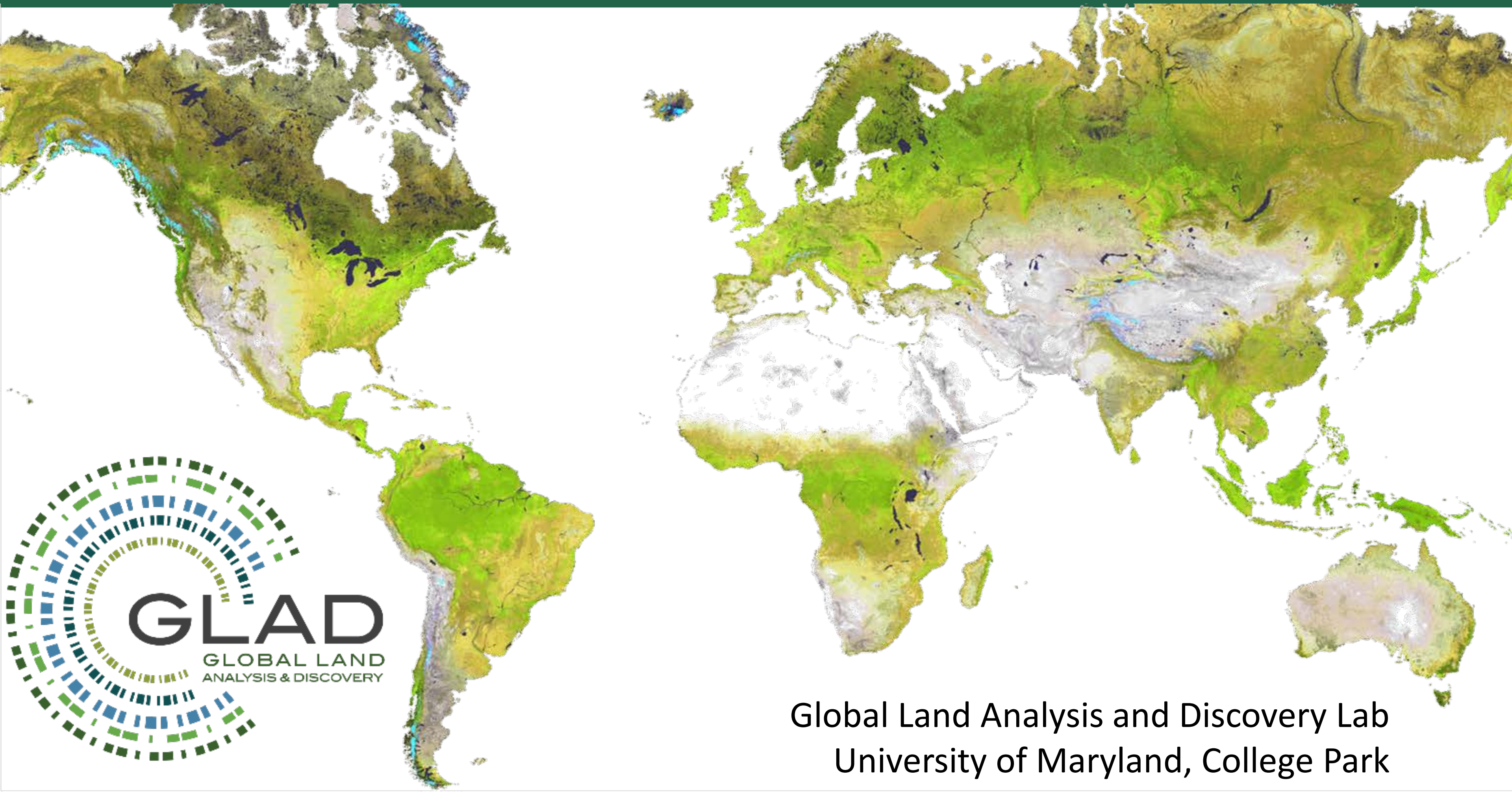
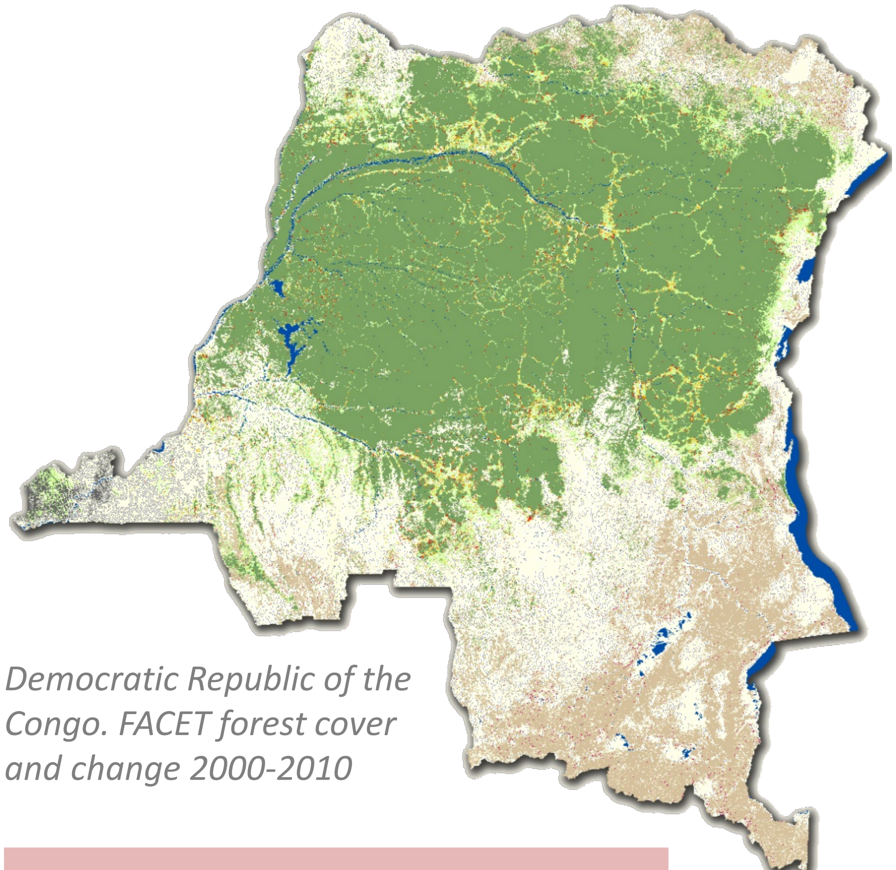
Estimating Tree Cover Area and Change Using Sample-based Analysis



Global Land Analysis and Discovery Lab
University of Maryland, College Park

Statistical Sampling

Spatially exhaustive (wall-to-wall) mapping

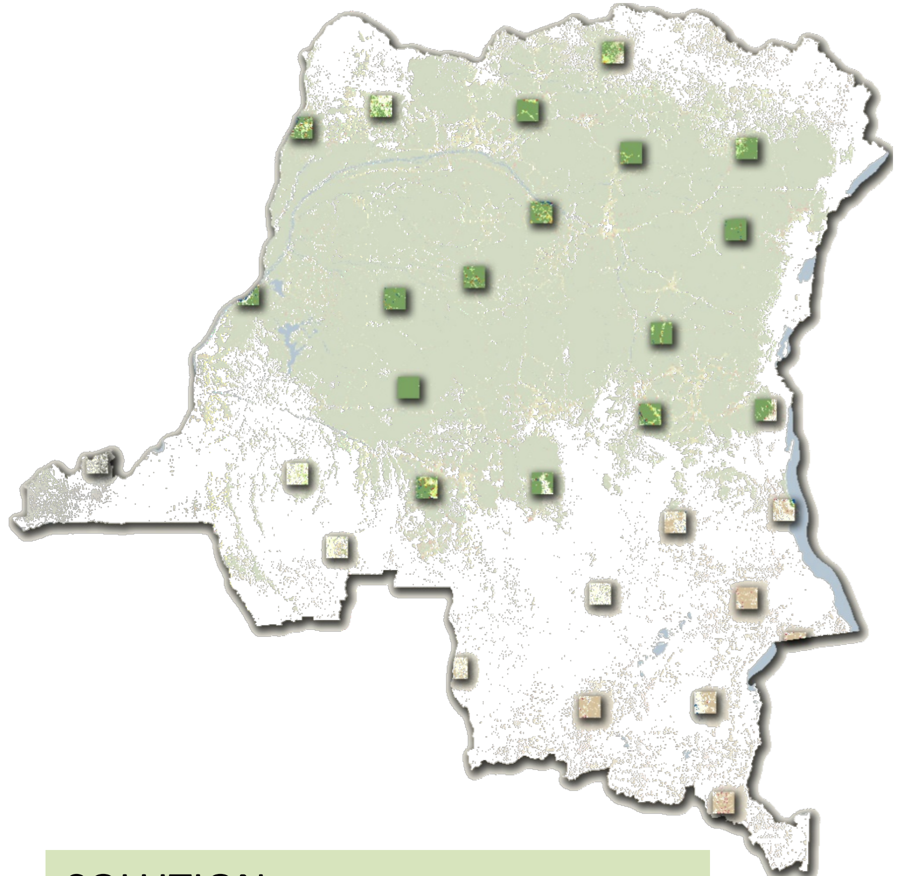


Democratic Republic of the Congo. FACET forest cover and change 2000-2010

PROBLEM

All maps produced using remotely sensed data have errors, which bring bias to the areas calculated from the map

Statistical sampling

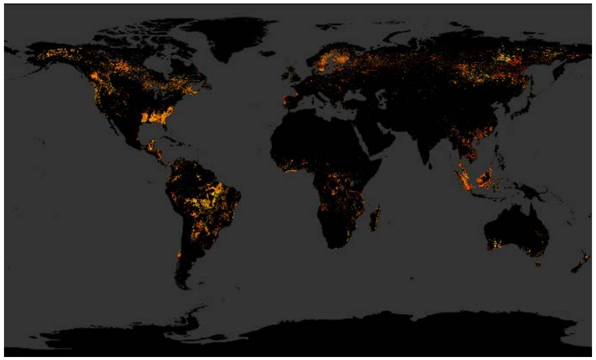


SOLUTION

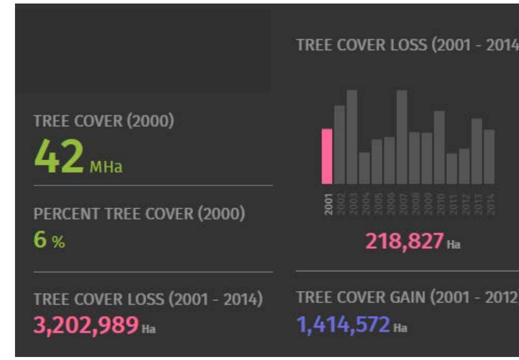
Reference sample data can be used to produce an unbiased estimate of area of map classes with known uncertainty (Olofsson et al. 2013, 2014)

Statistical Sampling

Wrong way



Direct area extraction from the global map



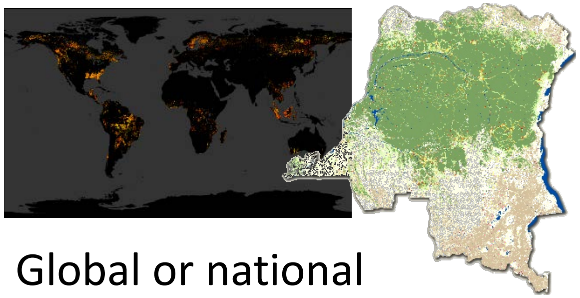
Global forest extent and change products provides spatially consistent, wall-to-wall data…

However:

- All maps derived from remotely sensed data contain errors due to data limitation, classification/change detection algorithm limitation, analyst errors and bias, etc.
- Errors on the global overview maps usually introduce bias in area estimations. Most of the overview maps provide “conservative” estimates of rare classes, i.e. they underestimate forest change.
- The global map errors may be spatially biased (e.g. due to different characterization model sensitivity within different environments).
- The uncertainty of classification may not be estimated from the map alone.

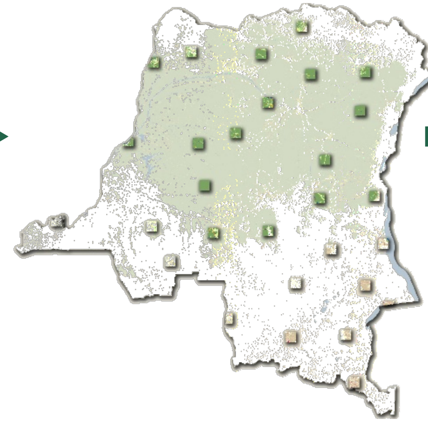
Statistical Sampling

Good practice



Global or national
wall-to-wall TC change maps

Statistical
sampling



Sample-based:

- Map accuracy
- Area
- Uncertainty

Spatially exhaustive (wall-to-wall) maps

- Provide information on spatial allocation of forest cover and change.
- Allow sampling design/area estimation with improved efficiently and precision.
- Global maps may have limitations and should be substituted with regional/national maps when possible.

Sample-based assessment (reference sample data)

- Provides highest quality determination of the forest cover and change conditions per sample unit
    - Serves as reference data for map **accuracy assessment.**
    - Allows **unbiased area estimation** with known **uncertainty.**

Statistical Sampling

Probability sampling allows to:

- Quantify map accuracy
  (Overall, User's, Producer's).

- Estimate "true" (unbiased) areas of mapped classes.

- Estimate uncertainty of the mapped classes area.

- Perform value-added thematic analysis based on visual sample interpretation (e.g. differentiate various types of forest or forest disturbance).

Sampling design

Primary stages of sampling assessment:

1. **The sampling design**: how to select the reference sample.
2. **The response design**: how to determine the “ground truth” for each observation in the reference sample.
3. **The estimation and analysis protocol**: how to estimate area and uncertainty and quantify the accuracy of the map.

Sampling design

Basic principles of sampling design for TC/TCC assessment

- The **entire area of analysis** should be included into sampling frame.
- Samples should be allocated using **probability sampling** (e.g., randomly). Spatial autocorrelation does not usually affect sample-based estimates. Random allocation is preferred in most cases.
- Samples should **NEVER** be used as classification training.
- Samples should be **in sufficient number** (typically large) to reduce the uncertainty of accuracy metrics. For stratified sampling, at least 100 samples per strata is recommended.
- The number of samples is not correlated with the total population (number of pixels in the map). Only the **total number of samples drives the precision**, not the fraction of the area sampled.
- Each valid sample should have map data and reference data.

Sampling design

Sampling unit

Sampling units

point
(no areal extent)

areal:
- **one pixel**
- pixel block (3x3; 5x5)
- polygon (e.g. land cover unit, segment)
- fixed-area plot (rectangular, circular)

Considerations when choosing sampling unit:
- Cost/time of deriving reference value;
- Sensitivity to location error (boundary pixels and polygons);
- Ability to retain identity under map revisions (e.g. map polygons may change in case of a map reclassification).

Stehman and Czaplewski (1998): "No consensus exists on which sampling unit is best, and it is unlikely that any one sampling unit is optimal for all applications"

Sampling design

Sampling design – the protocol by which the reference sampling units are selected

Probability sampling:
all sampling units have nonzero inclusion probability

⬇

statistically valid estimates can be computed

Nonprobability sampling:
inclusion probabilities for the samples can not be defined

⬇

should not be used for the accuracy assessment or area estimation

Examples of probability sampling designs:

- Simple random
- Systematic
- Stratified random
- Stratified systematic
- Cluster random
- Cluster systematic
- Stratified random cluster
- Stratified random systematic

Examples of nonprobability sampling:

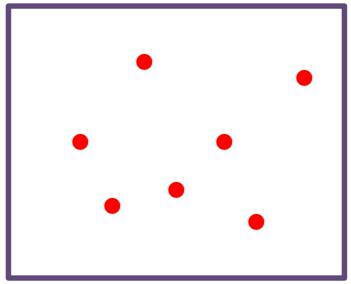
- Purposefully selecting training data for a supervised classification;
- Selecting reference samples from conveniently accessible sites;
- Using available aerial photography or high resolution imagery.

from Stehman and Czaplewski, 1998

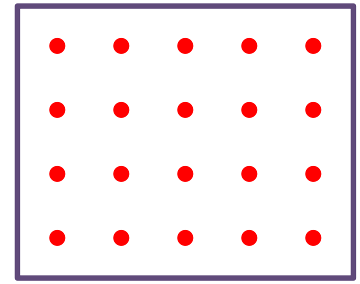
Sampling design

Common probability sampling designs

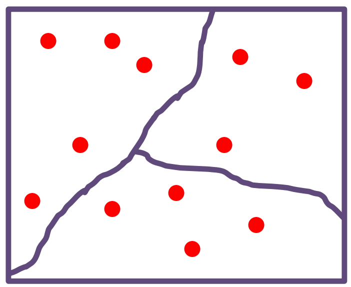
1. Simple random



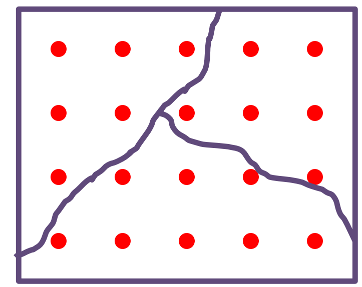
2. Systematic



3. Stratified random

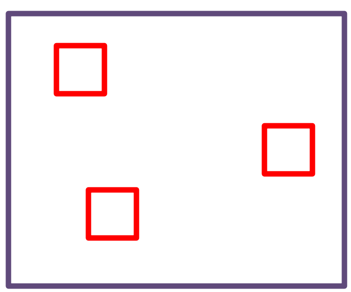


3. Stratified systematic



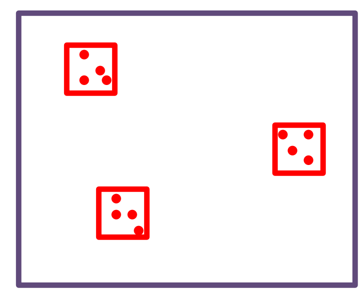
4. Cluster random one-stage

Reference data obtained for all pixels in the block (cluster)



4. Cluster random two-stage

Reference data obtained for a sample of pixels in the block (cluster)



Sampling design

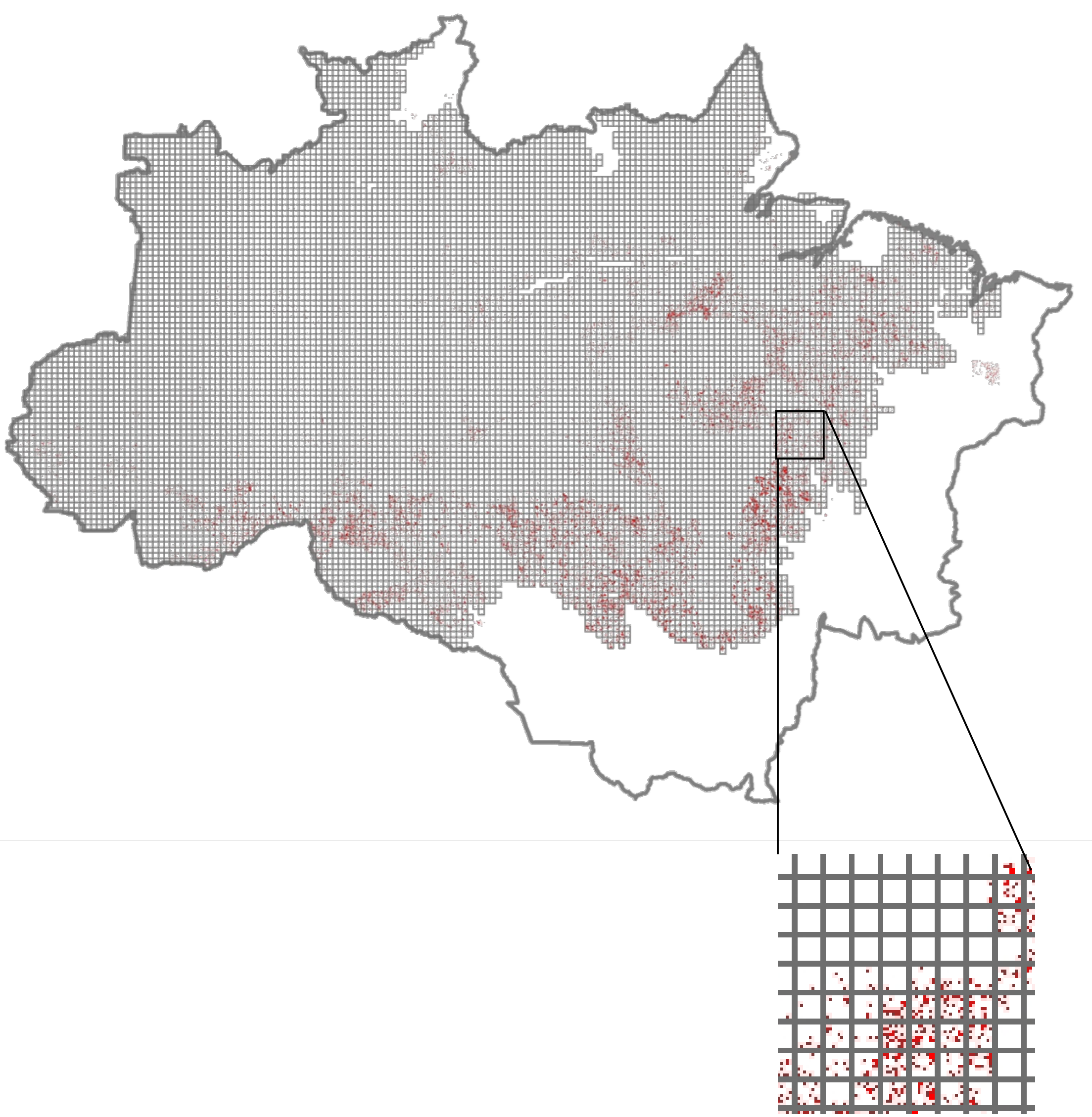
Test data:
PRODES Landsat-mapped forest cover loss 2000-2005

Broich et al. (2009)

Sampling design

Test data:
PRODES Landsat-mapped forest cover loss 2000-2005

Sampling frame:
18.5x18.5km sample blocks

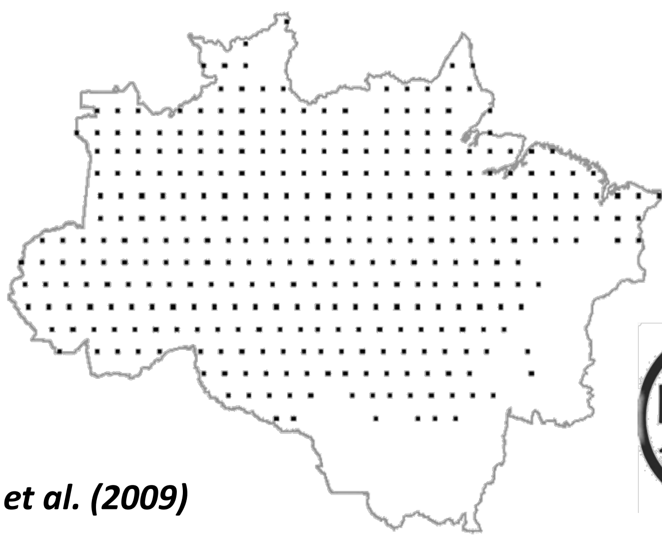


Broich et al. (2009)

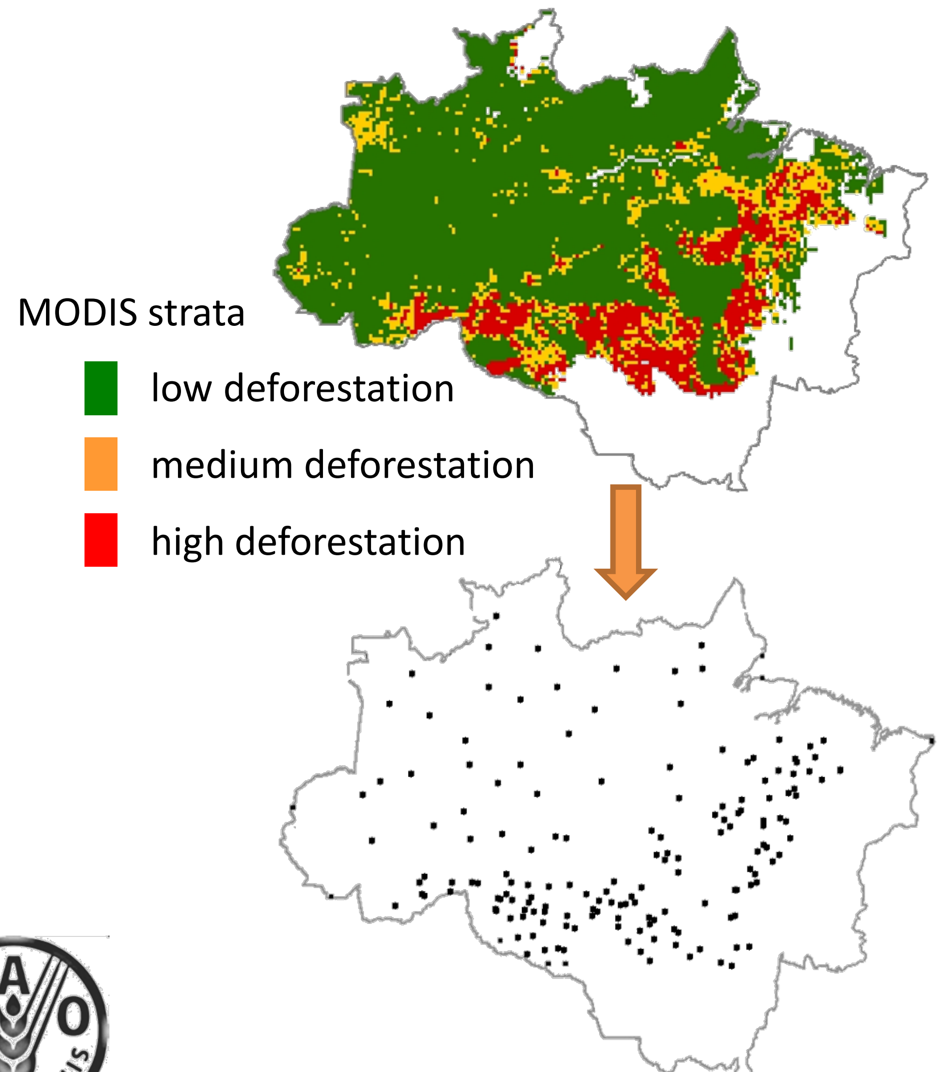
Sampling design

Random sampling

Systematic sampling



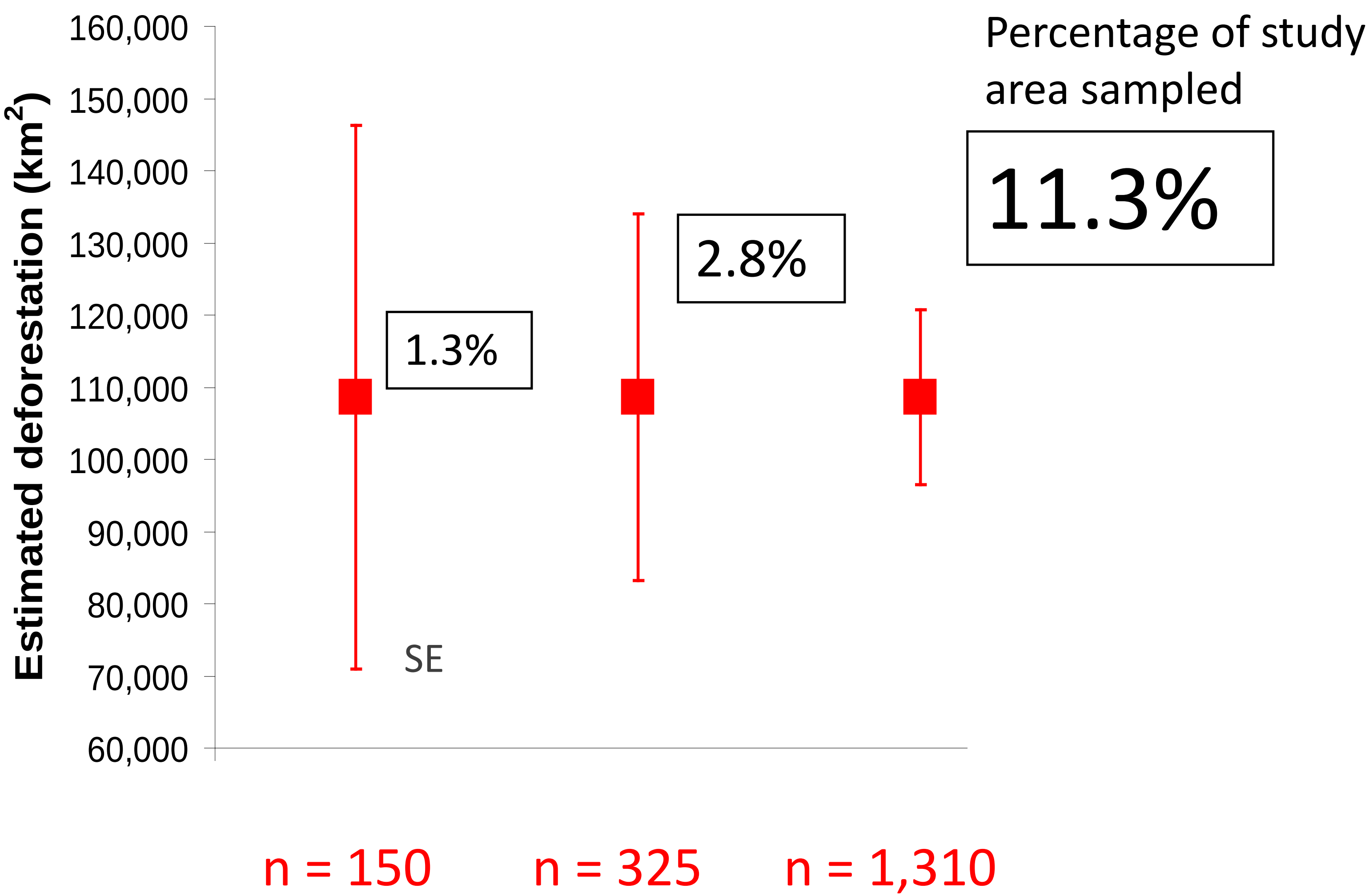
Stratified sampling



Broich et al. (2009)

Sampling design

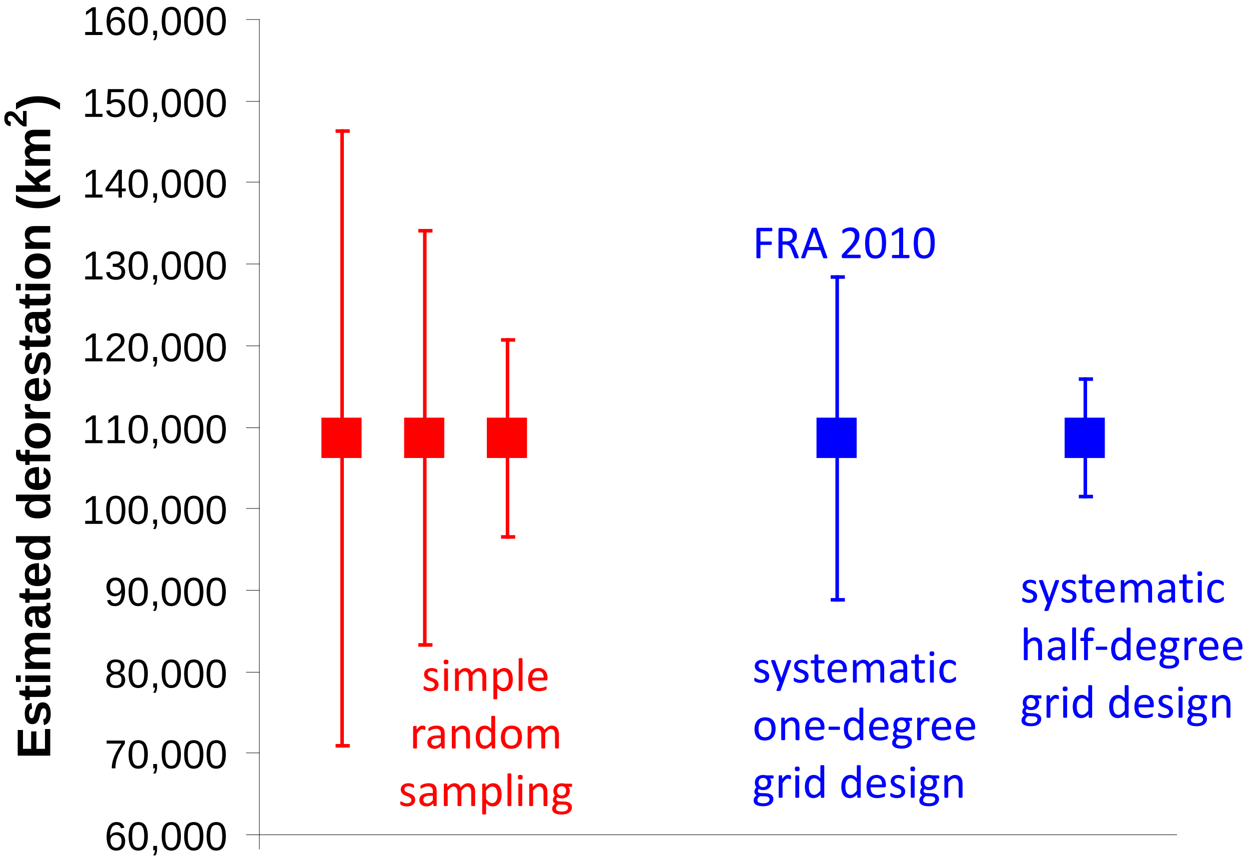
Random sampling



Broich et al. (2009)

Sampling design

Random **Systematic sampling**



n = 150 | 325 | 1,310

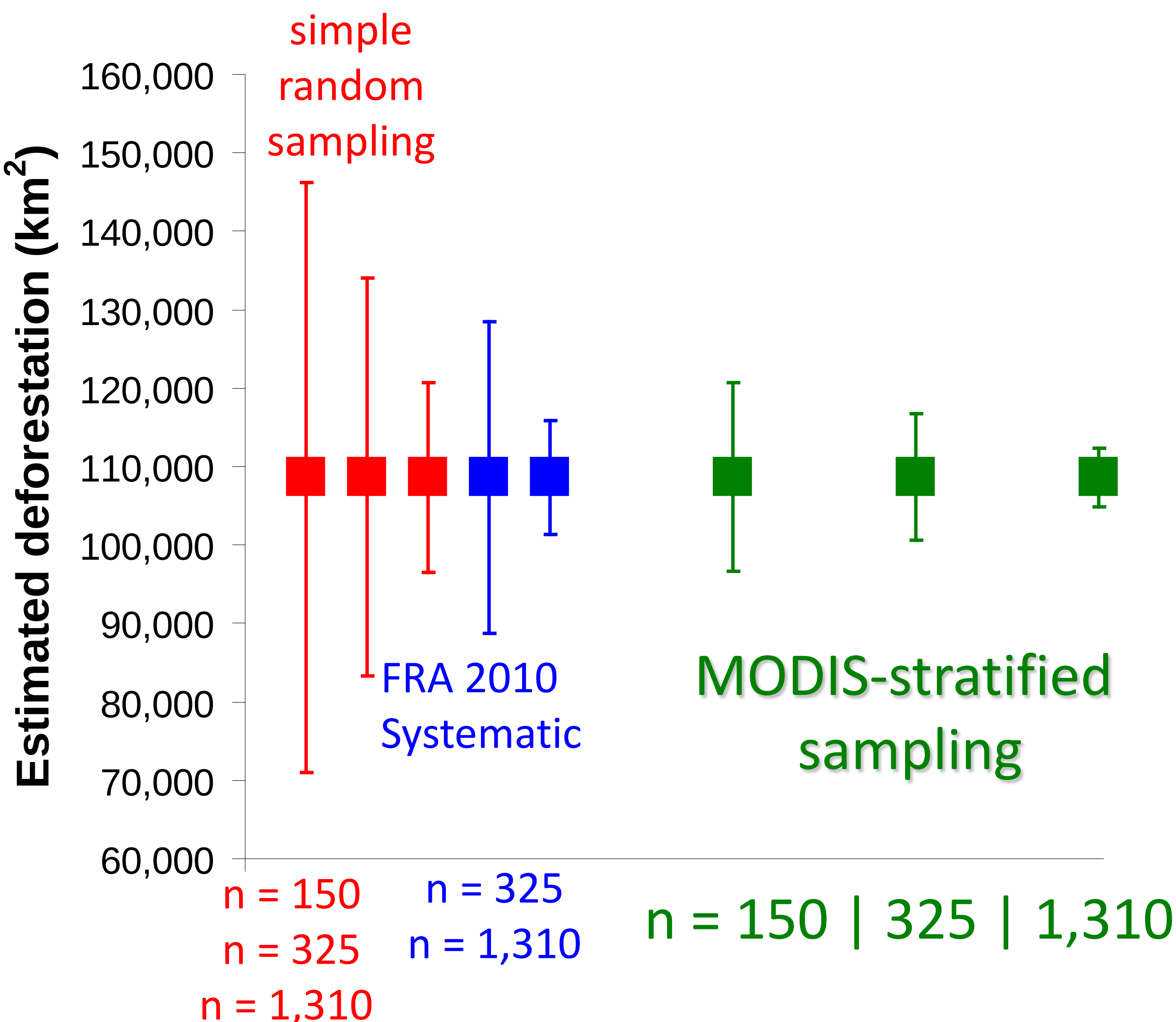
n = 325

n = 1,310

Broich et al. (2009)

Sampling design

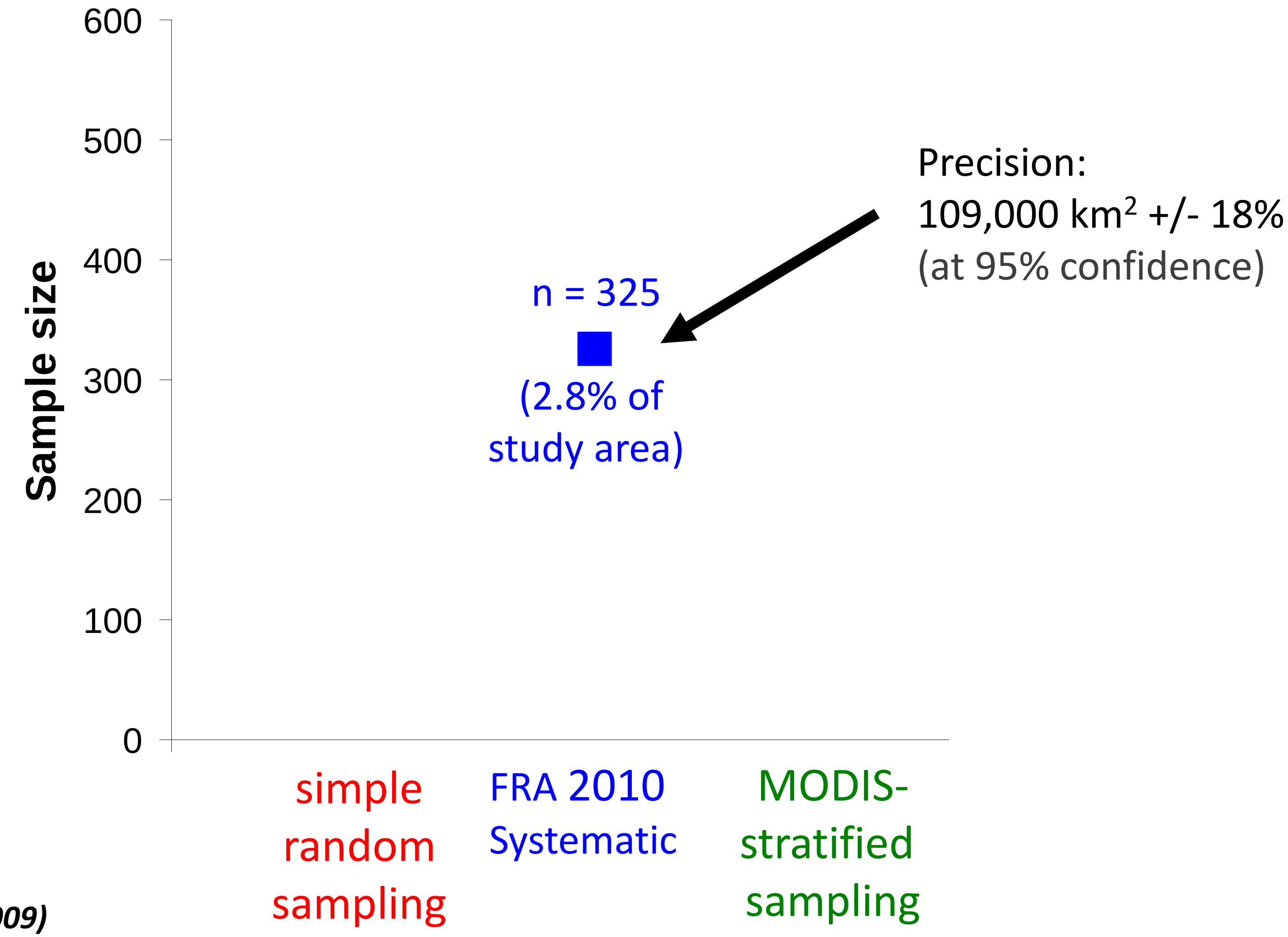
Random **Systematic** **Stratified sampling**



Broich et al. (2009)

Sampling design

Sample size needed to achieve precision of FRA 2010 (systematic one-degree grid design)



Broich et al. (2009)

Sampling design

Common probability sampling designs

From Stehman (2009):

Table 4. Relative strengths and weaknesses of basic sampling designs according to desirable design criteria. The criteria are: *C1*) probability sample, *C2*) practical, *C3*) cost, *C4*) spatial balance, *C5*) precise estimates of class-specific accuracy, *C6*) ability to estimate standard errors, and *C7*) flexible to change in sample size. The rating symbols are ●=strength and ○=weakness; absence of a symbol indicates the design is 'neutral' with regard to that criterion. See also section 5.4 in text.

Design	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*
D1: Simple random	●	●	○	○	○	●	●
D2: Systematic	●	●	○	●	○	○	○
D3: Stratified (land cover) random	●	●	○	○	●	●	●
D4: Stratified (land cover) systematic	●		○		●	○	○
D5a: Stratified (spatial) random (n_h=1)	●	●	○	●	○	○	
D5b: Stratified (spatial) random (n_h>1)	●	●	○		○	●	●
D6: Stratified (spatial) systematic	●	●	○	●	○	○	○
D7: Cluster random	●		●	○	○	●	
D8: Cluster systematic	●		●		○	○	○
D9: Stratified random cluster	●		●	○			
D10: Stratified systematic cluster	●		●			○	

Olofsson et al. (2014):

Stratified random sampling is a recommended "good practice" sampling design

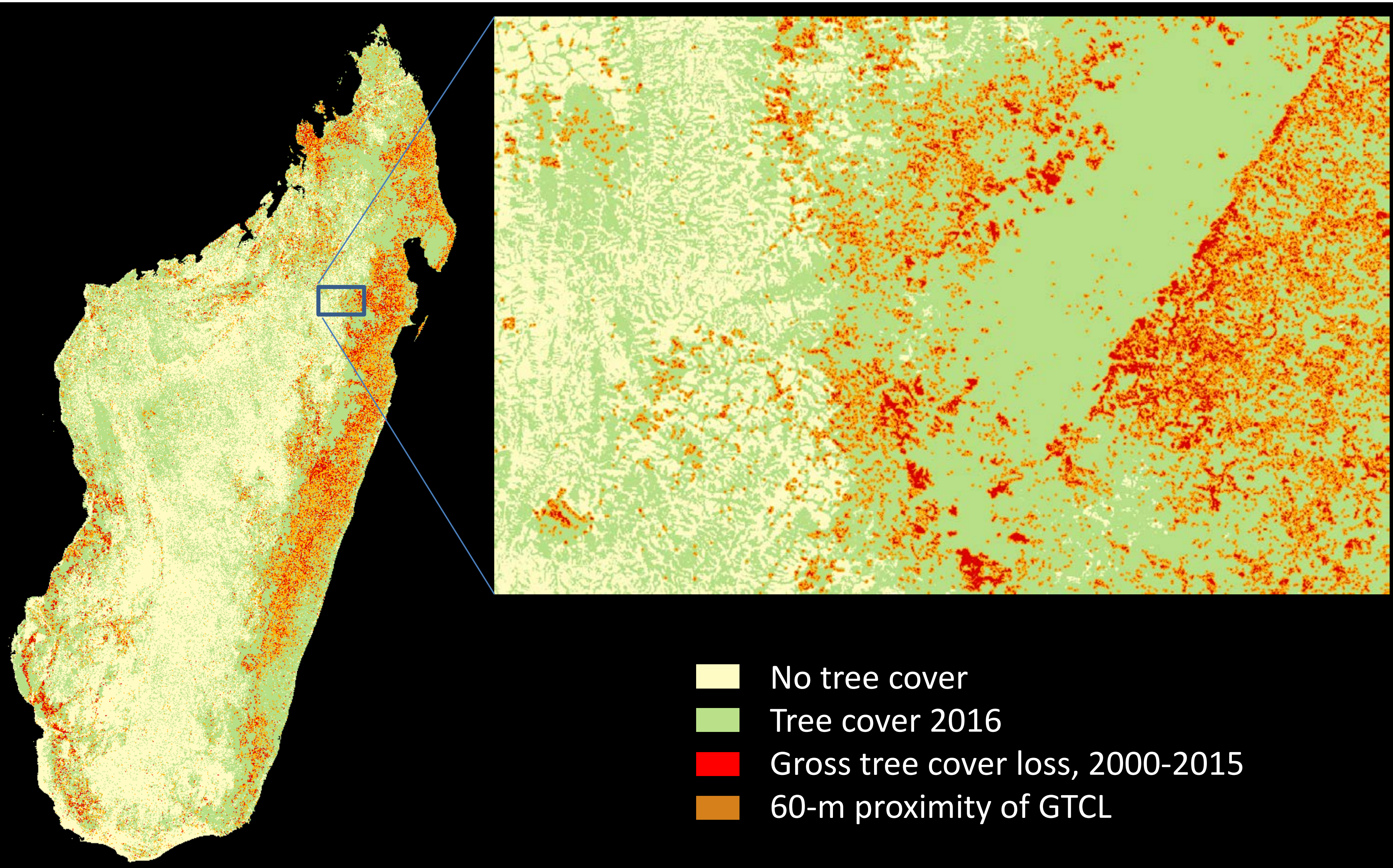
Sampling design

Principles of stratified random sampling design

- Assign all pixels to groups (strata). Strata should represent areas with low variability of the measured quantity (e.g. forest change). Alternatively, "natural" strata may be used (e.g. land-cover classes). In this case, however, stratification may not have effect on the uncertainty of the estimate.
- The large number of strata will require large number of samples and will complicate accuracy and area estimation. If required, post-strata may be added later to characterize specific regions or land cover types.
- Specify sample size for each stratum. Equal, proportional, or other allocations may be used. Ensure that rare classes (strata) appear in the sample. Sample may be added later to strata which contribute most to the overall uncertainty.

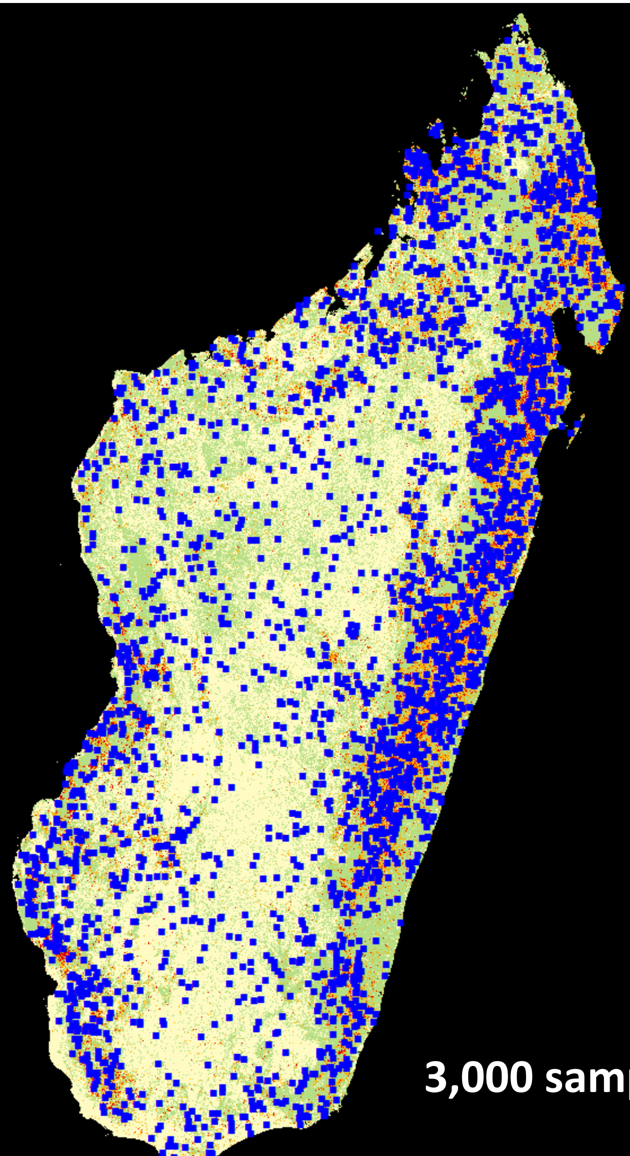
Sampling design

Sampling design to quantify tree cover change in Madagascar, 2000-2015



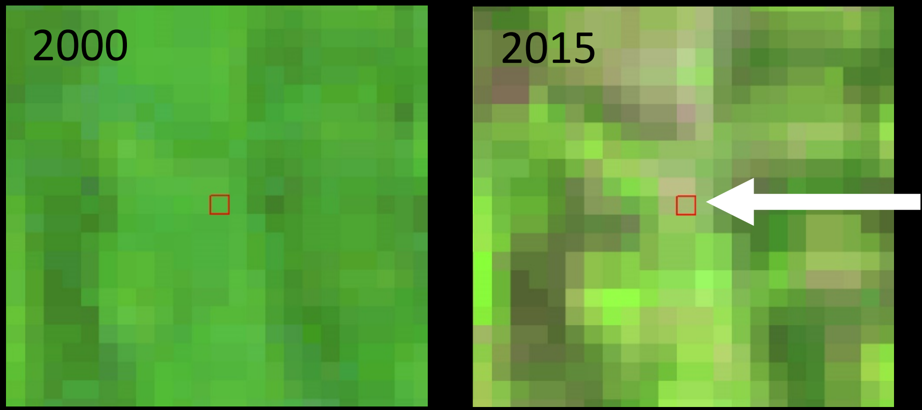
Sampling design

Sampling design to quantify tree cover change in Madagascar, 2000-2015



3,000 samples

Stratum	area, ha	count, 30x30m pixels	% total	Total samples	Training goal
No loss / no trees	25,141,547	348008206	43	200	50
No loss / tree cover	23,815,964	327272139	40	800	150
Loss 2001-2015	2,658,505	36480651	4	1000	150
Buffer around loss	7,528,648	103251036	13	1000	150
Total	*59,144,663*	*815012032*		*3000*	*500*



Sample (30x30 m)

No tree cover

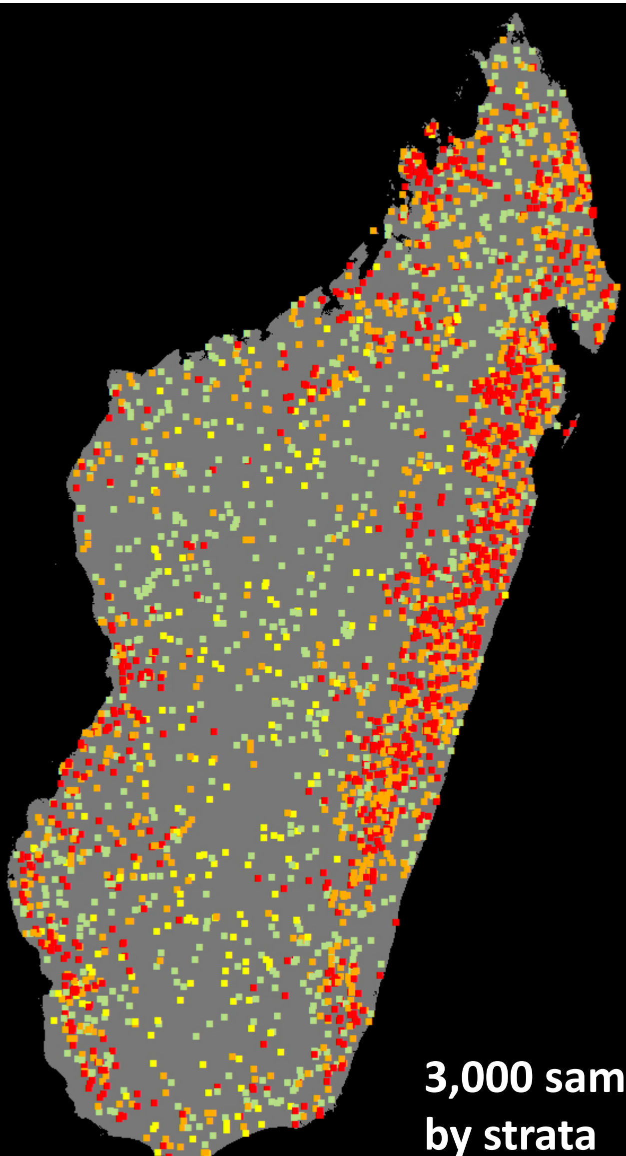
Tree cover 2016

Gross tree cover loss, 2000-2016

60-m proximity of GTCL

Sampling design

Sampling design to quantify tree cover change in Madagascar, 2000-2015



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Total	*59,144,663*	*815012032*		*3000*	*500*

3,000 samples by strata

No tree cover
Tree cover 2016
Gross tree cover loss, 2000-2016
60-m proximity of GTCL

Response design

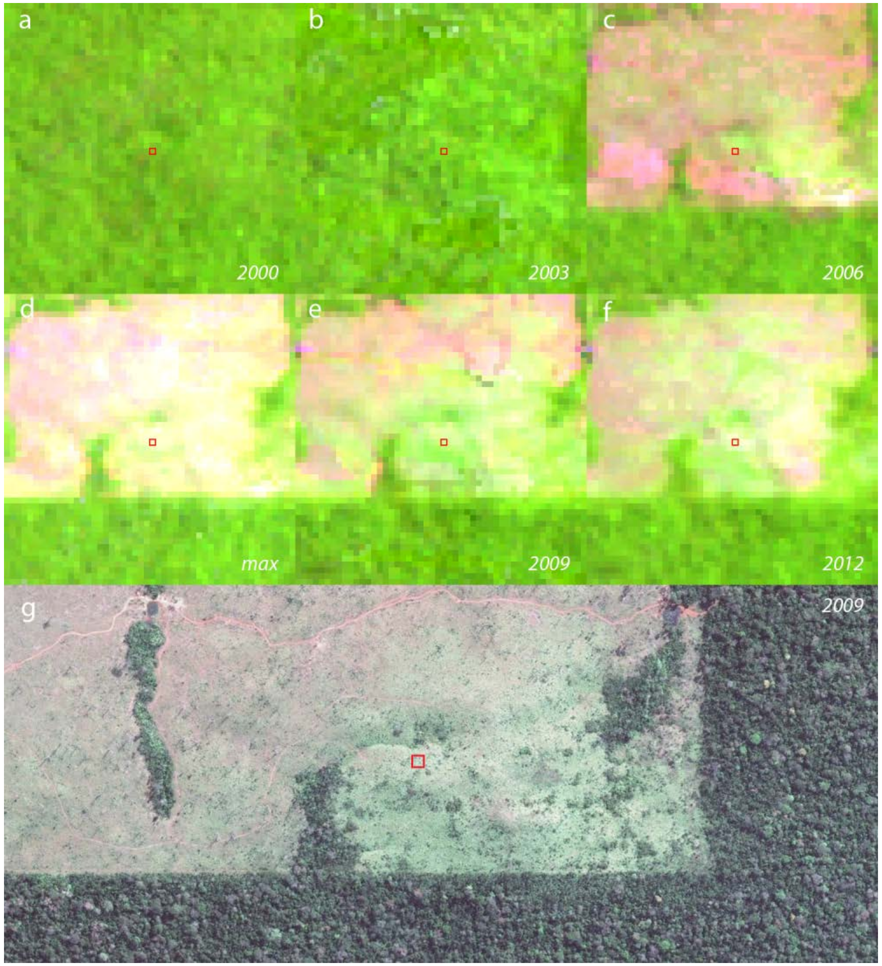
Reference classification should be:

- Of higher quality than what was used to create the map (e.g. high resolution imagery to validate Landsat-based map);

OR

- Created in a more accurate way, if the same data were used for both the map and reference classifications (e.g. visual interpretation of Landsat time-series to validate Landsat-based map derived using supervised classification).

Reference labeling protocol and rules for defining agreement between reference and map should be established prior to validation



Mato Grosso, Brazil

Possible sources of error in reference classification:

- Geolocation errors (spatial mismatch between reference data and map)
- Interpretation uncertainty (interpreter error in the assignment of reference class and difference between interpreters)

from Olofsson et al., 2014

Response design

Collecting sample (reference) data

Field data collection steps

1. Define sample locations (i.e. allocate samples randomly within the entire area, or within accessible area).
2. Develop efficient plan for visiting sites and contingencies for unreachable sites.
3. Use GPS (satellite images, on-line and off-line maps) to find pre-determined reference sites.
4. Use explicit definitions of the classes to insure that reference data are consistent

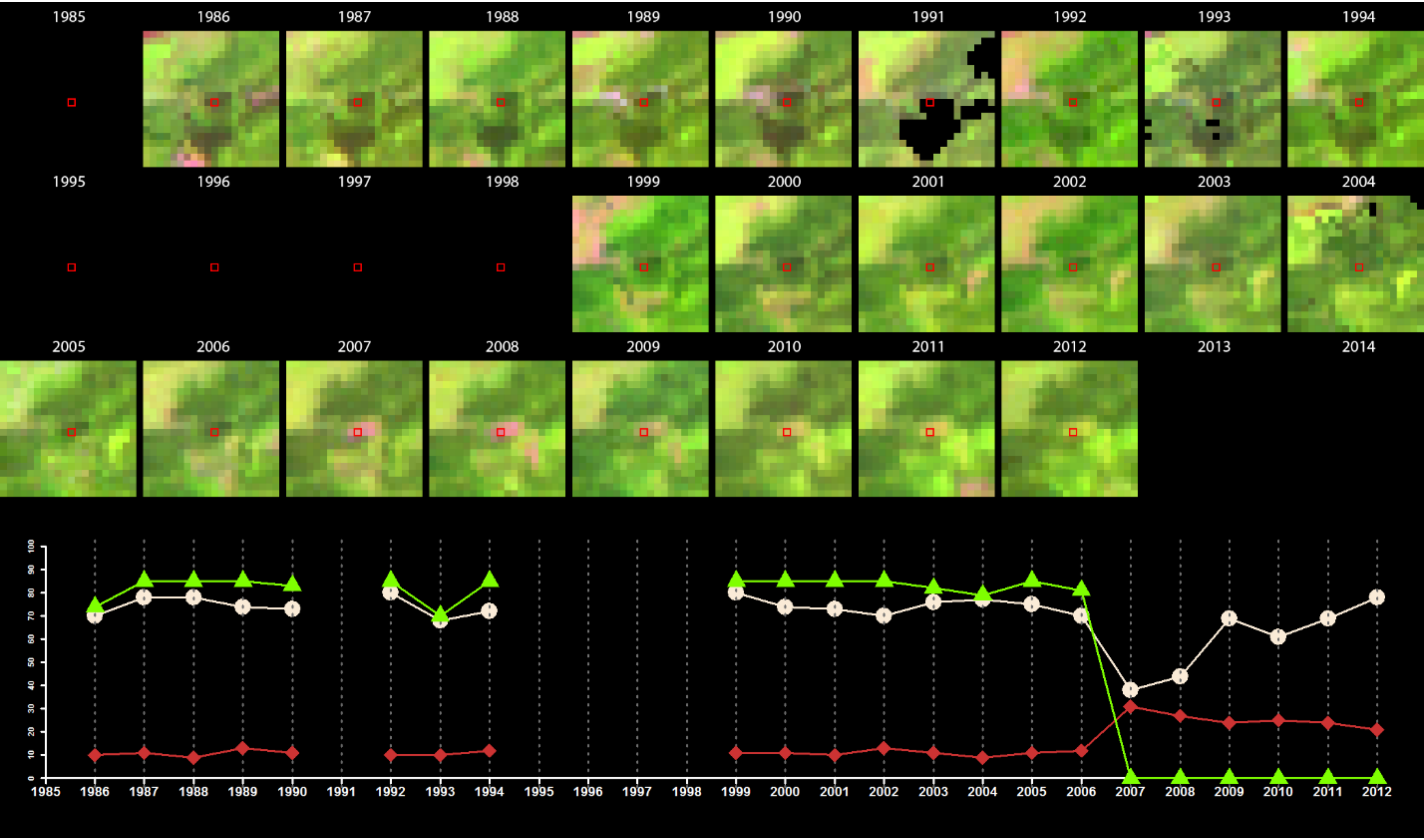
National Park Service image (nps.org)

Response design

Collecting sample (reference) data

Using high-resolution images

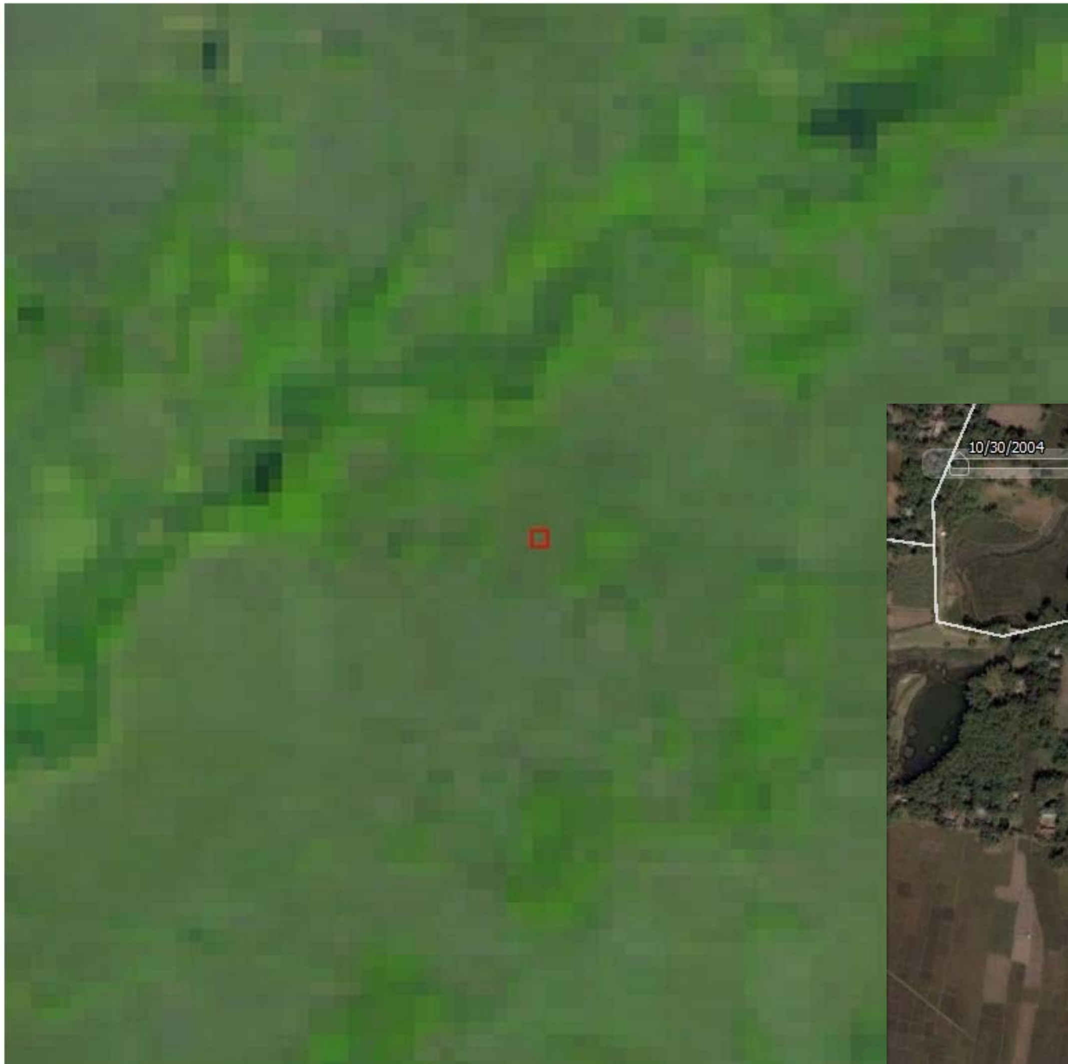
Response design



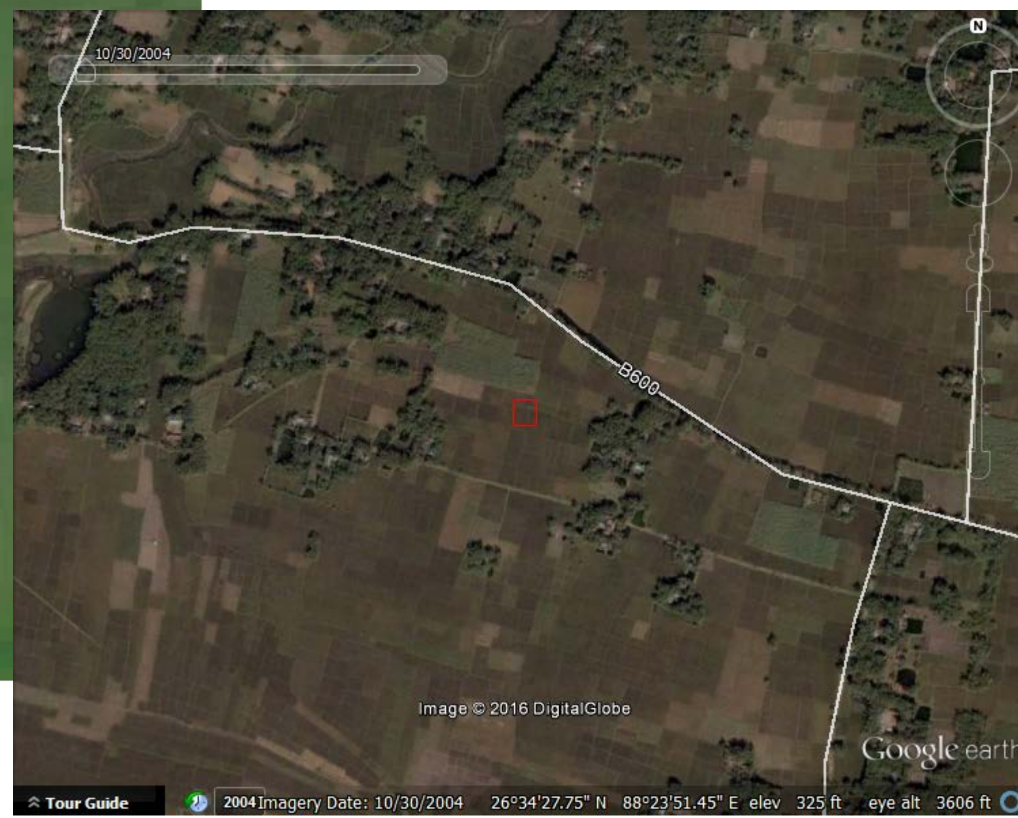
Landsat annual time-series as reference data

Response design

Return to Index <<   Sample 1 Google Earth KML   >> Next   Return to Index

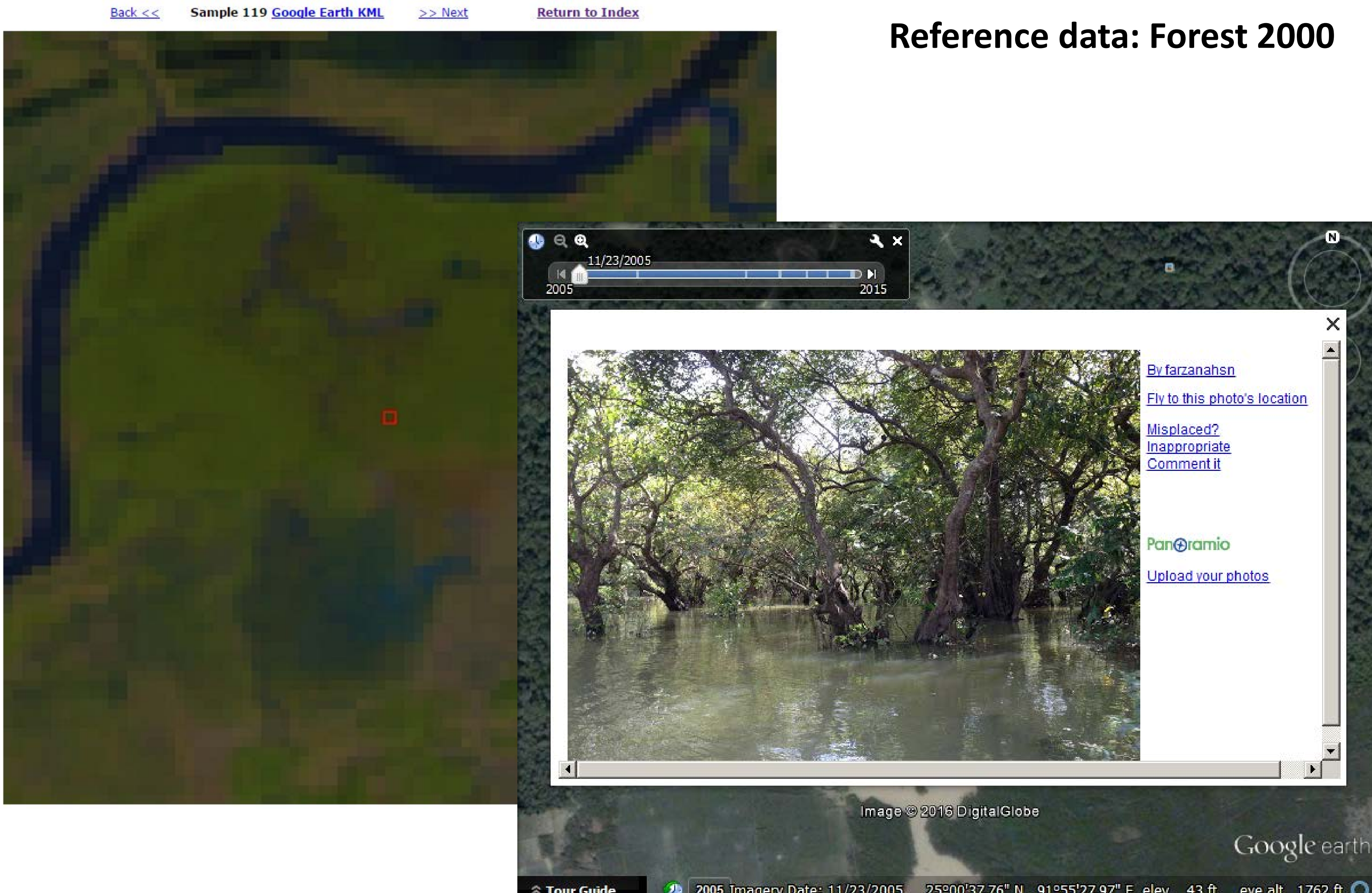


Reference data: Forest 2000

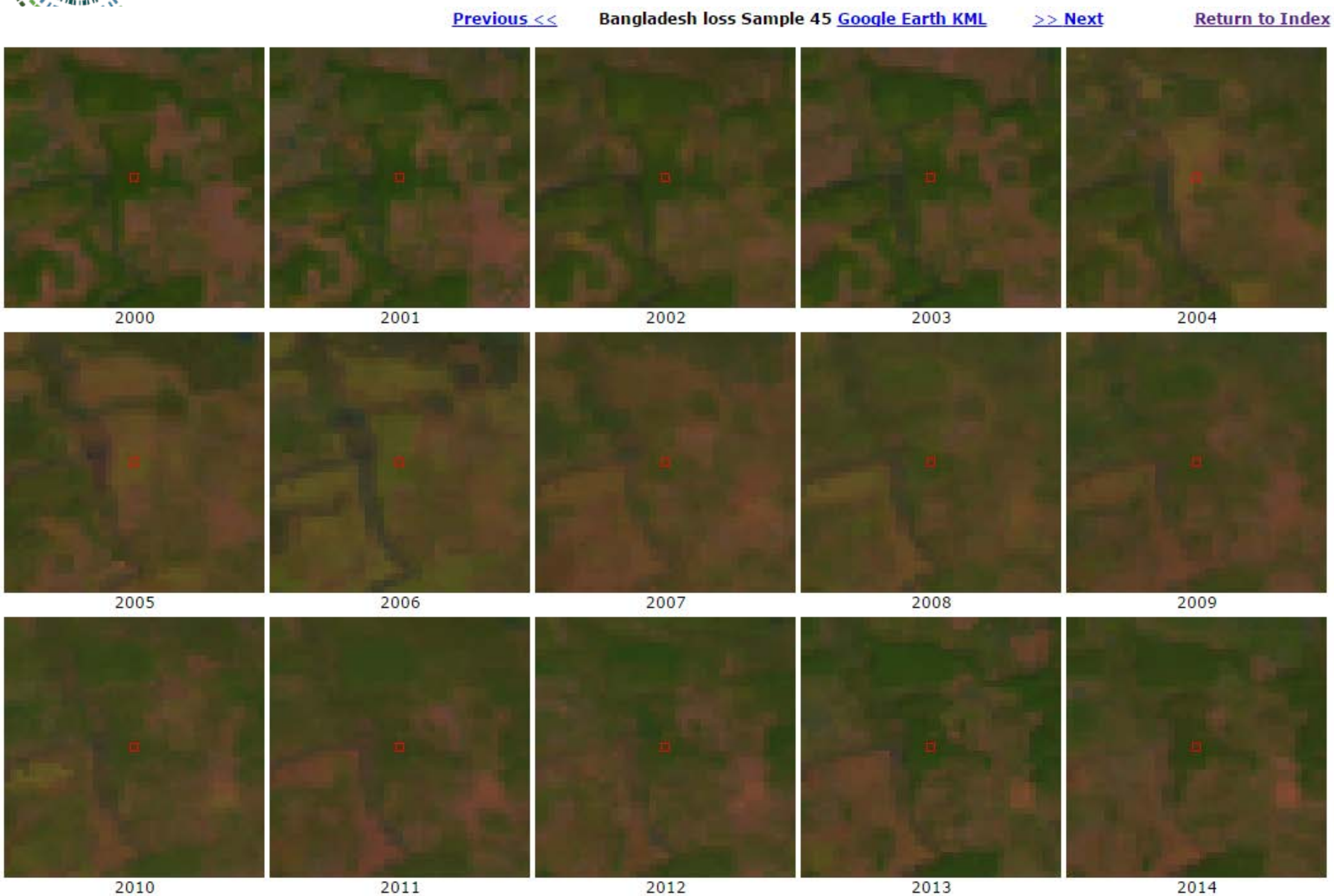


Response design

Reference data: Forest 2000

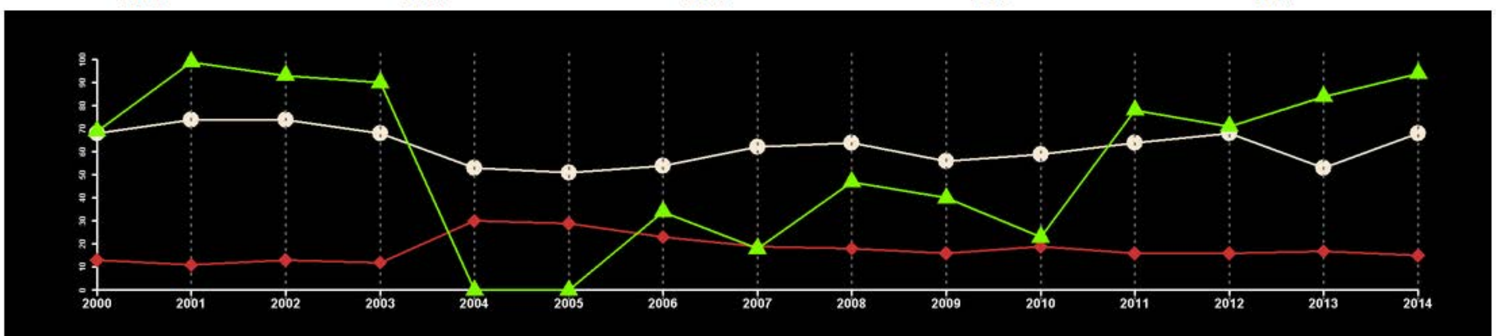


Response design



Reference data

Forest loss

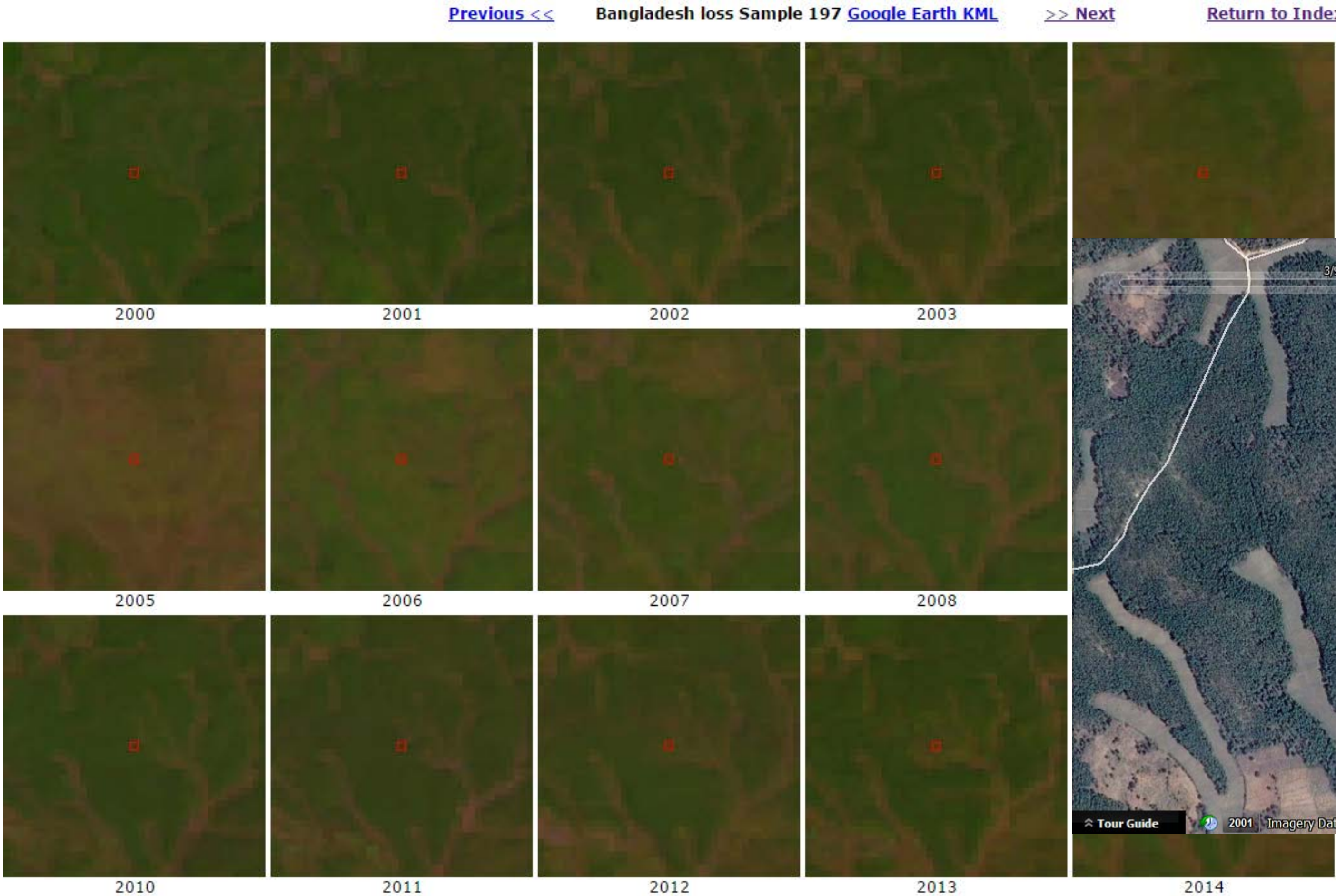


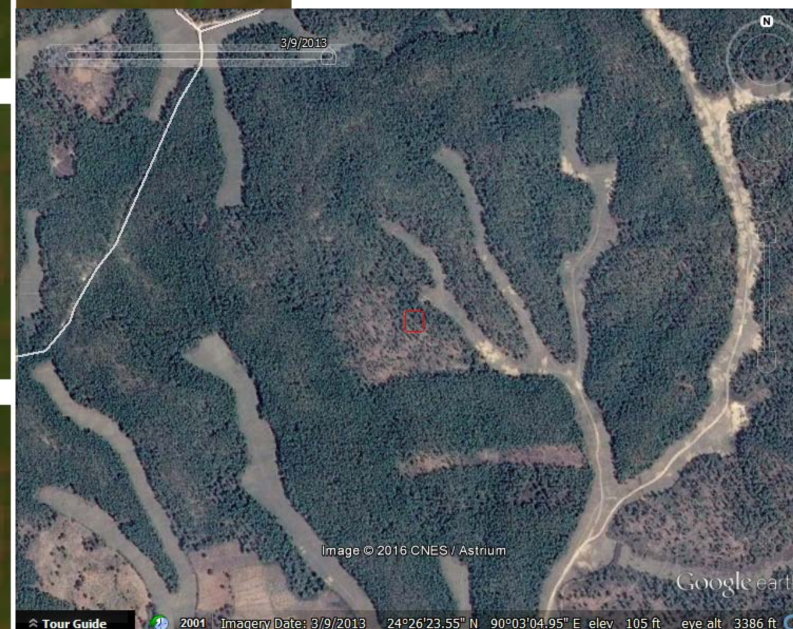
Annual min NDVI

Annual max SWIR reflectance

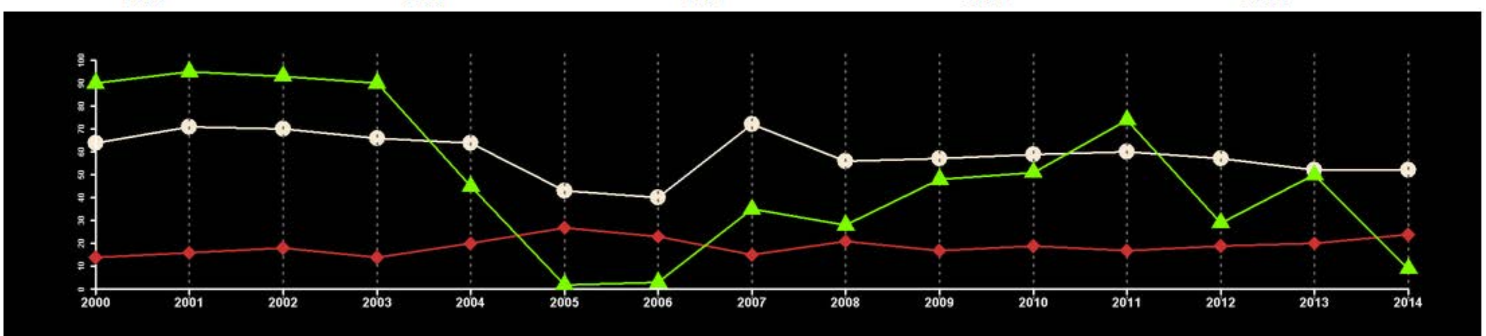
Annual Tree Canopy Cover

Response design





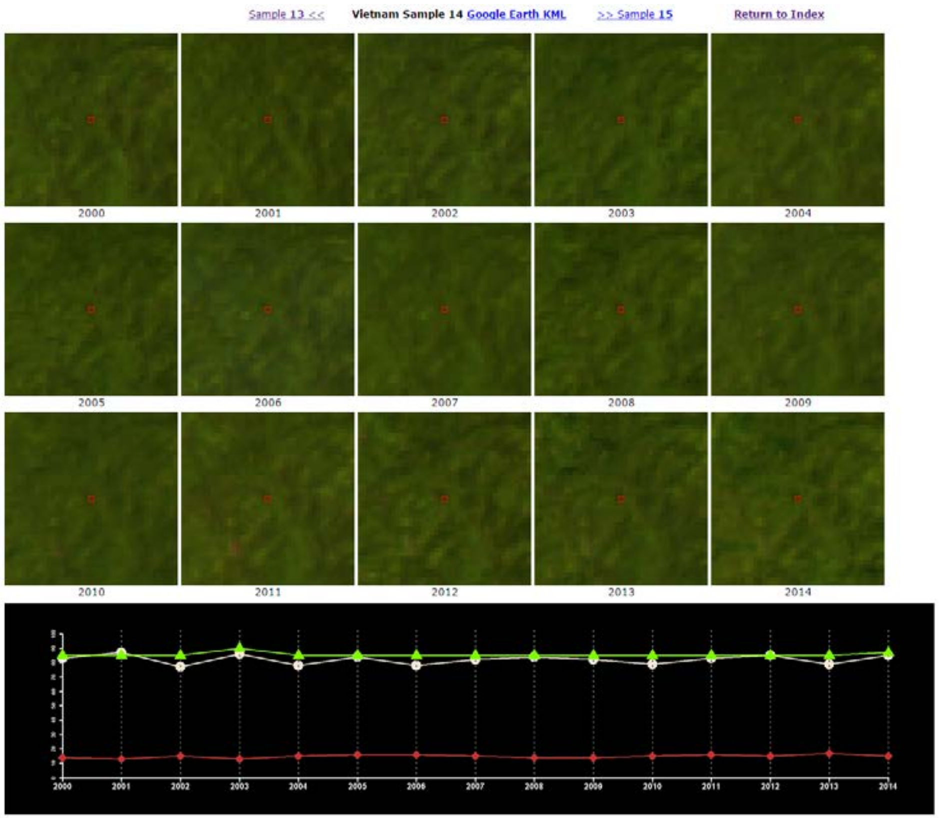
Reference data
Forest loss

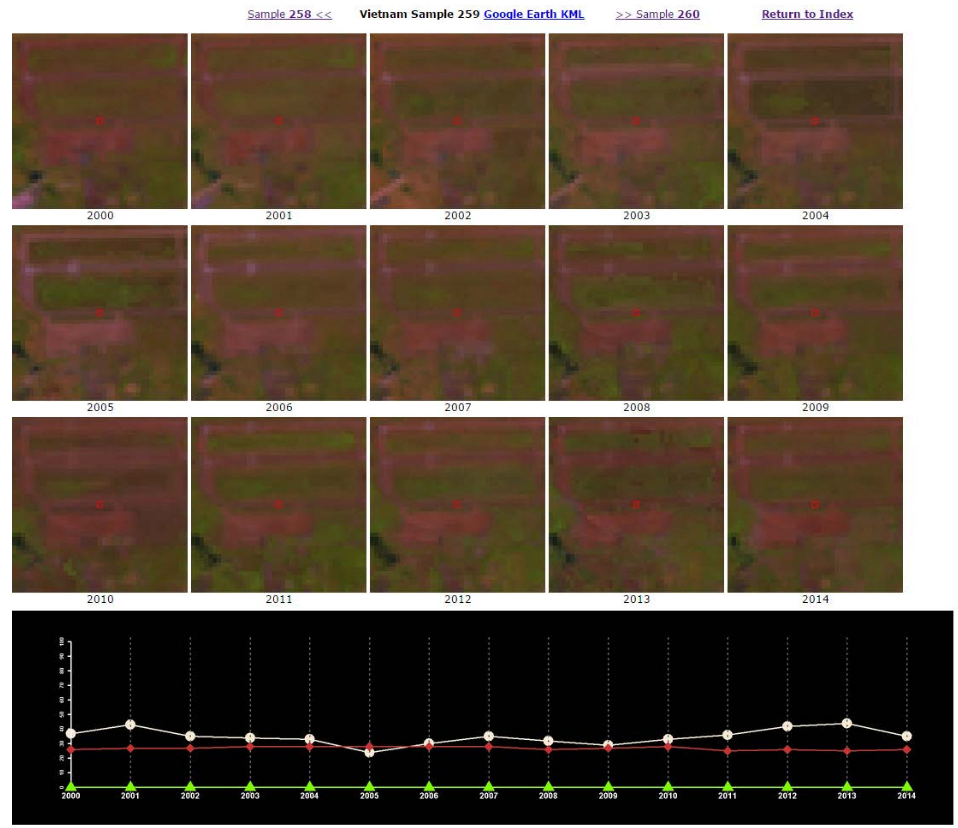


Annual min NDVI
Annual max SWIR reflectance
Annual Tree Canopy Cover

Response design

Reference data

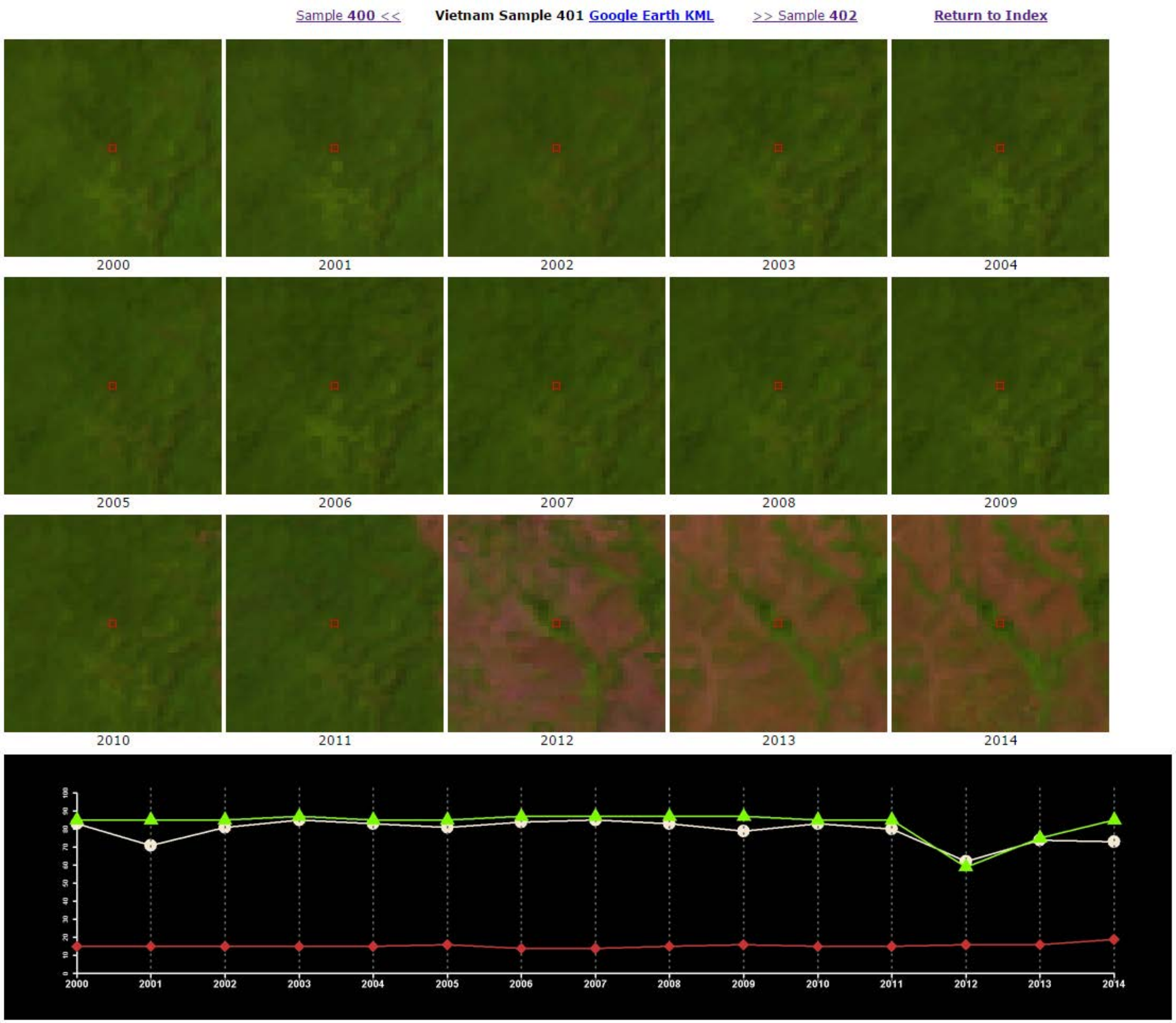




Annual min NDVI
Annual max SWIR reflectance
Annual Tree Canopy Cover

Response design

Reference data



Google Earth (TM) Data

2000

2012

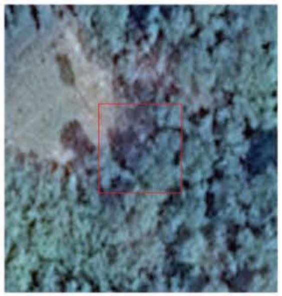
Response design

Tree canopy cover loss samples

Sample 1

2004

2014



Sample 2

2002

2011

Sample 3

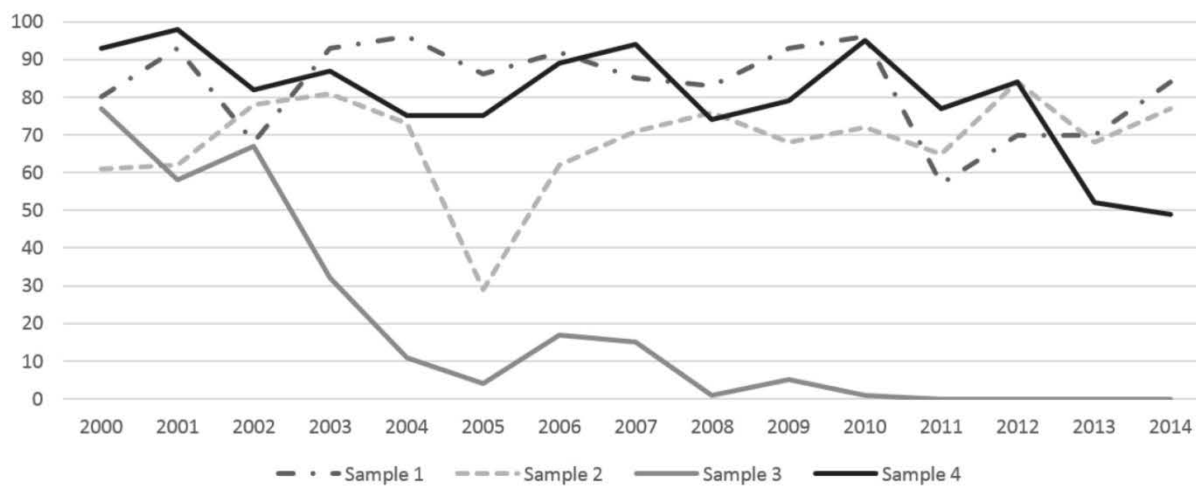
2004

2014

Sample 4

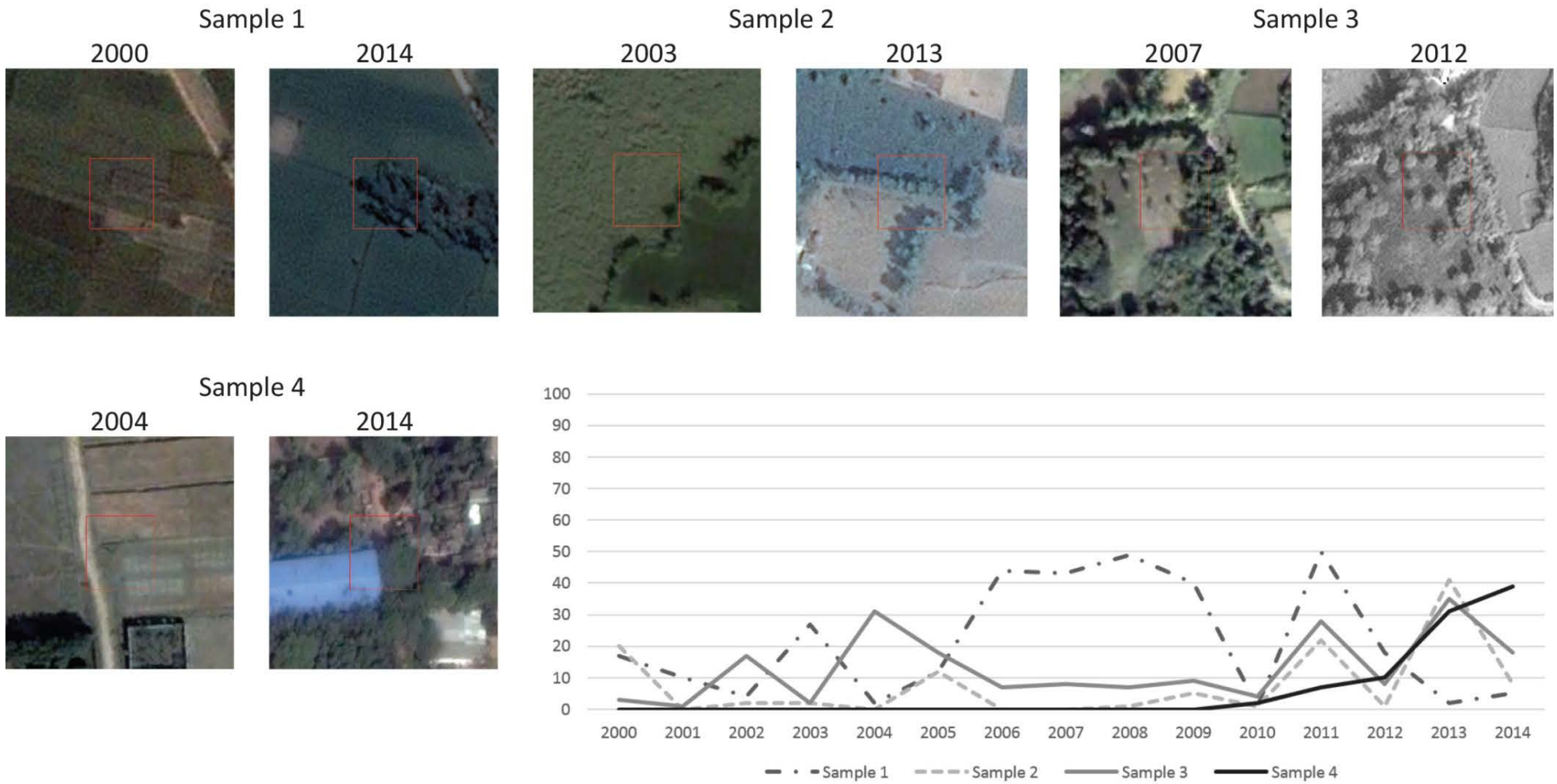
2009

2013



Response design

Tree canopy cover gain samples



Statistical Sampling

Probability sampling allows to:

- **Quantify map accuracy (Overall, User’s, Producer’s).**
- Estimate “true” (unbiased) areas of mapped classes.
- Estimate uncertainty of the mapped classes area.
- Perform value-added thematic analysis based on visual sample interpretation (e.g. differentiate various types of forest or forest disturbance).

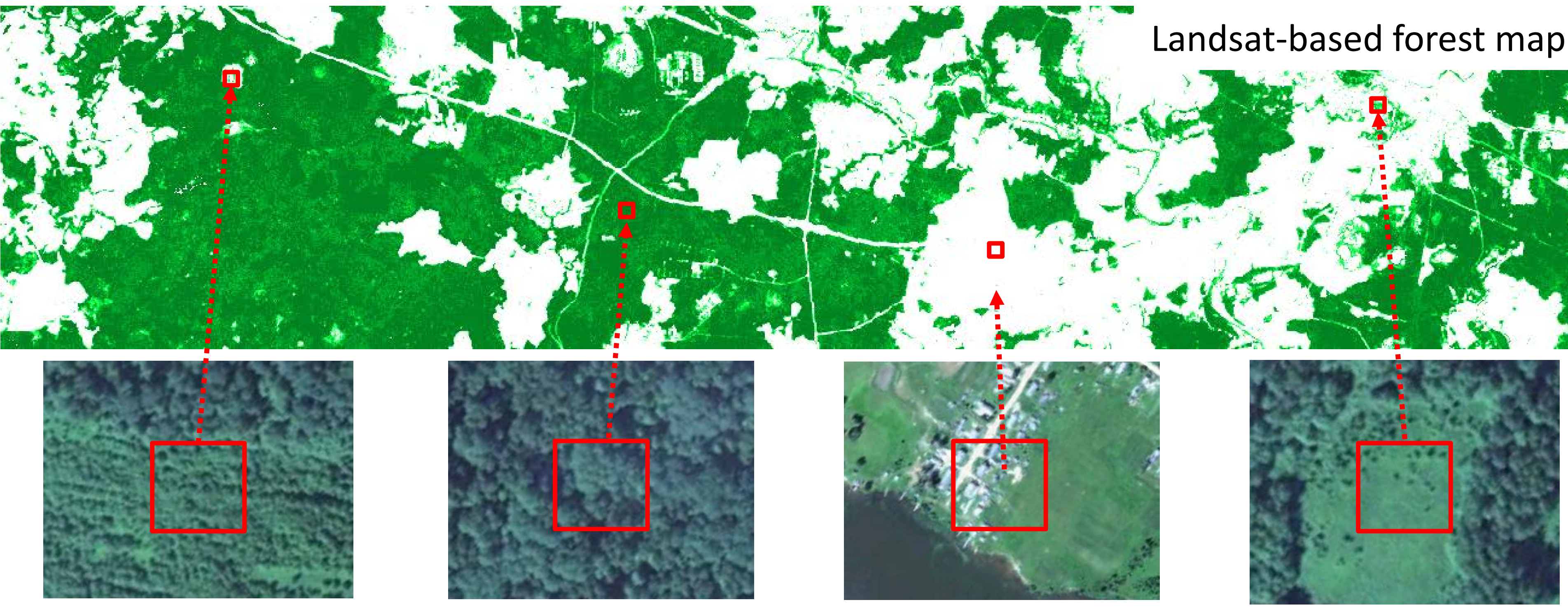
Accuracy Assessment

All maps derived from remotely sensed data have errors

(from data limitations, analyst biases, classification process)

Errors of commission
(false positive)

Errors of omission
(false negative)



Map: non-forest
Reference: forest

Map: forest
Reference: forest

Map: non-forest
Reference: non-forest

Map: forest
Reference: non-forest

Accuracy Assessment

Confusion matrix (or error matrix) summarizes the relationship between the two sources of information (e.g. map and reference sample point data).

	Reference	
Map	*Forest*	*Non-forest*
Forest	True positive	False positive (error of commission)
Non-forest	False negative (error of omission)	True negative

Full population (wall-to-wall) reference data are usually absent, so a reference sample has to be used instead

Confusion matrix outputs:

- Quantification of map uncertainty:
  - Overall accuracy
  - User's accuracy (represent commission error)
  - Producer's accuracy (represent omission error)

- Estimation of the "true" area of mapped classes.

Accuracy Assessment

Accuracy measures

Overall accuracy represent the percent of correctly mapped sample points of total number of sample points.

$$OA = \frac{\text{Number of correct plots}}{\text{total number of plots}}$$

User's accuracy is a measure of the commission error. This statistic indicates the probability of how well the classified sample represents what is found on the ground.

$$UA = \frac{\text{Number correctly identified as a given map class}}{\text{Number claimed to be in that map class}}$$

Producer's accuracy is a statistic that specifies the probability of a ground reference data being correctly classified and it is a measure of the omission error. This statistic is calculated because the producer may want to know how well an area can be classified.

$$PA = \frac{\text{Number correctly identified test sites}}{\text{Number actually in that class}}$$

Accuracy Assessment

Accuracy measures

	Reference	
Map	*Forest*	*Non-forest*
Forest	True positive (TP)	False positive (FP) (error of commission)
Non-forest	False negative (FN) (error of omission)	True negative (TN)

- Overall accuracy
- User's accuracy (represent commission error)
- Producer's accuracy (represent omission error)

$$\textbf{Overall accuracy} = \frac{TP+TN}{TP+TN+FN+FP} * 100\%$$

$$\textbf{User's accuracy (for forest class)} = \frac{TP}{TP+FP} * 100\%$$

$$\textbf{Producer's accuracy (for forest class)} = \frac{TP}{TP+FN} * 100\%$$

Accuracy Assessment

Some causes of poor accuracy

Classification limitation

- Insufficient classification training
- Classes not separable (with chosen algorithm/parameters)

Data limitation

- Spatial scale of remote sensing instrument does not match classification scheme
- Classes are not separable using the spectral data used
- Insufficient data correction (e.g. atmospheric effects)
- Data pre-processing and correction introduce artifacts precluding correct classification (overcorrection)

Incorrect reference data

- Positional error
- Field identification error
- Mixed pixel
- Confused land cover with land use

Statistical Sampling

Probability sampling allows to:

- Quantify map accuracy
  (Overall, User’s, Producer’s).

- **Estimate “true” (unbiased) areas of mapped classes.**

- **Estimate uncertainty of the mapped classes area.**

- Perform value-added thematic analysis based on visual sample interpretation (e.g. differentiate various types of forest or forest disturbance types).

Area Estimation

- Sample-based analysis provides the best available reference data. Sample-based data is most suitable for national-scale area estimation for LC/LU and change classes.
- Unlike map, sample data provides unbiased estimation of class areas with known uncertainty (precision).
- The same approach used for accuracy analysis (confusion matrix) is suitable for class proportion estimation.
- Availability of the complete map may be beneficial to sample-base analysis:
  - It may be used for stratification to increase sampling efficiency and estimate precision
  - It may be used in the form of regression estimator to increase area estimation precision

Area Estimation

from Cochran, 1977
Stehman, 2013

Simple random sampling

Area calculation

Proportion of class $\boldsymbol{i}$ from total sampling area: $\boldsymbol{p_i = \frac{n_i}{n}}$; where $\boldsymbol{n_i}$ – number of samples, identified as class *i*
$\boldsymbol{n}$ – *total number of samples*

Area of class $\boldsymbol{i}$: $\boldsymbol{A_i = A_{tot} \times p_i}$; where A_{tot} - total sampling area

Variance calculation

If sampling units are

Points
(infinite sampling population)

$$\boldsymbol{V(p_i) = \frac{p_i(1 - p_i)}{n}}$$

Areal units (pixels, blocks)
(finite sampling population)

$$\boldsymbol{V(p_i) = \frac{p_i(1-p_i)}{n} \frac{(N-n)}{(N-1)}}$$

where $\boldsymbol{N}$ – total number of sampling units in the population

Standard Error calculation

As a proportion from total area: $SE(p_i) = \sqrt{V(p_i)}$

In units of area: $SE(A_i) = A_{tot} \times \sqrt{V(p_i)}$

Area Estimation

from Cochran, 1977
Olofsson, 2013
Stehman, 2013

Stratified random sampling

Area calculation

Sampling units – pixels

Mean proportion of class $\boldsymbol{i}$ in stratum $\boldsymbol{h}$:

$$\bar{p}_{ih} = \frac{\sum_{u \in h} p_u}{n_h}$$

$p_u = 1$ if a pixel is identified as class *i*,
and $p_u = 0$ otherwise
n_h – number of samples in stratum *h*

Proportion of class $\boldsymbol{i}$ from total area:

$$p_i = \sum_{h=1}^{H} \frac{N_h}{N} \bar{p}_{ih}$$

N_h – total number of pixels in stratum *h*
H – number of sampling strata
N – total number of pixels in the sampling region

Area of class $\boldsymbol{i}$:

$$A_i = A_{tot} * p_i$$

A_{tot} - total sampling area

Variance calculation

$$V(p_i) = \sqrt{\sum_{h=1}^{H} \left(\frac{N_h}{N}\right)^2 \frac{\bar{p}_{ih}\,(1 - \bar{p}_{ih})}{n_h - 1}}$$

Standard Error calculation

As a proportion from total area: $SE(p_i) = \sqrt{V(p_i)}$

In units of area: $SE(A_i) = A_{tot} \times \sqrt{V(p_i)}$

Statistical Sampling

Probability sampling allows to:

- Quantify map accuracy
  (Overall, User's, Producer's).

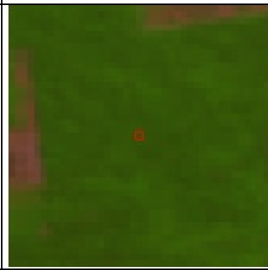
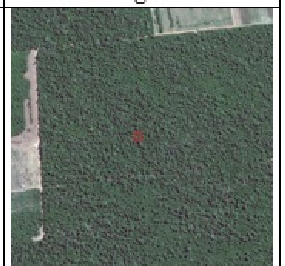
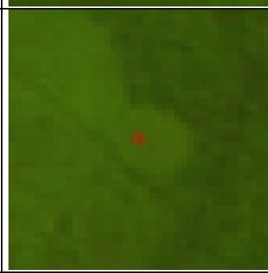
- Estimate "true" (unbiased) areas of mapped classes.

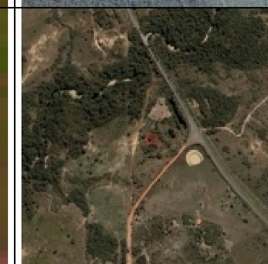
- Estimate uncertainty of the mapped classes area.

- **Perform value-added thematic analysis based on visual sample interpretation (e.g. differentiate various types of forest or forest disturbance).**

Value-added Analysis

Pre-disturbance forest type

Pre-disturbance vegetation type		Pre-disturbance Landsat	Pre-disturbance high resolution imagery from Google Earth™
Dense (>60% canopy cover) tropical forests	Primary		
	Secondary		

Pre-disturbance vegetation type		Pre-disturbance Landsat	Pre-disturbance high resolution imagery from Google Earth™
Woodlands (40-60% canopy cover) and parklands (10-40% canopy cover)	Natural (primary)		
	Secondary		
Forest plantations and other tree crops			

Value-added Analysis

Proximate causes of forest loss in Brazil

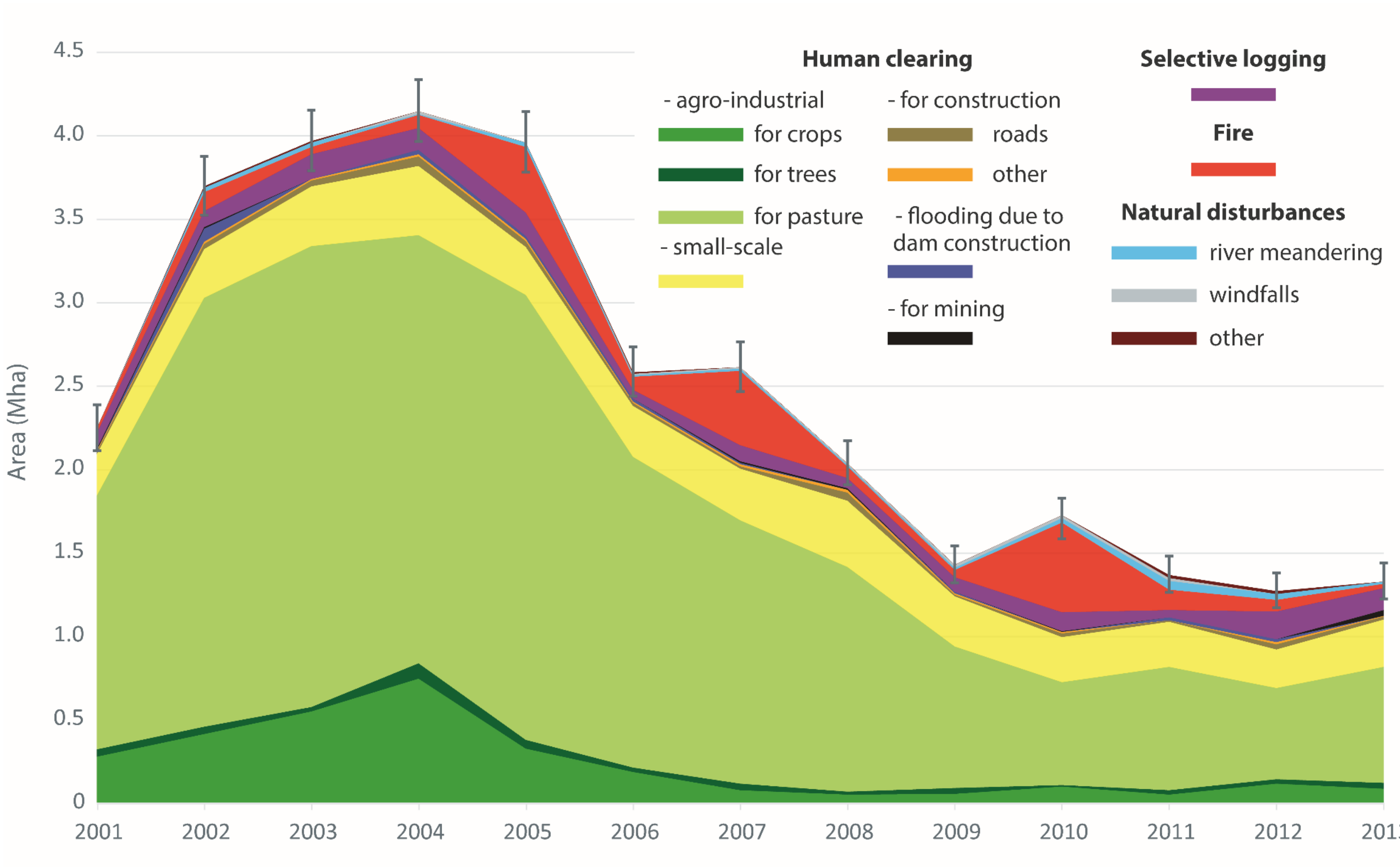
Cropland conversion

Selective logging

Construction

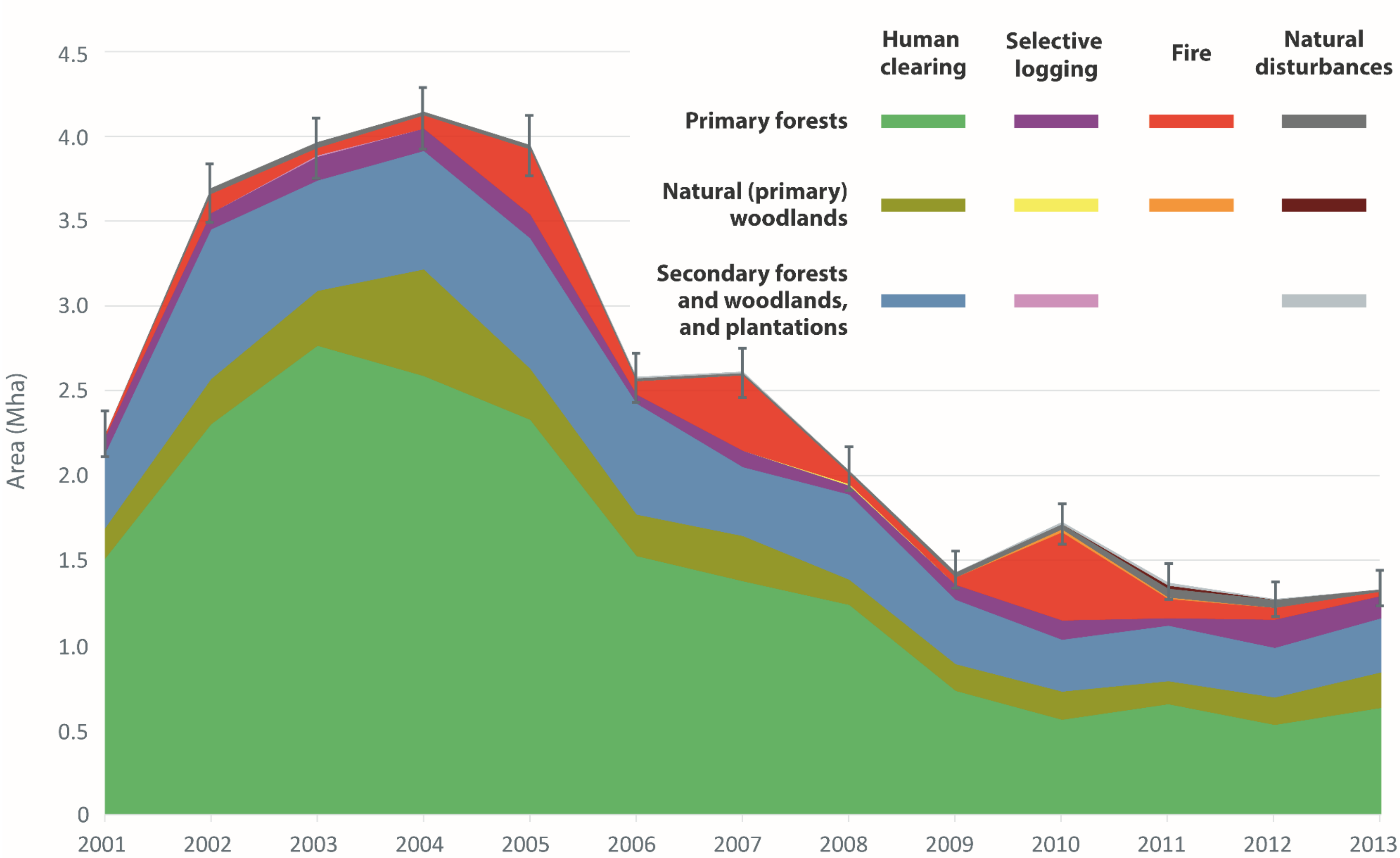
Value-added Analysis

Annual tree cover loss in BLA by disturbance cause



Value-added Analysis

Annual tree cover loss in BLA by pre-disturbance forest type and disturbance cause group



Value-added Analysis

Sample interpretation legend (to be discussed)

Year 2000

- Tree cover (yes/no or percent of the pixel)
- Forest type (primary/secondary/plantation/agroforestry or forest/woodland/shrub)

Change 2000-2016

- Tree cover loss (yes/no or percent of the pixel)
- Date of the (first) disturbance event
- Disturbance type (logging, plantation rotation, conversion (outcome), landslide, fire)

Year 2016 land cover outcome (in case of disturbance)

- Tree cover restoration (yes/no or percent of the pixel)
- Forest type or land cover type

For all samples

- Certainty (overall or each category)
- Boundary (edge) pixel (separate for tree cover 2000 and change)

Sample Analysis Manuals and Recommendations

Good practice recommendations and step-by-step calculation guidelines:

1. GFOI (2014) Integrating Remote-Sensing and Ground-Based Observations for Estimation of Emissions and Removals of Greenhouse Gases in Forests: Methods and Guidance from the Global Forest Observations Initiative Version 1 (January 2014) (Geneva, Switzerland: Group on Earth Observations)
2. Olofsson P., Foody G.M., Stehman S.V., Woodcock C.E. Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation. Remote Sensing of Environment 129, 122-131 (2013)
3. Stehman S.V. Estimating area from an accuracy assessment error matrix. Remote Sensing of Environment 132, 202-211 (2013)
4. Stehman, S. V. Estimating area and map accuracy for stratified random sampling when the strata are different from the map classes. International Journal of Remote Sensing 35.13 (2014)

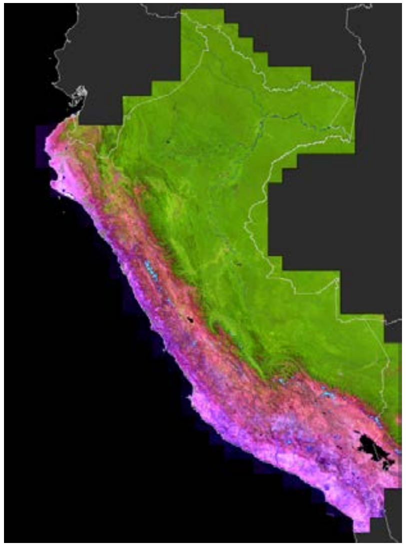
General principles of sampling design:

1. Cochran W.G. Sampling Techniques. New York: Wiley (1977)
2. Stehman S.V. and Czaplewski R.L. Design and analysis for thematic map accuracy assessment: fundamental principles. Remote Sensing of Environment 64, 331-334 (1998)
3. Stehman S.V. Sampling designs for accuracy assessment of land cover. International Journal of Remote Sensing 30 (20), 5243-5272 (2009)
4. Stehman S.V. Impact of sample size allocation when using stratified random sampling to estimate accuracy and area of land-cover change. Remote Sensing Letters 3 (2), 111-120 (2012)

Peru REDD+ project example

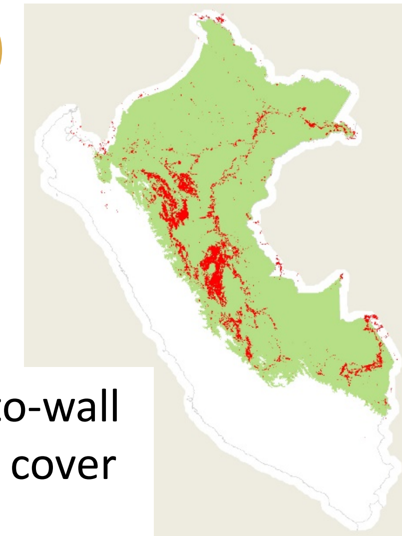
Example of wall-to-wall mapping and sample-based validation in Peru

1



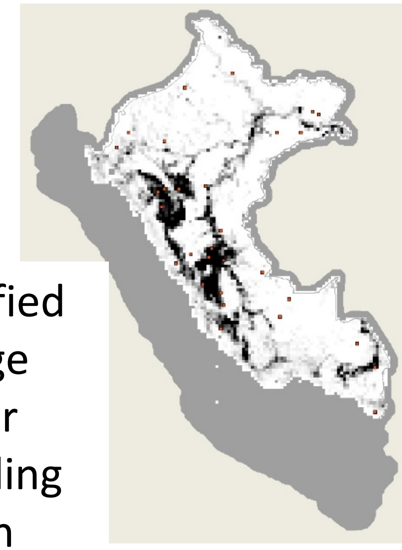
Landsat data composites and metrics

2



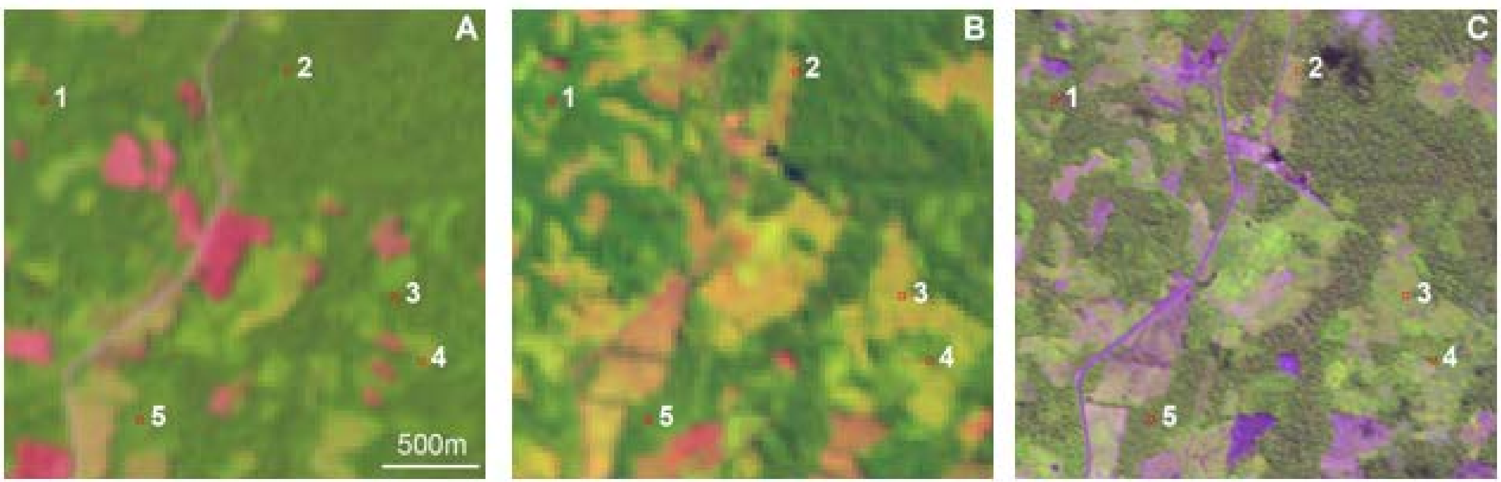
Wall-to-wall forest cover loss

3



Stratified 2-stage cluster sampling design

4



Individual sample block analysis (2-stage clustered sampling design)

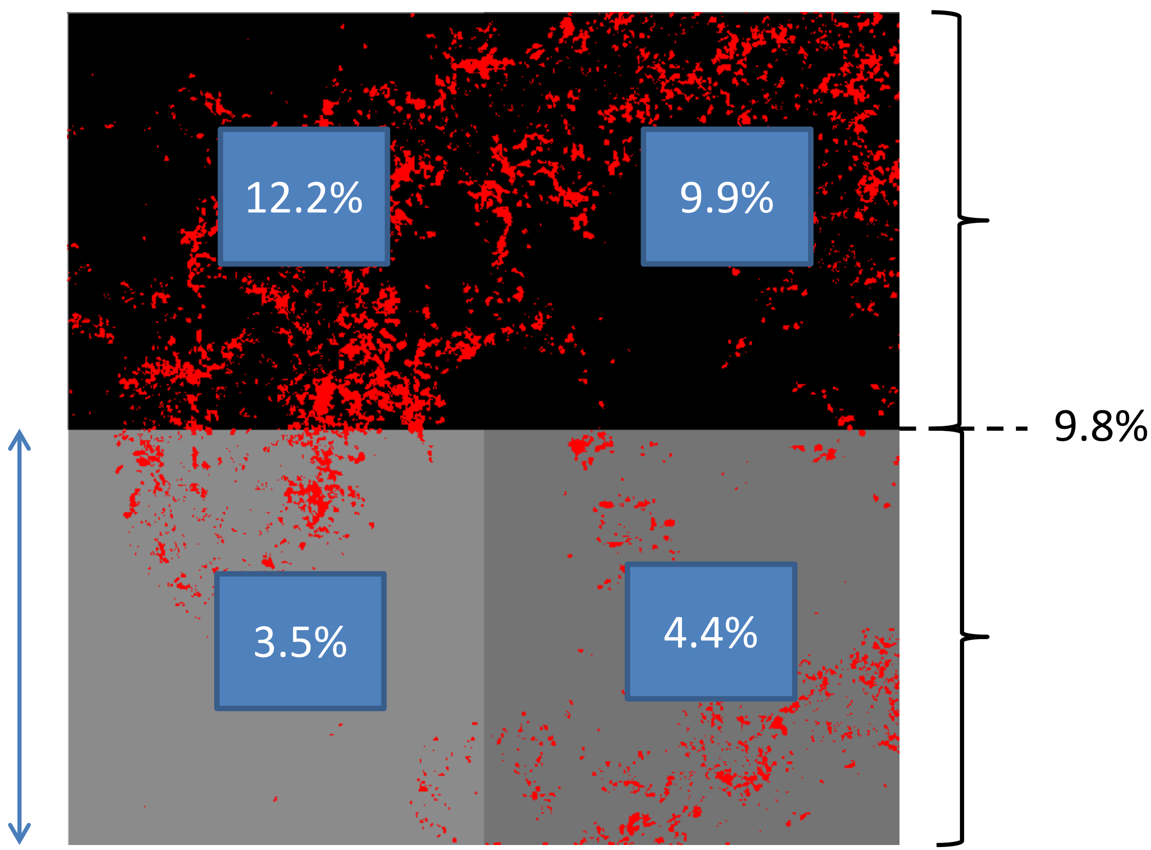
Peru REDD+ project example

Sampling frame

Two-stage cluster sampling:
1. 12x12 km blocks (30 RapidEye scenes)
2. 100 random points within a block

   1. Stratified random sampling, based on proportion forest cover change within a block:

Red – change mapped using 30m Landsat data

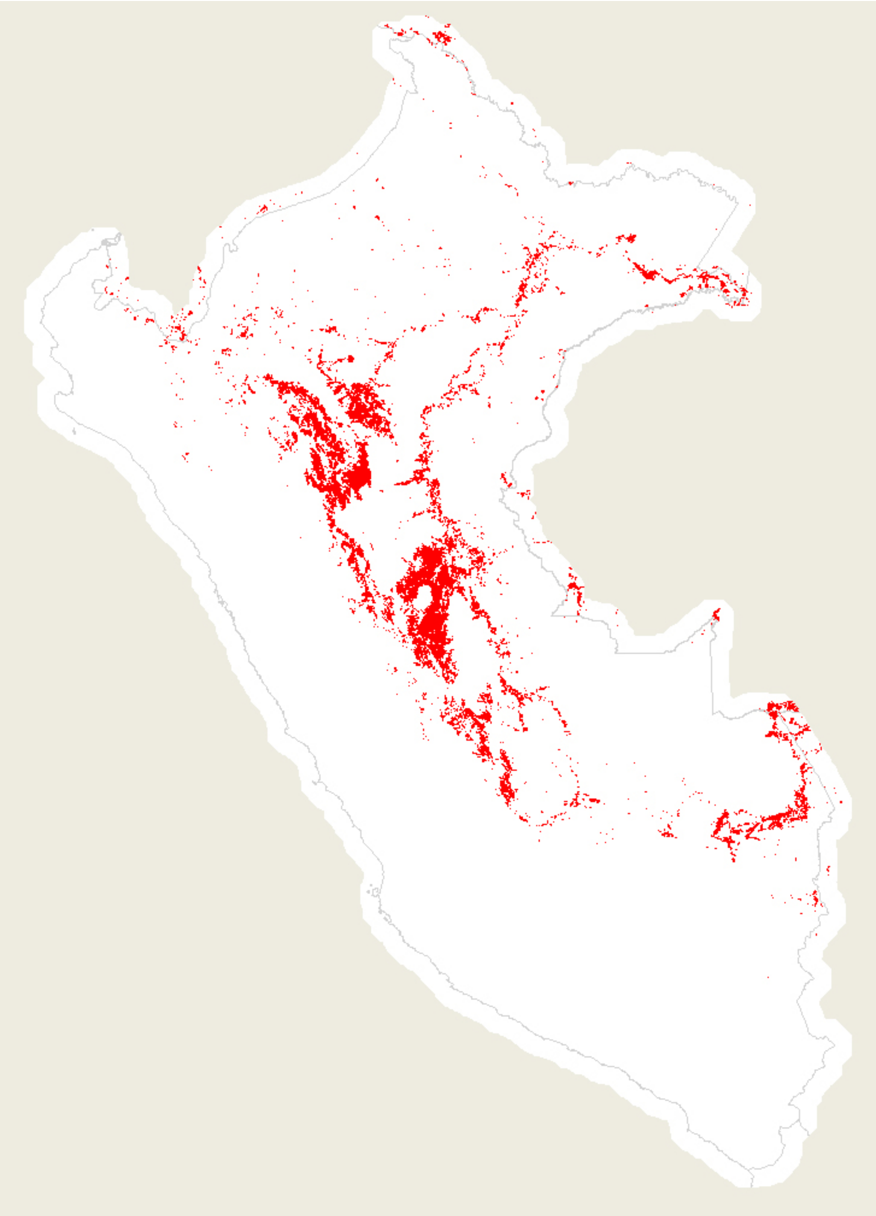


Sample block (12x12 km)

high change stratum

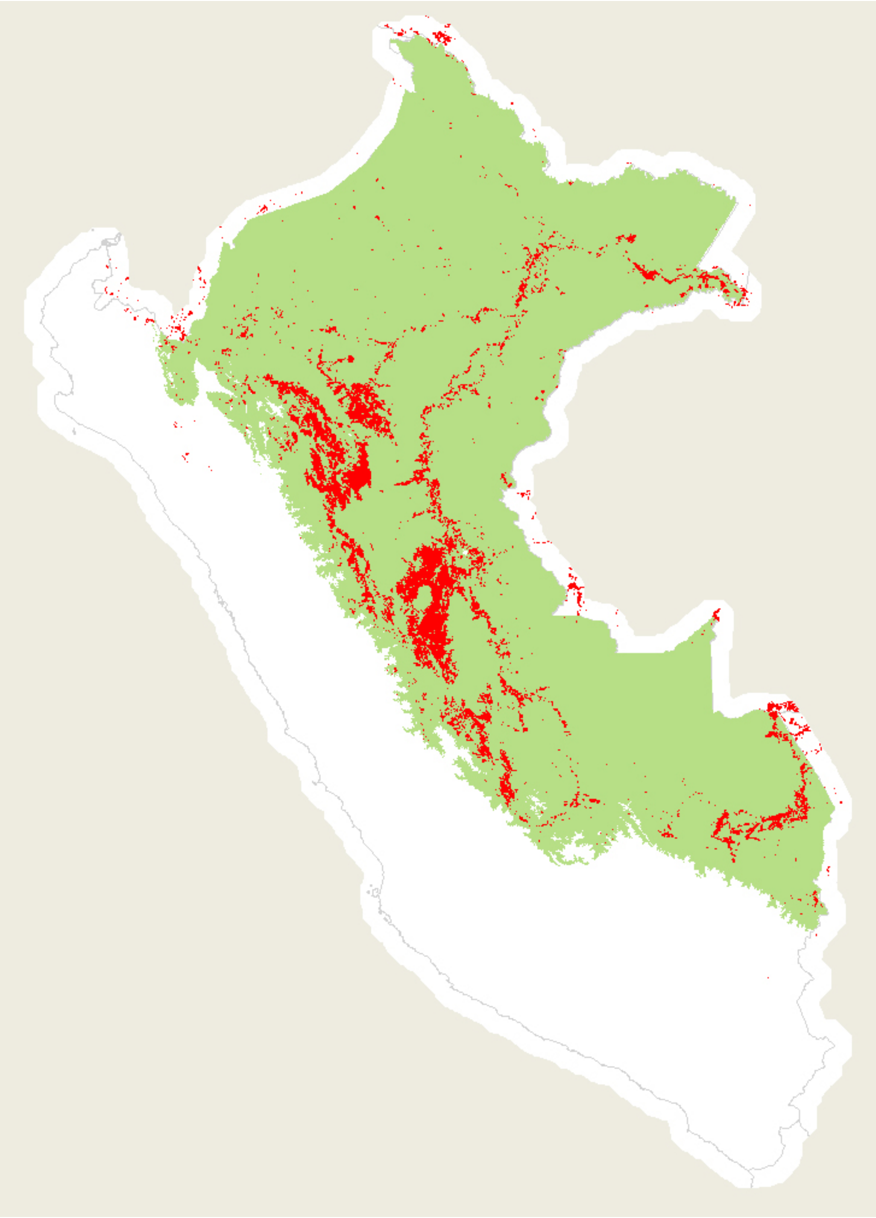
low change stratum

Peru REDD+ project example



Forest cover loss mask at 30m, 2000-2011

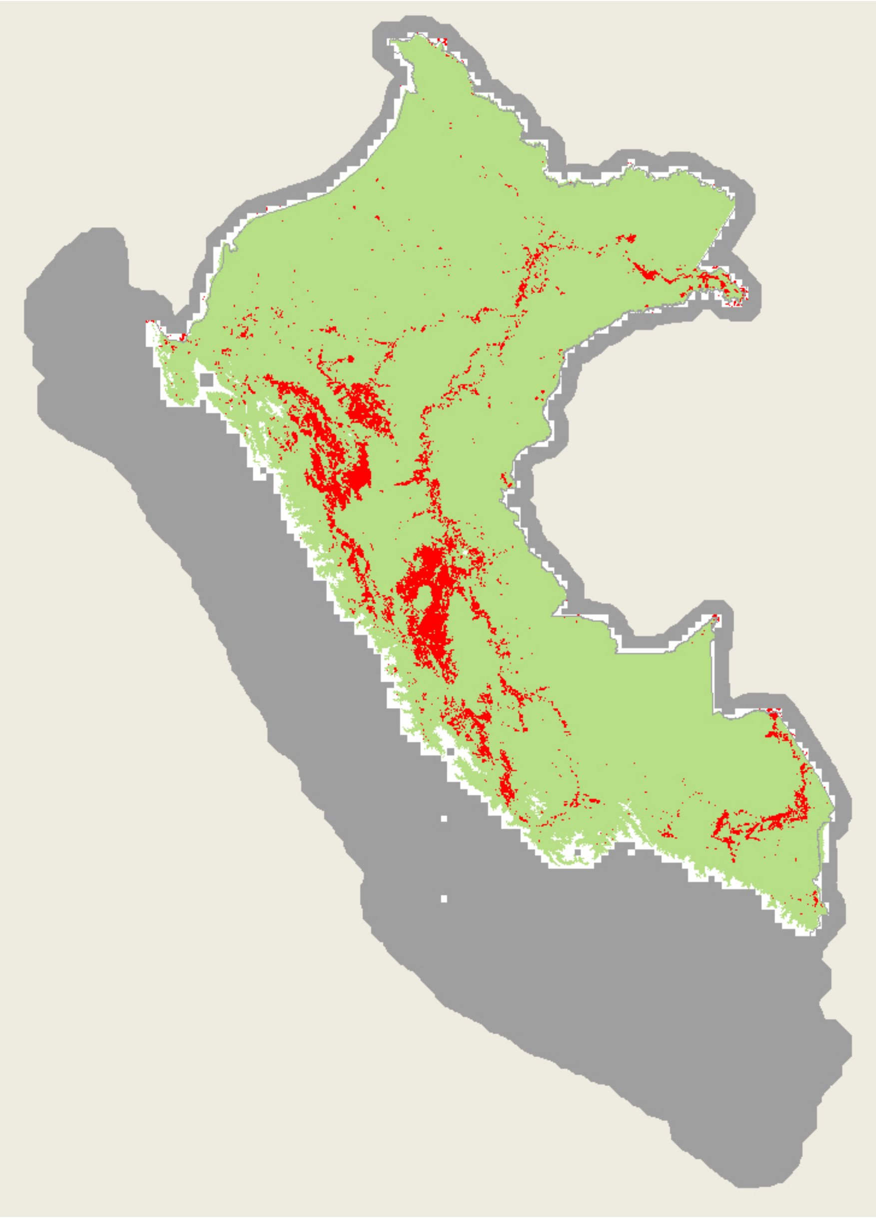
Peru REDD+ project example



Forest cover loss mask at 30m, 2000-2011

Humid tropics mask, 2000

Peru REDD+ project example

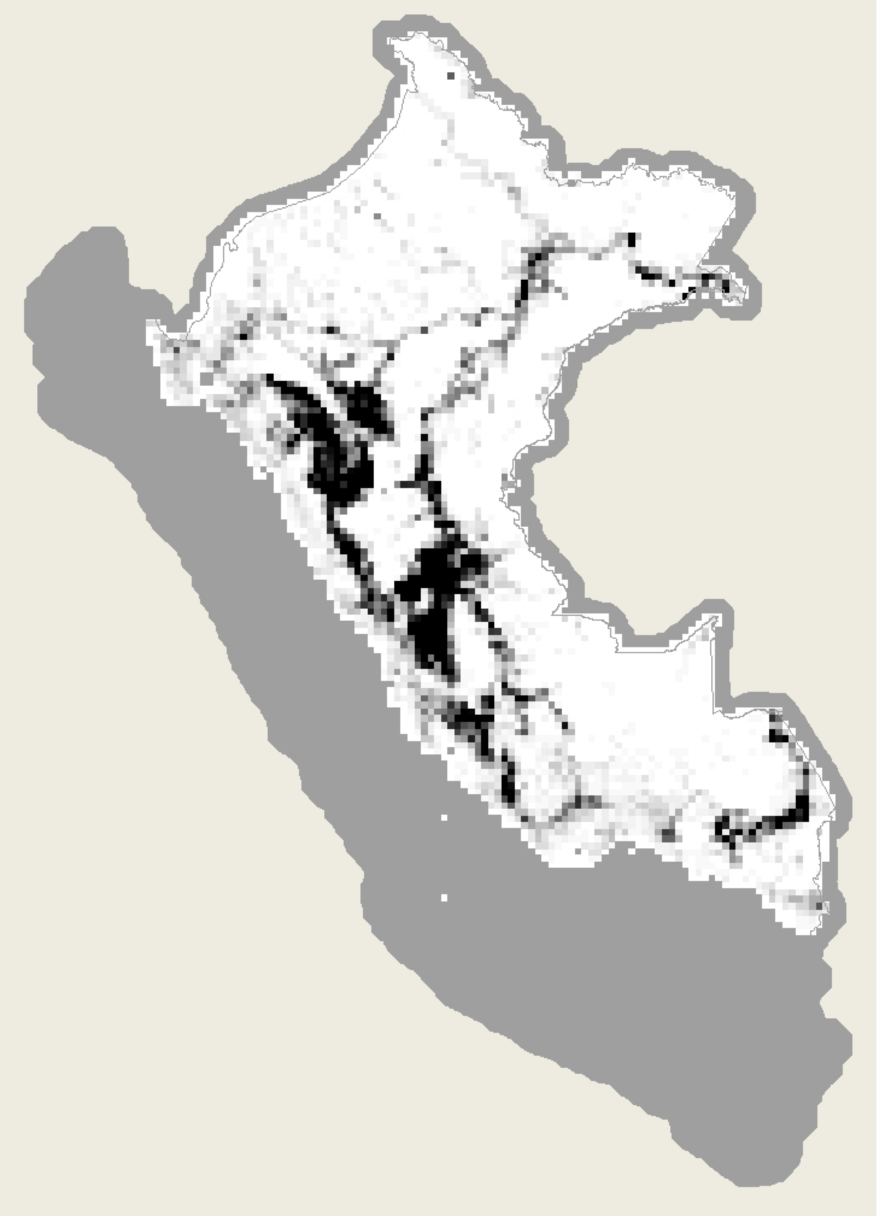


Forest cover loss mask at 30m, 2000-2011

Humid tropics mask, 2000

Sampling frame. Blocks with any proportion of forest mask are shown. Blocks with <40% forest mask were excluded from sampling.

Peru REDD+ project example



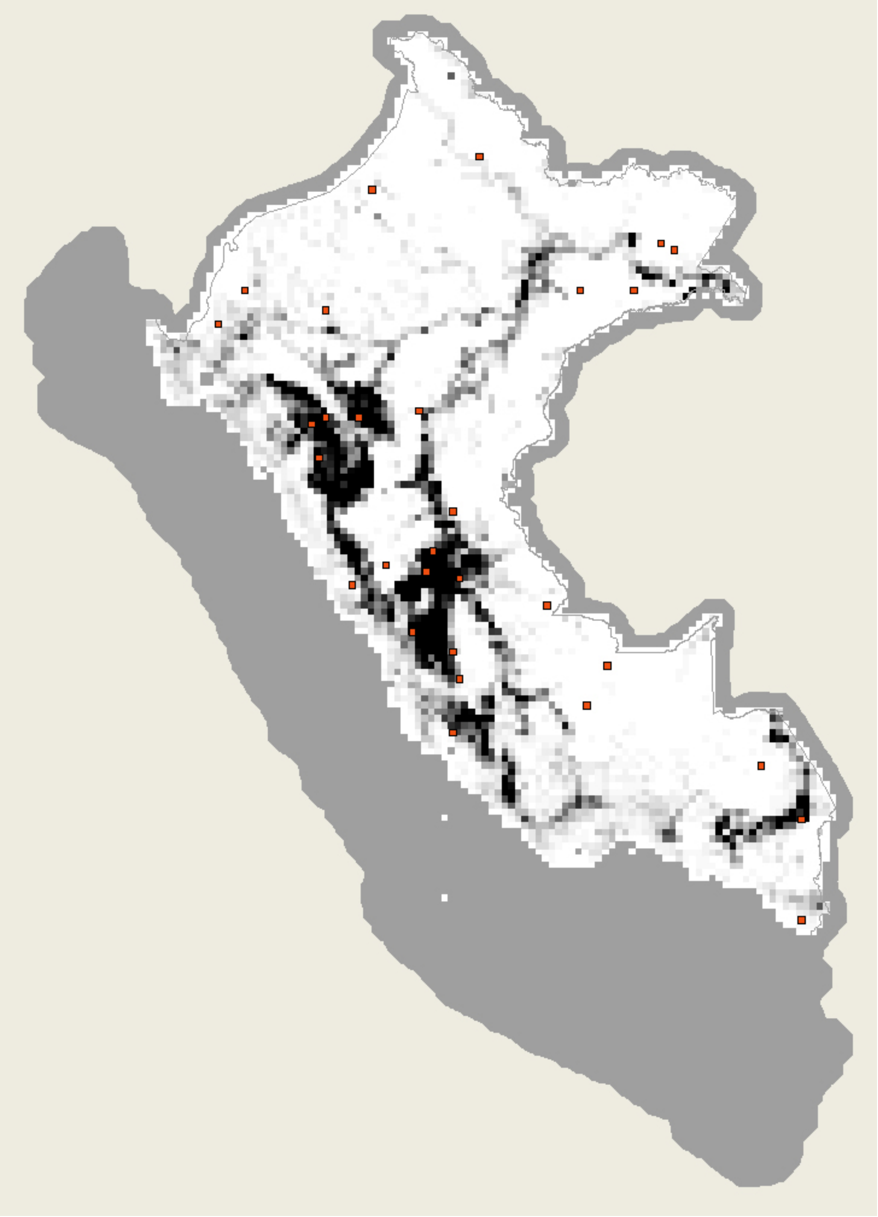
Forest cover loss mask at 30m, 2000-2011

Humid tropics mask, 2000

Sampling frame. Blocks with any proportion of forest mask are shown. Blocks with <40% forest mask were excluded from sampling.

% forest loss per 12x12 km sample block within sampling frame.

Peru REDD+ project example



Forest cover loss mask at 30m, 2000-2011

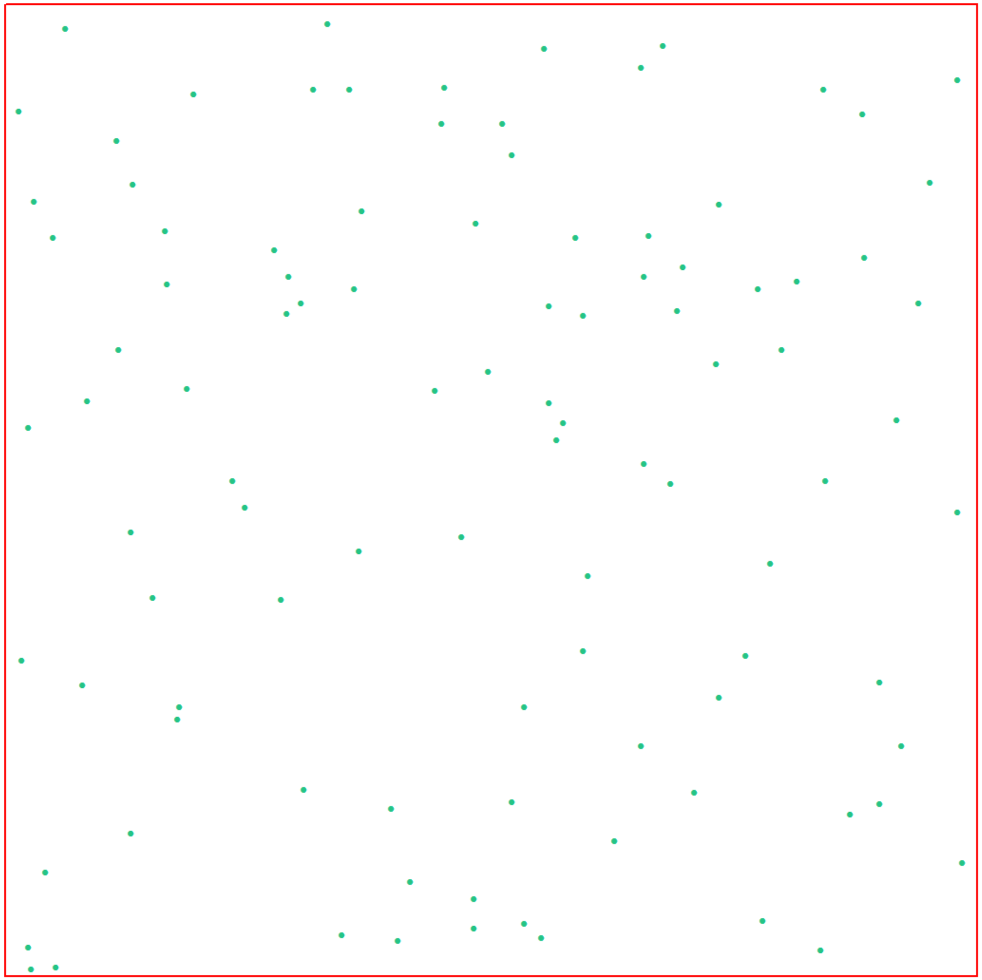
Humid tropics mask, 2000

Sampling frame. Blocks with any proportion of forest mask are shown. Blocks with <40% forest mask were excluded from sampling.

% forest loss per 12x12 km sample block within sampling frame.

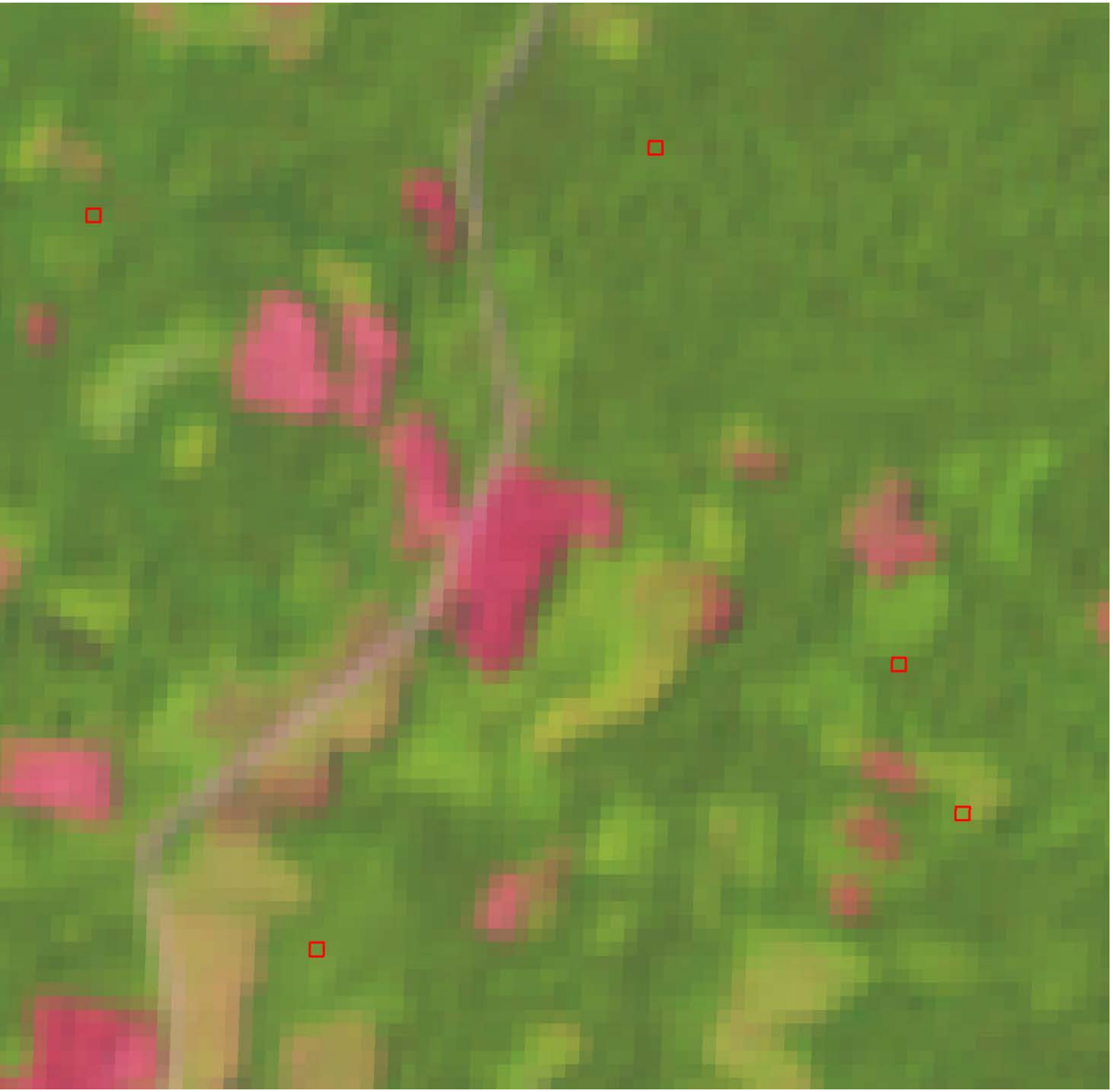
Selected sampling blocks (30 total)

Peru REDD+ project example



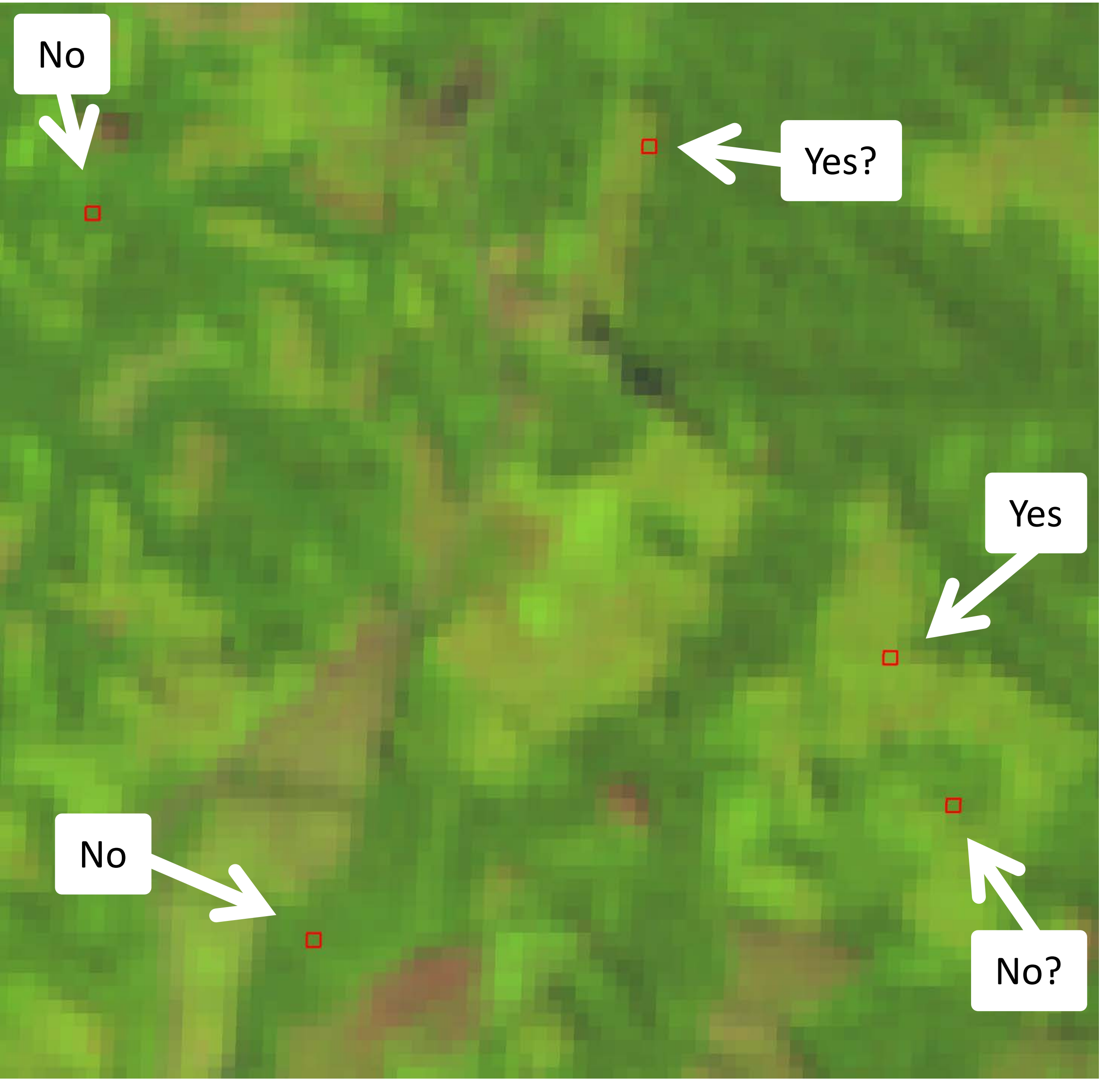
Sample block with 100 random sample points (Landsat pixels)

Peru REDD+ project example



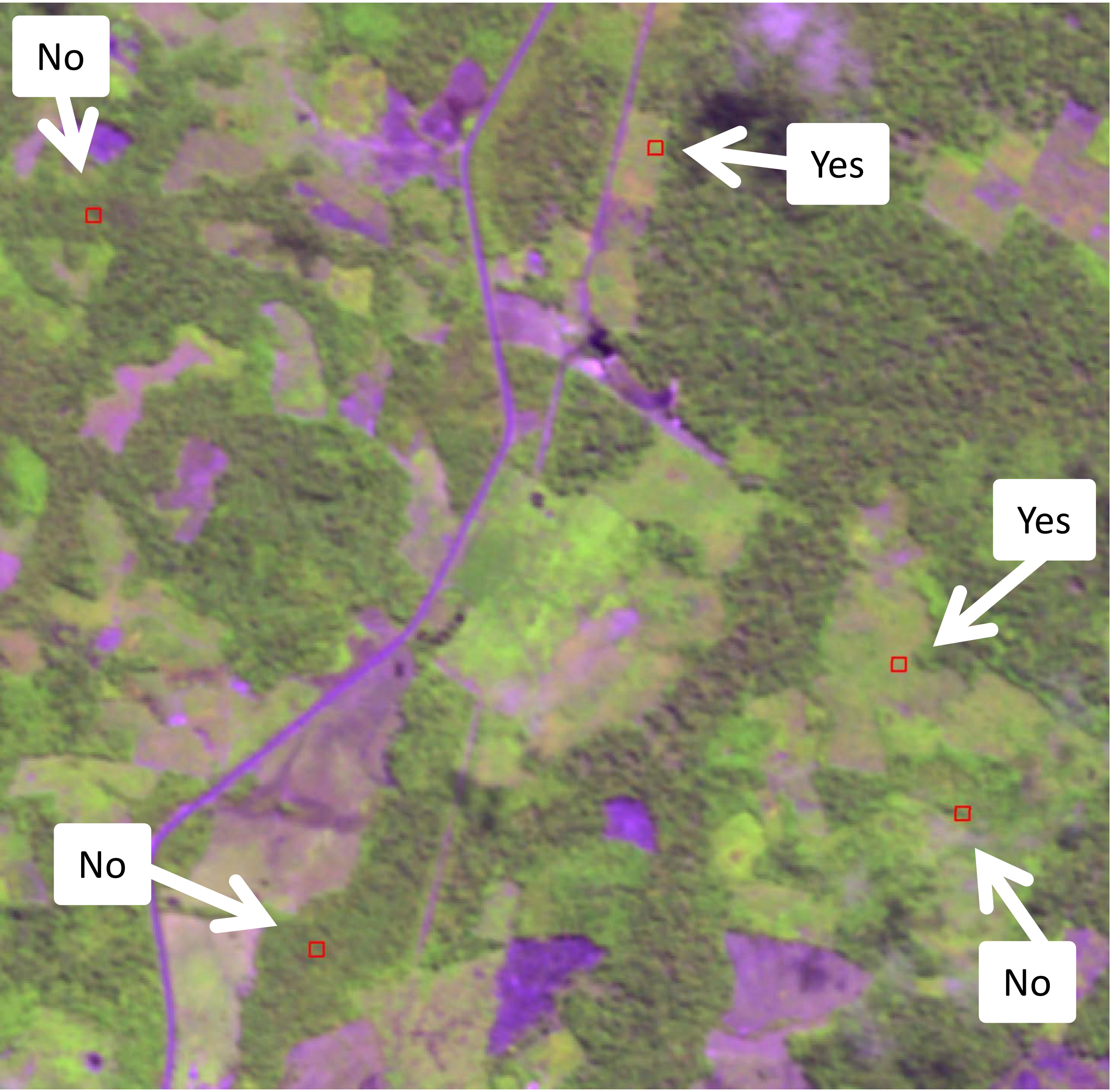
Sample points (pixels) over year 2000 Landsat image

Peru REDD+ project example



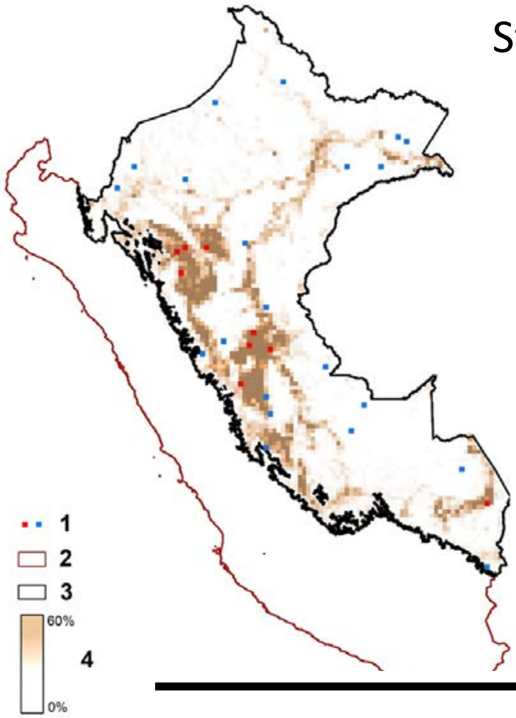
Sample points (pixels) over year 2011 Landsat image

Peru REDD+ project example



Sample points
(30m pixels) over year
2011 RapidEye image

Peru REDD+ project example



Stratified 2-stage cluster sampling design

*** For stratified sampling design we use not the number of samples, but the proportion of total sample area**

Confusion matrix for gross forest cover loss validation

		Reference			
		No change	Forest loss	Total	User's accuracy (SE)
Map	No change	97.990 *	0.465	98.455	99.5% (0.2%)
	Forest loss	0.120	1.426	1.546	92.2% (1.9%)
	Total	98.110	1.891	100.00	—
Producer's accuracy (SE)		99.8% (0.1%)	75.4% (2.5%)	Overall accuracy (SE) = 99.4% (0.2%)	