

StatEO

5-7 May 2026 | ESA-ESRIN | Frascati (Rome), Italy

SYNERGIES BETWEEN AUTOMATED EO IMAGE ANALYSIS AND “IN SITU” OBSERVATIONS



1. Introduction

2. Key requirements to be EO-compatible

1. Typology

2. Sampling design

3. Response design

1. Introduction

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1. Typology

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In situ data

- Thematically richer
- More accurate
- More reproducible in time

Remote sensing

- Wall to wall spatial coverage
- More frequent updates
- Objective context information
- More consistent in space (always the same errors)

Why do we need in situ data for area statistics?

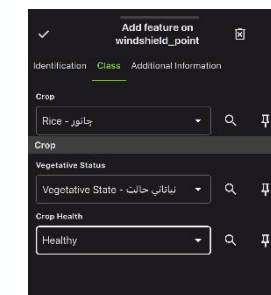
1. For calibration to train (AI) models for EO processing

In situ data need to cover the diversity of situations existing in the study site in order to represent the range of possible signatures for the different elements of interest and ensure the algorithm's performance

2. For validation to assess the quality of EO-derived products

Statistically-sound sampling to estimate the products accuracy (with a confidence interval) in a way that is objective and independent

3. For production of unbiased area estimation at different aggregation levels



Current state of the art



<https://lpvs.gsfc.nasa.gov/documents.html>

Guidelines on the 3 validation components

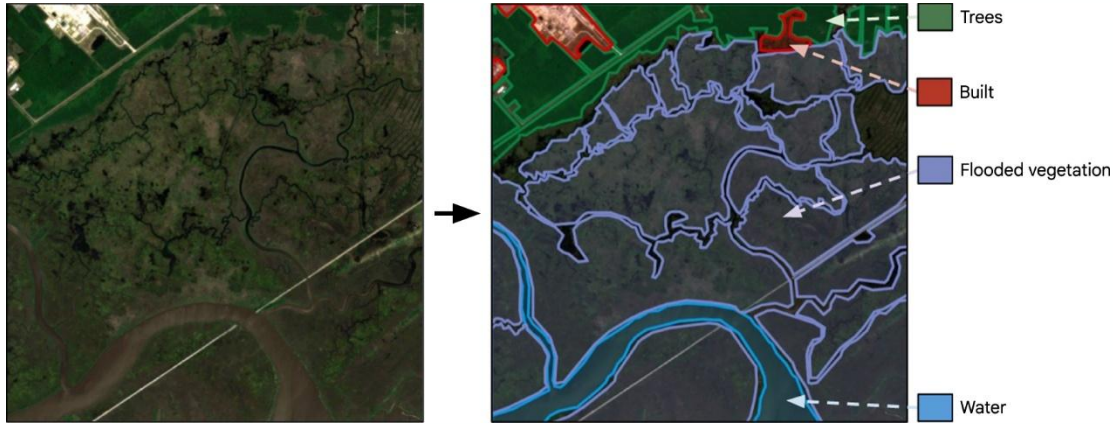
- Sampling design
- Response design
- Accuracy metrics

E. A. Tyukavina, S. V. Stehman, G. Foody, S. Bontemps, A. Komarova, N. Tsendbazar and J. Nickeson (Eds.), *Good Practices for Satellite Derived Land Product Validation*, (p. 188): Land Product Validation Subgroup (WGCV/CEOS), doi:10.5067/doc/ceoswgcv/lpv/lc.001

Comparison of global products validation strategies to determine optimal sampling/response design in relation to community practices

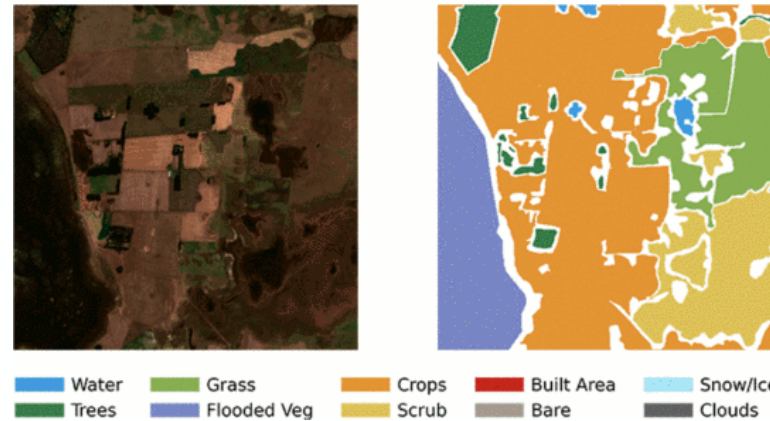
Dynamic World

Brown et al. (2022). Dynamic World, Near real-time global 10 m land use land cover mapping. *Scientific Data*, 9(1), 251.



ESRI LULC (Karra et al., 2021)

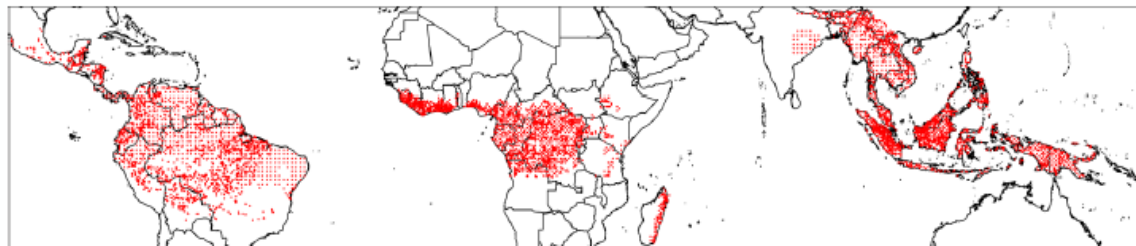
Karra et al. (2021, July). Global land use/land cover with Sentinel 2 and deep learning. In *2021 IEEE international geoscience and remote sensing symposium IGARSS* (pp. 4704-4707). IEEE.



Tropical Moist Forests (TMF)

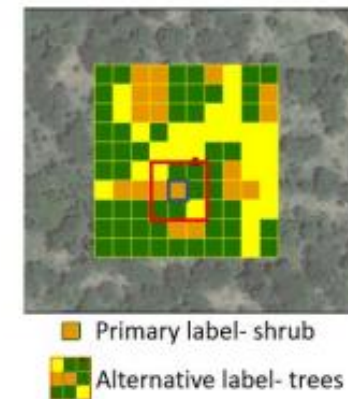
Vancutsem et al. (2021). Long-term (1990–2019) monitoring of forest cover changes in the humid tropics. *Science advances*, 7(10), eabe1603.

Fig. S8 Sampling plots (5250) used for the validation and accuracy assessment.

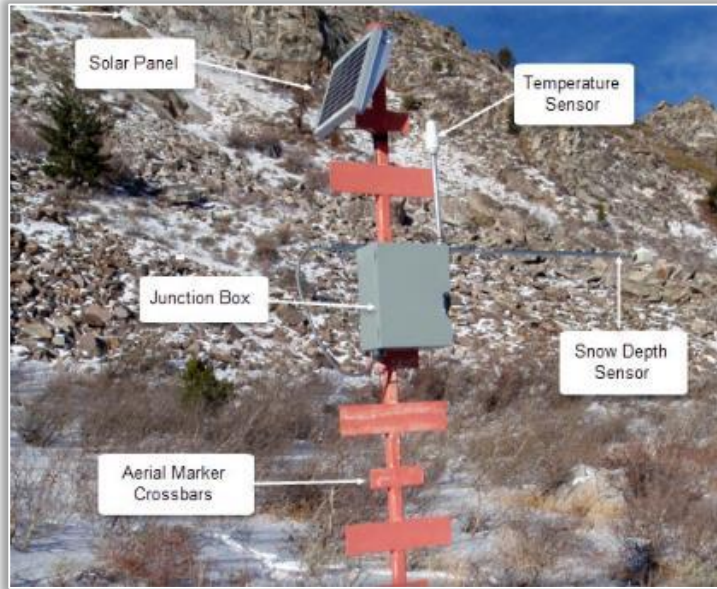


ESA WorldCover (Zanaga et al., 2022)

Zanaga et al. (2022). ESA WorldCover 10 m 2021 v200.



Many ways to collect in situ data



Snolite sites

https://www.wcc.nrcs.usda.gov/about/mon_automate.html

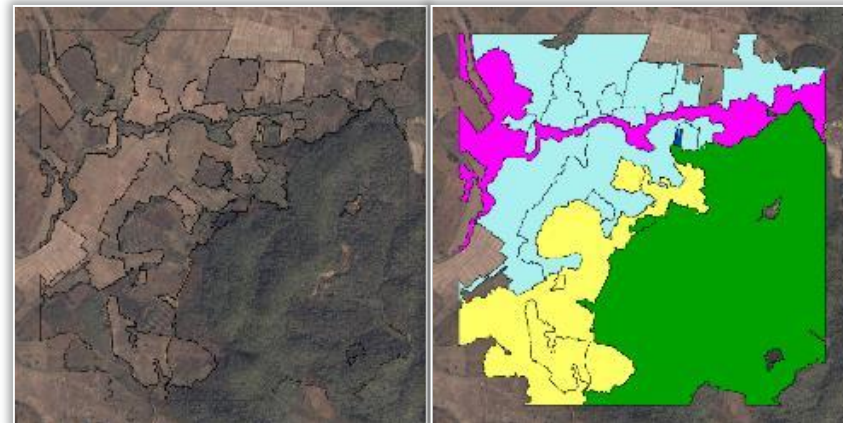


Yield measurement (Senegal)

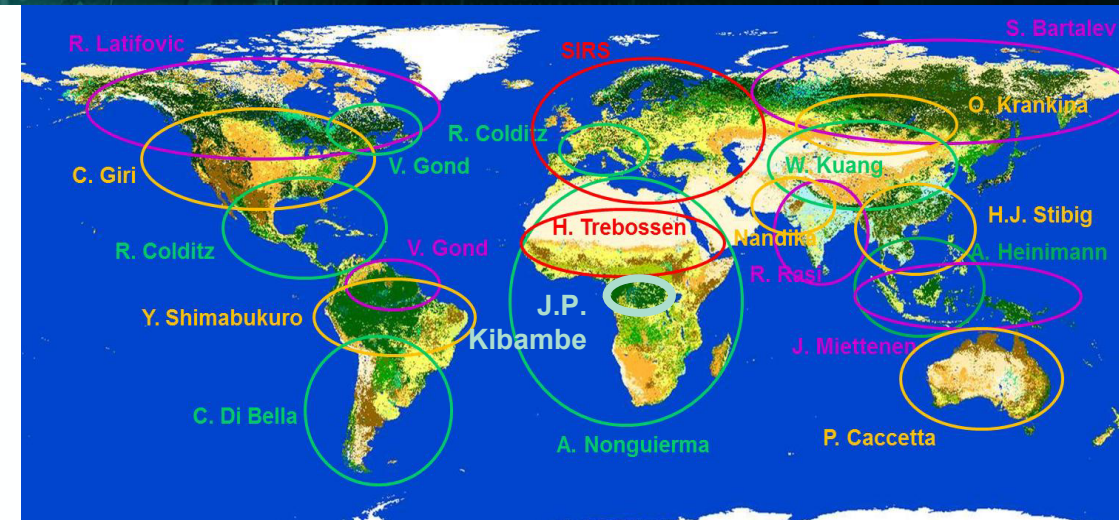
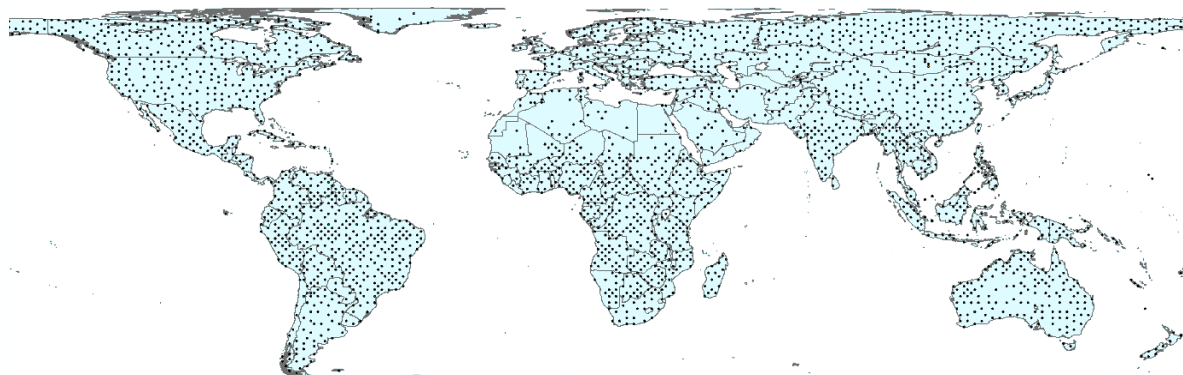


LAI measurement (Ethiopia)

Land Cover on-screen interpretation
(ESA CCI Land Cover project)

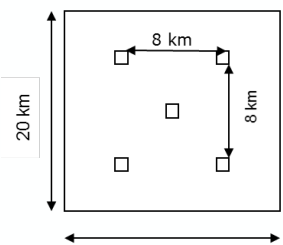


ESA Climate Change Initiative – Land Cover: reference data collection protocol



2-stage systematic sampling frame

- 2600 Primary Sampling Units (PSU) - 10*10 km
- 5 Secondary Sampling Units (SSU) per PSU - 900*900 m => 13.000 potential units



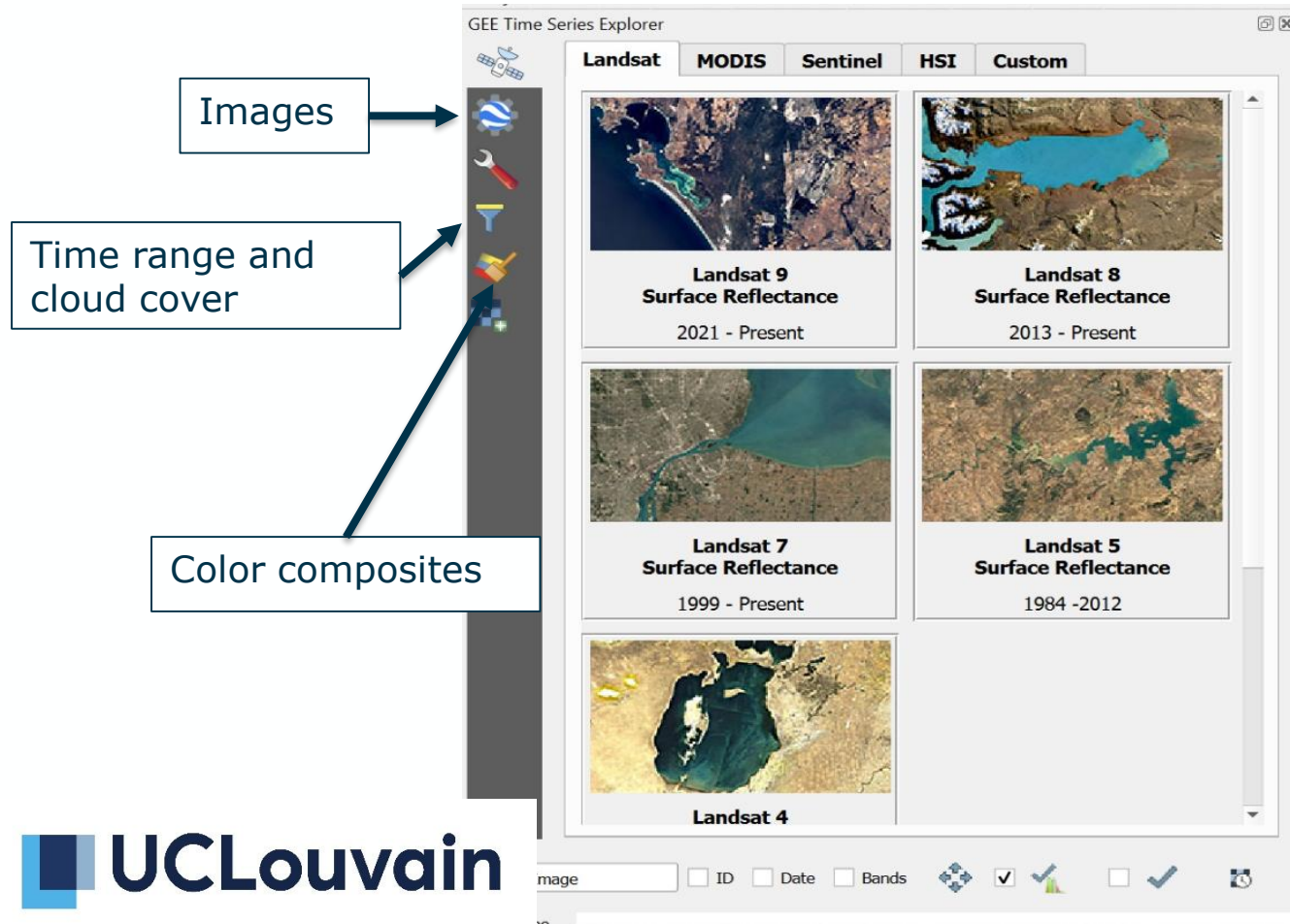
LC Change 2005 & 2000 + level of certainty



ESA Climate Change Initiative – Land Cover: Reinterpretation of major land cover change

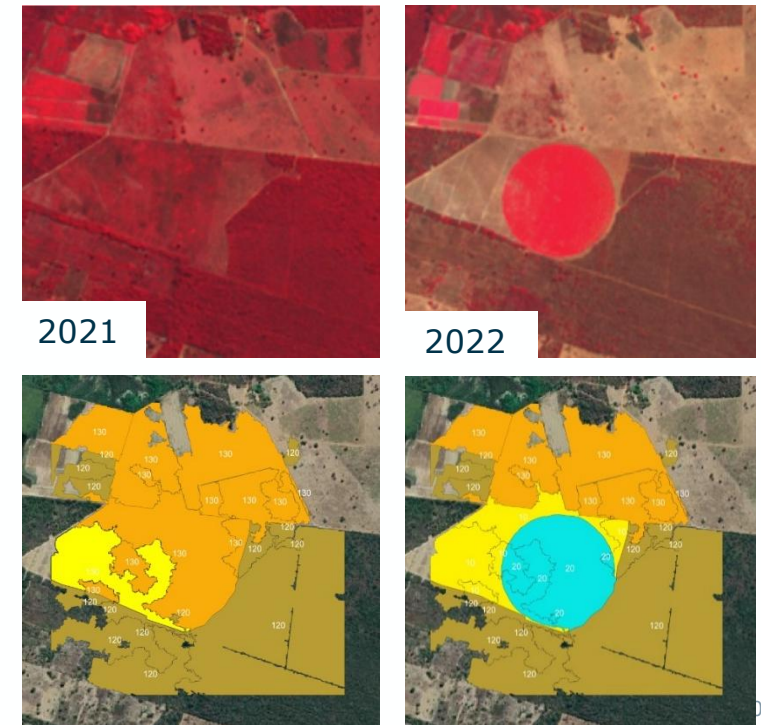


GEE Time Series Explorer QGIS plugin



Land cover change from rainfed cropland to irrigated cropland, Brazil

- High resolution satellite imagery
- Delineation of change
- Independent reinterpretation of LC

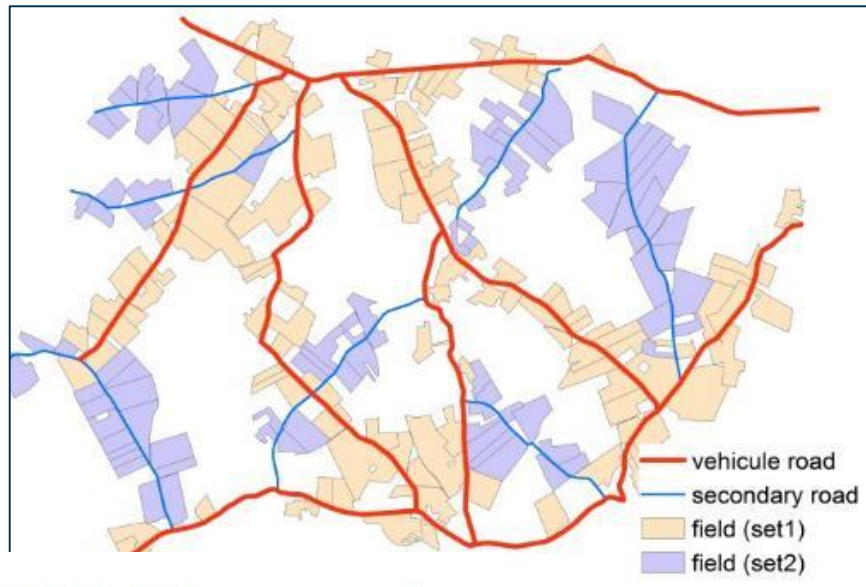


Windshield survey – opportunistic data collection



“Windshield survey”

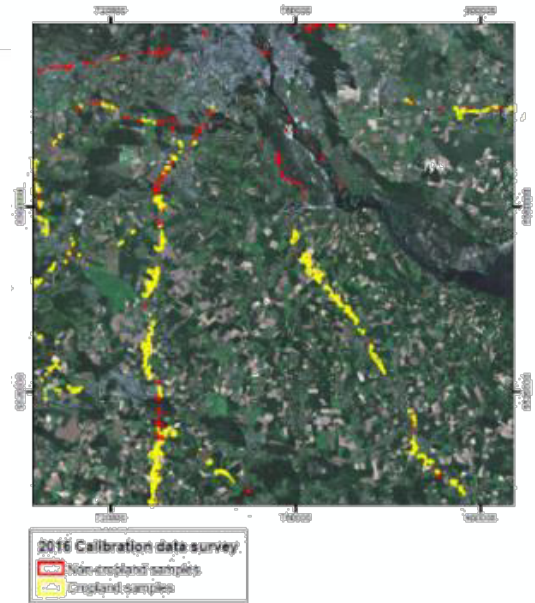
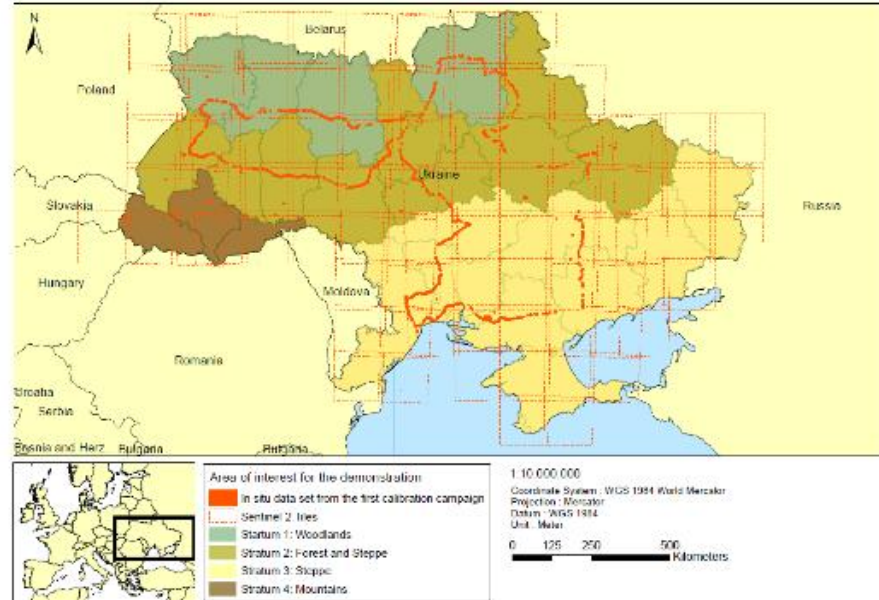
With motorized vehicles (car, motorbike) selecting a set of appropriate roads (set 1) and complemented by regular additional transect (set 2) using secondary roads and tracks to try to reduce the spatial bias brought about by roadside sampling



UCLouvain

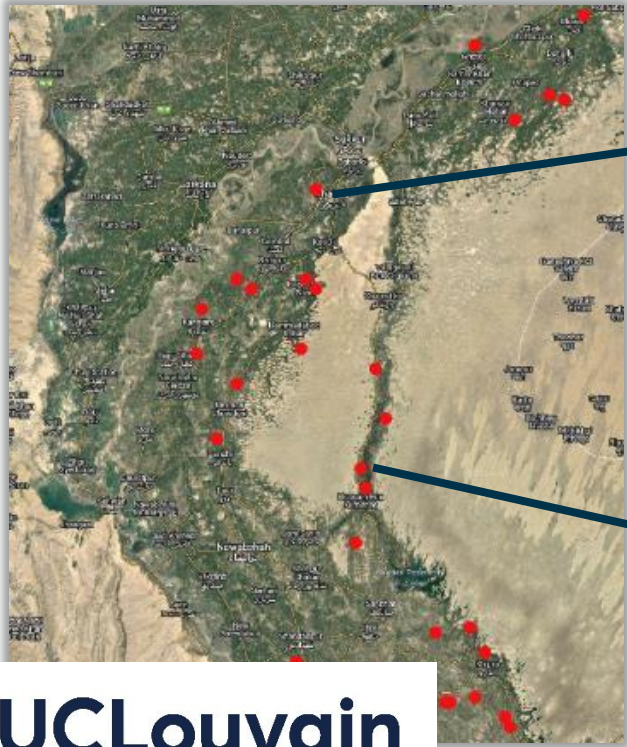
ESA Sentinel-2 for Agriculture

First calibration field campaign over Ukraine (21-23 March 2016):
Repartition of the in situ data set



Fast-track area sampling frame in Pakistan

- Square segments with points to be visited
- Random selection



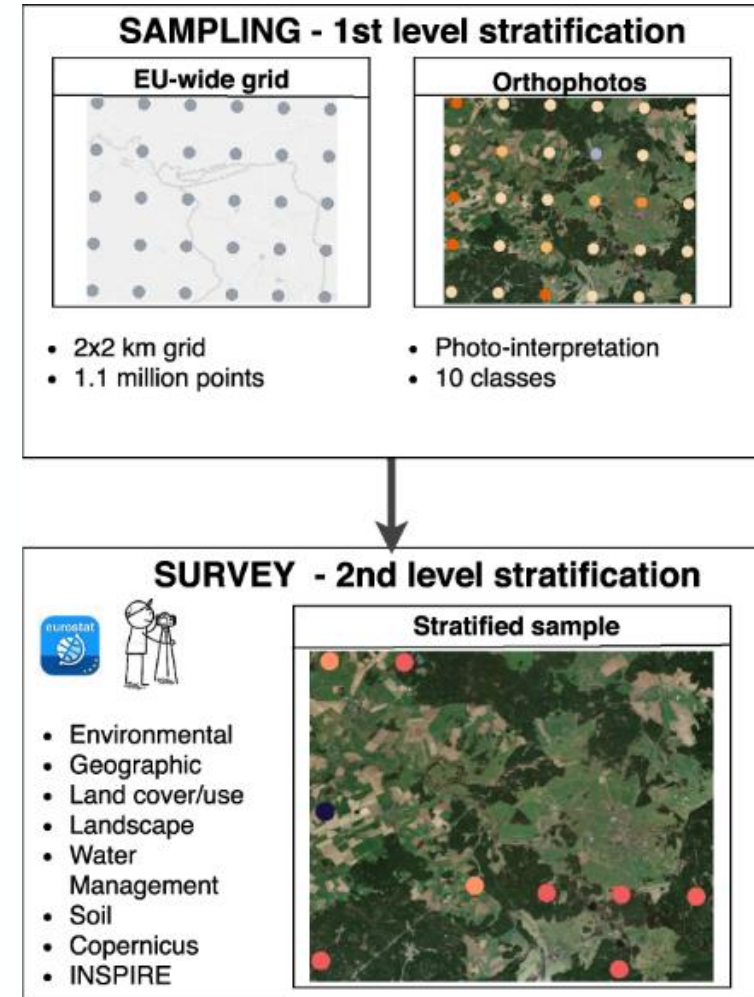
European Land Use/Cover Area frame Survey (LUCAS)

LUCAS = tri-annual surveyed sample of land cover and land use collected since 2006

- 1.351.293 observations at 651.780 unique locations for 106 variables + 5.4 million photos
- Recent effort to build an harmonize database - d'Andrimont et al. 2020. *Sci Data* 7, 352

2-phase sample survey

- 1st phase: systematic selection of points on a grid with a 2 km spacing in Eastings and Northings covering the whole of the EU's territory (around 1.1 million points). Each point is classified in one of ten land-cover classes via visual interpretation of ortho-photos or satellite images
- 2nd phase: select sub-sample of points (statistical soundness by LC class), with field visits by surveyors to collect additional information that cannot be assessed remotely



1. Introduction

2. Key requirements to be EO-compatible

1. Typology

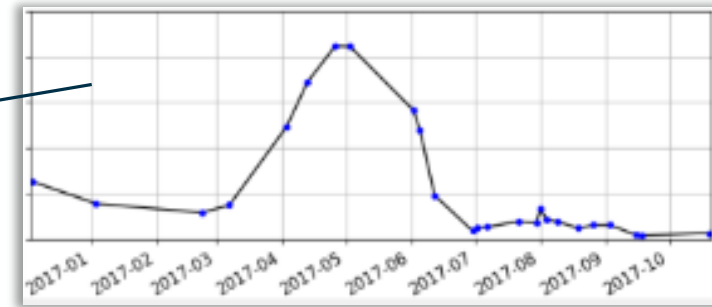
2. Sampling design

3. Response design



Pre-requisite to couple satellite images and in-situ data

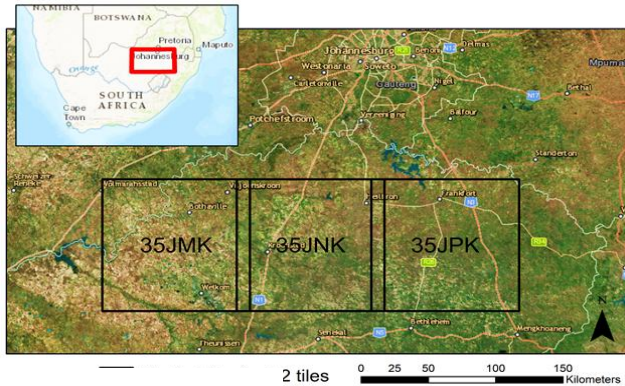
EO data will be useful **ONLY IF** they can be coupled with in-situ data
=> geographic link



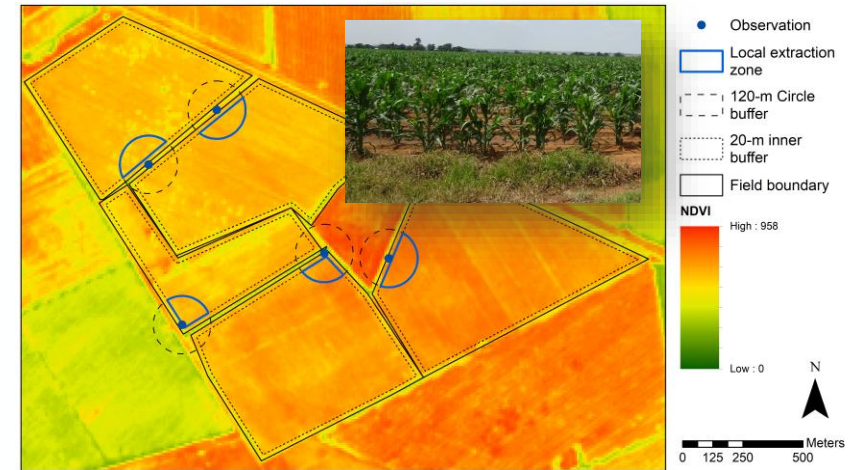
Large in situ georeferenced datasets are collected... ...but most georeferencing are not EO compatible

Example 1: Great in situ dataset from insurance company for corn in Free State, South-Africa

Parcel delineation available



Georeferenced in situ observation on the road... but for which roadside ?

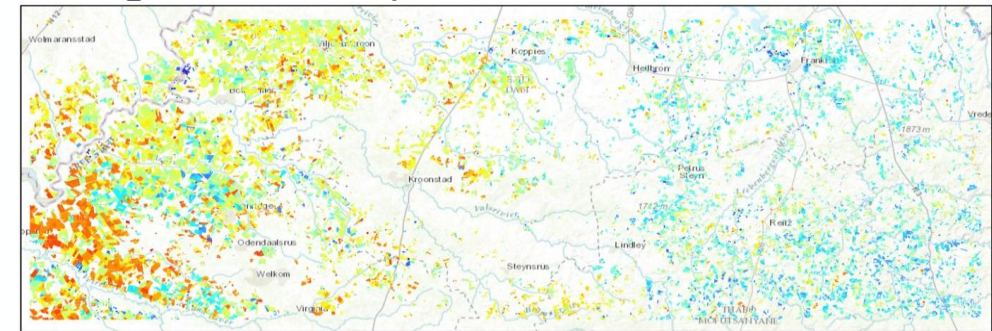


Complementary in situ dataset



ECoLaSS Project

Emergence date map for 2016 maize

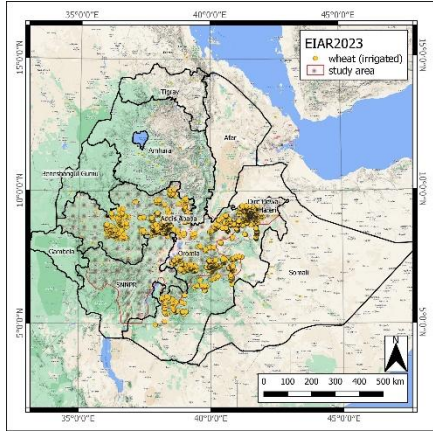


Emergence date	10-19 - 10-23	11-02 - 11-05	11-14 - 11-17	11-27 - 12-01	12-12 - 12-16	12-27 - 01-02
	10-05 - 10-11	11-06 - 11-09	11-18 - 11-21	12-02 - 12-06	12-17 - 12-21	01-03 - 01-20
	10-12 - 10-18	10-29 - 11-01	11-10 - 11-13	11-22 - 11-26	12-22 - 12-26	01-21 - 02-18

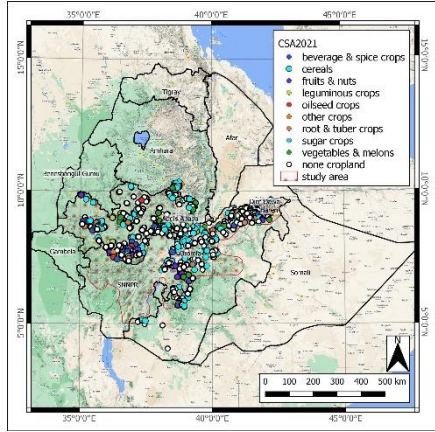
Large in situ georeferenced crop datasets are collected... ...but most georeferencing are not EO compatible



Example 2: Great Ethiopian datasets could not be used for Sen4Rust mapping



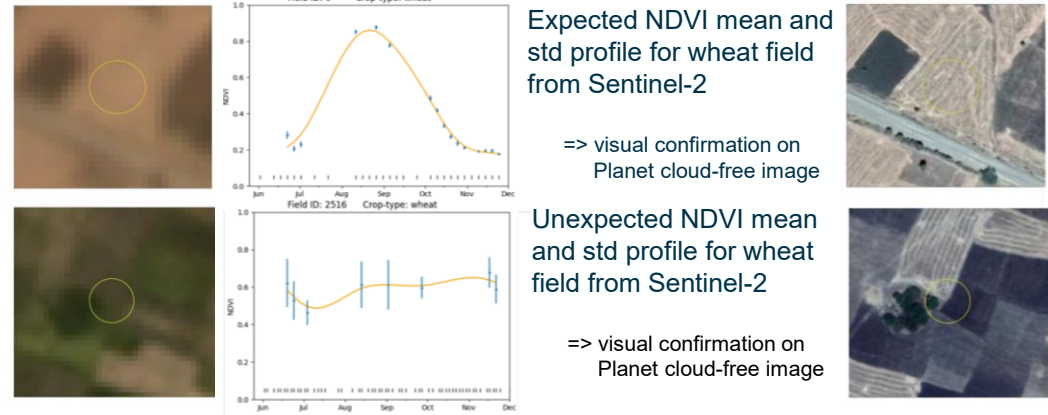
EIAR 2023: 16,278 samples in field clusters of irrigated wheat with GPS coordinates from cluster centroids



CSA 2021: 25,598 samples but GPS locations clustered and multiple crops for single sample



Intensive quality control combining 3 in situ data sources



Leading to **2,793** harmonized, quality-controlled georeferenced in situ samples over Ethiopia

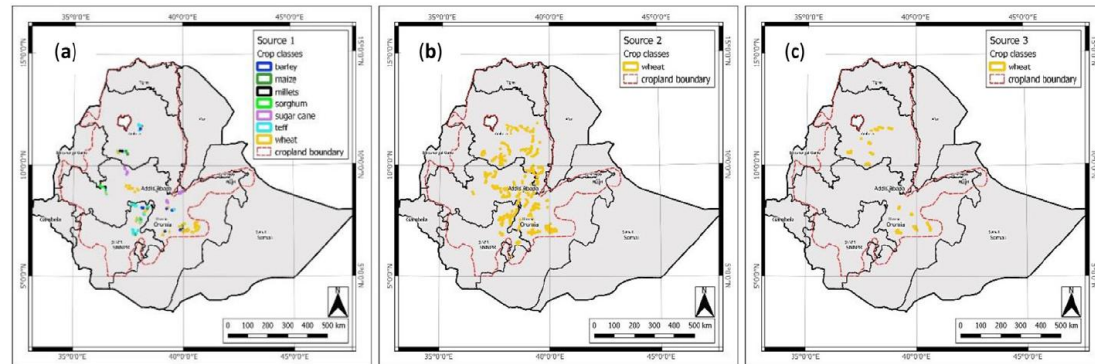
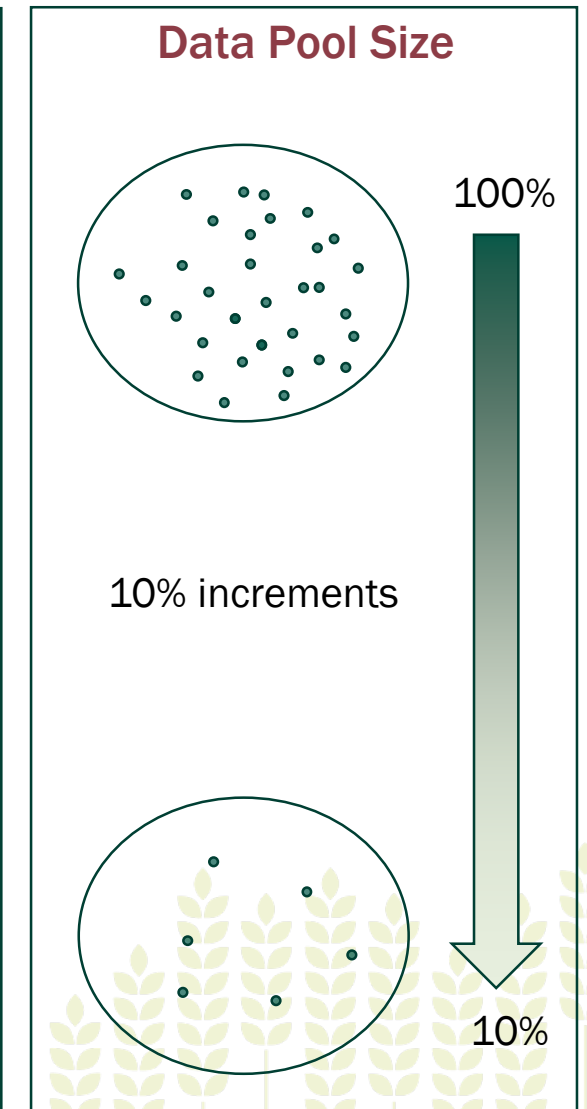
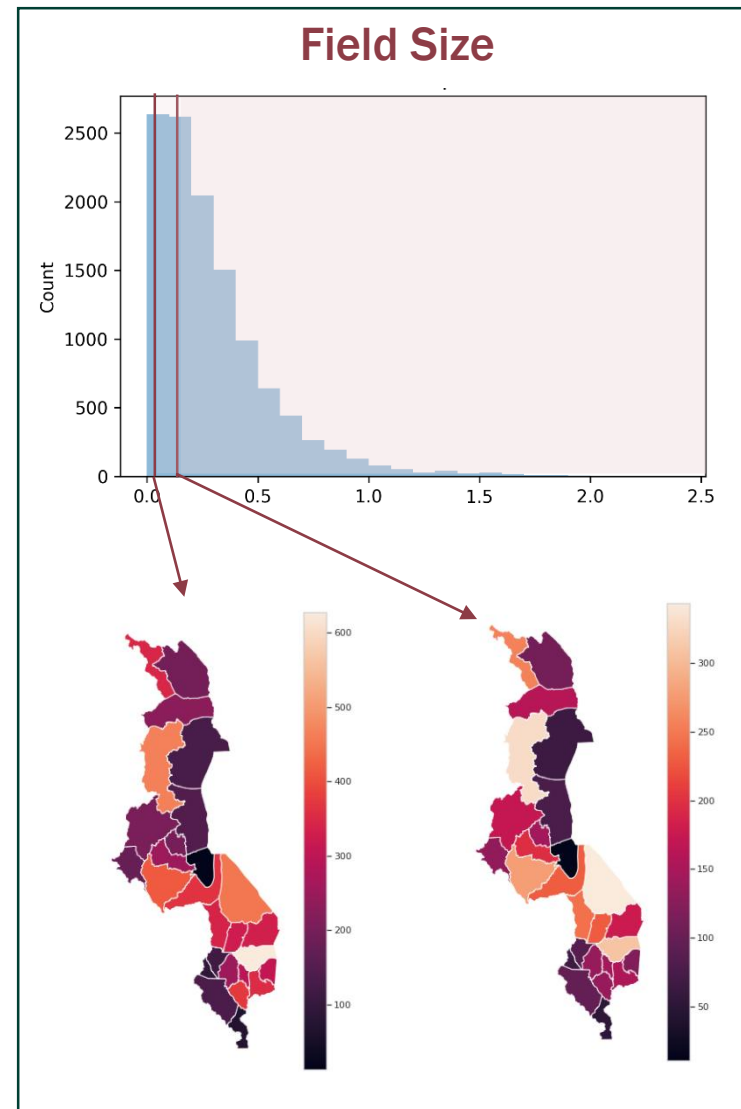
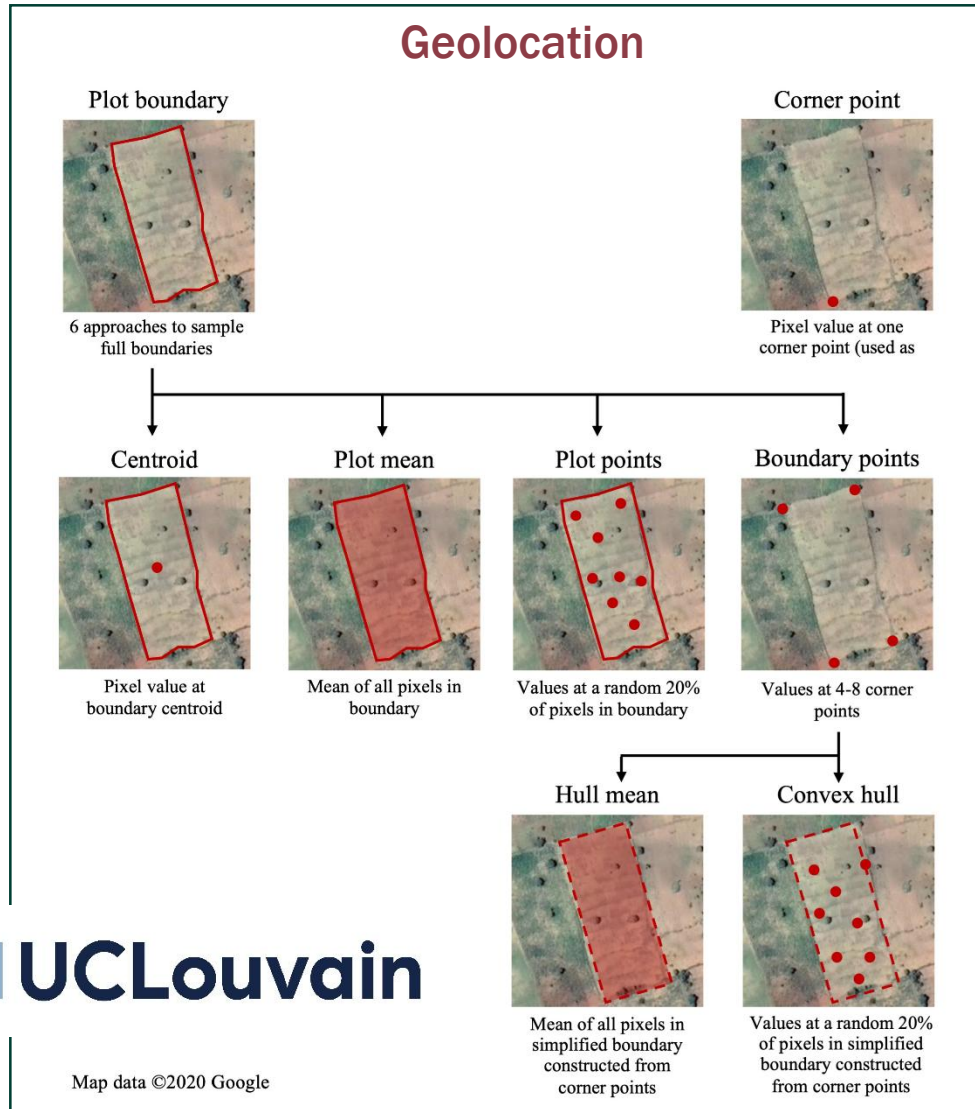


Fig. 2. Location of the source datasets and the distribution of the fields, showing crop classes (a) Source 1 – Ground Data Collection Campaign (GDCC); (b) Source 2 – Wheat Rust Toolbox (WRTB); and (c) Source 3 – Farm Household Survey Database (FHSD).
(Blasch et al. 2024 – *EthCT2020*)

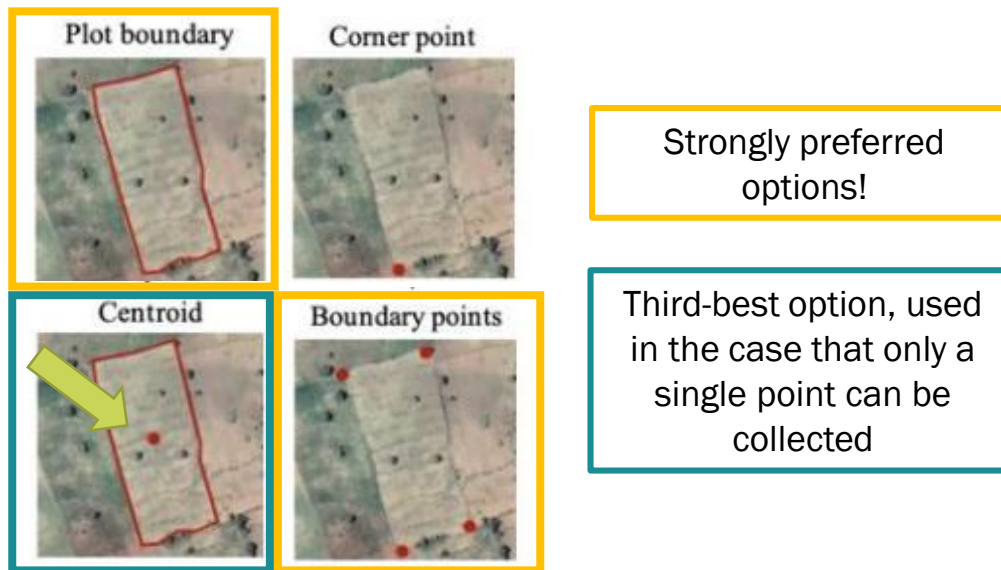
HOW DO WE COLLECT GEOREFERENCED DATA TO INFORM EARTH OBSERVATION-BASED APPLICATIONS?

RESEARCH EFFORTS – DATA COLLECTION SCENARIOS



HOW DO WE COLLECT GEOREFERENCED DATA TO INFORM EARTH OBSERVATION-BASED APPLICATIONS?

RESEARCH CONCLUSIONS



Seemingly-small erosion in classification performance under less preferable approaches to georeferencing plot locations **results in large differences in total crop area estimated** - by as much as 50%.

- **No plot observations should be excluded** from model training based on a minimum plot area threshold.
- Classification performance peaks with **~50-65% of the training data** under preferred approaches to georeferencing plot locations.
- **Optical features alone** can provide sufficient signal to maximize prediction quality.
- **Inclusion of weather** is generally beneficial to model performance.

1. Legend / typology
 1. Interoperable legend and field protocol
 2. Clear Minimum Mapping Unit
 3. Appropriate classification system – label must be unique and suitable to the spatial resolution of the EO datasets
2. Sampling design to allow deriving accurate statistics
 1. Stratification + sampling probability
3. Response design
 1. Appropriate sampling unit (with spatial resolution, legend, etc.)
 2. Accounting for EO signal and pre-processing (PSF, bidding, etc.)
 3. Managing geometric differences
 4. On field precision (GPS, dGPS, map-based)
 5. Quality above quantity

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Terms **land cover** and **land use** are often used interchangeably, but their actual meanings are quite distinct

Land Cover

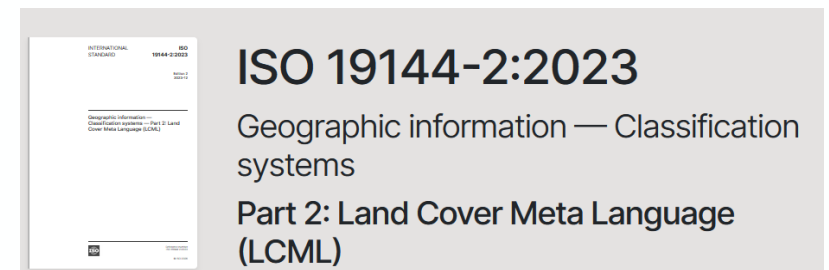
- Observed (bio)physical cover on the Earth's surface (Di Gregorio 2016)
- Physical and biological cover of the earth's surface including artificial surfaces, agricultural areas, forests, (semi-) natural areas, wetlands, water bodies (DIRECTIVE 2007/2/EC of the European parliament and of the Council, Annex II)
- Refers to the surface cover on the ground, e.g. vegetation, manmade structures, water, bare soil or other

Land Use

- Refers to the purpose the land serves (e.g. managed forest, settlement, wildlife habitat, or agriculture)
- Territory characterized according to its current and future planned functional dimension or socio-economic purpose, e.g. residential, industrial, commercial, agricultural, forestry, recreational (DIRECTIVE 2007/2/EC of the European parliament and of the Council, Annex III)
- Connected to the arrangements, activities and inputs humans undertake within a specific land cover type to produce, change or maintain it

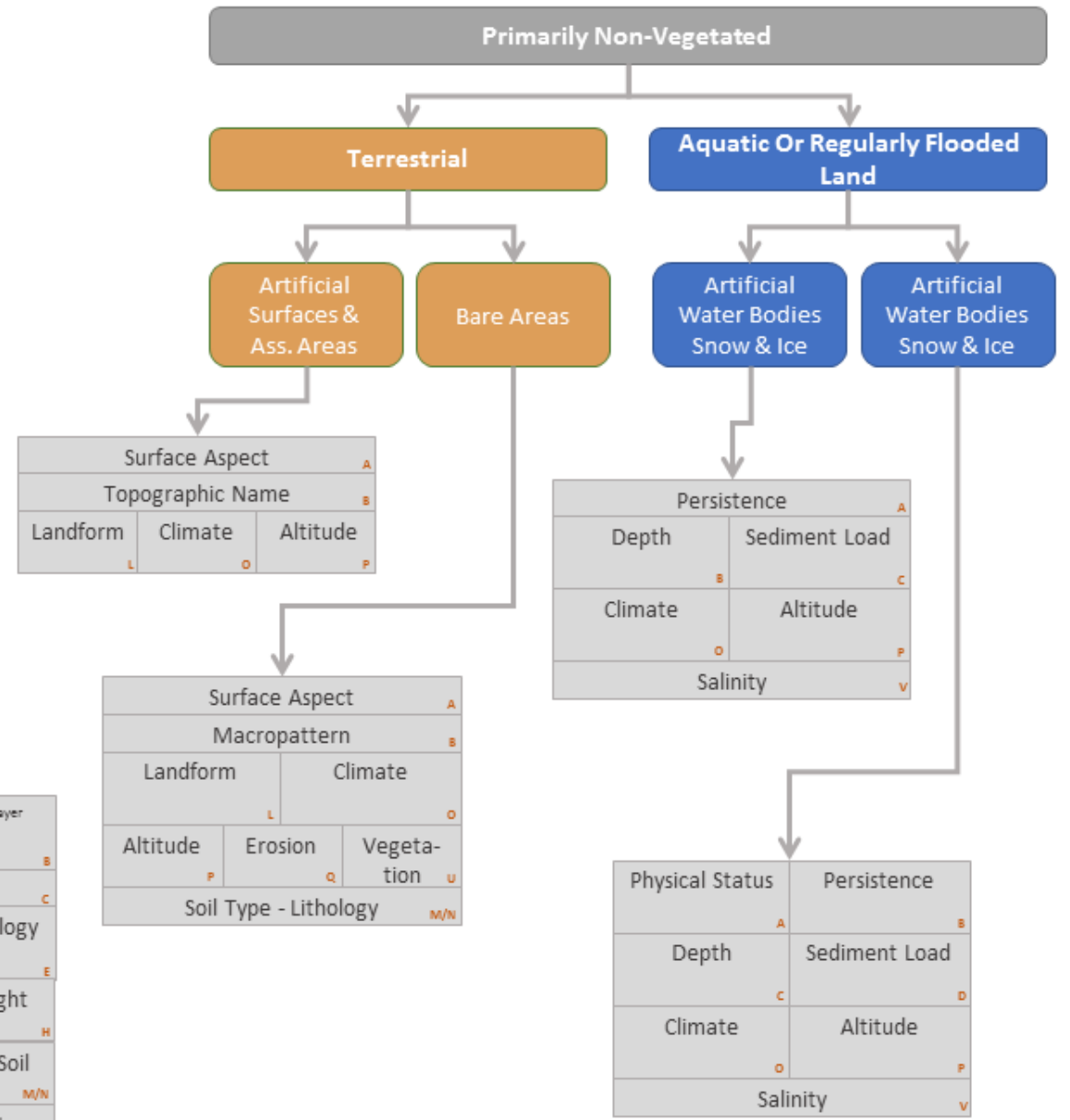
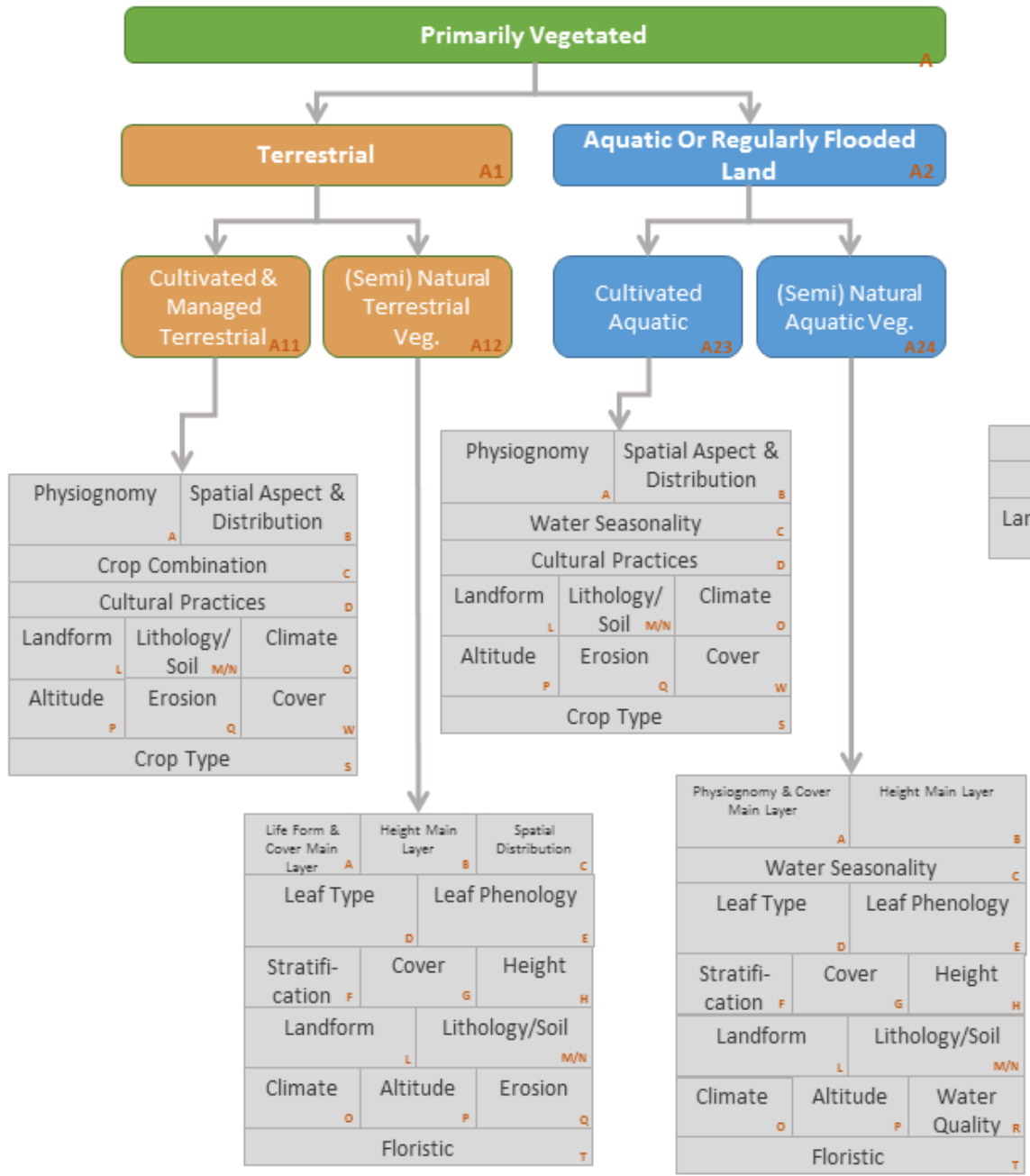
In short, LC indicates the physical land type and LU indicates how people are using the land
EO provides imagery of LC whereas info on LU requires additional human interpretation

- Image classification involves categorization = complex task, as nature is more like a continuum (always a part of arbitrary)
- Land Cover Classification Systems help to produce consistent and comparable classifications of remote sensing data
 - abstract tools describing the situation in the field using well-defined rules and criteria's
 - systematic framework with the name of the classes and the criteria used to distinguish them, and the relation between classes:
 - information structured in accordance with logical principles (exhaustiveness, absence of overlaps, unequivocal definition of classes, rules for representing objects in the classification),
 - also taking account of user needs and existing information stocks (pragmatic approach)



Dichotomous Phase

Modular Hierarchical Phase



Overview of LCCS, its phases and classifiers (after Di Gregorio & Jansen 1998)

Ecotopes (1 m resolution) / Ecopatches (10 m resolution)

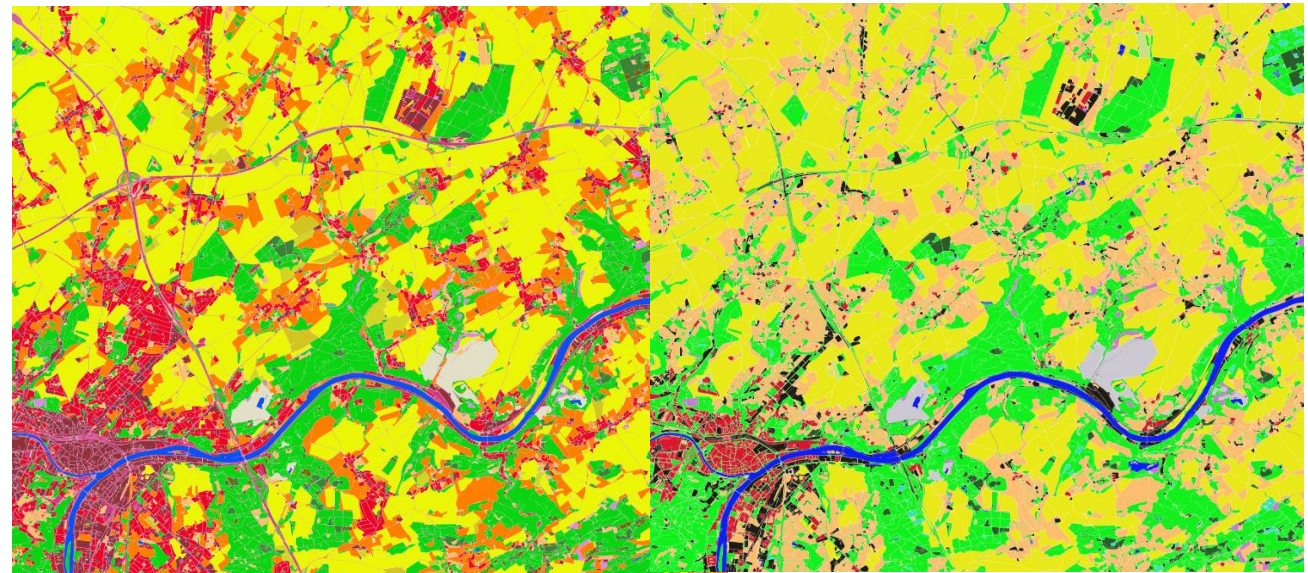
Multiple typologies for the same land cover proportions

Land cover composition

measured inside each polygon

LCCS

Majority



detail in the ecotope:



250m around the ecotope:



500m around the ecotope:



1km around the ecotope:



31 years of consistent 300 m global LC map series 1992-2022 (37 classes, incl. 15 regional LC classes)



Value	Label	Color
0	No Data	
10	Cropland, rainfed	
11	Herbaceous cover	
12	Tree or shrub cover	
20	Cropland, irrigated or post-flooding	
30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	
50	Tree cover, broadleaved, evergreen, closed to open (>15%)	
60	Tree cover, broadleaved, deciduous, closed to open (>15%)	
61	Tree cover, broadleaved, deciduous, closed (>40%)	
62	Tree cover, broadleaved, deciduous, open (15-40%)	
70	Tree cover, needleleaved, evergreen, closed to open (>15%)	
71	Tree cover, needleleaved, evergreen, closed (>40%)	
72	Tree cover, needleleaved, evergreen, open (15-40%)	
80	Tree cover, needleleaved, deciduous, closed to open (>15%)	
81	Tree cover, needleleaved, deciduous, closed (>40%)	
82	Tree cover, needleleaved, deciduous, open (15-40%)	
90	Tree cover, mixed leaf type (broadleaved and needleleaved)	
100	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	
110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	
120	Shrubland	
121	Evergreen shrubland	
122	Deciduous shrubland	
130	Grassland	
140	Lichens and mosses	
150	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	
151	Sparse tree (<15%)	
152	Sparse shrub (<15%)	
153	Sparse herbaceous cover (<15%)	
160	Tree cover, flooded, fresh or brakish water	
170	Tree cover, flooded, saline water	
180	Shrub or herbaceous cover, flooded, fresh/saline/brakish water	
190	Urban areas	
200	Bare areas	
201	Consolidated bare areas	
202	Unconsolidated bare areas	
210	Water bodies	
220	Permanent snow and ice	



[Overview](#)
[Download data](#)
[Quality assessment](#)
[Documentation](#)

Maps and documentation available on the CDS Clear all

Year

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<input checked="" type="checkbox"/> 2022					

Clear all

How would you label this ?



How would you label this ?



How would you label this ?



How would you label this ?



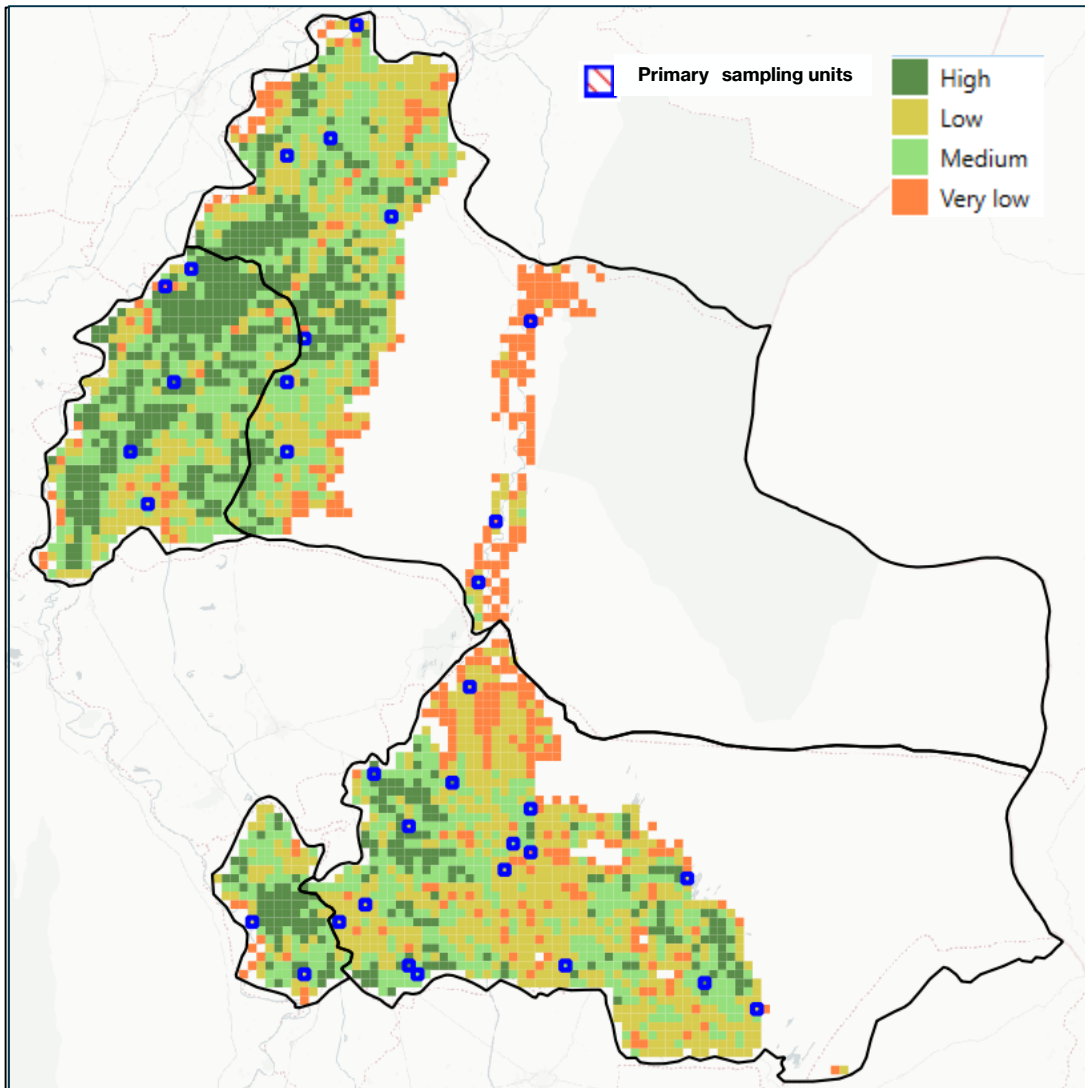
1. Introduction
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1. Typology

2. **Sampling design**

3. Response design

Definition of a population, stratification and sampling within an area sampling frame



Definition of a population of 2 by 2km square segments

Overlay of an existing map on the population grid

Definition of strata limits based on the existing map or any other prior information available (e.g. cropland extent layer)

Sampling of sample units within the population according to a given allocation strategy accross strata

Many sampling design variations based on budget constraints, field realities and the target variable

The objective of the stratification is to **divide the population into homogeneous subpopulations** which can lead to an **increase in the precision of the estimate** if the stratification is efficient **compared to a random sampling strategy**

→ Many sampling design variations on top of stratified vs non stratified sampling

Sample unit and population definition: Square segments (which can vary in size depending on Ag. Landscape), administrative units, points, ...

Sampling: Systematic vs non systematic, one stage vs 2 or more stages, ...

Stratification: Which map to use as prior information, how to allocate samples accross strata based on sample accessibility and travel cost, ...

→ Sampling probability has to be documented for each sample for unbiased stats

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Driven by the legend

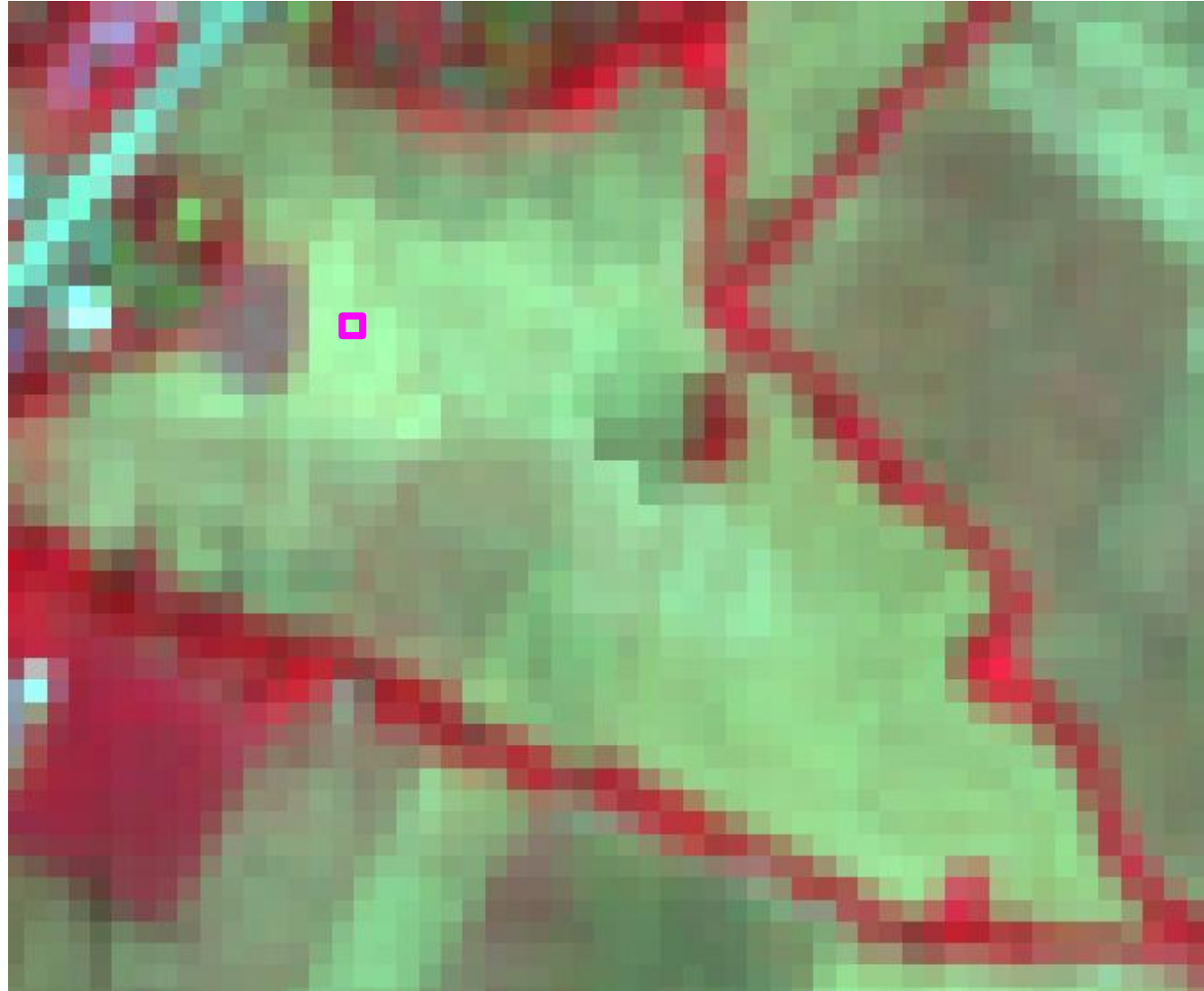
Must manage natural heterogeneity

Sensors measure larger areas than the pixel footprint

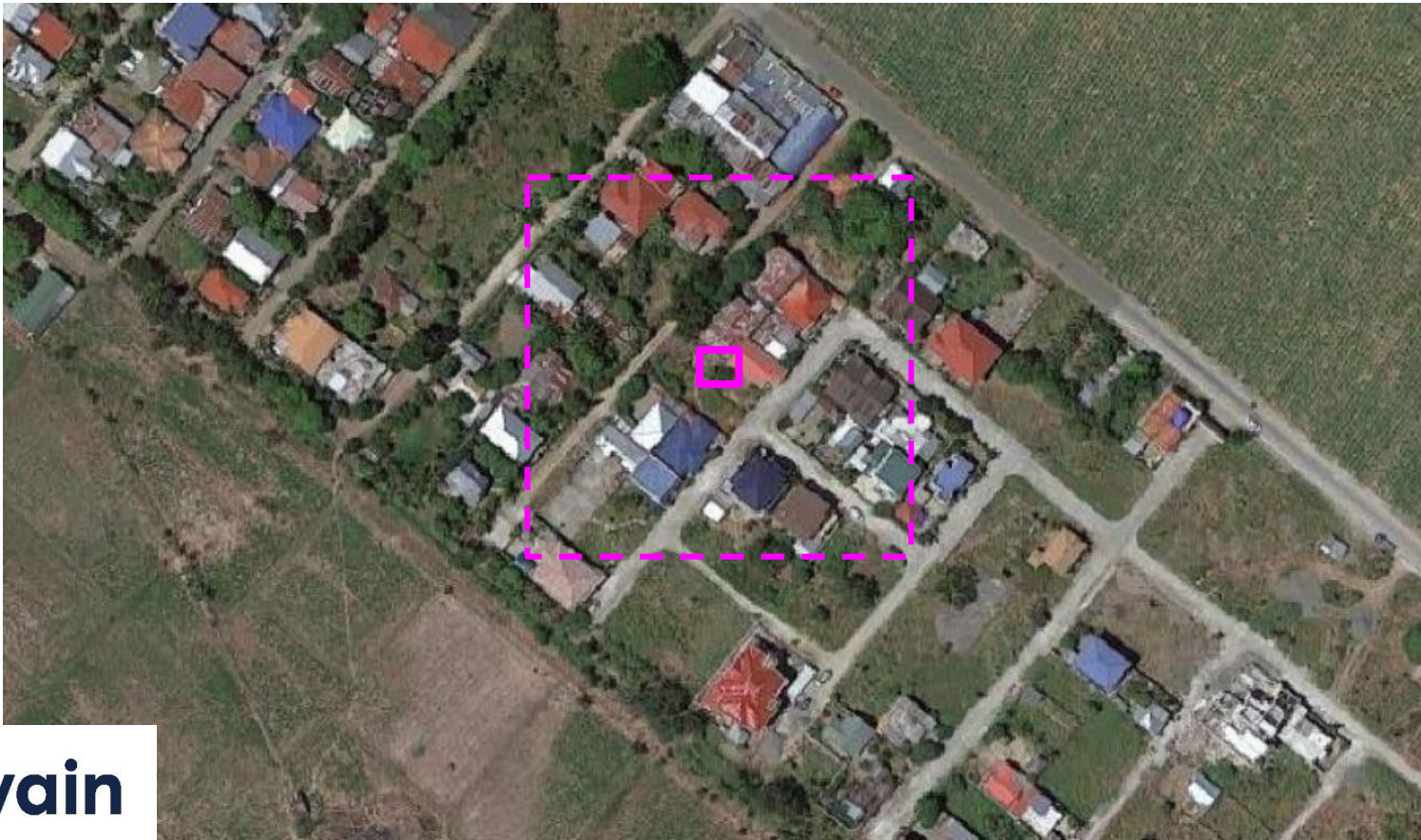
Point spread function = distribution of the landscape contribution to single pixels

- Sampling unit: unit that has been selected in the sample
- Assessment unit: spatial scale at which the reference labels are assigned
- Spatial support unit: area that is taken into account when assigning reference labels to the assessment unit (MMU)

- Pixel for the 3 units: individual map pixels are sampled, assessed, and land cover class definitions do not contain criteria of minimum patch area that would require a spatial support unit larger than a map pixel

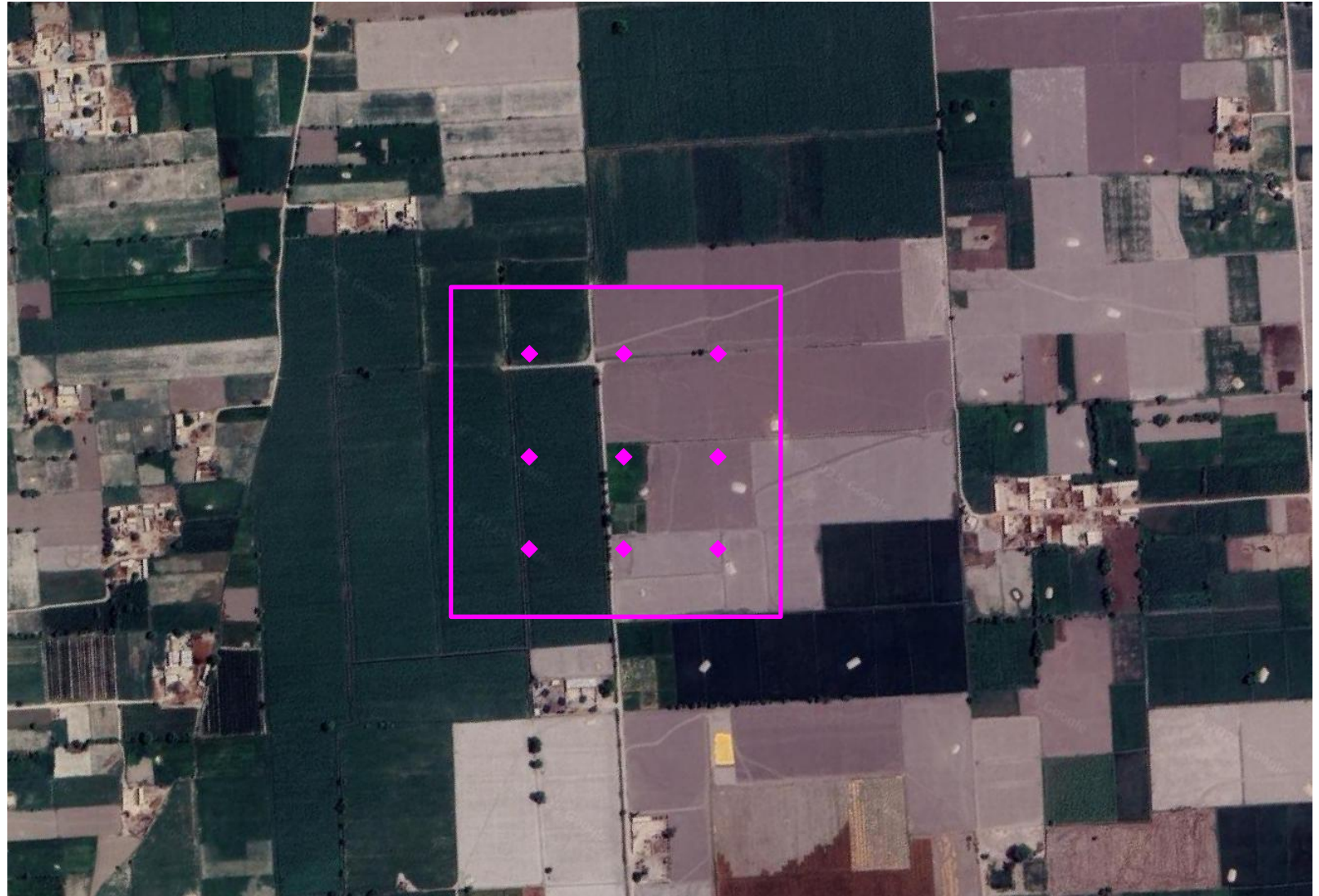


- Pixel sampled and assessed but larger landscape context (spatial support unit), e.g., 100 m², could be considered while labeling reference sample units



- PSU as sampling unit (clustered sampling), pixel as assessment unit (all pixels within the PSU are labelled)

DO NOT AGGREGATE PIXELS AT POLYGON-LEVEL FOR PIXEL ACCURACY ESTIMATE (only area estimate)



- Apply the same rules to the reference sample labeling protocol and to the classification
 - Make sure your legend is well-defined, with mutually exclusive classes
 - Ideally, each map unit is assigned to a single category -> is homogeneous
- This might not be possible for:
- patches smaller than the map unit
 - some land cover/land use classes which are composed of a set of elementary landscape components or might not have abrupt boundaries (e.g., ecotone zone along the forest edge, tree savannahs, urban areas)
- ⇒ Mixed classes with appropriate guidelines
- Estimating proportions of land cover classes/components within map units

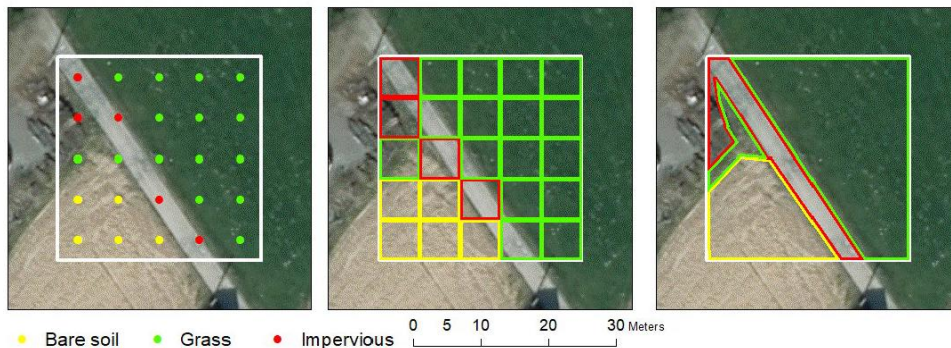
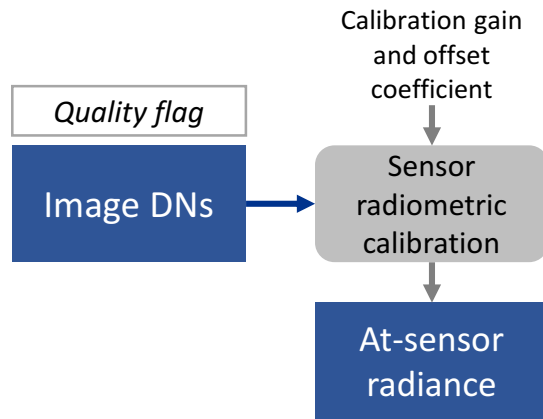


Figure 4.1 Estimating proportions of land cover classes inside a 30x30 m pixel assessment unit using a subsample of points (left) or partitioning an assessment unit into a grid of squares (center) or into irregular polygons (right). In this case, the three response designs would consistently assign 'grass' as the majority class with proportions of 60% with points, 64% with squares and 60% with irregular polygons. Figure by Julien Radoux.

EO preprocessing – from image DNs to at-sensor radiance



Radiance value of a pixel depends on the surface properties corresponding to the measurement and not to the pixel size.

What is IN a pixel?

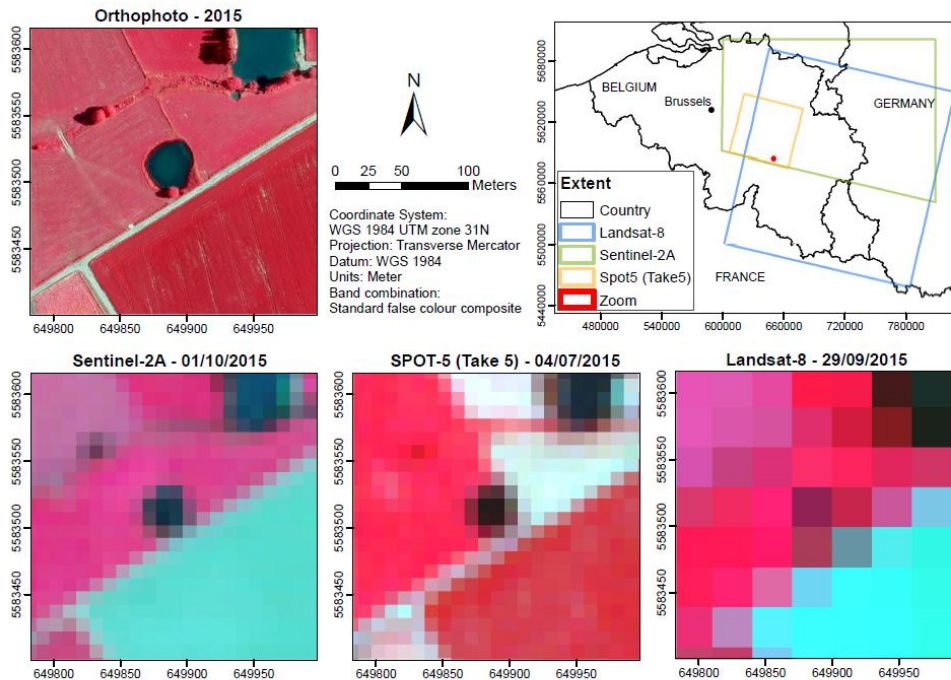
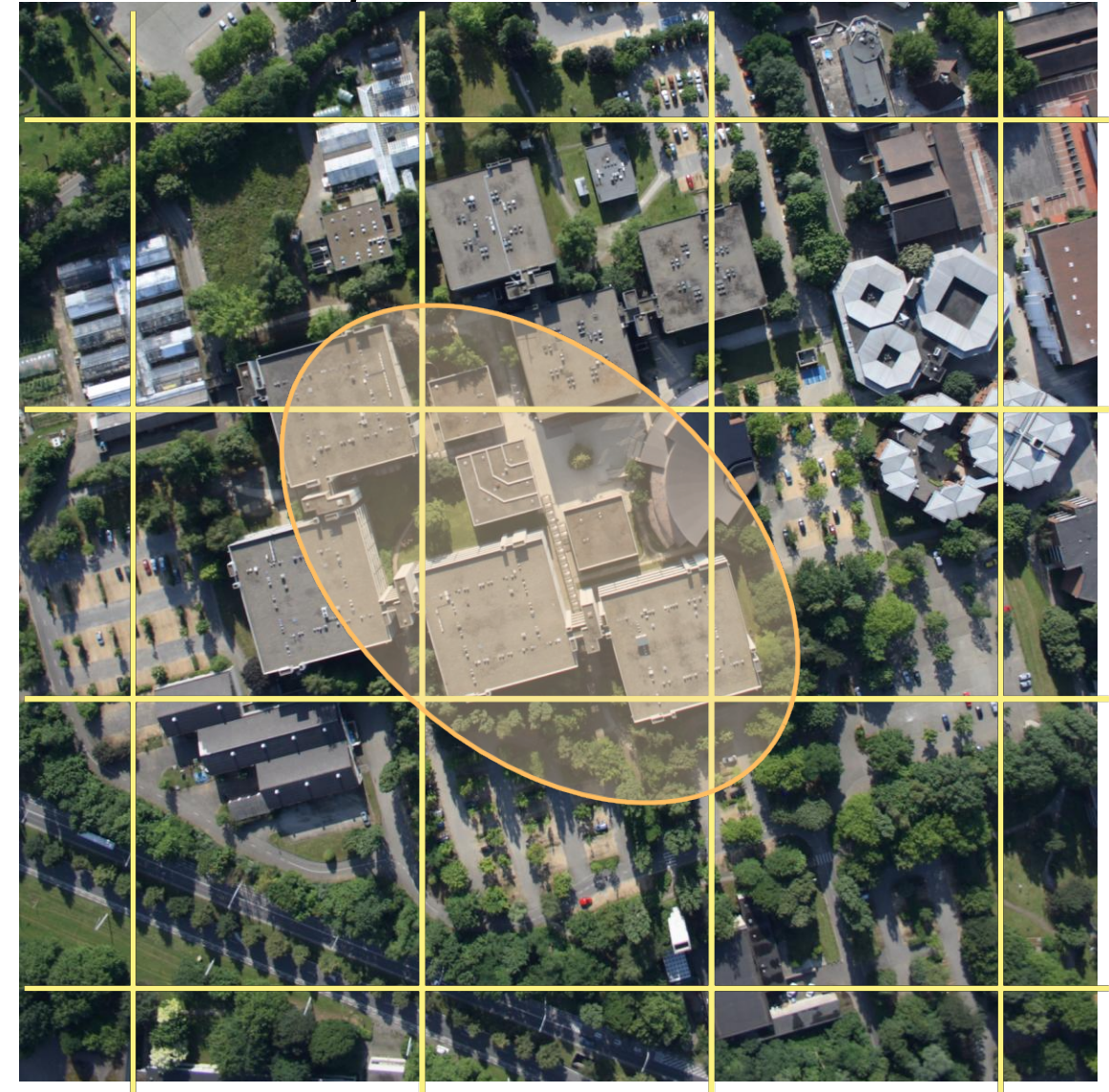
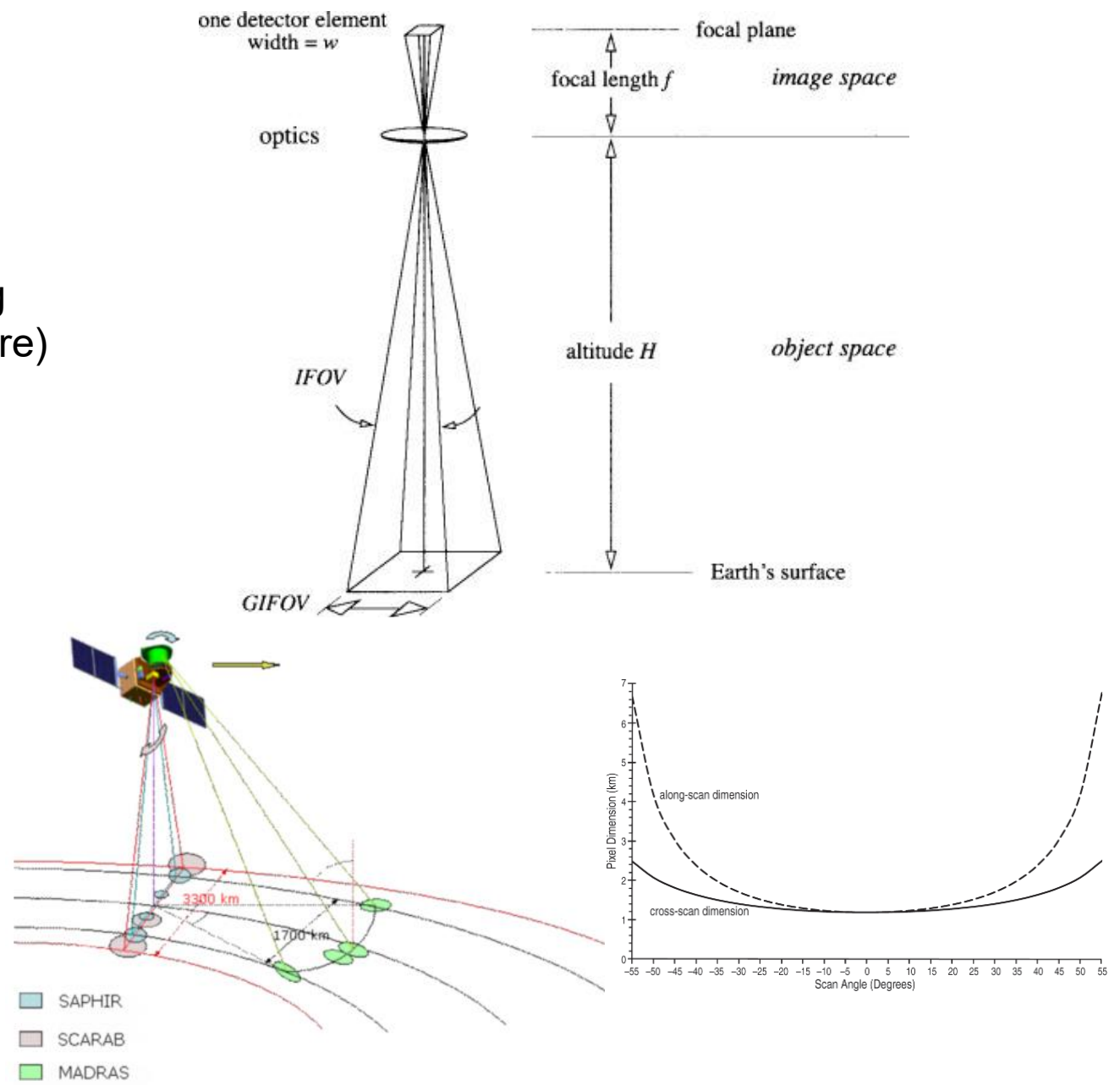
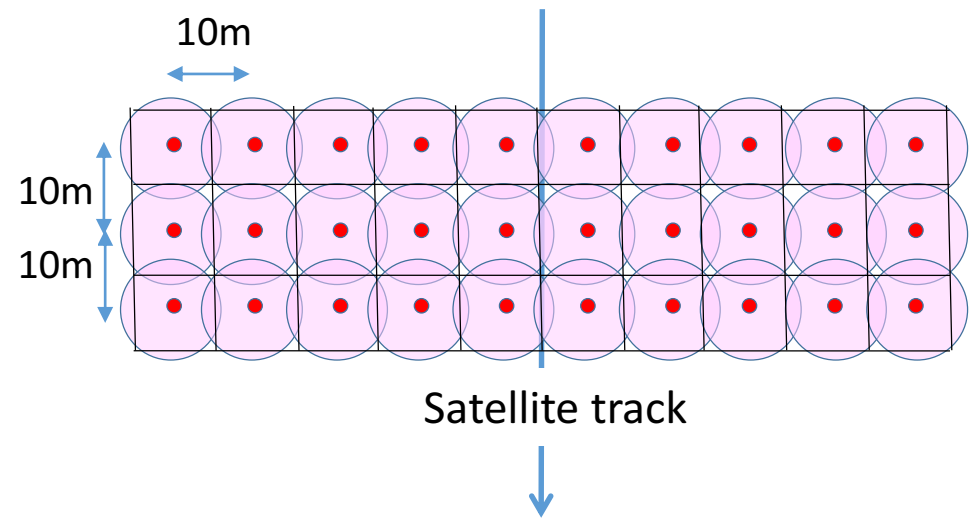


Figure 7. Snapshots of an orthophoto (25 cm), Sentinel-2A (10 m), SPOT-5 (Take 5) (10 m) and Landsat-8 (30 m) images of a small pond (30 m × 30 m) surrounded by permanent grassland in the South of Belgium. The four images are presented using the same standard false color bands combination (R: NIR_{wide} , G: Red, B: Green).

EO preprocessing – from image DNs to at-sensor radiance

Spatial resolution *versus* pixel size (optical domain)

- Instantaneous Field of View (IFOV)
- Ground IFOV (Ground-projected IFOV varying across track and enhanced by Earth curvature)
- Ground Sampling Interval (GSI)

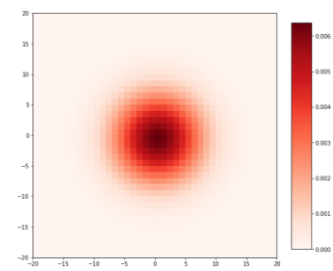


(Waldner, Duveiller and Defourny, 2018)

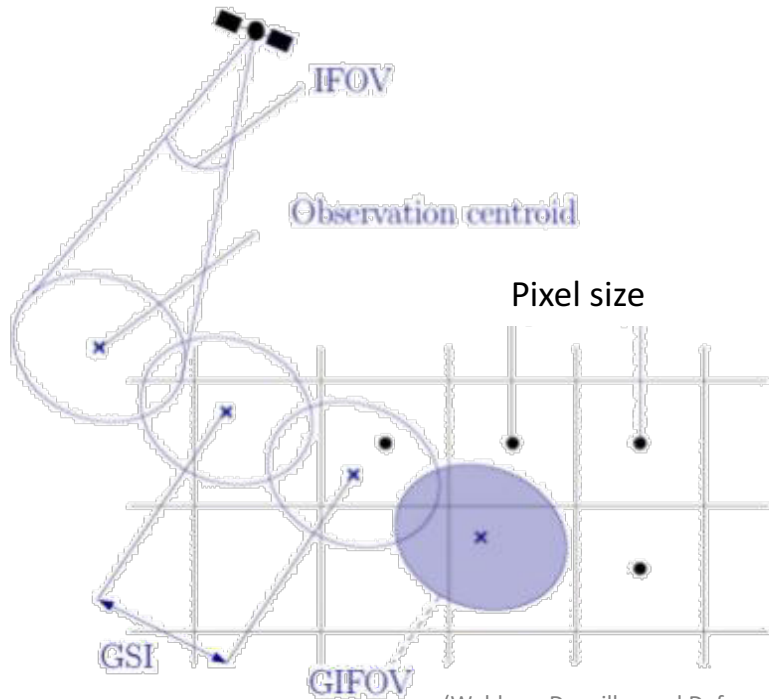
EO preprocessing – from image DNs to at-sensor radiance

In-orbit instrument observation footprint \neq pixel size

- Instantaneous Field of View (IFOV)
- Ground IFOV (Ground-projected IFOV varying across track and enhanced by Earth curvature)
- Ground Sampling Interval (GSI)

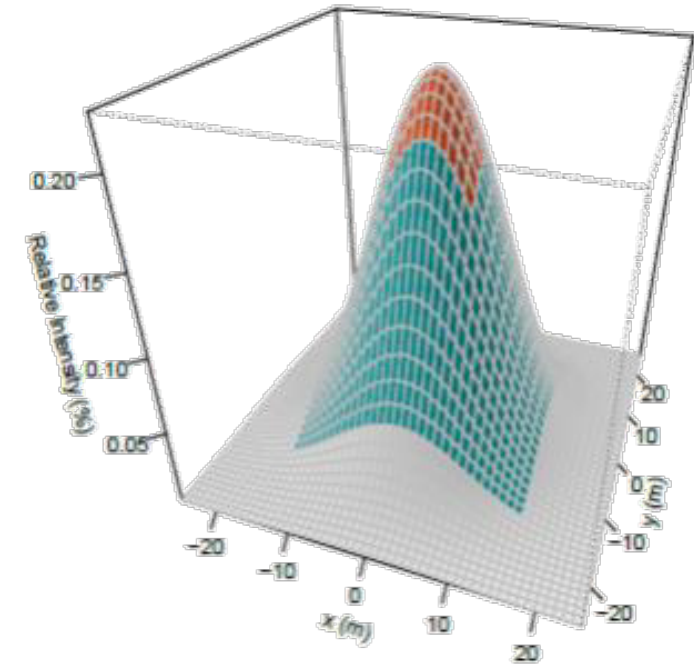
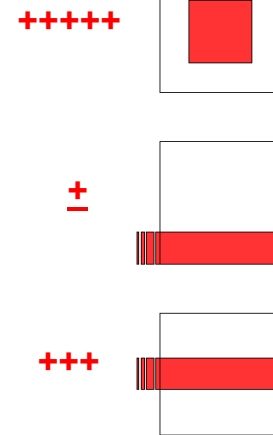


Point Spread Function (PSF) describing the response of an imaging system to a point object



(Waldner, Duveiller and Defourny, 2018)

Object position in a pixel influences its contribution to the radiance, not only its area !



Relative contribution to a 10 m instrument measurement

Red : GIFOV area

Red + Blue: effective contributing area to radiance measurement

(Radoux et al., 2016)

EO preprocessing – from image DNs to at-sensor radiance

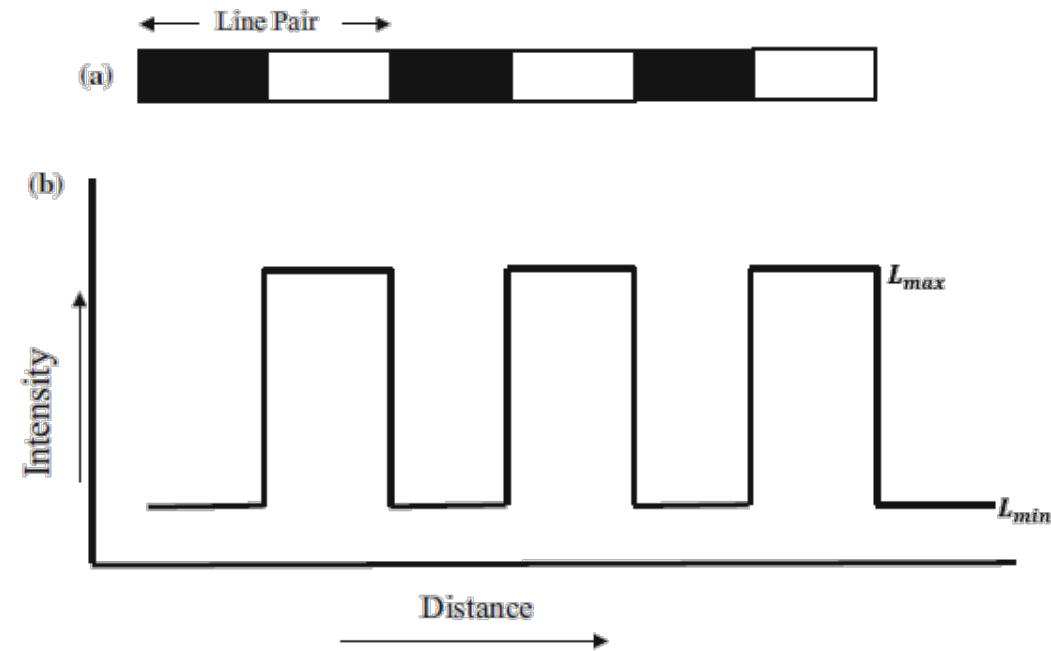
Spatial resolution *versus* pixel size

- Point Spread Function (PSF)
- Modulation Transfer Function (MTF) being equivalent to the PSF in the frequency domain

PSF (or MTF) application is very important to:

- Understand the **size** of detectable features
- **Design in situ ground measurements** used for calibration/validation
- **Simulate** different spatial resolutions
- Change image pixel size to **downscale** a product to a lower resolution

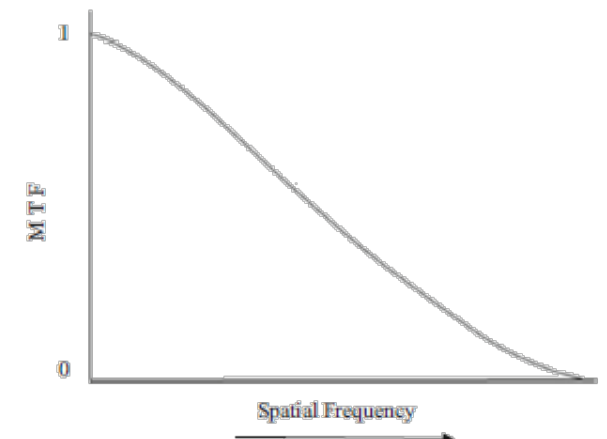
Fig. 2 Concept of contrast ratio a black and white target, and b the intensity distribution



$$C_M = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \quad (3)$$

The contrast modulation is always positive with values ranging between zero and one. When a target is imaged by a camera, the instrument further reduces the contrast so that the contrast in the image plane is less than what is in the object space. This reduction in contrast from object space to image space is represented by Modulation Transfer Function (MTF). That is

$$MTF = \frac{\text{contrast modulation in image space}}{\text{contrast modulation in object space}} \quad (4)$$



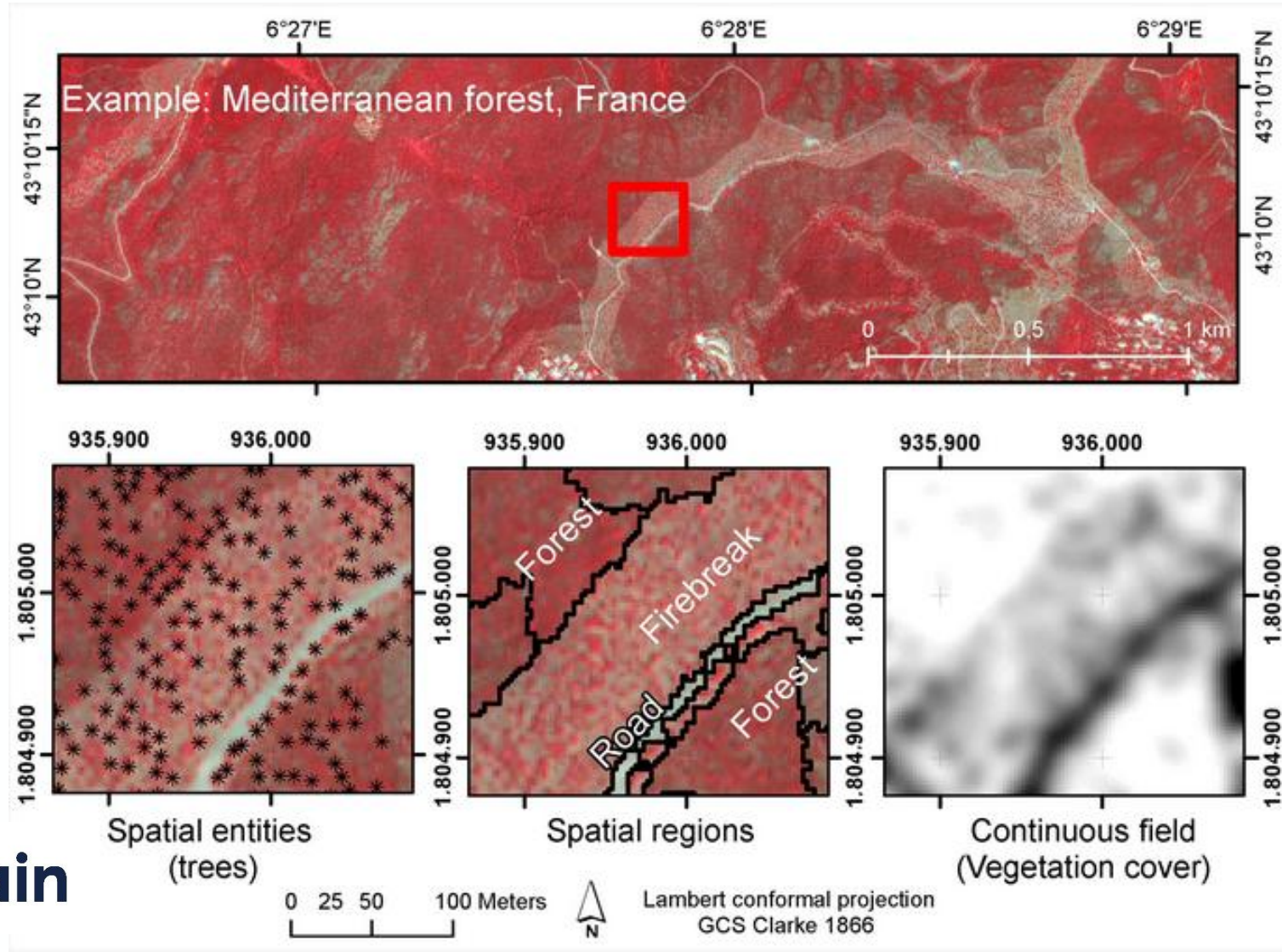
Joseph G., 2020

Driven by field protocol

- Punctual information
- Subjective surrounding
- Homogeneous neighborhood (e.g. LUCAS polygons)
- Object-based (e.g. LPIS parcel)

Precision depends on sampling design and number of samples

In situ must consider the spatial model



Clearly defines spatial objects

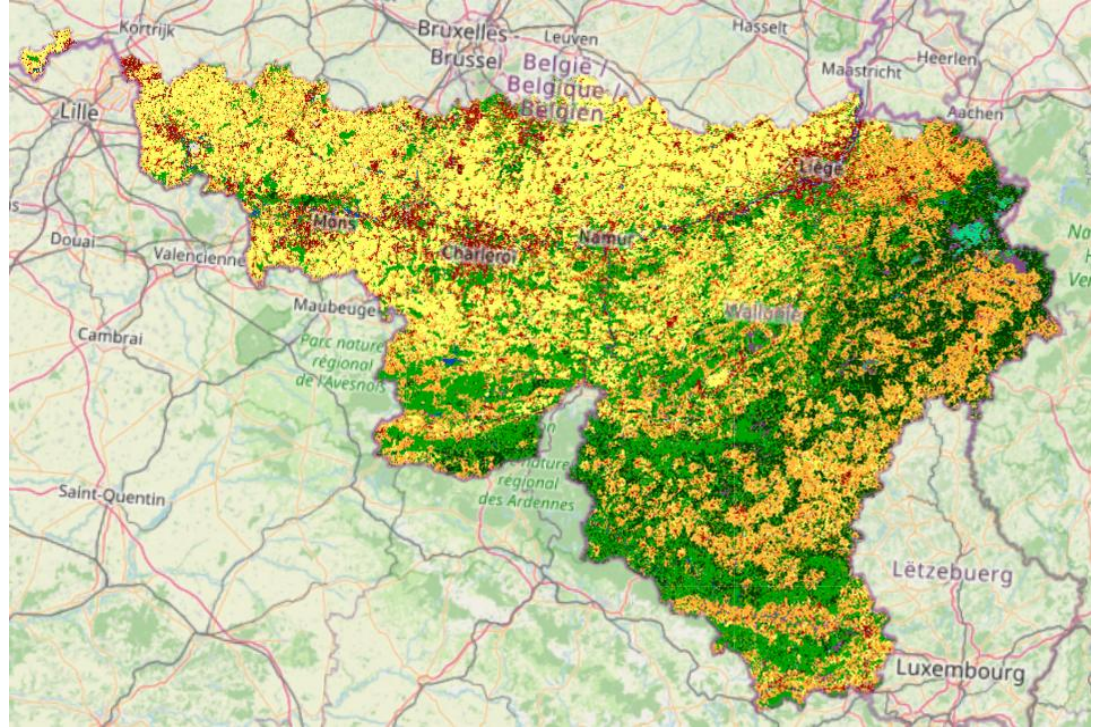
Things that can be embraced on the field. E.g.

- What is a tree ?
 - Vegetation type
 - Lignous
 - More than 3 m (at maturity)
- What is a crop ?
 - Vegetation type
 - Managed
 - Provides food, fuel...
- Now, what about perennial tree crops ?

Photointerpretation can reduce costs, but...

Untrained operator : ~80% accuracy on LC
Consolidation with multiple operators
Trained operator : ~95% accuracy on LC

Our map of Wallonia : 93,7%
=> photointerpretation is not good enough



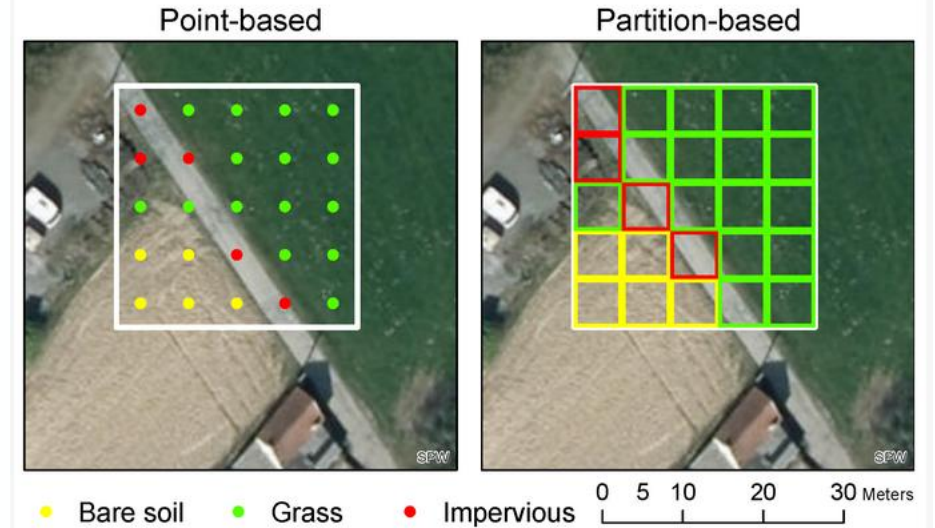
In situ data on uncertain points (does not protect from all systematic errors)

In situ data on subsample (Radoux and Bogaert, 2020)

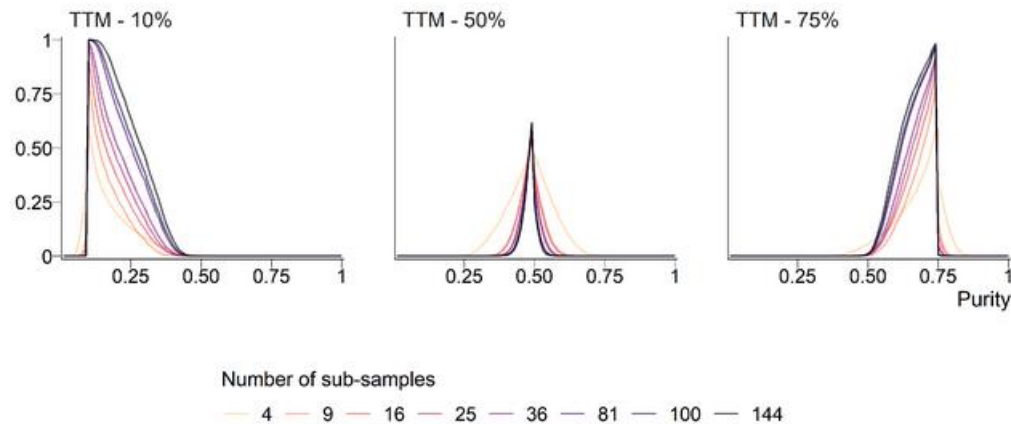


For coarse resolution: estimation of proportions

Needs subpixel description



Label uncertainty strongly increases near class thresholds (Radoux, Waldner, Bogaert, 2020)



Geolocation uncertainty with very high resolution

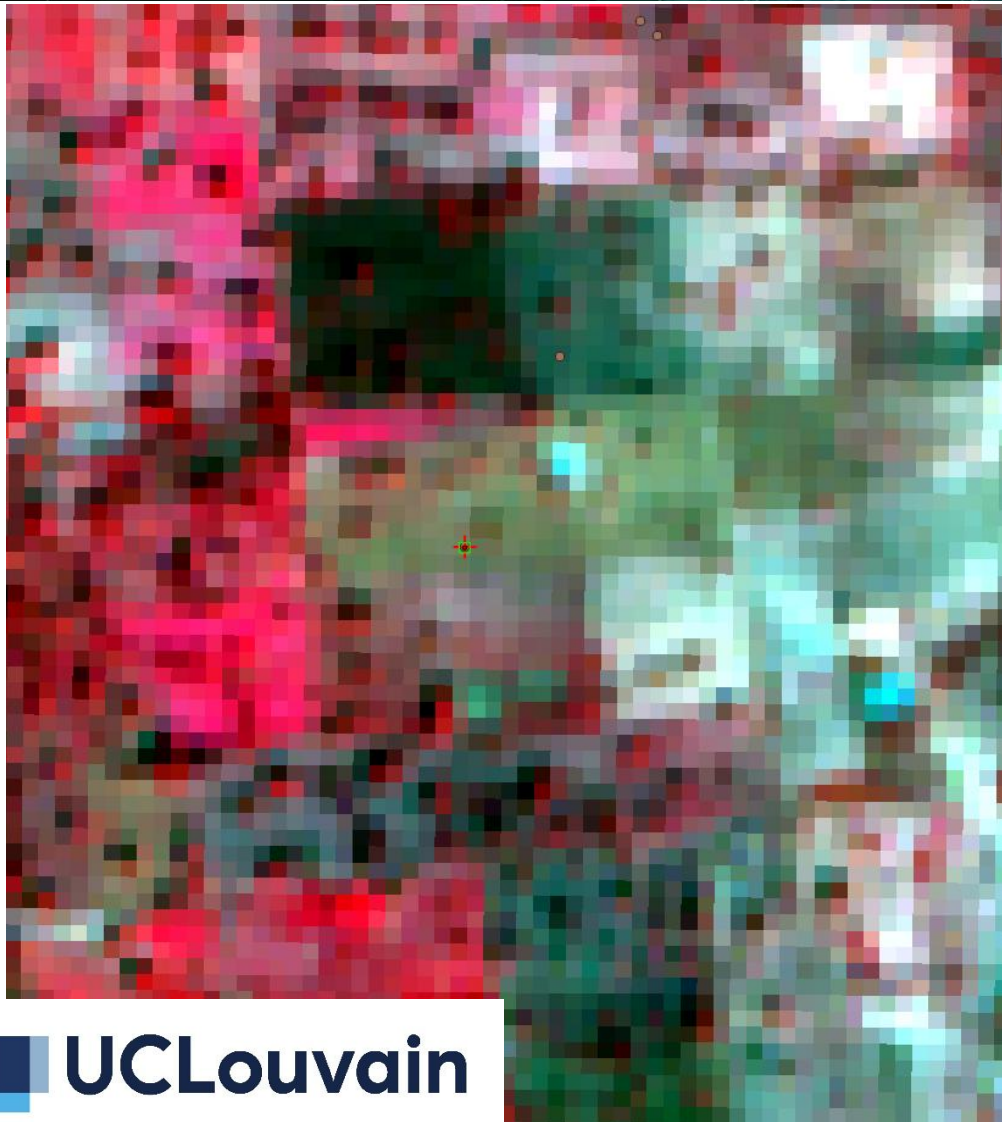
Pixels often smaller than spatial objects

Photointerpretation on same data does not detect geolocation errors

Horizontal shift and shadows also impact HR data



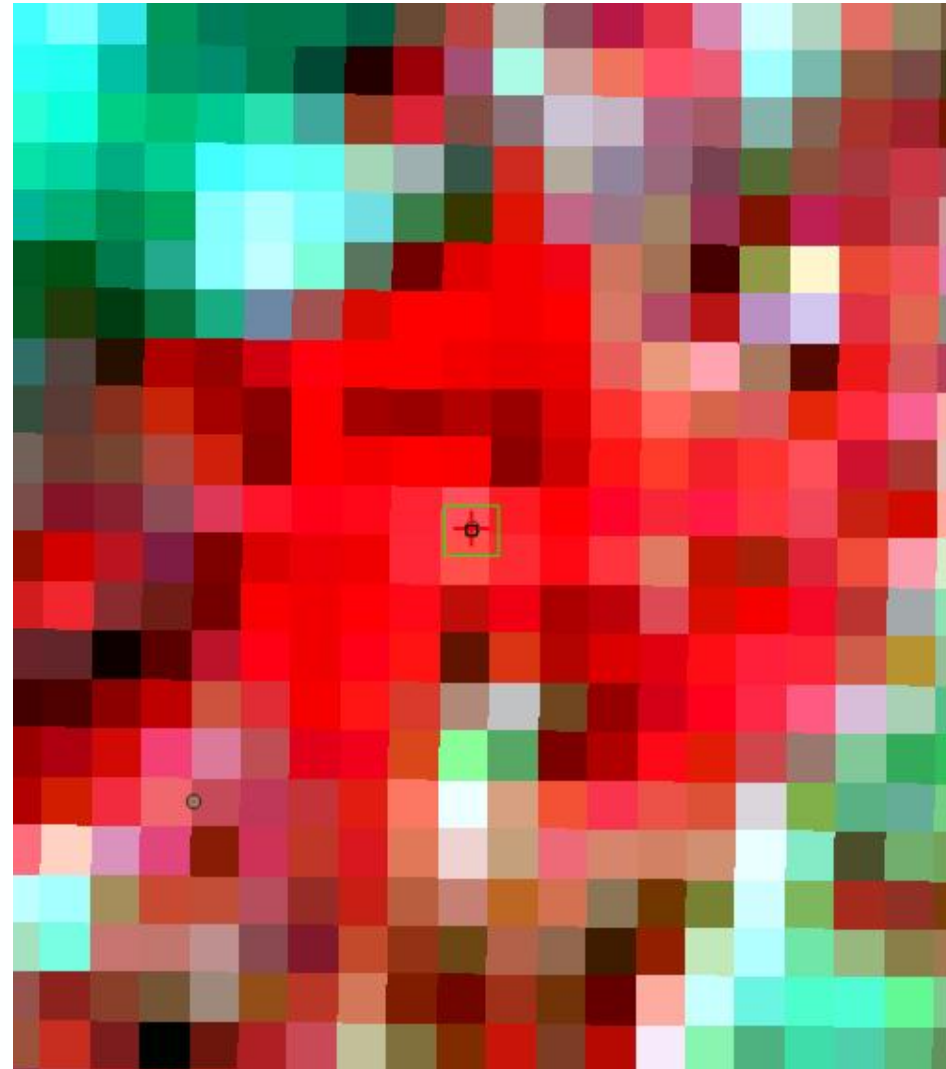
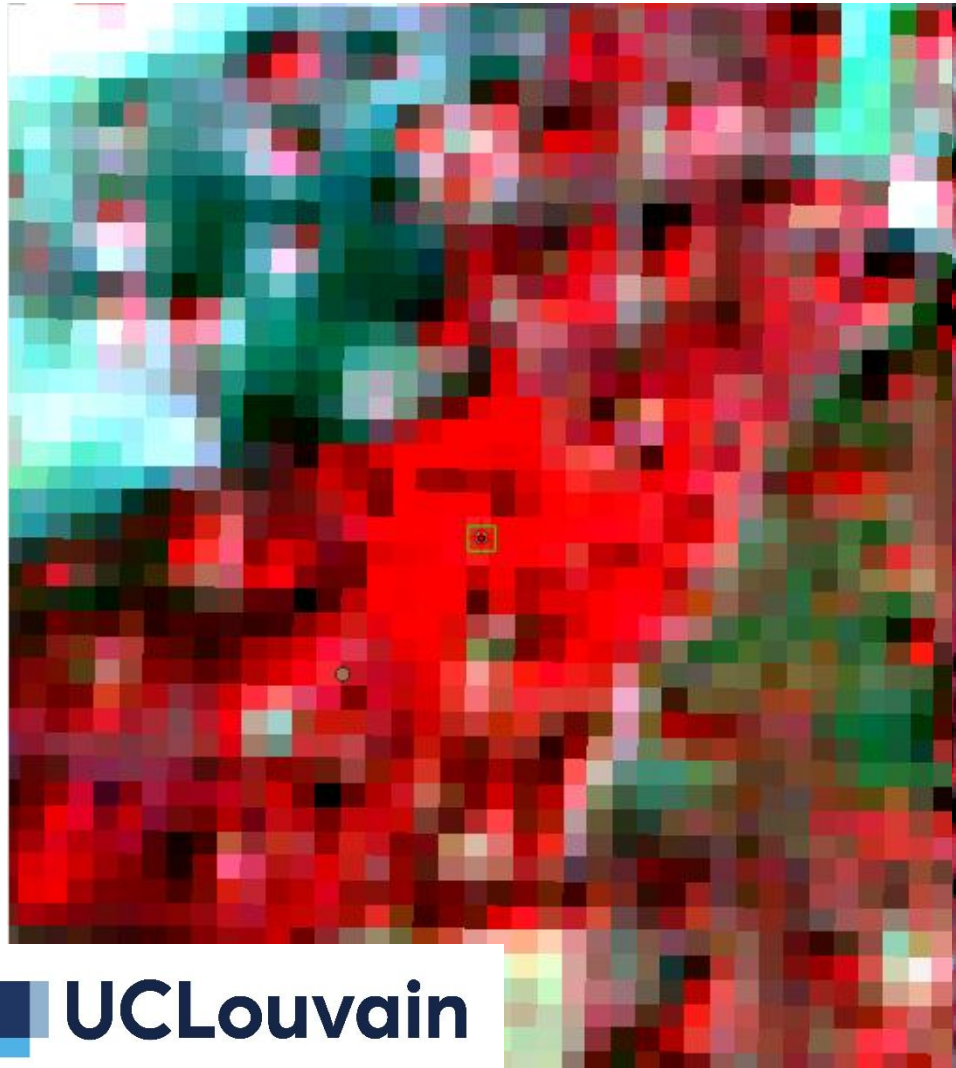
How would you label this ?



- Tree cover
- Cropland
- Sparsely vegetated area
- Other

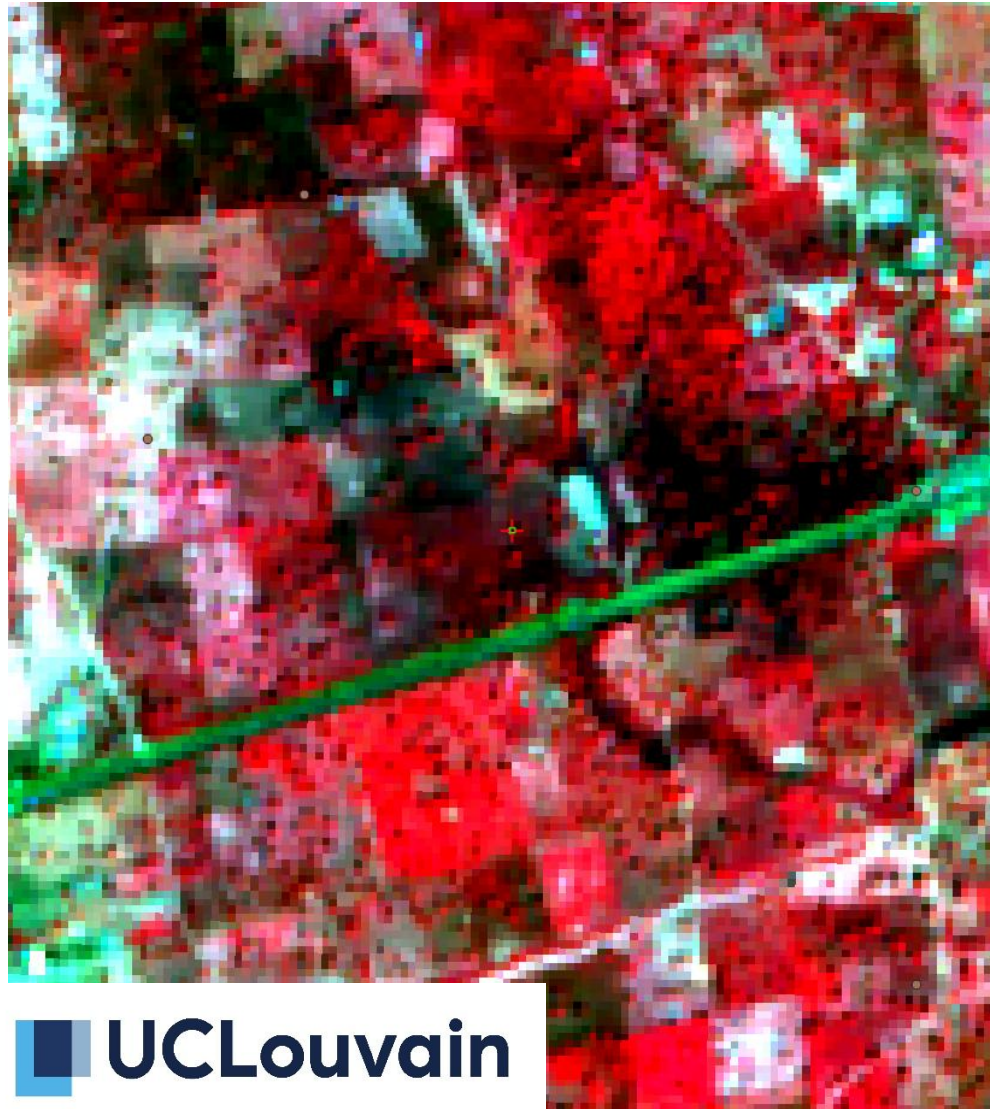
UCLouvain

How would you label this ?



- Cropland
- Tree cover
- Other vegetated area
- Other

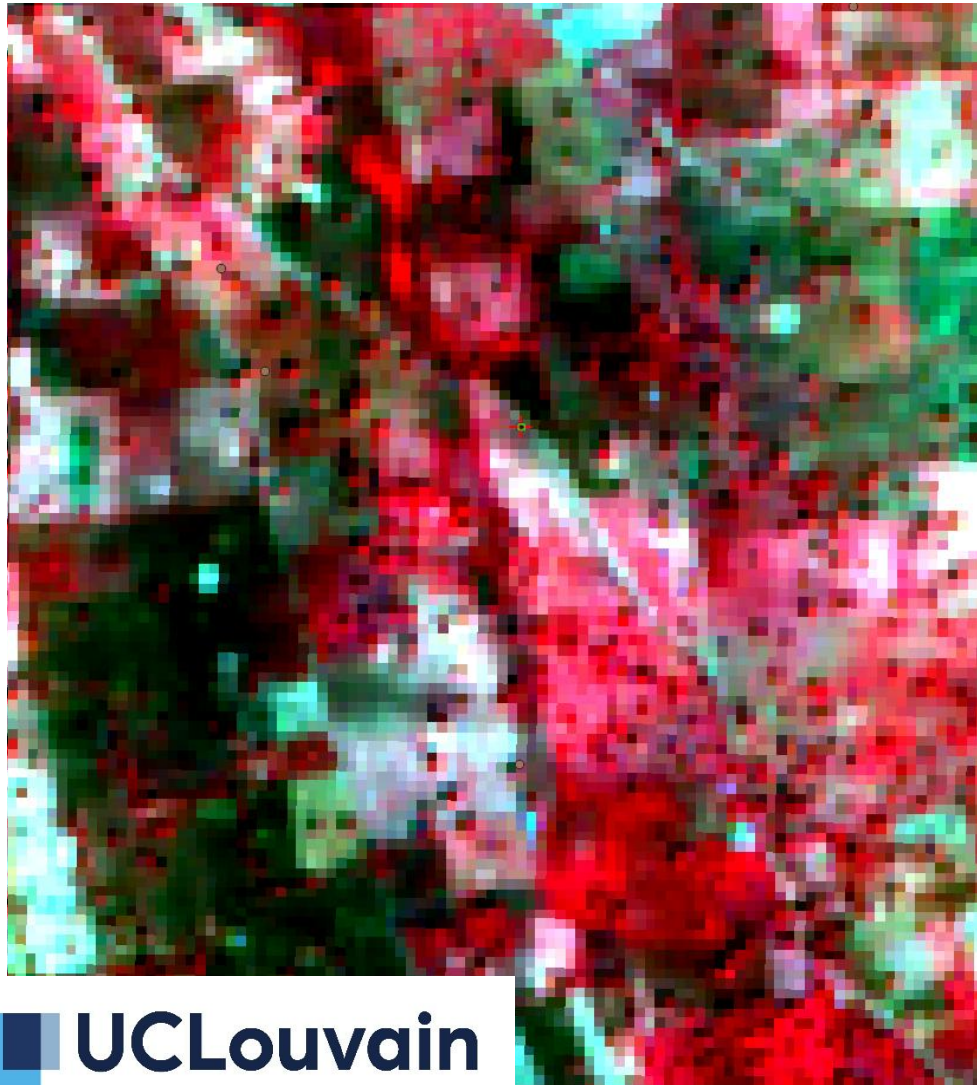
How would you label this ?



- Cropland
- Tree cover
- Tree shadow
- Other / impossible to tell

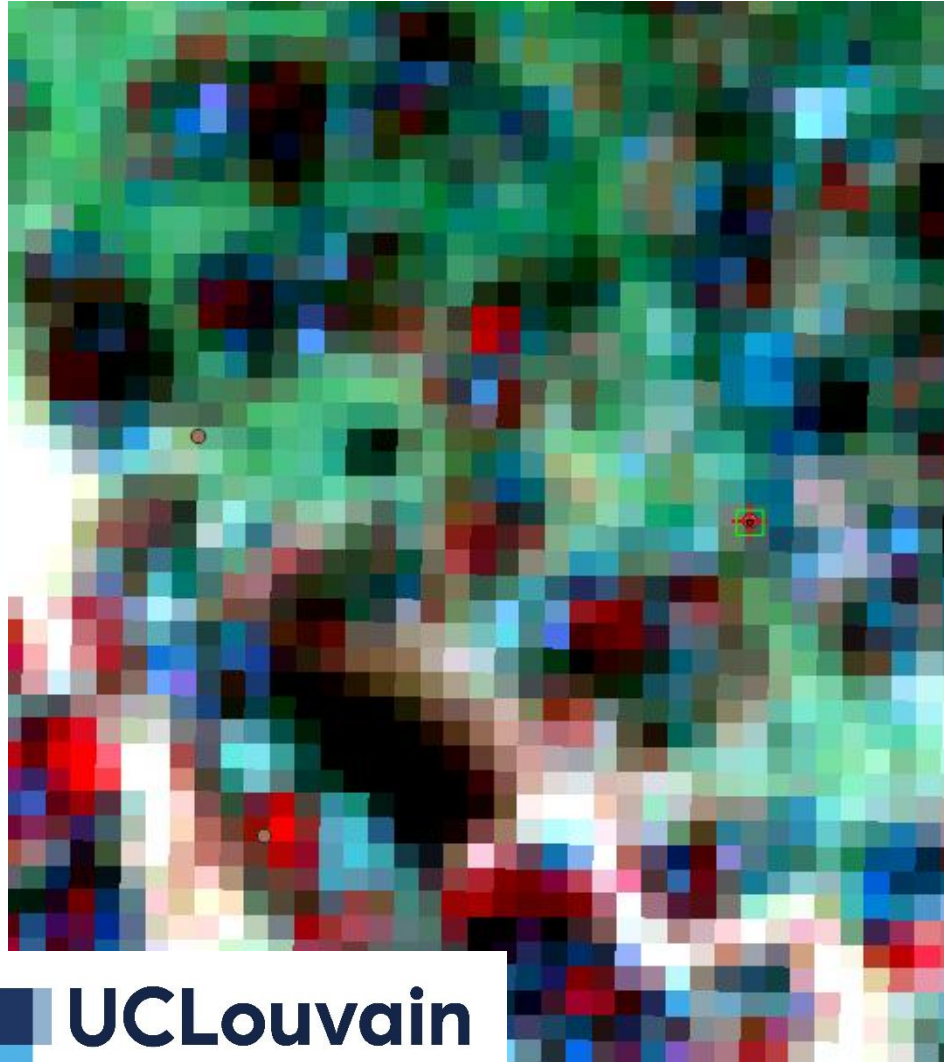
 UCLouvain

How would you label this ?



- Cropland
- Waterway
- Bare soil
- Other

How would you label this ?



- Built-up area
- Bare soil
- Tree cover
- Other

Interoperable **semantics** between RS legend and field protocol

Sampling probability must be included

Quality of in situ is more important than quantity