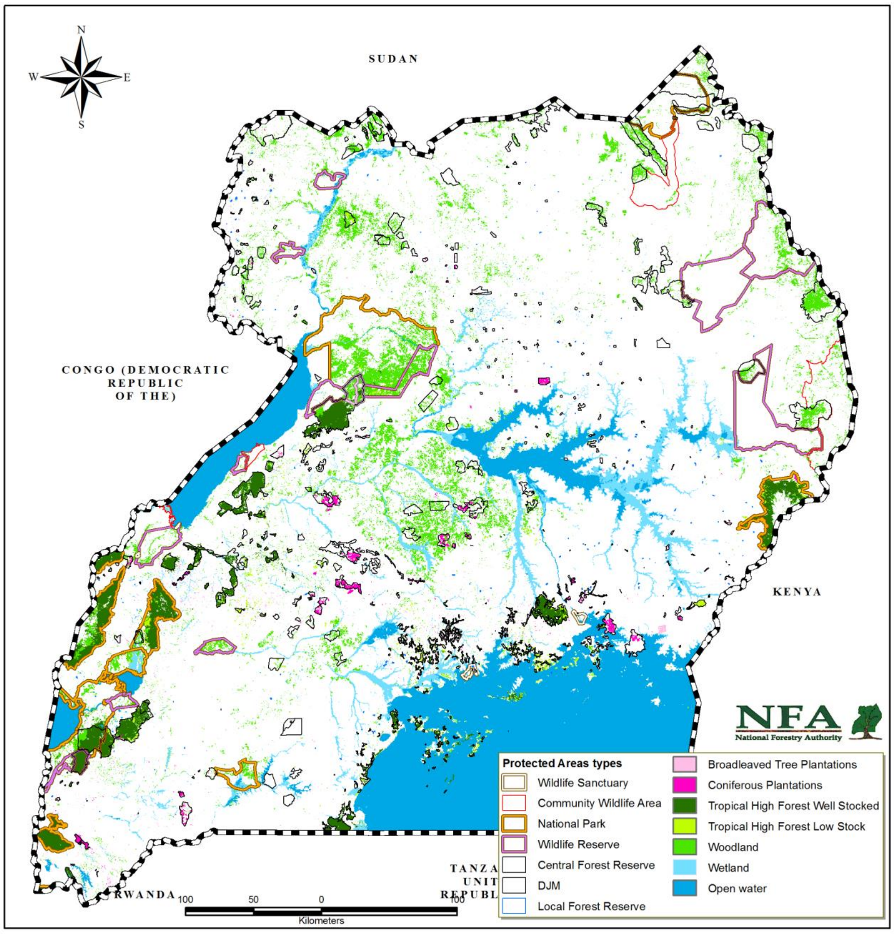
Map accuracy assessment methodology and results for establishing Uganda's FRL



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Acronyms

AA	Accuracy Assessment
AD	Activity Data
CFR	Central Forest Reserve
CI	Confidence Interval
EF	Emission Factor
F	Forest
FAO	Food and Agriculture Organization of the United Nations
FRL	Forest Reference Level
GFOI	Global Forest Observations Initiative
IPCC	Intergovernmental Panel on Climate Change
LULC	Land Use Land Cover
MIC	Mapping and Inventory Centre
NFA	National Forestry Authority
NF	Nonforest
OA	Overall Accuracy
PA	Producer's Accuracy
Pl	Plantation
THF	Tropical High Forest
UA	User's Accuracy
UWA	Uganda Wildlife Authority
WL	Woodlands

1 Introduction

Accurate and consistent information on forest area and forest area change is important given the reporting requirements for countries to access results based payments for REDD+. Forest area change estimates usually provide data on the extent of human activity resulting in emissions (e.g. from deforestation) or removals (e.g. from afforestation), also called activity data (AD). A basic methodological approach to estimate greenhouse gas emissions and removals (IPCC, 2006), is to multiply AD with a coefficient that quantifies emissions per unit activity (e.g. tCO2e per ha), also called an emission factor (EF) (FAO, 2016).

Activity data as part of emission/removal estimates should follow the IPCC good practice principle of neither over- nor underestimating emissions/removals and reducing uncertainties as far as is practicable. Methods that estimate areas from maps alone provide no assurance that these principles are met since they do not account for (systematic) classification errors. Therefore, it is common practice to compare the map classes against carefully classified reference data (e.g. 'truth') to provide such assurance. The reference data, also called accuracy assessment data, helps to correct for systematic map classification errors and provides the information necessary for estimating the uncertainty of map classes and construction of confidence intervals. Correcting for map bias and transparently reporting uncertainty of the estimates enhances compliance with IPCC good practice guidance (GFOI 2016).

Uganda is currently in the process of submitting its FRL. For this purpose, national land use land cover (LULC) maps are used which were ground-truthed in production, but no formal accuracy assessment has been conducted. The need for an accuracy assessment, especially of LULC change, has been addressed and the steps taken and results obtained are documented in this paper.

All steps are based on the guidance provided by Olofsson et al. (2013, 2014) and FAO (2016).

2 Process and institutions involved

The National Forestry Authority (NFA) of Uganda is mandated to do the national LULC mapping, and thus also providing the base for the information used to construct the activity data for the FRL. NFA has a long history of LULC mapping, with the first map being developed in the 1990s, and a dedicated team at the Mapping and Inventory Centre (MIC).

In order to facilitate the training of all MIC team members, and developing a common approach, without disturbances from daily office activities, two retreats were organised as follows:

- **First retreat, Fort Portal, 26 June - 8 July 2016**
  Main objectives: finalize manual assessment of change in LULC maps, develop map AA approach, train all team members on map AA
  Participants: 4 NFA MIC staff members, alternate REDD+ focal point, FAO GIS consultant, FAO MRV Expert, FAO REDD+ RS/GIS Expert

- **Second retreat, Mbale, 31 October 2016 - 4 November 2016**
  Main objectives: finalize reference data collection, discuss preliminary results
  Participants: all 5 NFA MIC staff members, FAO GIS consultant, FAO REDD+ RS/GIS Expert

3 Objectives of the map AA

The main objective of the map accuracy assessment is to assess the accuracy of the LULC change from 2000 - 2015 (the designated reference period for the FRL), especially regarding changes within and from the designated forest classes, and thus providing bias-corrected area estimates.
Uganda had decided to consider three forest strata for the FRL, namely plantations, tropical high forest (THF) and woodlands (WL). Furthermore, it defines REDD+ activities based on three management types, namely private land, land managed by NFA, and land managed by Uganda Wildlife Authority (UWA). In order to provide bias-correct area estimates for each management type, separate map accuracy assessments were conducted for each of the three areas.

In addition, it was decided to design the map AA methodology in such a way that it could serve also other purposes in the future:

- To assess the accuracy of all classes of the LULC map for 2015 in order to evaluate its appropriateness as base for future LULC mapping
- To collect data on tree cover on all LULC classes, not only on forest classes, in order to get a first idea about trees outside forests and to understand the differences between national data and Global Forest Change data (Hansen et al. 2013) better
- To derive recommendations on how to improve future mapping cycles

This document focuses on reporting the results regarding the main objective for Uganda's FRL, and adds on the explanations given in the main FRL submission.

4 Map data

4.1 Data on protected areas

In order to define the three management types, the most up-to-date boundaries of protected areas were used (see Figure 1). The protected wildlife estate, managed by UWA, is currently comprised of 11,231 km^2 of national parks, 7910 km^2 of wildlife reserves, 713 km^2 of wildlife sanctuaries, and 3174 km^2 of community wildlife areas. Central forest reserves (CFRs) cover 11,123 km^2 whereas local forest reserves have a total area of 50 km^2.
Each of the three management types – private land, land managed by NFA, land managed by UWA – was considered as a separate area for the map accuracy assessment and therefore handled independently from each other.

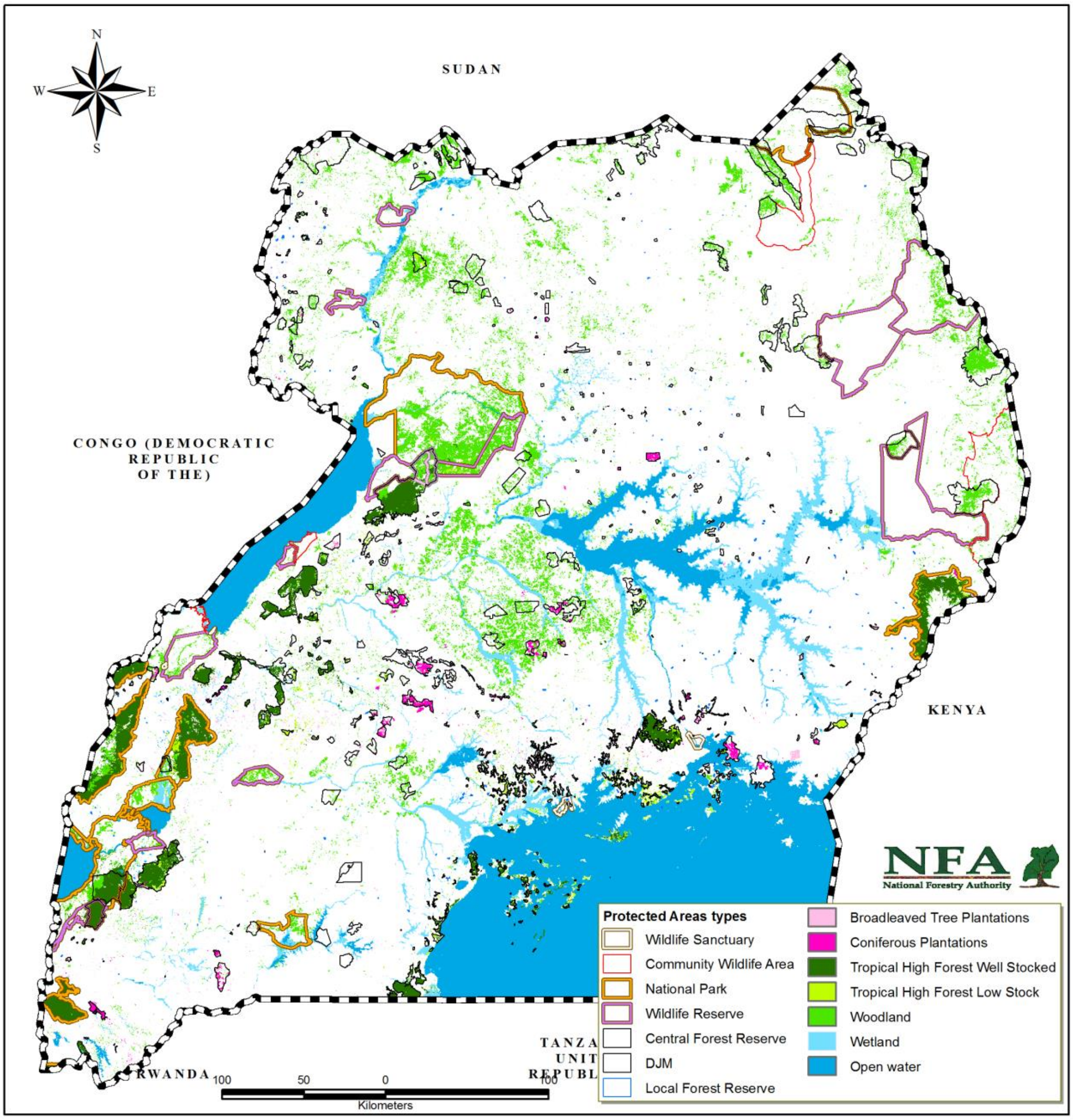

Figure 1: Forest cover and protected areas in Uganda (2015).

4.2 LULC change maps and strata

The methodology of creating the LULC change maps is described in section 3.4.1 in the main document of Uganda's FRL submission. The change maps are based on national LULC maps for the years 2000, 2005, 2010 and 2015, and underwent a manual review and revision and an automatic consistency check before being considered for accuracy assessment. Areas with stable water were excluded from the map AA.

In this submission, changes between 2000 and 2015 were considered. This resulted in six stable forest classes, three forest loss class, one forest gain class and stable nonforest. Map areas for each of these classes in each management type are reported in tables 7 – 9.

5 Sampling design and spatial assessment unit

As spatial assessment unit, polygons were chosen for two reasons. First of all, it is difficult to visually assess change on pixel level. Secondly, the polygon better represents the nature of the maps which were not created on pixel level, but on segments with a minimum mapping unit of 2 ha. Furthermore, the object-based assessment is less influenced by geolocation errors (Radoux et al. 2010) which could be an important error source taking into account the different map methodologies.

Random stratified sampling method was chosen for the sampling of the reference data locations, with the map strata being the ones as discussed under section 4.2 “Map data”. The minimum sample size for all classes was calculated using the formula provided (Cochran, 1977).
It takes as input the map areas for the classes to be assessed, a target standard error for overall accuracy, and expected user accuracies. A target standard error for overall accuracy of 0.01 has been used in the computation. For stable classes (NF remaining NF, Pl remaining Pl, THF remaining THF, and WL remaining WL), the estimate of expected UA has been set to 0.9, while it has been set to 0.7 to all other classes. The result is the overall minimum sample size.

The formula provided by Cochran et al. (1977) usually applies to pixel-based assessment, so the sample size is in terms of pixels that need to be sampled. The spatial assessment unit for Uganda is not the pixel, but polygon, so the overall sample size was distributed in polygons. As polygons cover a bigger area than single pixels, this procedure seemed appropriate as it would rather result in over- than in undersampling, and thus decrease the uncertainties even further.

The minimum sample size was distributed proportionally between the classes, but applying a minimum sample size of at least 20 samples per class to ensure that rare transition classes were sufficiently sampled. Final sample sizes are reported in Tables 1 – 3.

After drawing the sample, polygons with an area of smaller than 0.5 ha were excluded for three reasons:

- The same as pixels, such small polygons are very difficult to assess visually.
- These small polygons would have had very little or no influence on the results anyway because the area of the polygons is taken into account in the analysis
- All maps were produced using a minimum mapping unit (MMU). In most cases, the MMU was 2 ha. Overlaying the maps can result in smaller polygons. However, such small polygons are often rather the result of small geolocation errors or inaccuracies than of real features in the landscape.

6 Response design

The response design encompasses all steps of the protocol that lead to a decision regarding agreement or disagreement of the reference and map classifications (Olofsson et al., 2014). It has four major features: the spatial unit for assessment (discussed under sampling design), the sources of information used to determine the reference classification, the labeling protocol, and a definition of agreement.

6.1 Sources of reference data

The reference data must be of better quality than the map data, which can be achieved in two ways (Olofsson et al. 2014):

- The reference source has to be of higher quality than what was used to create the map classification (i.e. higher resolution satellite imagery)
- The process to create the reference classification has to be more accurate than the process to create the map classification if both processes use the same source material (i.e. if both classifications rely on Landsat data)

For reference data collection, a custom survey in Open Foris Collect Earth was used. Collect Earth "facilitates access to multiple freely available archives of satellite imagery, including archives with very high spatial resolution imagery (Google Earth, Bing Maps) and those with very high temporal resolution imagery (e.g., Google Earth Engine, Google Earth Engine Code Editor)" (Bey et al. 2016, p. 1). This open-source tool developed by FAO has been widely used to collect reference data for map accuracy assessment. In addition, time-series images of Landsat and Sentinel-2 imagery were used to facilitate the assessment of the land cover dynamics (see Figure 3). This combination of very high resolution imagery, mainly available through Google Earth, and time-series of medium and high resolution imagery, including spectral bands characteristic for the discrimination of vegetation, improves the quality of the visual interpretation drastically.

For Uganda, a custom survey in Collect Earth was developed taking into consideration the spatial assessment unit (polygon) and the three objectives of the accuracy assessment. Therefore, the survey collects information on the following variables:

- LULC class 2015 (all 13 LULC classes)
- Confidence for land cover class 2015
- Land cover change categories between forest and non-forest (F-F, F-NF, NF-NF, NF-F)
- Confidence of land cover change category
- Year of change (if applicable, i.e. excluding NF-NF)
- Forest class before change (for F-F and F-NF)
- Tree cover for most recent very high resolution image
- Comments

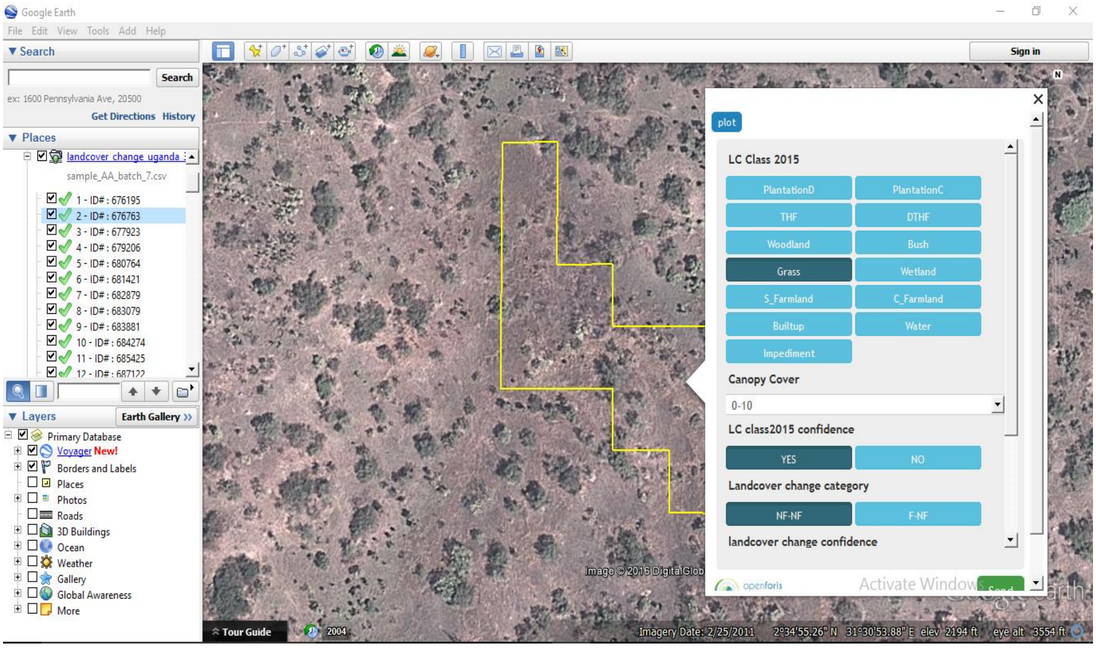

Figure 2: Survey used for reference data collection with Collect Earth survey interface.

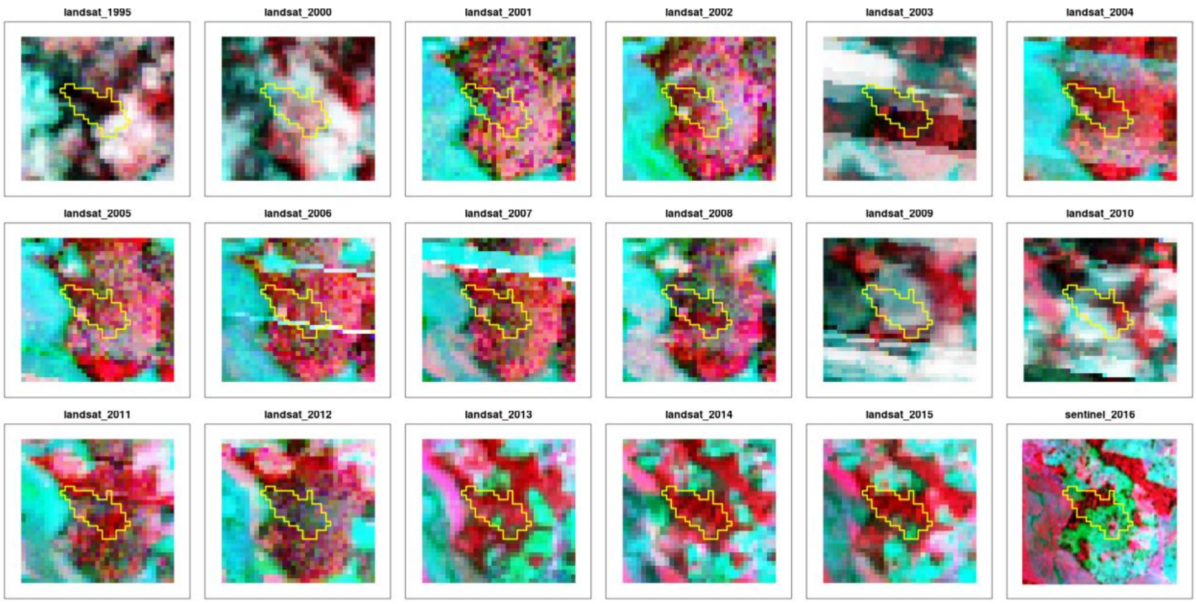

Figure 3: Landsat and Sentinel-2 snippets for one example polygon. The forest area, shown in red, is disappearing from 2013 onwards.

6.2 Labeling protocol

The NFA GIS team has a lot of experience in the visual interpretation of satellite imagery, especially for the purpose of creating LULC maps, and links them to their experience from intensive ground-truthing. In addition to the well-established routines and ongoing discussions on the interpretation of certain spectral signatures, the following rules were established for the purpose of map accuracy assessment:

- If a polygon covers more than one class, the majority class is assigned. If no majority class exists, the polygon is marked as no confidence for the respective variable, and hence excluded from analysis.
- Tree cover estimation was aided by a square grid of 50x50m.
- Protected area boundaries were loaded in Google Earth in order to make use of the local knowledge, especially regarding CFRs and the establishment of plantations within them.
- If more than one change was observed, the original and final LULC class were recorded, omitting the intermediate class. For example in CFRs, multiple changes were observed - mainly encroachment on natural forests that were then replanted as plantations. The change from natural forest to subsistence farmland to plantation was therefore recorded only as change from natural forest to plantation.

All samples were distributed randomly between the interpreters in order to avoid bias.

6.3 Defining agreement

The data collected through Collect Earth can easily be translated into the map classes - both in terms of LULC 2015 and in terms of forest – nonforest change. Therefore, agreement between reference and map data was defined as when the respective classes (LULC 2015 or forest change) matched.

7 Analysis and results

The analysis follows the guidance by Olofsson et al. 2004 and was done in R, based on scripts developed by FAO.

7.1 Creation of confusion matrix

The confusion matrix or error matrix is a simple cross-tabulation of the class labels allocated by the classification of the map data against the reference data (Olofsson et al. 2014). For polygon-based assessments, the confusion matrix can either be a cross-tabulation based on object-counts (number of polygons allocated by the classification of the map data against the reference data), or area-weighted (sum of the area of the polygons allocated to a certain map versus reference data combination). The area-weighted area matrix was chosen because the objective was to evaluate the proportion of the map that is correctly classified, and not the proportion of objects being correctly classified (Radoux et al. 2010).

This means that the areas of polygons falling into a certain category of combination of map and reference data were summed up in order to create the confusion matrix. The diagonal highlights the correct classifications where map and reference data agree in their classification. All cells off-diagonal show omission and commission errors. Tables 1 – 3 show the confusion matrices in terms of absolute area for 2000 – 2015 for each of the management types, including number of polygons sampled per map class.

Table 1: Confusion matrix, LULC change 2000 – 2015, private land, areas in ha. Marked in grey are the cells where map and reference data classifications correspond.

			Reference data												
			F – F						F – NF			NF – F	NF - NF		
			Pl-Pl	THF – Pl	THF-THF	THF-WL	WL-Pl	WL-WL	Pl-NF	THF-NF	WL-NF	NF-Pl	NF-NF	Total area	Number of polygon samples
Map data	F - F	Pl-Pl	15	0	3	0	1	21	49	1	0	0	13	103	21
		THF-Pl	7	0	1	0	0	14	0	3	6	0	18	49	27
		THF-THF	27	0	92	0	6	29	0	8	40	0	27	230	81
		THF-WL	2	0	4	5	0	73	0	4	54	0	16	158	41
		WL-Pl	34	0	0	0	0	43	0	0	41	0	25	143	33
		WL-WL	35	0	10	0	0	174	0	0	18	0	170	407	80
	F – NF	Pl-NF	20	0	0	0	0	5	0	2	1	0	96	124	50
		THF-NF	36	0	2	2	0	28	0	67	55	0	60	250	71
		WL-NF	10	0	1	1	0	55	0	0	64	0	489	619	122
	NF – F	NF-Pl	37	0	2	0	1	11	3	4	1	0	66	124	55
	NF – NF	NF-NF	34	0	7	7	2	62	0	6	40	0	3200	3358	525
		Total	257	0	122	15	10	515	52	95	319	0	4179	5565	1106

Table 2: Confusion matrix, LULC change 2000 – 2015, land, managed by NFA, areas in ha. Marked in grey are the cells where map and reference data classifications correspond.

			Reference data												
			F - F						F – NF			NF – F	NF - NF		
			Pl-Pl	THF – Pl	THF-THF	THF-WL	WL-Pl	WL-WL	Pl-NF	THF-NF	WL-NF	NF-Pl	NF-NF	Total area	Number of polygon samples
Map data	F - F	Pl-Pl	52	0	3	0	8	3	2	0	3	0	6	77	37
		THF-Pl	2	2	35	1	7	10	0	8	0	0	18	83	27
		THF-THF	11	3	9281	73	2	691	0	12	9	0	30	10111	211
		THF-WL	0	0	109	20	0	6	0	25	5	0	18	183	49
		WL-Pl	137	0	1	0	29	20	0	0	4	0	77	267	49
		WL-WL	14	0	72	1	5	389	8	0	145	0	245	879	143
	F – NF	Pl-NF	34	0	5	0	1	1	1	2	3	0	89	136	44
		THF-NF	6	14	36	0	1	27	7	28	32	0	178	329	85
		WL-NF	18	0	6	0	22	63	0	1	31	0	175	317	126
	NF – F	NF-Pl	212	0	4	0	18	5	0	0	2	0	47	287	67
	NF – NF	NF-NF	26	0	4	0	10	112	0	1	34	0	1026	1214	230
		Total	512	19	9556	94	103	1327	17	77	267	0	1908	13882	1068

Table 3: Confusion matrix, LULC change 2000 – 2015, land managed by UWA, areas in ha. Marked in grey are the cells where map and reference data classifications correspond.

			Reference data												
			F - F						F – NF			NF – F	NF - NF		
			Pl-Pl	THF – Pl	THF-THF	THF-WL	WL-Pl	WL-WL	Pl-NF	THF-NF	WL-NF	NF-Pl	NF-NF	Total area	Number of polygon samples
Map data	F - F	Pl-Pl	114	0	0	0	0	0	0	0	0	0	3	117	31
		THF-Pl	1	0	12	0	0	0	0	0	0	0	4	18	18
		THF-THF	48	0	248	0	0	154	0	0	1	0	71	522	182
		THF-WL	0	0	53	0	0	32	0	0	0	0	10	95	40
		WL-Pl	1	0	0	0	0	4	0	0	0	0	28	34	14
		WL-WL	0	0	6	0	0	406	0	0	1	0	75	488	130
	F – NF	Pl-NF	27	0	0	0	0	3	2	3	0	0	22	58	36
		THF-NF	0	0	102	0	0	52	1	0	0	0	71	226	75
		WL-NF	2	0	4	0	0	188	0	8	19	0	587	809	125
	NF – F	NF-Pl	59	0	4	0	0	12	1	0	0	0	51	127	58
	NF – NF	NF-NF	14	0	1	0	0	430	0	1	3	0	3394	3843	409
		Total	266	0	430	0	0	1284	4	12	24	0	4316	6337	1118

7.2 Estimating accuracies

Three types of accuracy estimates are derived from the confusion matrix, using the formula 1 to 7 provided by Olofsson et al. (2014): overall accuracy (OA), user's accuracy (UA), and producer's accuracy (PA), including their 95% confidence intervals. Results are presented in tables 4 – 6 for each of the management types.

Overall accuracy ranges between 59% (land managed by NFA) and 81% (private land). Producer's and user's accuracy exhibit very different numbers, with much higher accuracies for the stable classes than for change classes. For the change classes, loss of tropical high forest (THF – NF) has high user's accuracies for private and NFA land, whereas woodlands are generally more difficult to detect.

Table 4: Accuracy estimates for private land. PA = producer's accuracy, UA = user's accuracy, OA = overall accuracy. CI = confidence interval. UA is NA when area of reference data for that map stratum was 0.

Forest transition	Stratum	PA	CI of PA	UA	CI of UA
F - F	Pl-Pl	14.27	0.07	0.09	0
	THF-Pl	0	0	NA	0
	THF-THF	39.98	0.06	34.08	0.11
	THF-WL	3.3	0.03	1.2	0.01
	WL-Pl	0	0	0	0
	WL-WL	42.74	0.05	31.6	0.04
F – NF	Pl-NF	0	0	0	0
	THF-NF	27.03	0.06	74.56	0.13
	WL-NF	10.35	0.02	44.67	0.08
NF – F	NF-Pl	0	0	NA	0
NF –NF	NF-NF	95.28	0.01	86.45	0
				OA	**80.81 ± 0.01**

Table 5: Accuracy estimates for land managed by NFA. PA = producer's accuracy, UA = user's accuracy, OA = overall accuracy. CI = confidence interval. UA is NA when area of reference data for that map stratum was 0.

Forest transition	Stratum	PA	CI of PA	UA	CI of UA
F - F	Pl-Pl	67.92	0.1	7.92	0.01
	THF-Pl	2.06	0.03	3.37	0.05
	THF-THF	91.79	0.01	88.19	0.02
	THF-WL	10.83	0.05	25.73	0.09
	WL-Pl	10.82	0.04	5.28	0.02
	WL-WL	44.29	0.03	43.2	0.03
F – NF	Pl-NF	0.6	0.01	1.25	0.03
	THF-NF	8.54	0.03	67.49	0.13
	WL-NF	9.91	0.03	28.23	0.07
NF – F	NF-Pl	0	0	NA	0
NF –NF	NF-NF	84.5	0.02	62.35	0.02
				OA	**59.18 ± 0.01**

Table 6: Accuracy estimates for land managed by UWA. PA = producer's accuracy, UA = user's accuracy, OA = overall accuracy. CI = confidence interval. UA is NA when area of reference data for that map stratum was 0.

Forest transition	Stratum	PA	CI of PA	UA	CI of UA
F - F	Pl-Pl	97.15	0.03	3.35	0.01
	THF-Pl	0	0	NA	0
	THF-THF	47.53	0.04	88.51	0.02
	THF-WL	0	0	NA	0
	WL-Pl	0	0	NA	0
	WL-WL	83.23	0.03	44.26	0.02
F – NF	Pl-NF	4.02	0.05	12.17	0.26
	THF-NF	0	0	0	0
	WL-NF	2.33	0.01	71.28	0.21
NF – F	NF-Pl	0	0	NA	0
NF –NF	NF-NF	88.31	0.01	82.7	0.01
				OA	**72.49 ± 0.01**

7.3 Estimating bias-corrected area

The main aim of the map accuracy assessment is to provide bias-corrected area estimates of the map strata (presented in table 7 – 9). These were calculated using formula 8 to 11 provided by Olofsson et al. (2014).

For private land, area of forest remaining forest is much higher in the bias-corrected area estimates than in the map estimates. This could be due to the fact that small forest patches remaining in nonforest land were previously not detected as forest, but maybe just as trees on agricultural land in the maps, due to the coarse resolution of Landsat data and the MMU of 2 ha being applied. Particularly striking is the difference for plantation remaining plantation, with less than 2000 ha in the map data and 290,000 ha in the bias-corrected area estimate. At the same time, no newly established plantations were detected.

Also for land managed by NFA, the bias-corrected area estimates show higher areas of stable plantations. Furthermore, it is the stratum with the most significant conversion from natural forests to plantations. The differences between map area and bias-corrected area estimate are small for stable natural forest.

On land managed by UWA, these difference are much bigger, with the map overestimating the occurrence of THF and underestimating the area of woodlands. This could be due to the fact that woodlands in protected areas from UWA are almost undisturbed and their closed canopy cover can be mistaken for THF in Landsat imagery. At the same time, open woodlands, especially on bare soil, can be mistaken for nonforest classes such as grasslands or impediments.

Overall, the analysis shows that the map data had overestimated forest area for 2000 and underestimated it for 2015. The resulting forest loss estimates from the bias-corrected estimates are therefore much lower than those directly from the map data.

Private land exhibits the highest forest loss among the three management types, but also has the highest area of stable forests, mainly comprised of plantations and woodlands (see Figure 4). The biggest area of THF is found on land managed by NFA. Protected areas exhibit much smaller forest losses than private land, with forest loss on land managed by UWA being almost not existent.

Table 7: Map area and bias-corrected area estimates for forest-nonforest change on private land, 2000 – 2015, including confidence intervals (CI), in ha.

Forest transition	Stratum	Map area	Bias-corrected area	CI bias-corrected area
F - F	Pl-Pl	1,768	290,772	554
	THF-Pl	4,599	0	0
	THF-THF	65,628	76,985	248
	THF-WL	12,353	33,874	223
	WL-Pl	5,653	8,406	101
	WL-WL	547,011	739,859	849
F – NF	Pl-NF	7,014	1,756	11
	THF-NF	320,721	116,259	267
	WL-NF	2,176,511	504,341	757
NF – F	NF-Pl	43,370	0	0
NF –NF	NF-NF	13,830,438	15,242,811	1253
Total		**17,015,066**	**17,015,066**	

Table 8: Map area and bias-corrected area estimates for forest-nonforest change on land managed by NFA, 2000 – 2015, including confidence intervals (CI), in ha.

Forest transition	Stratum	Map area	Bias corrected area	CI bias corrected area
F - F	Pl-Pl	7,486	64,209	62
	THF-Pl	4,592	2,812	13
	THF-THF	258,413	268,959	49
	THF-WL	6,715	2,826	6
	WL-Pl	10,500	21,499	56
	WL-WL	164,399	168,543	116
F – NF	Pl-NF	6,150	2,943	14
	THF-NF	60,464	7,653	22
	WL-NF	177,637	62,399	82
NF – F	NF-Pl	40,102	0	0
NF –NF	NF-NF	378,874	513,486	139
Total		**1,115,332**	**1,115,332**	

Table 9: Map area and bias-corrected area estimates for forest-nonforest change on land managed by UWA, 2000 – 2015, including confidence intervals (CI), in ha.

Forest transition	Stratum	Map area	Bias corrected area	CI bias corrected area
F - F	Pl-Pl	1,161	33,718	76
	THF-Pl	290	0	0

	THF-THF	285,342	153,247	127
	THF-WL	6,389	0	0
	WL-Pl	89	0	0
	WL-WL	293,614	552,092	218
F – NF	Pl-NF	221	73	1
	THF-NF	18,939	2,737	18
	WL-NF	239,968	7,828	32
NF – F	NF-Pl	1,150	0	0
NF –NF	NF-NF	1,436,808	1,534,278	207
Total		**2,283,971**	**2,283,971**	

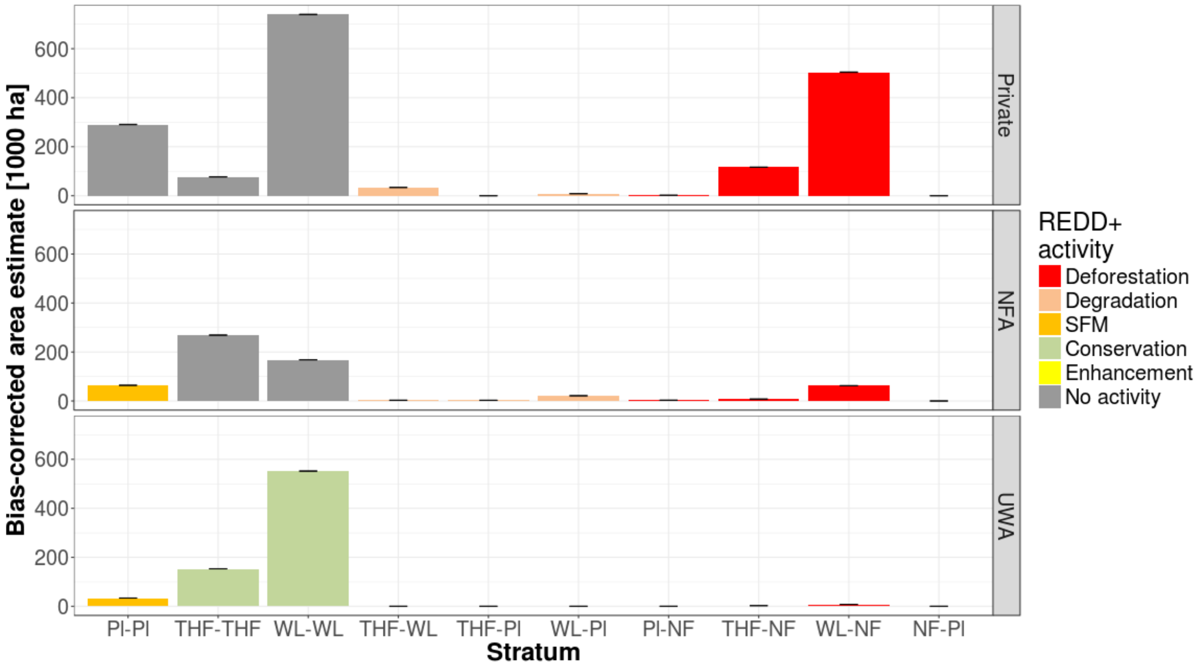

Figure 4: Bias-corrected area estimates for each management stratum, excluding stable nonforest, and attributed to the REDD+ activities as defined in Uganda's proposed FRL.

8 Conclusions

The analysis has shown the importance of collecting reference data for assessing the quality of the map data, and thus for deriving bias-corrected area estimates.

The reference data collection in Collect Earth, aided by Landsat and Sentinel-2 time series clips, proved to be practical and easy to implement. Especially the great local knowledge and experience in satellite image interpretation of the NFA MIC team aided the visual interpretation.

Compared to other map accuracy assessments, the bias-corrected area estimates of this exercise exhibit very small confidence intervals. This can be attributed to several factors. First of all, by using polygons as the spatial assessment unit, a bigger area was covered than with a pixel-based approach with the same amount of samples. Secondly, the map data was stratified much more, namely by three forest types and by management types, leading to lower variance within one stratum.

The polygon based approach has advantages and disadvantages. As mentioned before, polygons cover a bigger area than the same amount of samples as pixels, and therefore help in reducing confidence intervals. Secondly, polygons are easier to interpret than single pixels, especially regarding LULC change.
However, mixed polygons where more than one class are present can provide a challenge for interpretation. According to the labeling protocol, interpreters assigned the majority class as class label. This could, for example, have led to the high bias-corrected area estimate of stable plantations on private land. Plantations on private land are usually small, therefore often omitted in the national LULC maps because they are not detectable with Landsat imagery. On very high resolution imagery in Google Earth, they might be visible though, and polygons might be assigned that label even if the plantation only covers part of the polygon.

In the reference data interpretation, the discrimination between woodland and bushland was sometimes challenging, as well as between closed woodlands and THF. The combination of the very high resolution imagery in Google Earth and the time-series Landsat and Sentinel-2 data helped a lot in differentiating them, and especially assessing changes over time.

A remaining challenge in time-series analysis, however, is the change from nonforest to forest classes. In earlier exercises, map data had also been sampled including the conversion from nonforest to natural forest, but no evidence of these processes were collected in the reference data. Whereas it is not surprising for the regrowth of natural forests which is only expected to occur on degraded forest land, not completely deforested areas, this is unlikely for the establishment of plantations between 2000 and 2015, and should be further investigated.

An additional improvement will be to take the full map time series available into account, and therefore examine if the forest change dynamics remain constant over the full time period, or exhibit particular temporal trends.

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