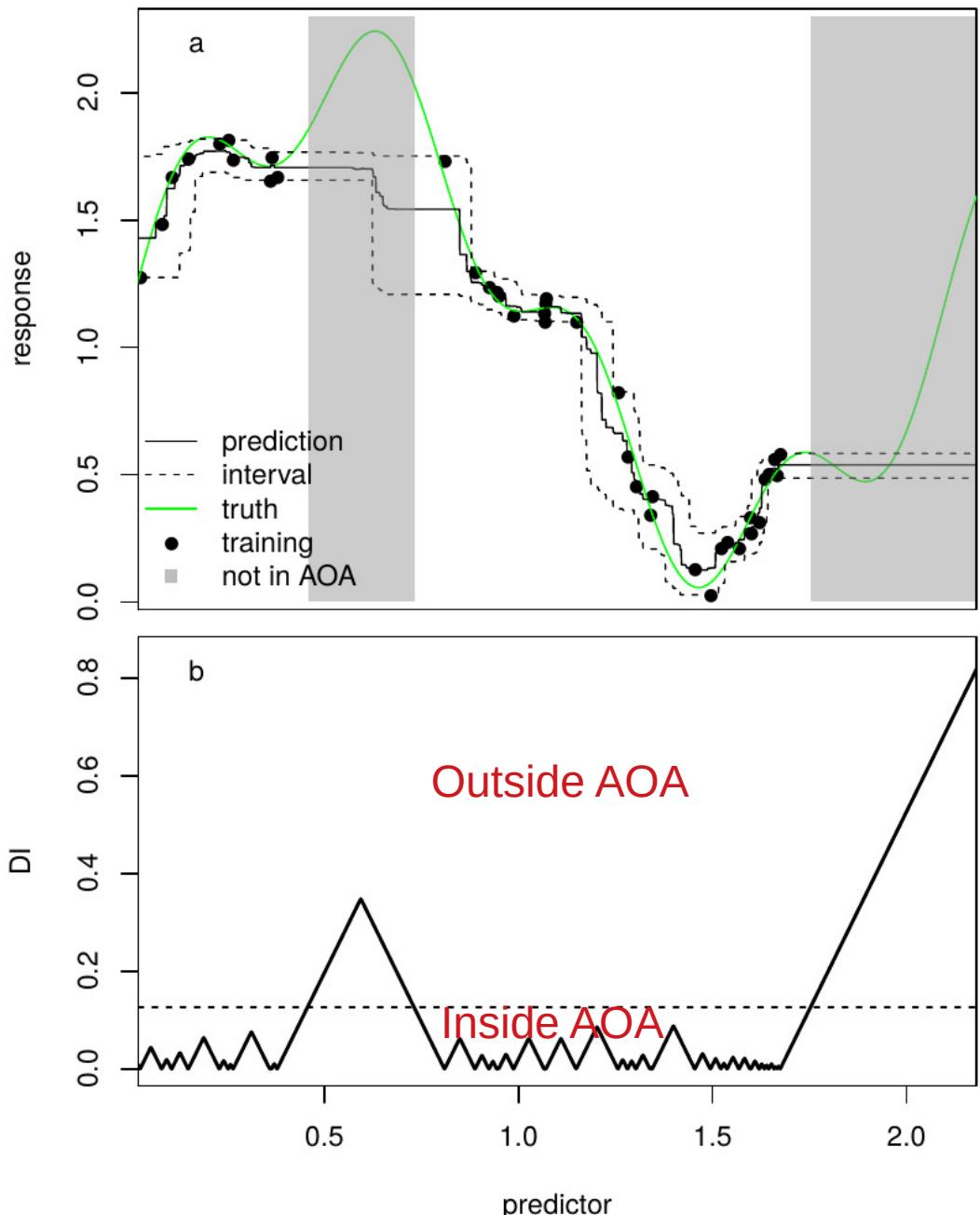
Step 3: Estimating the area of applicability

- Definition: The area for which, on average, the cross-validation error of the model applies

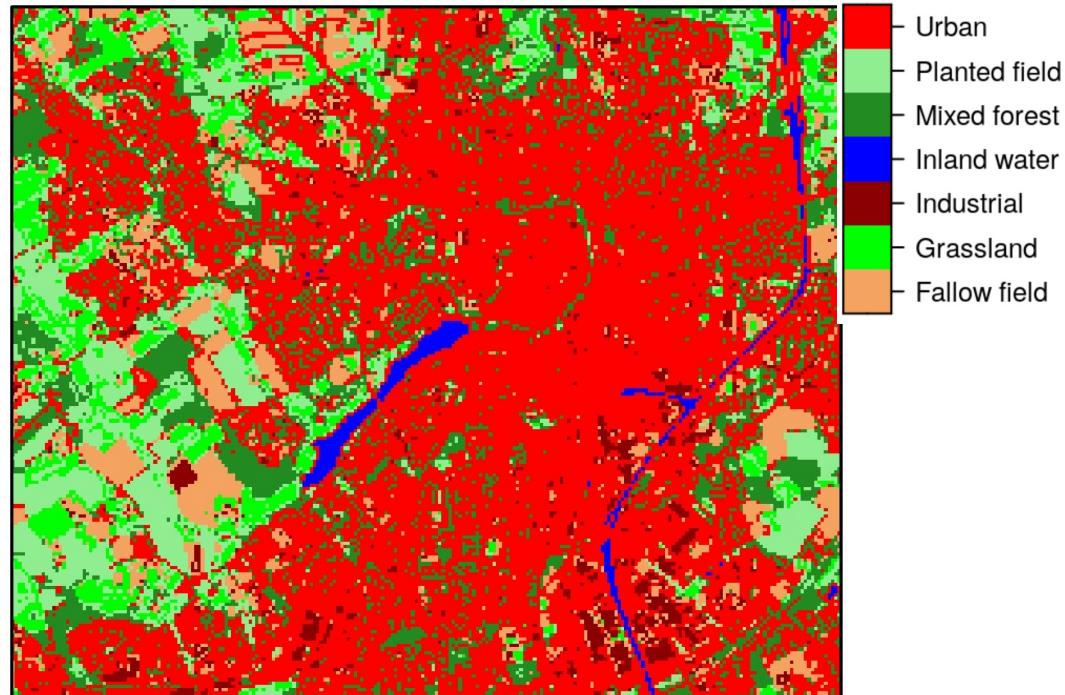


Step 3: Estimating the area of applicability

- Definition: The area for which, on average, the cross-validation error of the model applies
- Estimated using a threshold on the DI
- Threshold = DI of cross-validated training data (95% quantile)
- $DI < \text{threshold} = \text{inside AOA}$
 $DI > \text{threshold} = \text{outside AOA}$



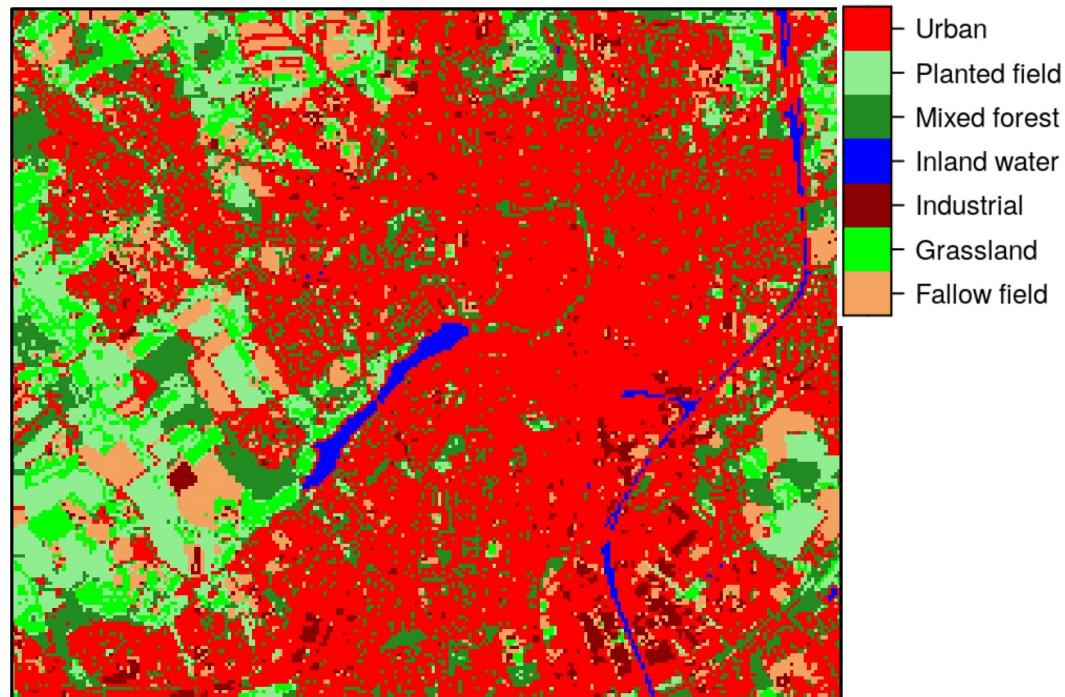
Step 3: Estimating the area of applicability



Technically we can make predictions for the entire area. But they only make sense if the predictor properties are known to the model

→ Estimate the area of applicability of the model

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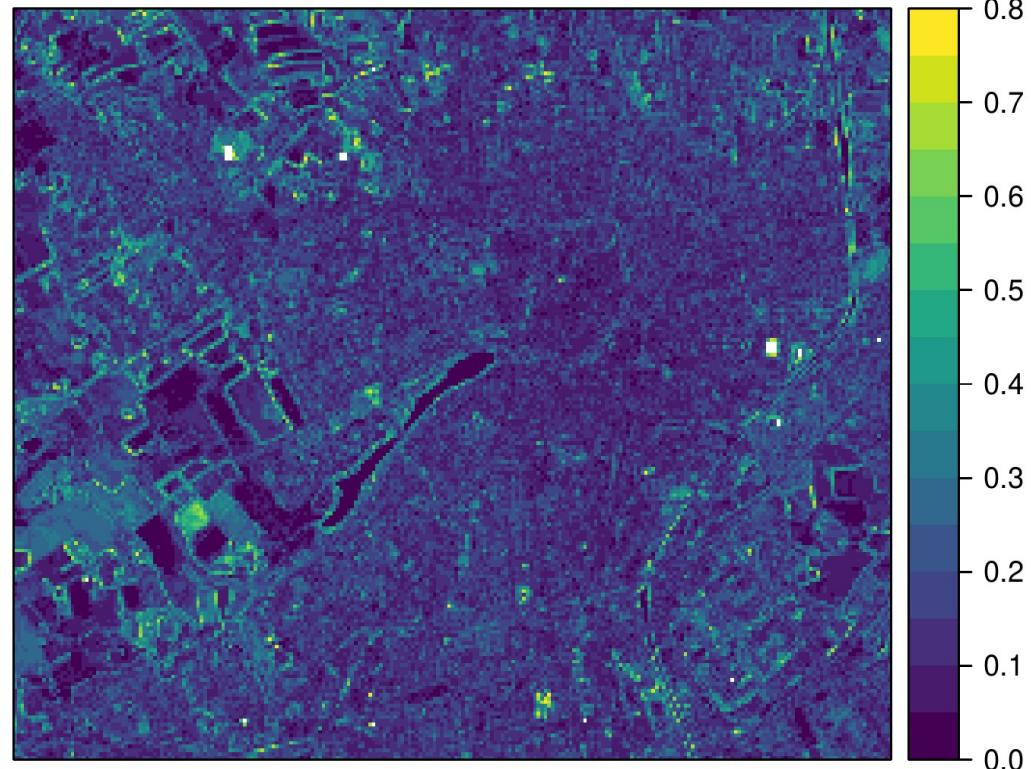
How to do it in R

```
AOA <- aoa(pred_sp,model)
```

Step 3: Estimating the area of applicability

Interpretation of the AOA

Dissimilarity Index

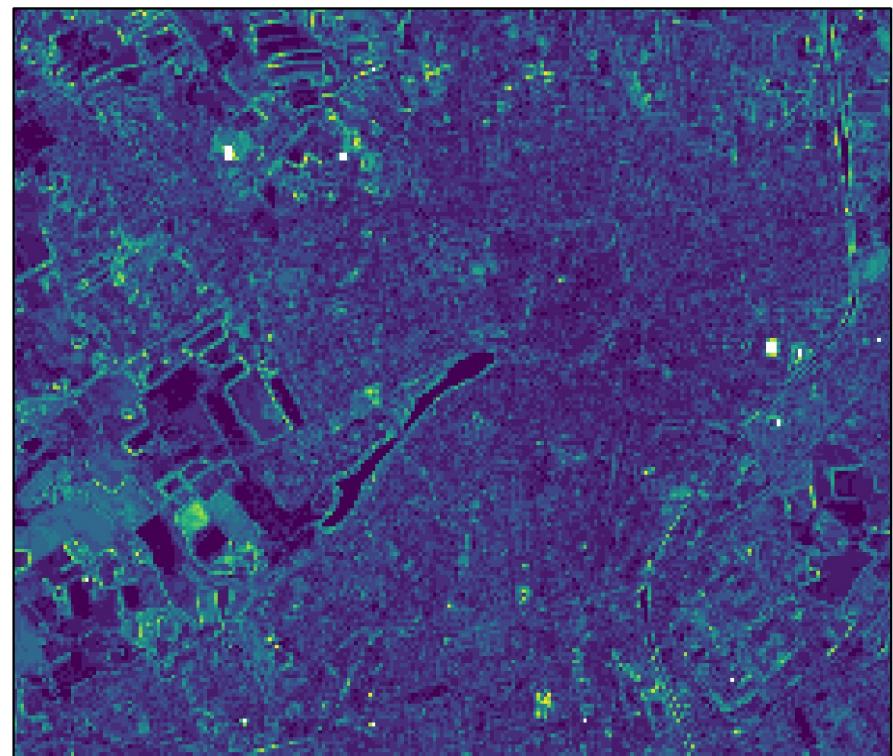


Can take values 0 to ∞

Step 3: Estimating the area of applicability

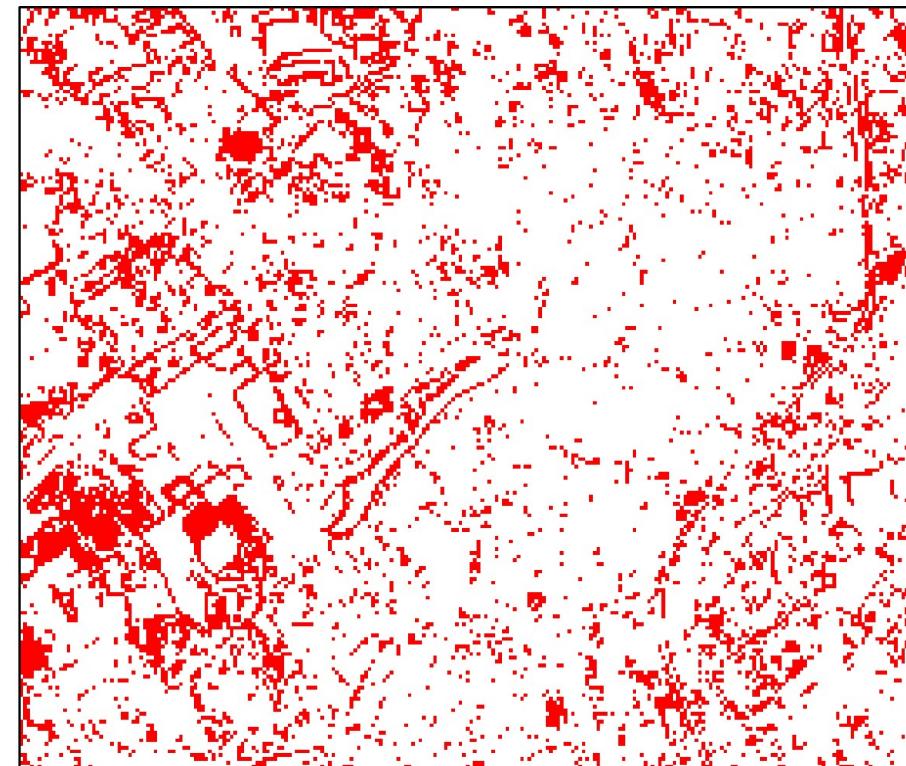
Interpretation of the AOA

Dissimilarity Index



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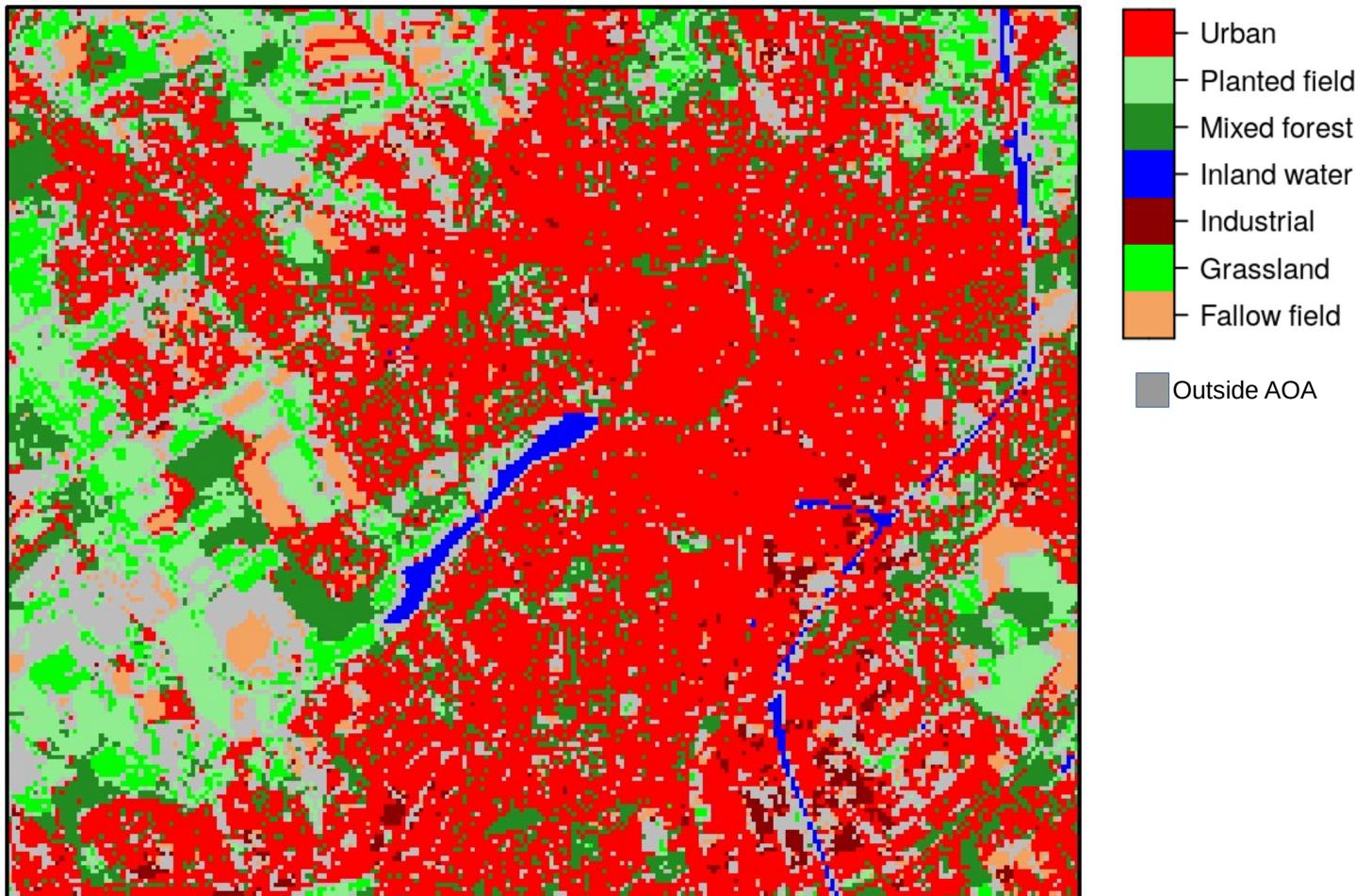
Area of Applicability



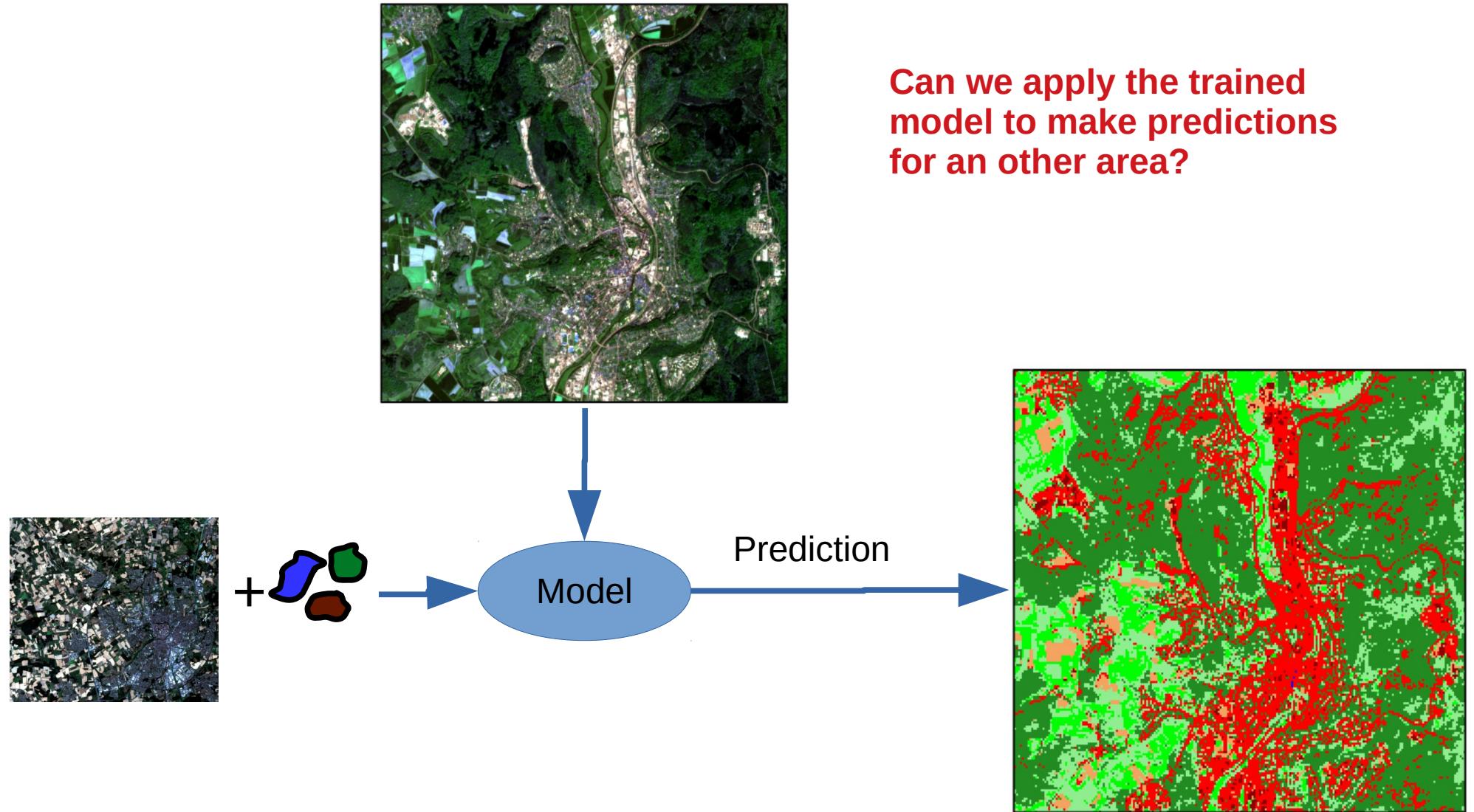
Can take values 0 = not in AOA
and 1= inside AOA

Step 3: Estimating the area of applicability

Interpretation of the AOA



Step 4 (optional): Model transfer



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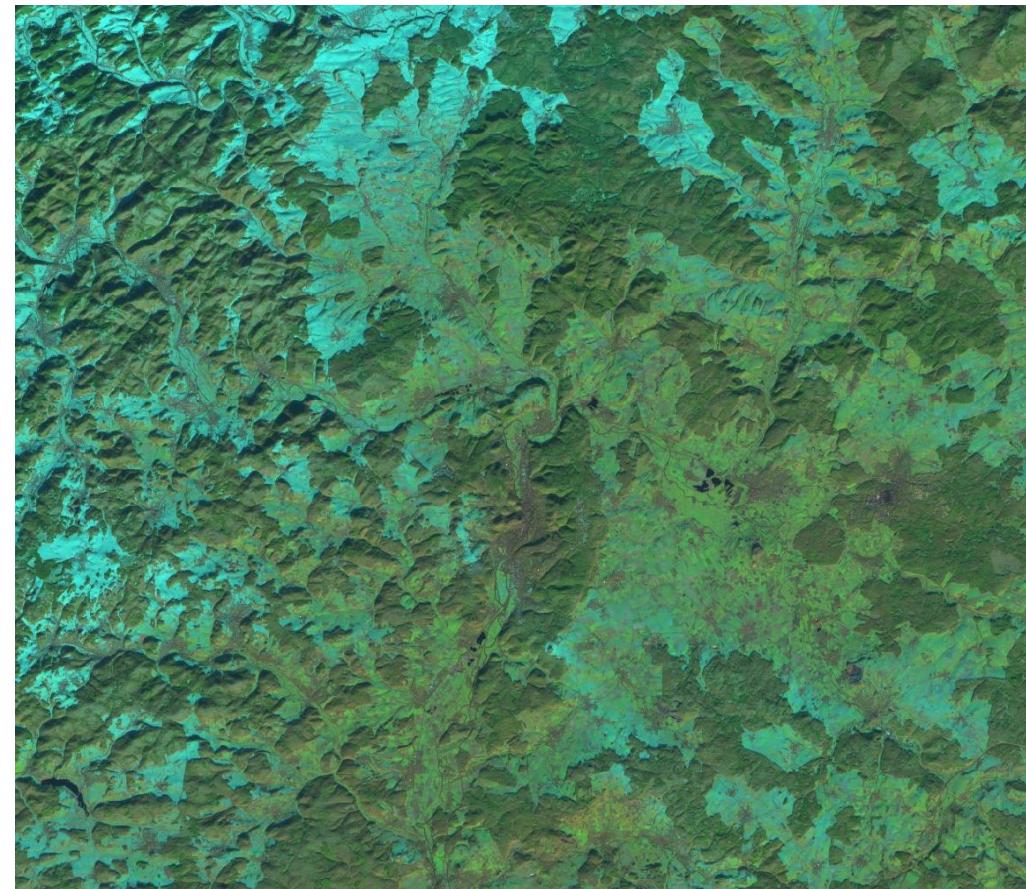
When can a model be transferred?

Model can only make reliable predictions if the environment (defined by predictors) is known!

Marburg in summer



Marburg in winter



Step 4 (optional): Model transfer

When can a model be transferred?



Sentinel-2 from
07.05.2020 and
09.05.2020

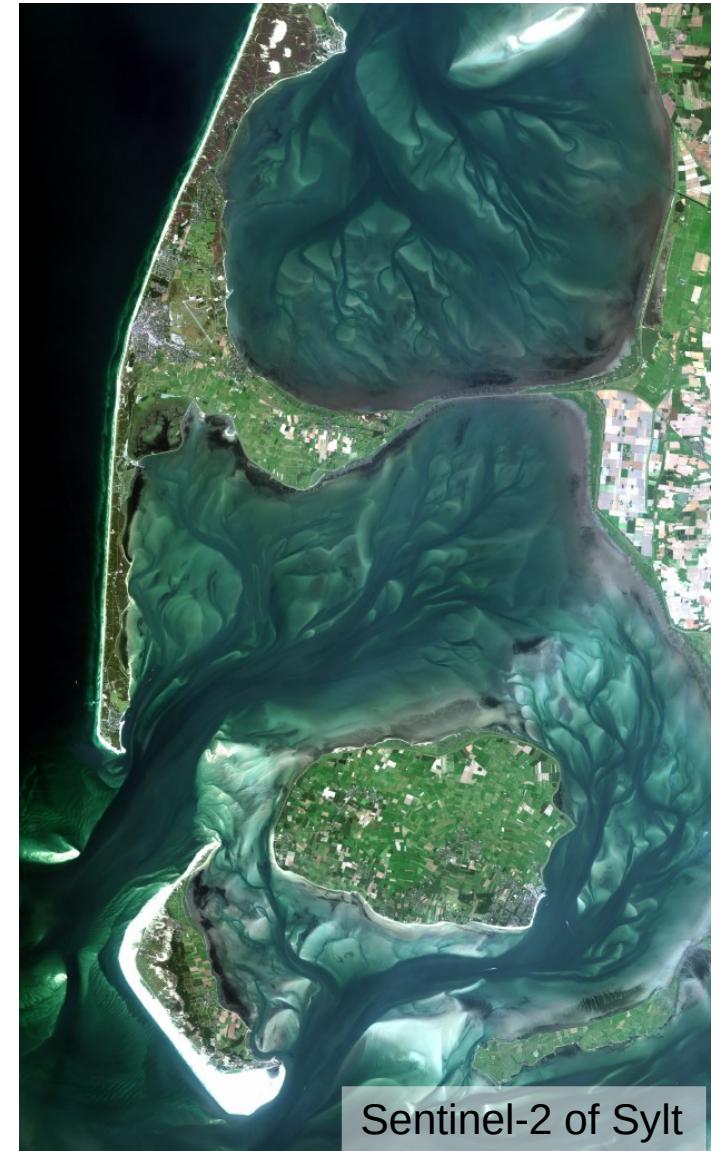


- Land cover classes might “look” different under different atmospheric conditions
- Intended model transfer would either require atmospheric corrections...
 - ...or assumption that we learn from data taken under variable conditions
 - Similar problem: images taken by different sensors

Step 4 (optional): Model transfer

When can a model be transferred?

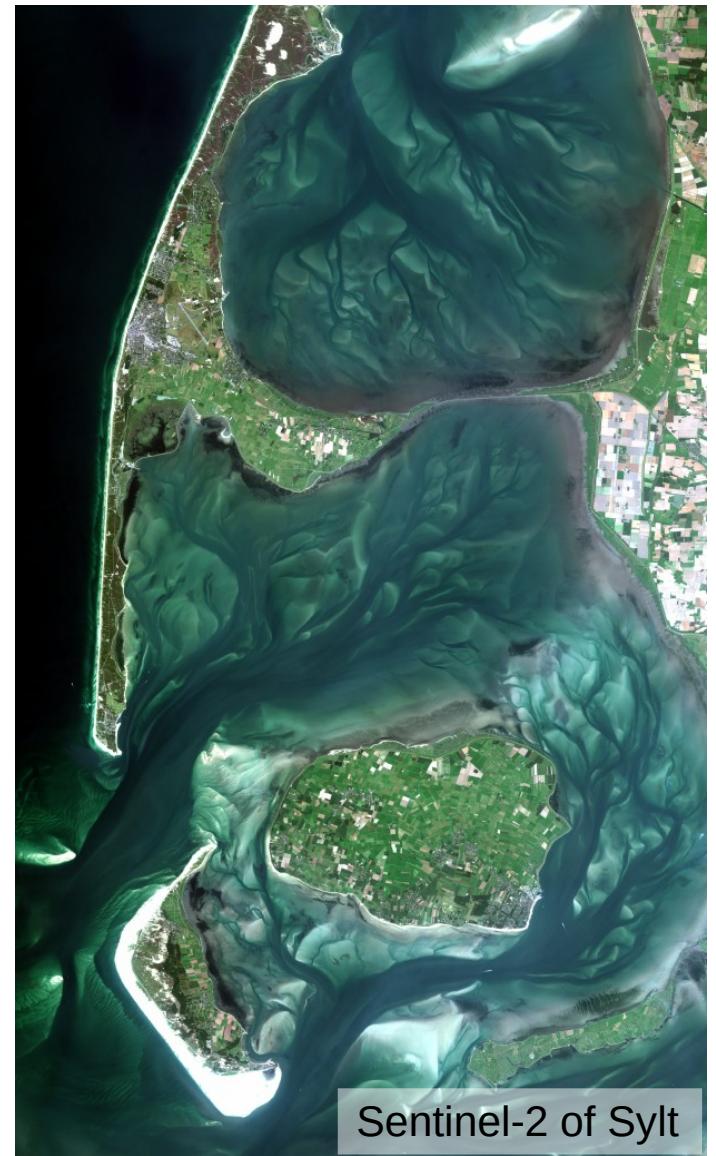
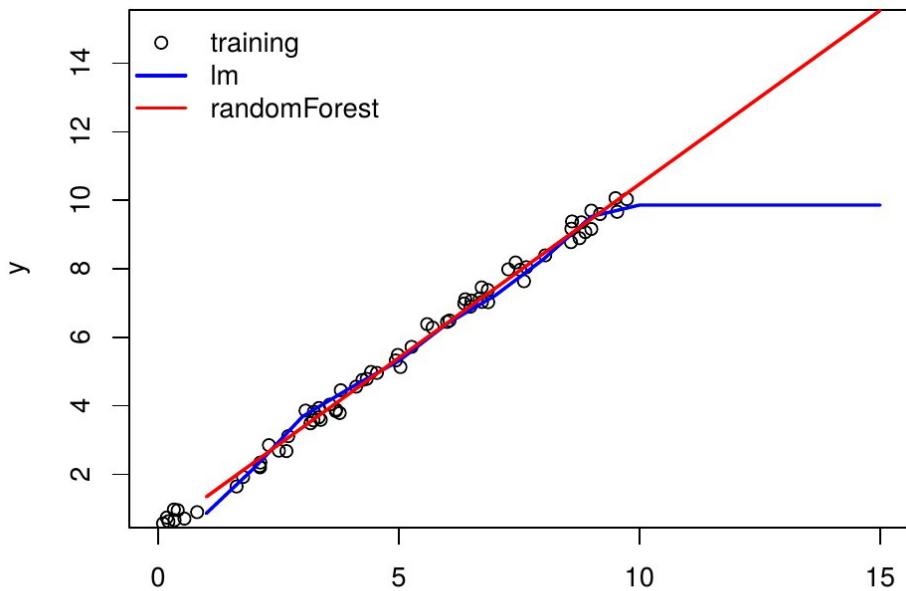
- ML cannot predict something new
- Land cover classes in new area must be part of the training data



Step 4 (optional): Model transfer

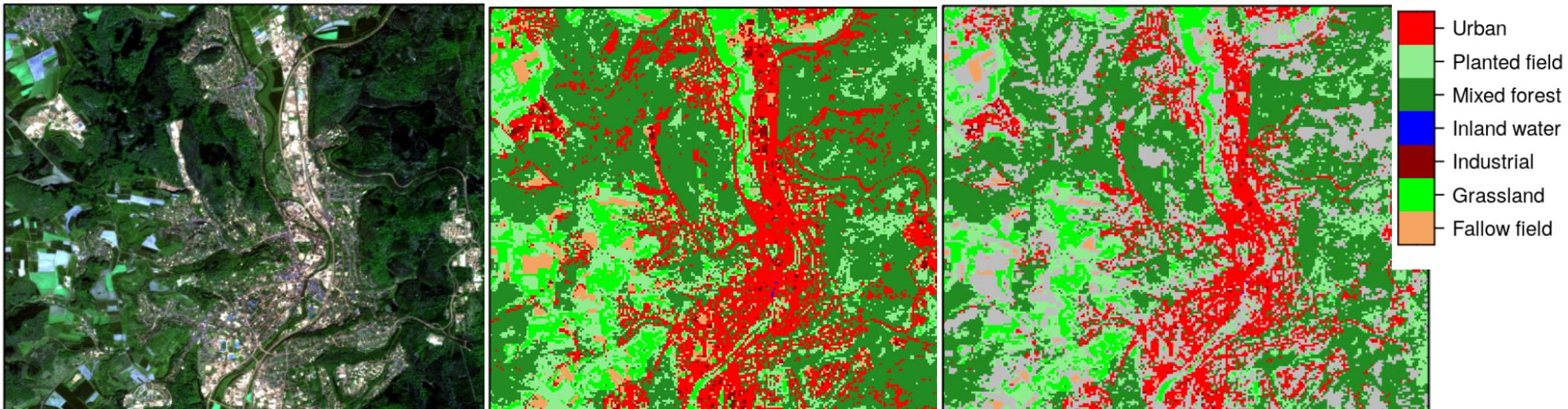
When can a model be transferred?

- ML cannot predict something new
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- (Regression models: Possible range of response in new area must be observed in training)



Step 4 (optional): Model transfer

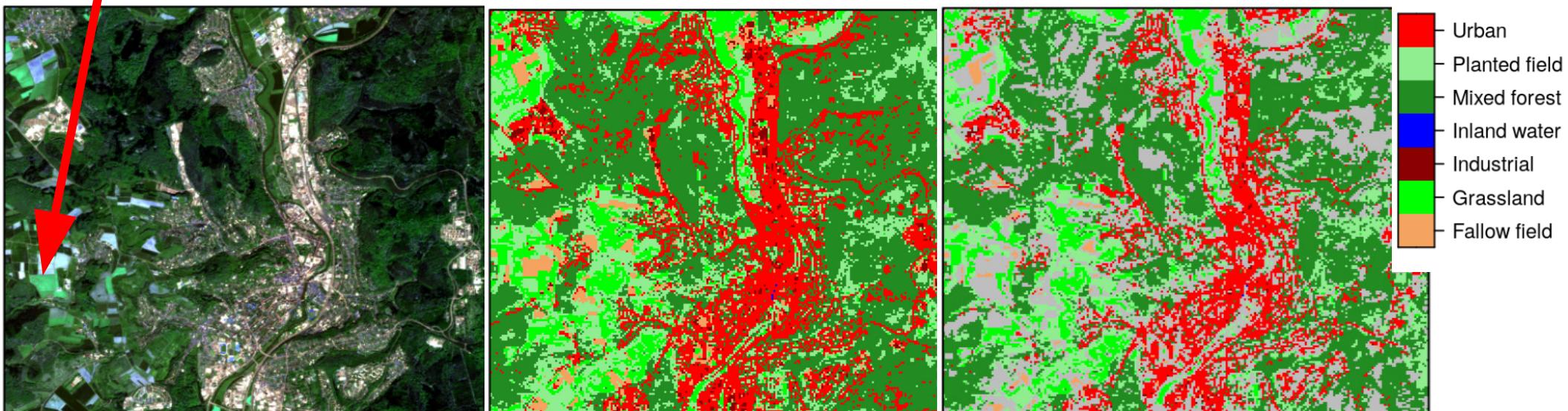
Estimate transferability by looking at the area of applicability



Step 4 (optional): Model transfer

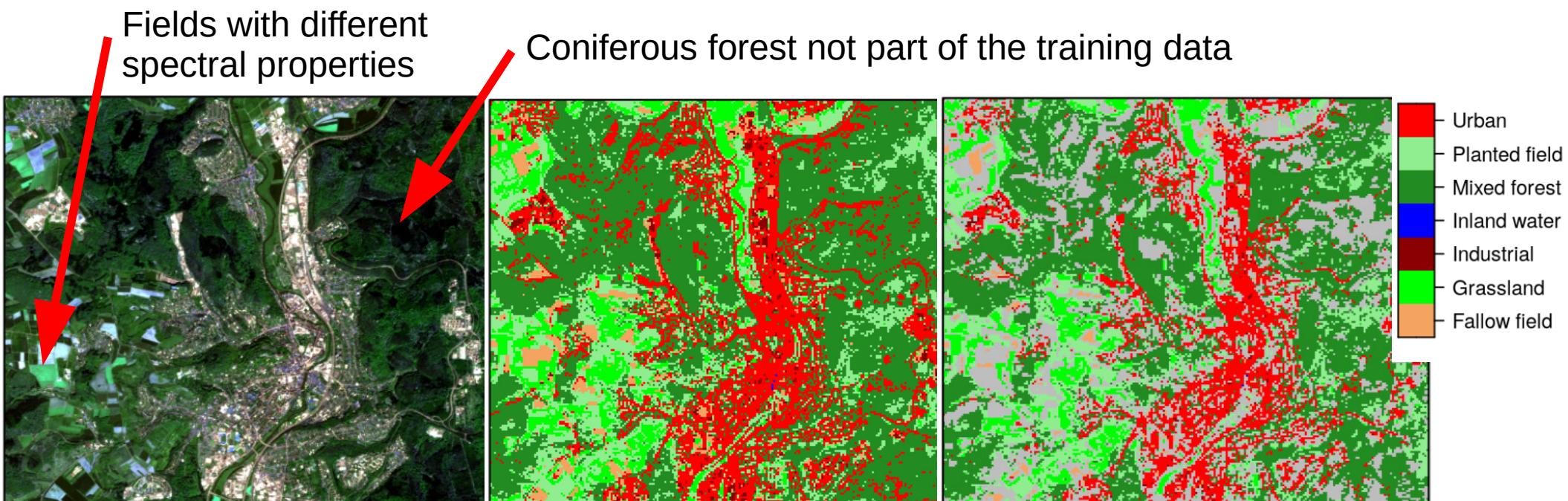
Estimate transferability by looking at the area of applicability

Fields with different spectral properties



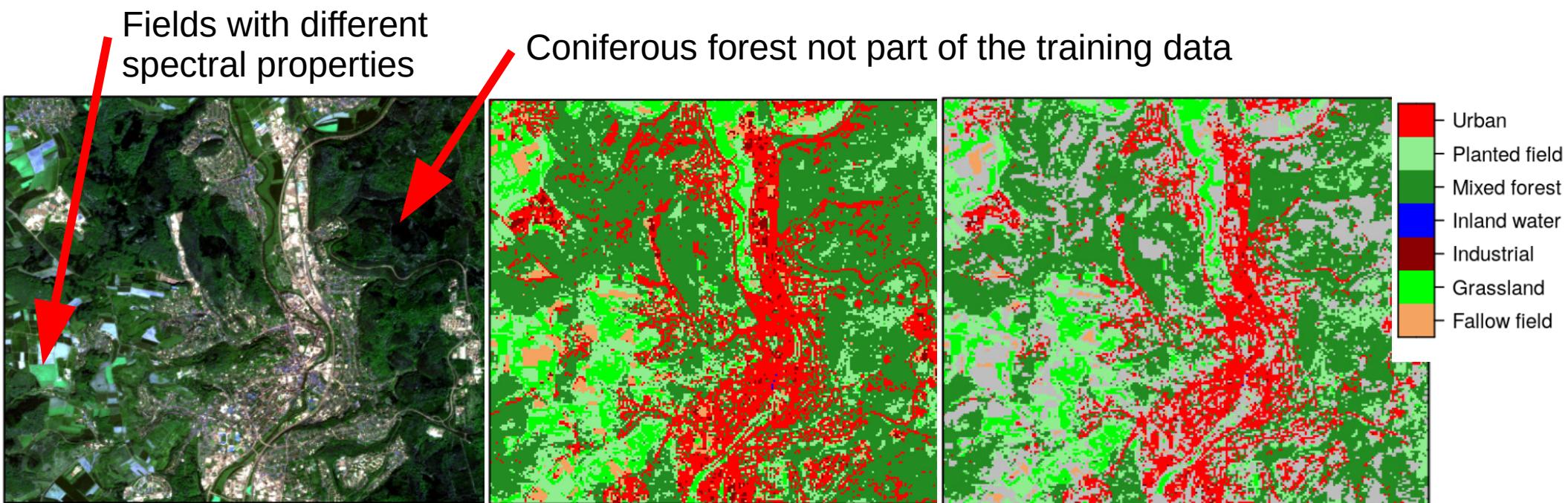
Step 4 (optional): Model transfer

Estimate transferability by looking at the area of applicability



Step 4 (optional): Model transfer

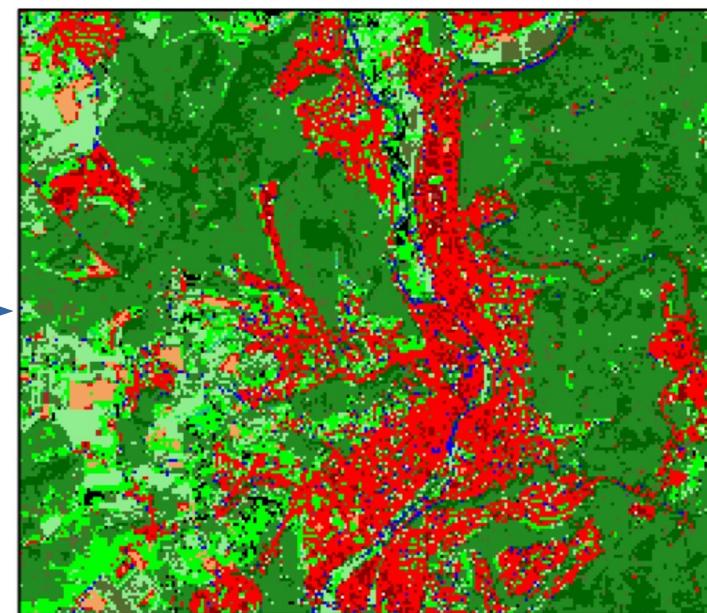
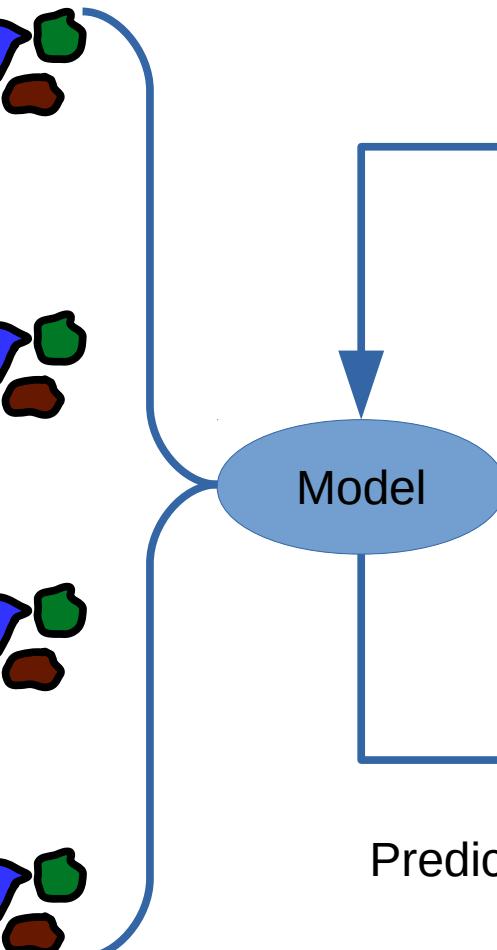
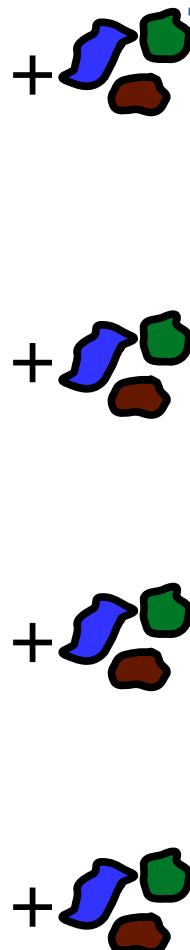
Estimate transferability by looking at the area of applicability



Large parts outside AOA.
How could we increase the AOA?

Step 4 (optional): Model transfer

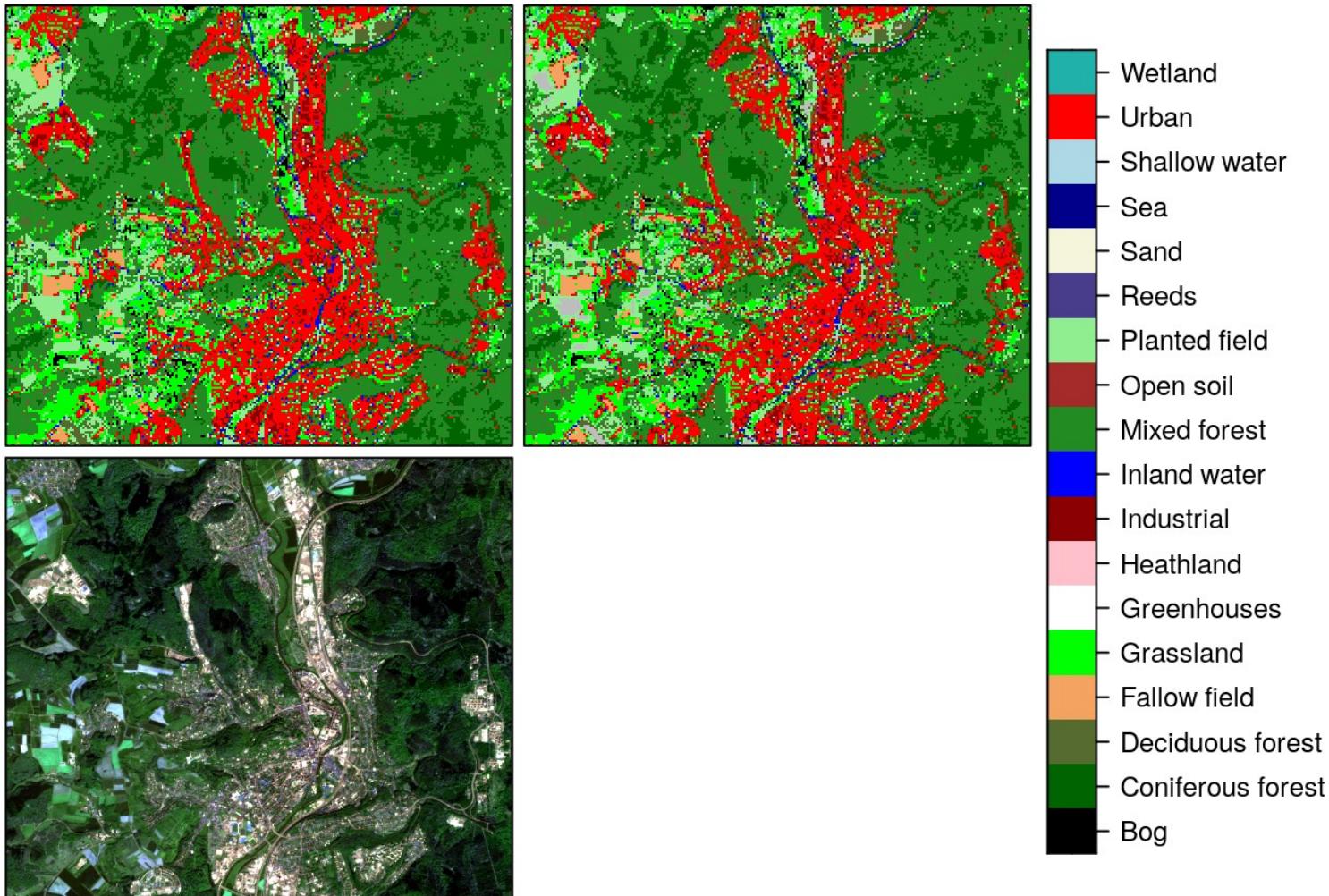
Multi-source model



Step 4 (optional): Model transfer

Multi-source model

Prediction (left), prediction only for the AOA (right) and RGB composite (bottom)



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- Hands-on: www.github.com/HannaMeyer/OpenGeoHub_2020