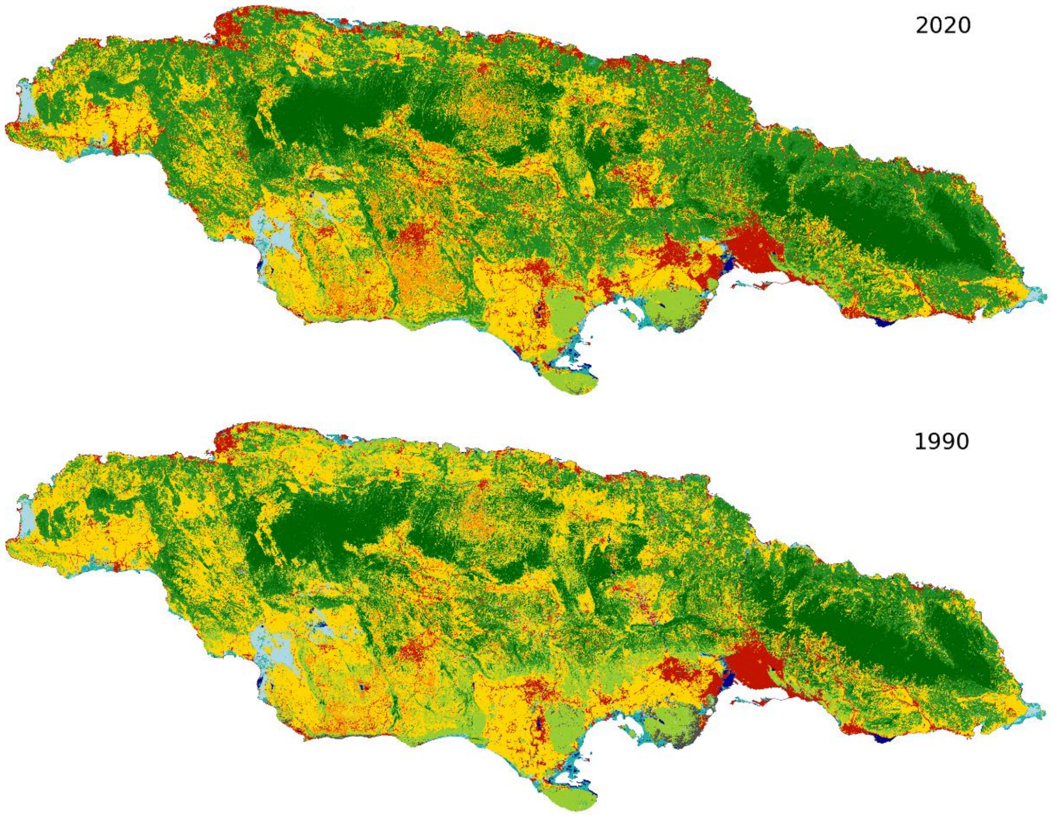
Monitoring land cover change in Jamaica



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February 2021

Contents

Latest updates

This document represents an updated version of the draft report submitted in December 2020. Since the submission of the original document, major updates are as follows.

Methodological changes:

- Classification training data are now derived from the Forestry Department's existing land cover maps, improving the volume and spatial distribution of training data and ensuring consistency of land cover definitions with existing datasets.
- The inclusion of new image features which has improved our ability to discriminate between map classes.
- Improvements to the generation of forest cover change data, with a focus on generation of more reliable forest regrowth data.

Validation:

- Qualitative validation by the geospatial working group has been supplemented by quantitative validation of map quality through the time series.

Updated statistics:

- Predictions of land cover, deforestation and forest regrowth have been used to generate updated statistical estimates.
- Change data have been analysed in detail, revealing the spatial patterns of forest change in Jamaica.

Analysing the drivers of change:

- A new analysis of the drivers of forest change has been conducted, identifying the main activities associated with deforestation and forest regrowth in Jamaica.

Next steps:

- An updated set of planned next steps has been produced, taking into account the latest requirements for land cover data in support of the REDD+ strategy.

Summary

- As part of the REDD+ readiness process, a time series of past and present land cover in Jamaica is under production in partnership with the Forestry Department. The purpose of the new dataset is to identify the current state of forest cover in Jamaica and quantify its change since 1984. This document describes methodological progress on this output, presents provisional results, and explains plans for future development.

- Tree covered areas dominate the land cover of Jamaica, accounting for 55.4% of total land area in 2020 (cover image). Most of the tree covered area is secondary forest, with 27% of forest recorded as dense or primary forest. Other significant land cover categories in Jamaica are croplands (31.3%) and settlements (8.9%).

- Forest cover in Jamaica appears to be stable or increasing over time, with a transition from agricultural land to secondary forest dominating land cover area changes.

- Rates of deforestation are low, averaging 0.46 %/yr over the past 20 years Significant sources of forest cover loss are likely to be urban development, infrastructure, bauxite mining, and agriculture.

- Forest regrowth is widespread, with observations suggesting that the extent of regrowth (estimated at 0.55 %/yr) matches or exceeds that of deforestation. Increases in tree cover are particularly apparent in agricultural regions, suggesting that increases are regrowth over former agricultural areas.

- A range of next steps are discussed, with the ultimate objective of producing robust statistical outputs to support Jamaica's REDD+ strategy, and providing lessons for Jamaica's forthcoming Forest Reference Emissions Level submission.

Map outputs can be interactively viewed on two web interfaces:

Annual land cover maps (1984 – 2020):

https://sambowers.users.earthengine.app/view/jamaicalandcoverv1

Change maps (2000 – 2020):

https://sambowers.users.earthengine.app/view/jamaicachangev1

1 Introduction

Jamaica is currently engaging in the first of three phases of Reducing Emissions for Deforestation and forest Degradation (REDD+), namely ‘readiness’ which will be followed by ‘implementation’ and ‘payments for results’. Those envisaged results-based payments are expected to be part of broader policy alignment behind the objective of REDD+ within Jamaica.

As part of the production of a REDD+ strategy of Jamaica, a series of geospatial analyses have been proposed to evaluate forest cover in Jamaica and its historical changes (Table 1). This document describes progress on the first and second of these outputs: a historical time series of land cover, and a first assessment of the drivers of deforestation.

Table 1 Proposed geospatial data products in support of Jamaica's REDD+ strategy This document relates to products 1 and 2.

Product	Method	Data from/via FD	Data from elsewhere	Link to ongoing work	Proposed training
1: Annual land cover maps for 2015 - onwards	Land cover classification, using open access satellite data, implemented on a cloud platform.	Reference data (e.g. existing land cover maps, and ground truth).	Images from Sentinel-1, Sentinel-2, ALOS PALSAR, Landsat	Supplement to existing decadal land cover maps. Method will be suitable for ongoing production of land cover maps on an annual basis. May provide data for future work on FREL.	Use of Google Earth Engine for land cover classification .
2: Assessment of the drivers of deforestation	Deforestation data combined with small Area Estimation modelling framework. Projections of future scenarios following Ryan et al. (2014).	Reference data of change activities (e.g. from FAO Collect Earth), socio-economic data on forest use (e.g. census, LSMS, DHS, agricultural surveys)	Global Forest Watch data for stratification	Requirement for effective REDD+ strategy, links to FREL	FAO Collect Earth
3: Biomass change and degradation estimates	Modification of McNicol et al. (2018) with data from Sentinel-1.	In situ biomass estimate (i.e. forest plots, transects)	Images from Sentinel-1, ALOS PALSAR	Estimation of C-stocks for GHG and FREL.	Linking Earth Observation with field measurements
4: Drivers of degradation	As 2	As 2	Outputs from 3.	Links to REDD+ strategy and FREL.	As 2.

Existing land cover mapping

Land cover mapping in Jamaica is currently conducted at approximately decadal intervals, with the most recent data existing for 1998 and 2013 (Figure 1) and an updated land cover map being planned for 2023. These data are constructed in a semi-automated process using classification and interpretation of high-resolution commercial satellite imagery.

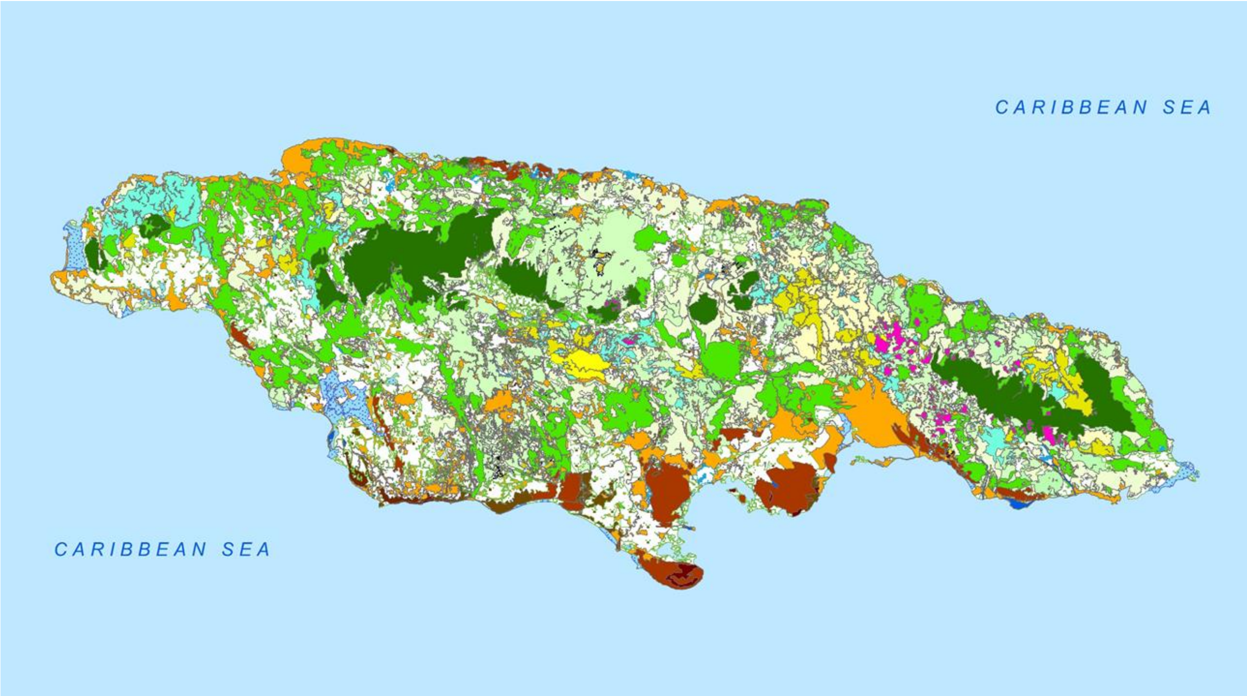


Figure 1 Existing data on land cover in Jamaica (2013). Image courtesy of Forestry Department.

While results are considered effective, for the purposes of REDD+ monitoring there are several shortcomings of the existing approach. The process of generating maps from high resolution data is time consuming and costly, making more frequent land cover estimates unfeasible. Given the time gap between maps, losses and gains in the intervening period may easily be missed. Issues around consistent land cover definitions have also been identified, with land cover definitions that have been developed over time and thus are not always comparable between maps. Deriving change statistics from one-time maps can also be susceptible to errors in each input map, with the result of high uncertainties in change estimates[1].

[1] For more information on good practice for change estimation, see the Global Forest Observations Initiative (GFOI) Methods and Guidance document https://www.reddcompass.org/download-the-mgd.

Specification of updated maps

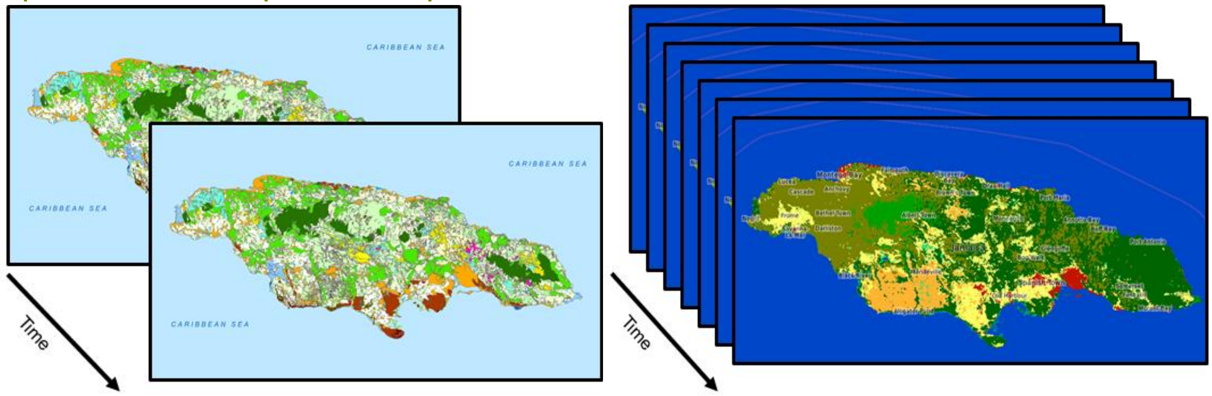


Figure 2 Jamaica currently produces land cover maps at approximately decadal time intervals (left). For the purposes of REDD+ this will not provide sufficient temporal information for effective planning. The method described here sacrifices some spatial resolution and thematic detail to obtain a dense time series of land cover (right).

With the geospatial working group of the National REDD+ steering committee, a new method is under development to provide estimates of land cover and its change that are generated at greater frequency, lower cost, and reduced manual effort (Figure 2). Rather than a replacement for existing approaches, the new data product aims to provide data that is complimentary to past and future land cover maps produced with existing methods.

Requirements for this new approach were identified as:

- **Robust**, with a clearly understood uncertainties.
- **Timely**, with estimates produced on an annual basis a lag of less than 1 year in generating statistics.
- **Practically achievable** with staff time requirements and technical barriers minimised.
- **Repeatable** year-on-year.
- **Affordable**, making use of open access satellite data.
- **Consistent** with existing data sources.

Map outputs were developed collaboratively with the geospatial working group, whose members have knowledge of Jamaica's major land cover categories and their distribution. The outputs presented in this report are derived using training data drawn from existing land cover maps, thus have similar definitions to existing land cover mapping efforts.

2 Methods

Cloud Processing

With the proliferation of open access satellite data since the opening of the Landsat archive[2], remote sensing studies are now commonly based on long time series of satellite images. With this change has arrived a new processing challenge, where local data processing infrastructure is no longer sufficient to support advanced remote sensing analyses. A particular limitation is internet connectivity, which forms a bottleneck to accessing large data archives.

To alleviate this issue, modern data processing methods make use of cloud computing and storage (Figure 3). Instead of downloading data to a local machine, instructions are sent to a remote server to process data, and only final outputs need to be downloaded. This has multiple advantages: local processing infrastructure need not be powerful, download speeds are no longer limiting, and users can take advantage of economies of scale in data processing.

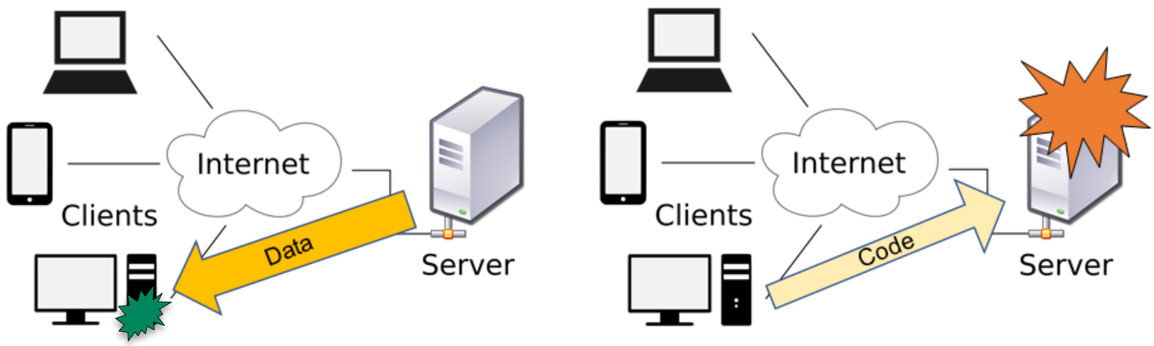


Figure 3 Processing of data on local equipment (left) is frequently limited by internet connectivity, particularly where large archives of satellite data are required. Modern processing methods use cloud processing capabilities (right), requiring only limited amounts of data to be transferred over the internet and larger processing tasks can be performed efficiently.

Multiple cloud platforms for EO data processing are available, each with its own advantages and disadvantages. For this application we used Google Earth Engine, which is currently the most widely used cloud platform, and has a large user community providing support and example scripts. Google Earth Engine is currently provided free of charge for research, education, and non-profit use. Processing scripts were written in Python, combining the power of Google Earth Engine with the flexibility introduced by Python's comprehensive geospatial data processing libraries.

Earth Observation Data

Open access optical Earth observation data of a suitable resolution and repeat-time for annual forest monitoring are currently provided by Landsat and Sentinel-2. Data from Landsat have a repeat time of ~16 days with a 30 m pixel resolution. Landsat has the advantages of a longer data archive (back to 1984), much of which has been atmospherically corrected and is available with a high-quality cloud mask. The Landsat archive is therefore the mainstay of forest monitoring across the world. Since 2016 a new data stream from Sentinel-2 has been available, offering a higher resolution (10 m) and more rapid repeat time (5 days) than Landsat.

[2] See Woodcock, C.E., et al. (2008) "Free access to Landsat imagery." *Science* 320, 1011.

The initial proposal to the Forestry Department was to use data from Sentinel-2 to take advantage of its superior resolution/repeat time (see Table 1), and strong guarantees of future data provision. This has been changed for data from Landsat with the following justification:

- Methods for producing land cover/change maps with Landsat time series are well-developed, with a substantial scientific literature to support mapping efforts.
- For the purposes of a REDD+ strategy, a time series of at least 10 years is preferred to short-term assessments.
- Rates of forest cover change in Jamaica are expected to be low, therefore to stand a reasonable chance of accurately quantifying change a long time series is preferable.

This method combines multiple images from Landsat by selecting cloud-free regions from each input image and combining into a composite image. Each composite is bounded by the calendar year (1st January - 31st December), and only images with less than 50% cloud cover over land are considered. Every year 1984 - 2020 is processed independently, combining the full time series of Landsat 4, 5, 7 and 8 for Jamaica (tier 1 imagery, with atmospheric and terrain correction and cloud masking). A total of 1768 images were processed to produce the land cover time series.

Feature Generation

Image stacks for each year are reduced to a series of metrics (or 'features') that together describe the state and temporal variability of vegetation cover in each year. Image features are designed to supply the classifier with sufficient information to reliably separate classes of interest. Percentiles are used to 'reduce' image stacks down to a single composite, an approach that tends to exclude residual clouds (high reflectance) and cloud shadows (low reflectance) from composites. Additional features were included that describe topographic position (data from the Shuttle Radar Topography Mission), and image texture. Image features used in land cover mapping are summarised in Table 2.

Table 2 Image features selected for classification of annual land cover maps.

Input	Method	Derived Features	Purpose
Median reflectance	$Blue = B1^{*}, B2^{\dagger}$ $Green = B2^{*}, B3^{\dagger}$ $Red = B3^{*}, B4^{\dagger}$ $NIR = B4^{*}, B5^{\dagger}$ $SWIR1 = B5^{*}, B6^{\dagger}$ $SWIR2 = B7^{*}, B7^{\dagger}$ $Temp = B6^{*}, B10^{\dagger}$ *TM/ETM+ Landsat 4-7 †OLI Landsat 8	50th percentile	Distinguishes land cover types based on characteristic spectral signatures.
Normalised Difference Vegetation Index (NDVI)	$NDVI = \frac{NIR - Red}{NIR + Red}$	10th percentile 25th percentile 50th percentile 75th percentile 90th percentile	Highlights vegetation and its intra-annual variability.
Normalised Burn Ratio (NBR)	$NBR = \frac{NIR - SWIR2}{NIR + SWIR2}$	10th percentile 25th percentile 50th percentile 75th percentile 90th percentile	Sensitive to burn scars and canopy disturbance.
Normalised Difference Water Index (NDWI)	$NDWI = \frac{NIR - SWIR1}{NIR + SWIR1}$	10th percentile 25th percentile 50th percentile 75th percentile 90th percentile	Highlights soil moisture and canopy water content, and its intra-annual variability.
Texture	5x5 square kernel on Green band	Entropy	Highlights the texture of vegetated vs cleared land
Digital Elevation Model (DEM)	Shuttle Radar Topography Mission	Slope Aspect	Provides ancillary information on the topography of a location.

Land cover definitions

In consultation with the geospatial working group, a working set of land cover definitions for Jamaica has been produced, building on existing land cover maps. Classes were selected for their importance for the objectives of REDD+ (focusing on forest classes), their ability to be discriminated using optical imagery, and for broad consistency with IPCC land cover categories[3]. These definitions are not yet finalised, and in future the Forestry Department and others may wish to modify this classification scheme to match other objectives.

Table 3 Proposed simplified land cover classification scheme for land cover time series. Map legends show RGB colours in HEX format.

Map class	Level 1 (IPCC)	Level 2 (National*)	Map legend
0	No data	No data	#000000
11	Forest land	Dense moist forest	#006400
12		Secondary moist forest	#228B22

[3] See Penman, J., et al. (2003) "Good practice guidance for land use, land-use change and forestry". IPCC.

13		Dry forest	#9ACD32
14		Mangrove forest	#20B2AA
21	Grassland†	Pasture†	#90EE90
22		Other grassland†	#FFFF00
31	Cropland	Cultivated cropland	#FFD700
41	Settlement	Settlement	#C31400
51	Wetland	Seasonally inundated	#ADD8E6
52		Permanent water	#00008B
61	Other land	Mining	#FF8C00
62		Quarrying	#C0C0C0
63		Other bare†	#4D4D4D

* Working definitions. † Training data for these classes do not currently exist.

Image classification

Image features were converted to land cover maps using a supervised classification method. Supervised classification requires example locations of each land cover class of interest to train an algorithm to predict land cover based on image features. Training data were selected over locations of stable landcover through the entire time series, an approach that allows for efficient production of temporally representative training data.

Training pixels were selected from stable locations from the 1998 and 2013 land cover maps (Figure 4). Only 'pure' land cover classes were included (i.e. no mixed land cover classes), and where unchanged pixels were assumed to have been stable in the interim period. For each year of imagery up to 5000 randomly sub-sampled reference pixels were drawn from each map class. Pixels were drawn from two years either side of the available time series (1996 – 2015), the period over which land covers were assumed to be unchanged.

Reference points were used to train a Random Forest classifier, a widely used and easy to parameterise machine learning approach that requires little tuning and is robust to non-parametric data. The classifier was set to output the probability of each pixel belonging to each map class for each year, providing an estimate of confidence in land cover classification.

A separate set of validation polygons were manually identified by the geospatial working group, representing all map classes of interest. These were selected from locations where there is a high degree of confidence in the land cover and its stability through the entire time series. A random sample of pixels were drawn from this subset, which were used to perform a simple assessment of map accuracy through time (Figure 4).

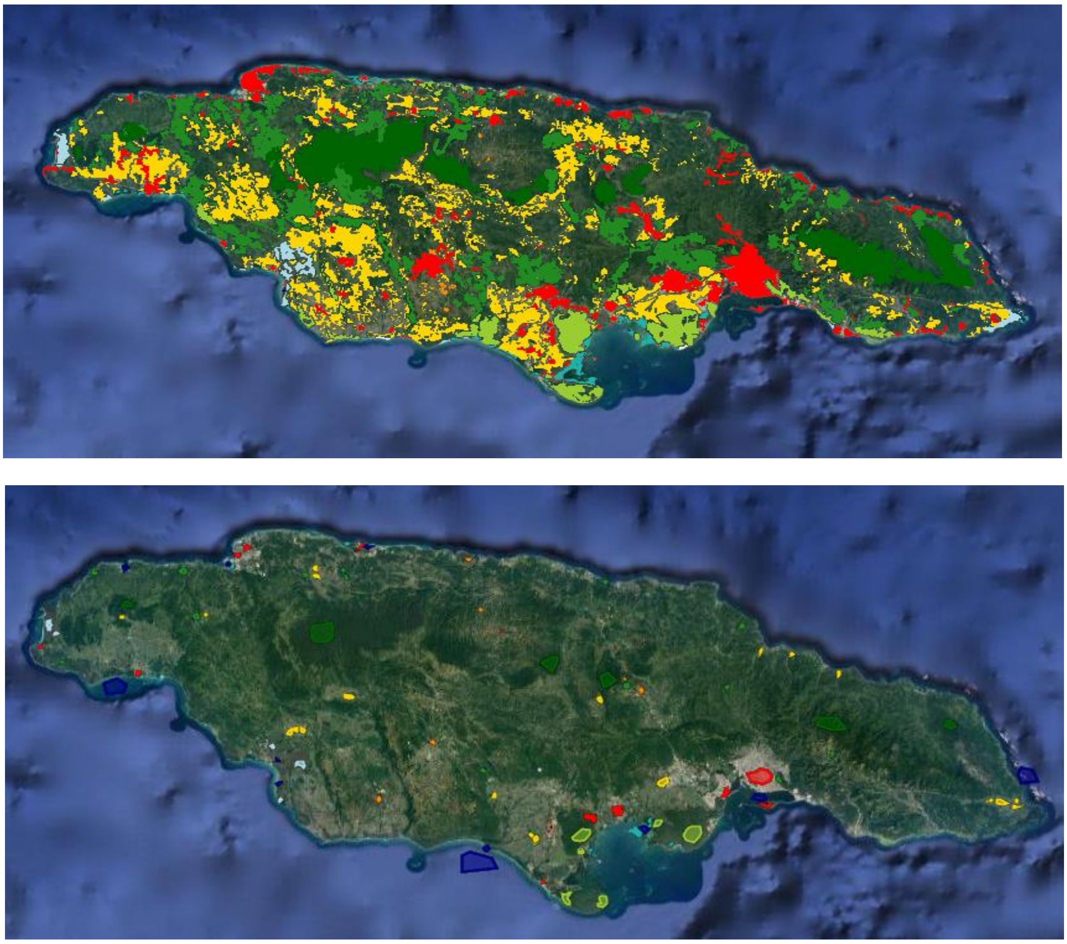


Figure 4 (a) Training data derived from stable locations from existing land cover maps, and (b) validation data from stable land cover locations manually identified in optical image composites.

Post-classification

When land cover classification is applied independently on multiple images through time it is common to find that map errors year-on-year account for larger area changes than true land cover change. As the objective was to produce ensure consistent measurements through time, images were post-processed to minimise false detections of change.

The proposed method uses a 'Hidden Markov Model' (HMM) to harmonise land cover time series[4]. In short, this method assigns an *a priori* probability of land cover transitions between each pair of land cover classes. For instance, from ecological theory we know that it's unlikely that land cover will change from cropland directly to dense forest, but more likely that the transition from cropland to secondary forest will occur. The HMM method combines the probability of each map class in each year with the probability of transitioning between each classes. Transitions between land cover classes are recorded where sufficient evidence has been built up that a land cover has changed, either through the land cover change being one that is expected or a change is recorded with a high probability in satellite observations.

The result of the HMM approach is a time series that is more consistent through time, with fewer examples of random fluctuation between class values and the clearer appearance of

[4] Described in Abercrombie, S. P., Friedl, M. A. (2015) "Improving the consistency of multitemporal land cover maps using a hidden Markov model." *IEEE Transactions on Geoscience and Remote Sensing* 54.2 703-713.

land cover trends[5]. The transition matrix is defined in Figure 5.This transition matrix still uses a working set of transition probabilities, and can be expected to be modified in future iterations.

	FROM	Forest: dense	Forest: secondary	Forest: dry	Forest: mangrove	Grassland: pasture	Grassland: other	Cropland: cultivated	Settlement: settlements	Wetland: seasonally inundated	Wetland: permanent water	Other land: mining	Other land: quarrying	Other land: other bare
TO		11	12	13	14	21	22	31	41	51	52	61	62	63
Forest: dense	11	1	2	4	4	4	4	4	4	4	4	4	4	4
Forest: secondary	12	2	1	4	4	3	3	3	4	4	4	3	3	3
Forest: dry	13	4	4	1	4	3	3	3	4	4	4	3	3	3
Forest: mangrove	14	4	4	4	1	3	3	4	4	4	4	4	4	3
Grassland: pasture	21	3	3	3	3	1	2	2	4	4	4	3	3	3
Grassland: other	22	3	3	3	3	2	1	2	4	4	4	3	3	3
Cropland: cultivated	31	3	3	3	4	2	2	1	4	4	4	3	3	3
Settlement: settlements	41	3	3	3	3	3	3	3	1	4	4	3	3	3
Wetland: seasonally inundated	51	4	4	4	4	4	4	4	4	1	4	3	3	3
Wetland: permanent water	52	4	4	4	4	4	4	4	4	4	1	3	3	3
Other land: mining	61	3	3	3	4	3	3	3	4	3	3	1	3	3
Other land: quarrying	62	3	3	3	4	3	3	3	4	3	3	3	1	3
Other land: other bare	63	3	3	3	3	3	3	3	3	3	3	3	3	1

Figure 5 Transition matrix showing *a priori* expectation of transition between map classes. Numbers represent pre-selected probability classes of 1 (stable) = 0.9, 2 (common transitions) = 0.1, 3 (rare transitions) = 0.025, and 4 (unlikely transitions) = 0.001.

Analysis

Land cover is presented for the year 2020, comparing predictions against high-resolution imagery and existing datasets. Land cover areas for each year are calculated from the sum of pixels in each class used to plot a temporal trend of land cover in Jamaica. Class accuracies are compared against reference polygons, providing a first estimate of where map outputs are performing effectively.

Deforestation is flagged in time series where any forest land cover (dense, secondary, dry, and mangrove forest) changes at least once to any other land cover type. Where multiple changes are detected, only the most recent change is considered. Forest regrowth is defined as the inverse of deforestation, and flagged where any non-forest land cover transitions to a forest cover at least once. Given the better availability of Landsat data from 2000 onwards, changes are only considered for the period 2000 – 2020.

Results are presented on as static figures in this report, although it is recommended to view interactive online versions for greater detail.

[5] Hermosilla, T., et al. (2018) "Disturbance-informed annual land cover classification maps of Canada's forested ecosystems for a 29-year landsat time series." *Canadian Journal of Remote Sensing* 44.1 67-87.

3 Results

The latest map outputs can be interactively viewed on two web interfaces:

Annual land cover maps:
https://sambowers.users.earthengine.app/view/jamaicalandcoverv1

Change maps: https://sambowers.users.earthengine.app/view/jamaicachangev1

Code to reproduce these results is available from Sam Bowers (sam.bowers@ed.ac.uk) on request.

Land cover in 2020

The spatial distribution of land cover predicted by the maps matches the known distribution of land cover in Jamaica (Figure 6). Forest is the largest land cover, with areas of dense forest associated with protected areas and mountainous regions correctly identified, and dry forest dominating in the south of the island. Secondary forest is the largest forest land cover on the island and is well-distributed across the island. There are limited extents of mangrove mostly confined to the southern coastline. Croplands were identified at known locations of agricultural production, while settlements largely capture the distribution of urban population in Jamaica. Smaller land covers were present in the majority of expected locations (e.g. seasonal wetlands), albeit with a number of missed detections (e.g. sandy areas mis-classified as settlements) in the smallest classes.

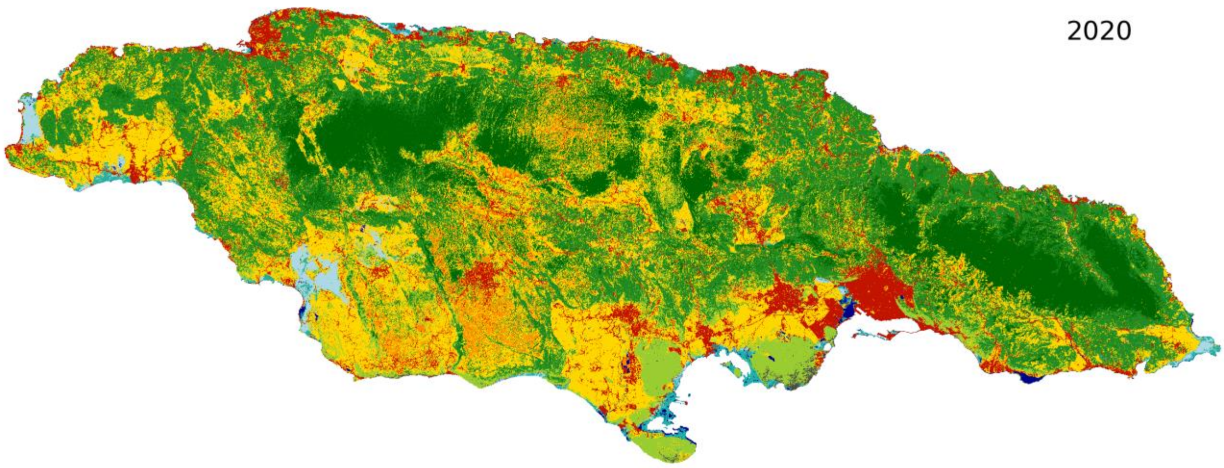


Figure 6 Land cover predicted for Jamaica in 2020. See Table 3 for class definitions.

By calculating the proportional coverage of each land cover class, the extent of each land cover can be estimated (Figure 7). Based on map outputs for 2020, the largest land cover in Jamaica is forests (55.4% of land area), followed by croplands (31.3%), and settlements (8.9%). It should be noted that areas calculated from mapped area should be treated with some caution, as there are commonly biases associated with pixel counts[6].

[6] See Olofsson, Pontus, et al. "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 (2013): 122-131.

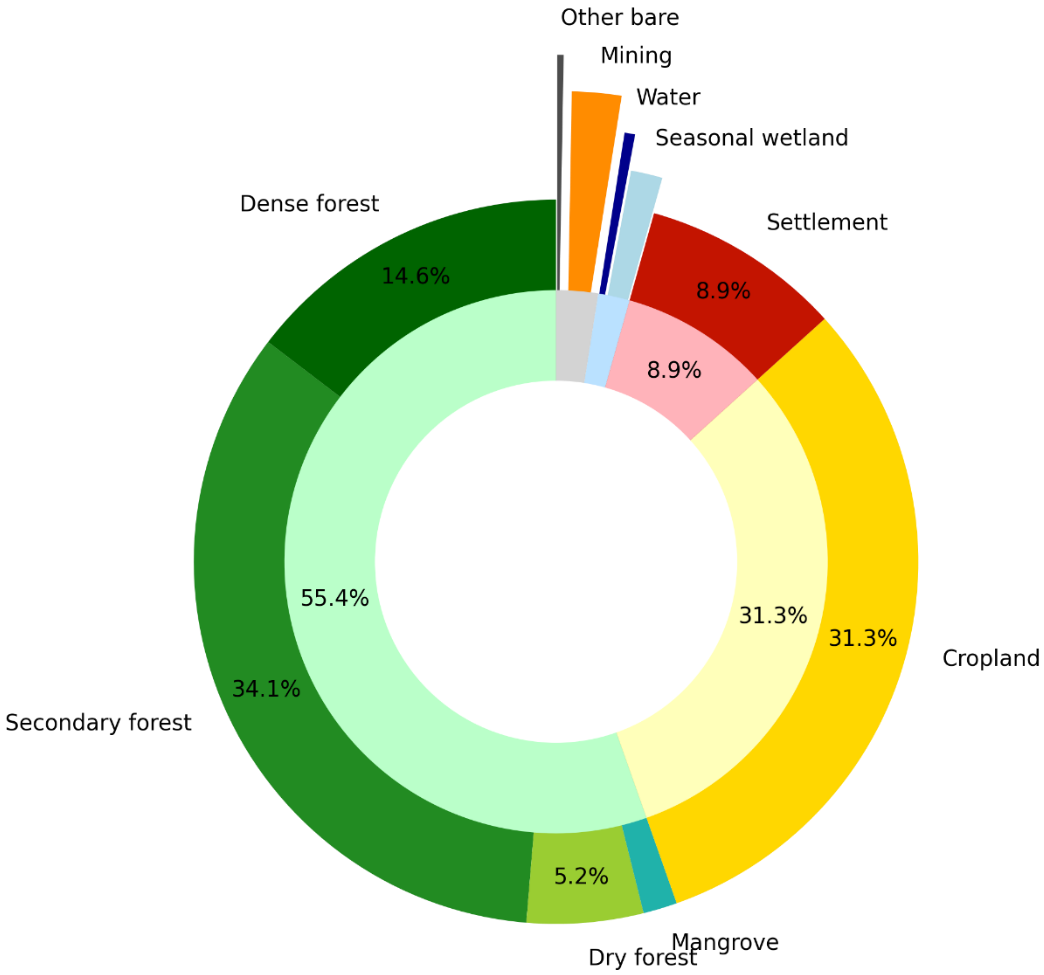


Figure 7 Proportional land cover in Jamaica for the year 2020. The outer chart shows level 2 national map classes, and the inner chart the area expressed as level 1 IPCC classes. Percentages are shown for the dominant land covers.

Land cover change in Jamaica

As a result of the post-processing applied to the time series of land cover (see section 0), land cover maps can be compared across the time series to visualise and quantify rates of change in forest cover (Figure 8). These data show a general 'greening' of the island through time.

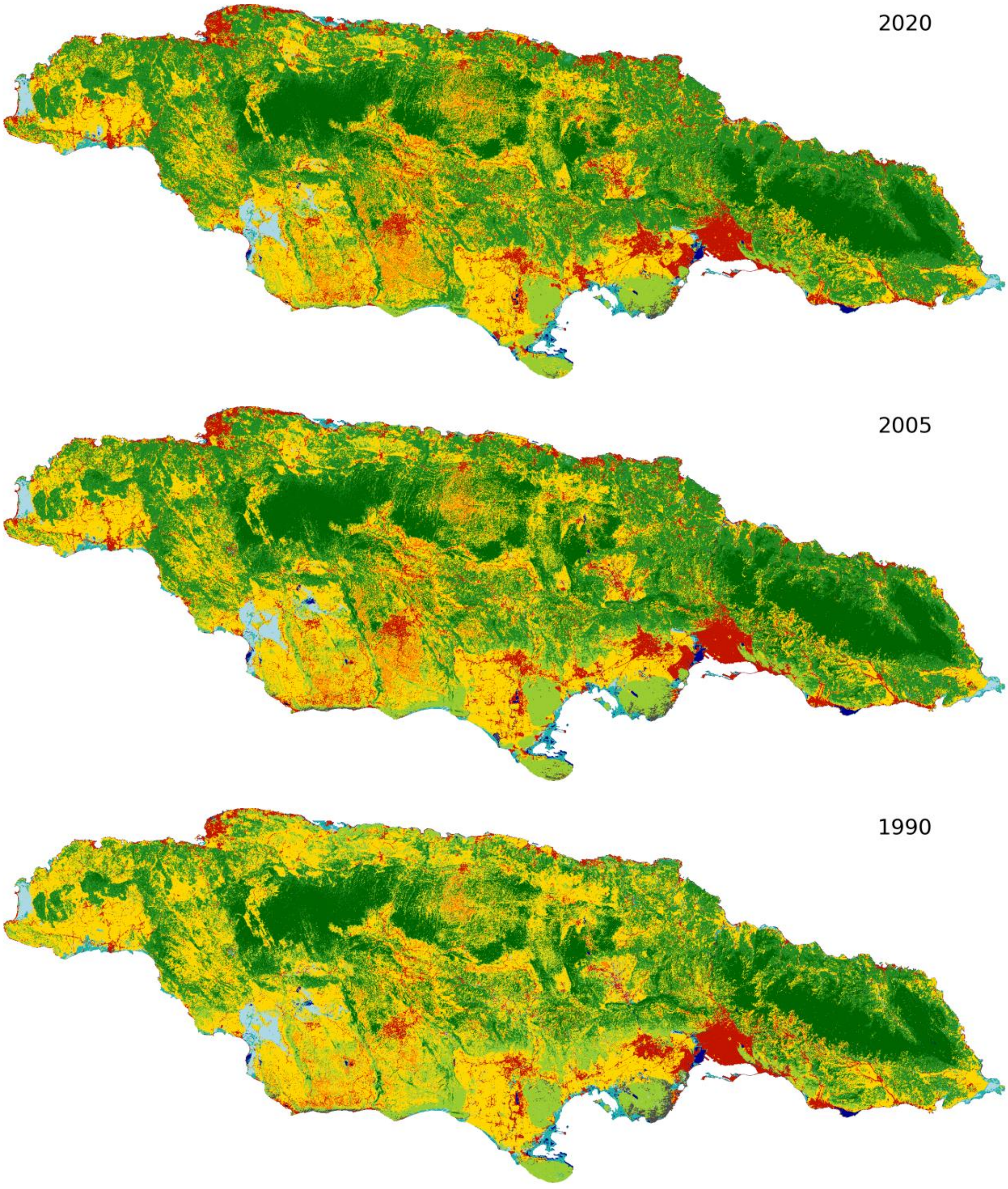


Figure 8 A 30 year time series of land cover in Jamaica, showing land cover in 2020 (top), 2005 (middle), and 1990 (bottom).

By totalling the pixel counts for each year of measurement, trends of land cover areas can be assessed (Figure 9). Most land covers in Jamaica are relatively stable over time, although this representation may mask dynamic changes between land covers. Notable is a significant net increase in secondary forest area, associated with reductions in the areas of dry forest and agricultural land. While the former is suspected to be associated with errors in the dry forest class, the latter likely represents a real trend. The implied net increase in forest cover in Jamaica over the past decades is an observation of particular importance to REDD+.

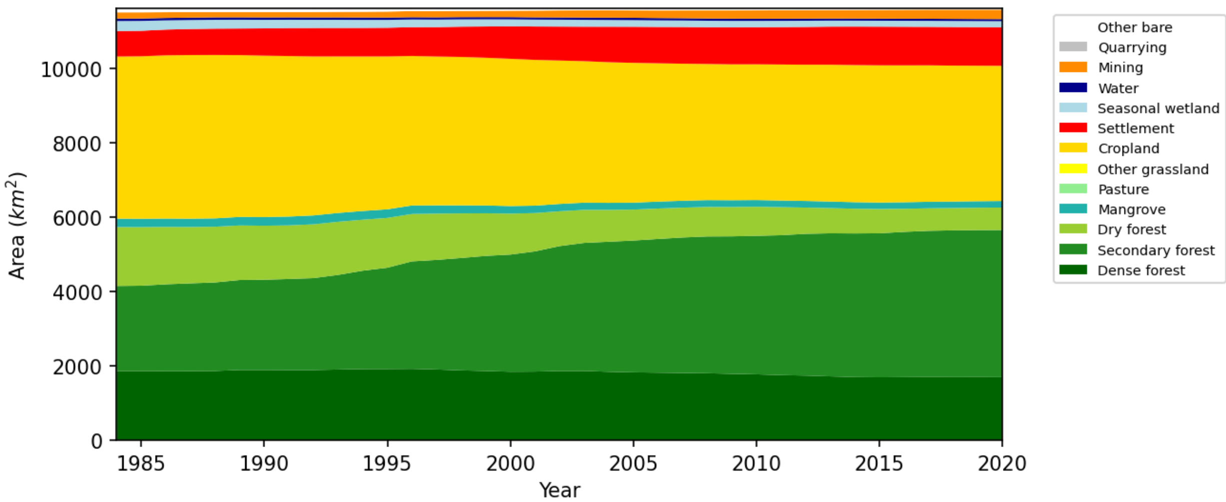


Figure 9 Temporal trend of land cover change in Jamaica. The largest changes in area are losses from the cropland and dry forest classes and increases to the secondary forest class, pointing at possible re-growth on fallow agricultural lands.

Trends in land cover can be alternately represented by flows between land cover classes (Figure 10). This representation also indicates a relatively stable dense forest class and increasing cover by secondary forest from cropland and dry forest classes. The rapid changes in the dry forest class indicate probable confusion between dry and secondary forests early in the time series.

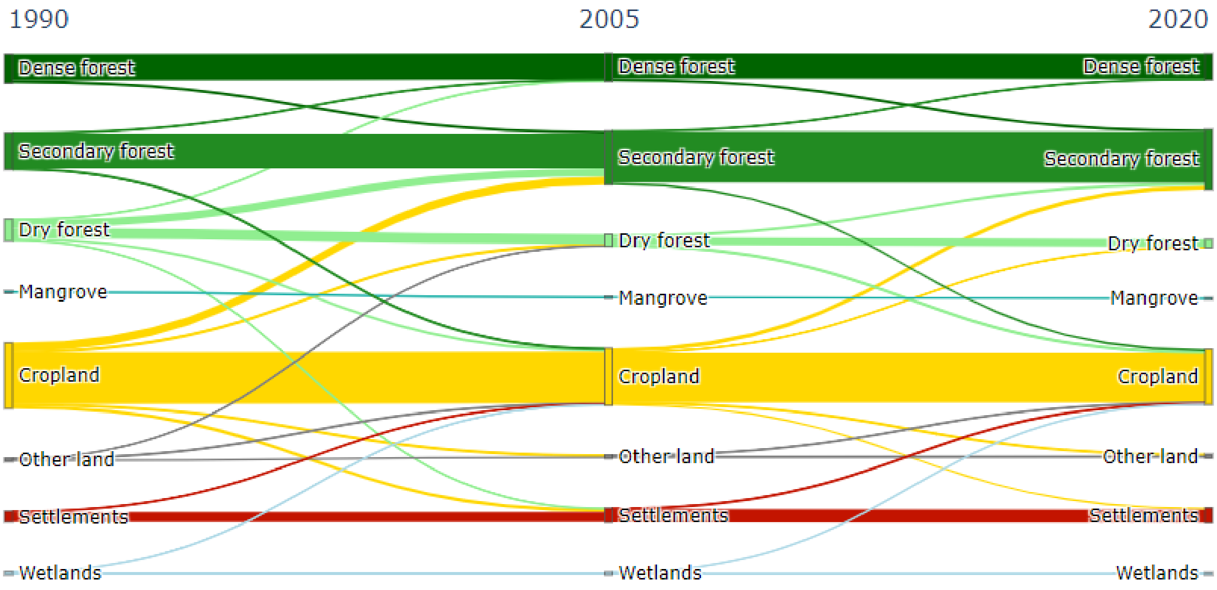


Figure 10 Flow diagram showing net changes of land cover for 1990, 2006 and 2020. Land covers are defined using the national land cover mapping scheme for forest classes and simplified to IPCC defaults for remaining classes. The width of links between land covers is proportional to the total area of change. Only large absolute changes between land covers (at least 25 km^2) are displayed.

Change detection

In addition to net changes in land cover, post-processing of the satellite data archive allows a first estimate of spatial pattern of land cover change. Changes were highlighted where they represented deforestation (change from any forest class to a non-forest class) and regrowth (change from a non-forest to any forest class). Estimates of change are an inherently tougher remote sensing challenge, so the following should be considered as first estimates only.

Deforestation

Maps of deforestation show locations where forest was lost over the period 2000 – 2020 (Figure 11). Forest losses were present across the island, with the largest proportional losses in Portland and St James, moderate losses in St Ann, Trelawny, St Elizabeth, Manchester and St Catherine, and relative stability in Hanover, St Mary, Westmoreland and Saint Andrew.

Map outputs provide a good visual indicator of the spatial distribution of deforestation and its causes. A visual review by the geospatial working group identified the main drivers of forest loss as settlement expansion, infrastructure development, bauxite mining, and agriculture. For more detail, see section 5 for a qualitative analysis of the drivers of change.

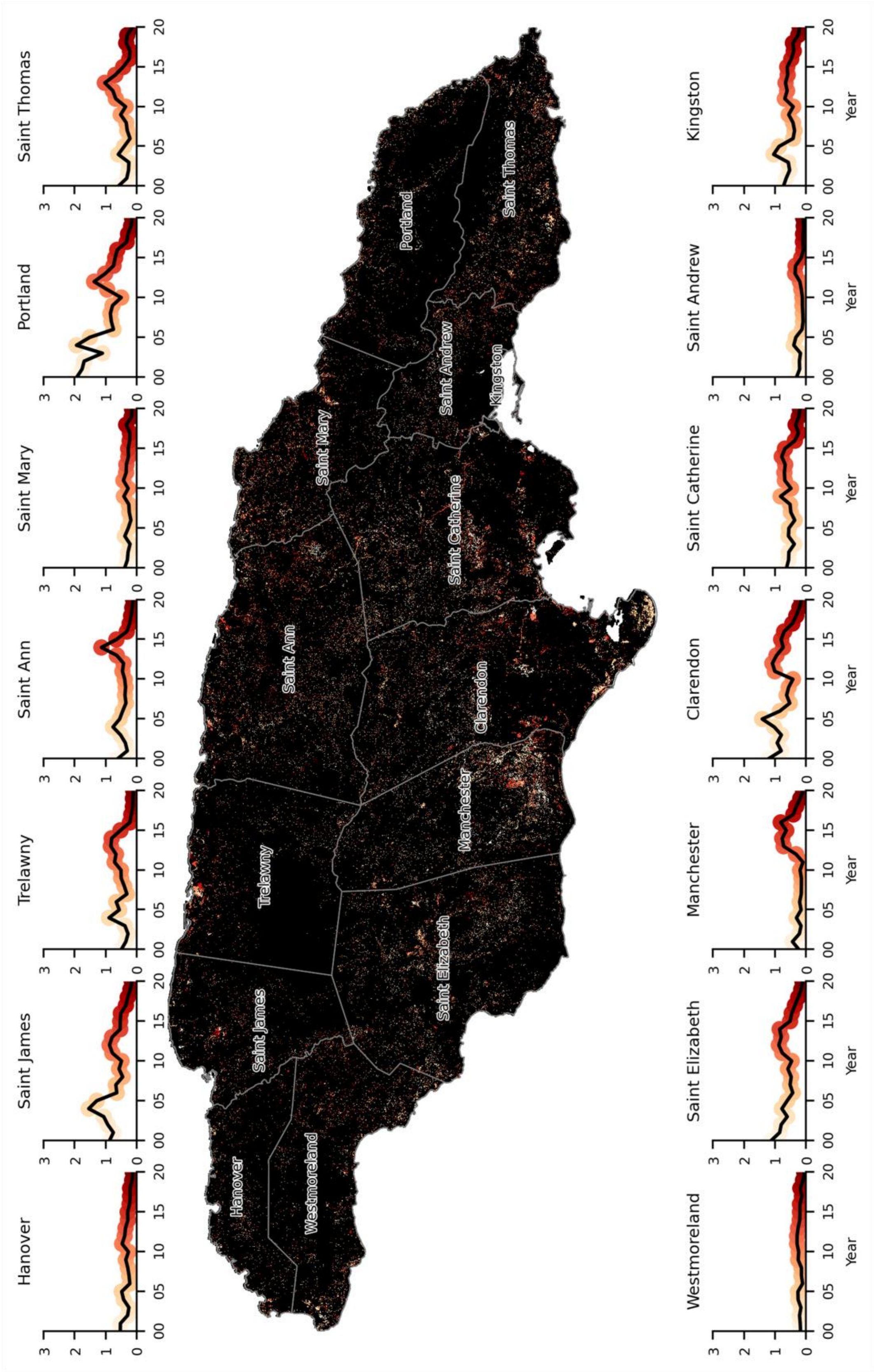


Figure 11 Locations of deforestation detected from 2000 – 2020 in the land cover time series. Pixels are colours by date, with darker reds showing more recent changes. Graphs show the trend of change in each province as a percentage.

Converting deforestation to a proportional rate of change indicates an annual deforestation rate of 0.46 %/yr for the period 2000 – 2020 (Figure 12). Rates of loss are largely stable for the period 2000 - 2015, with a peak in 2004/05 associated with a large fire in Portland Bight. There is a possible reduction of deforestation rates since 2016, although this may also represent an edge-effect associated with the end of the remote sensing time series and will require further investigation. In any case, the absolute rate of deforestation is low: these data provide no indication of rapid conversion of forest in Jamaica over the past two decades.

Figure 12 Estimated annual deforestation rate for Jamaica 2000 - 2020. Note: these figures are provisional, and subject to change.

Regrowth

Maps of forest regrowth indicate a large increase in forest cover for the period 2000 – 2020, covering an area greater than deforestation (Figure 13). Visual analysis of map outputs shows tree cover gains to be occurring in areas previously used for agriculture, supporting this idea that forest area increases constitute an increase in secondary forest. See also: section 5 for an analysis of the drivers of change.

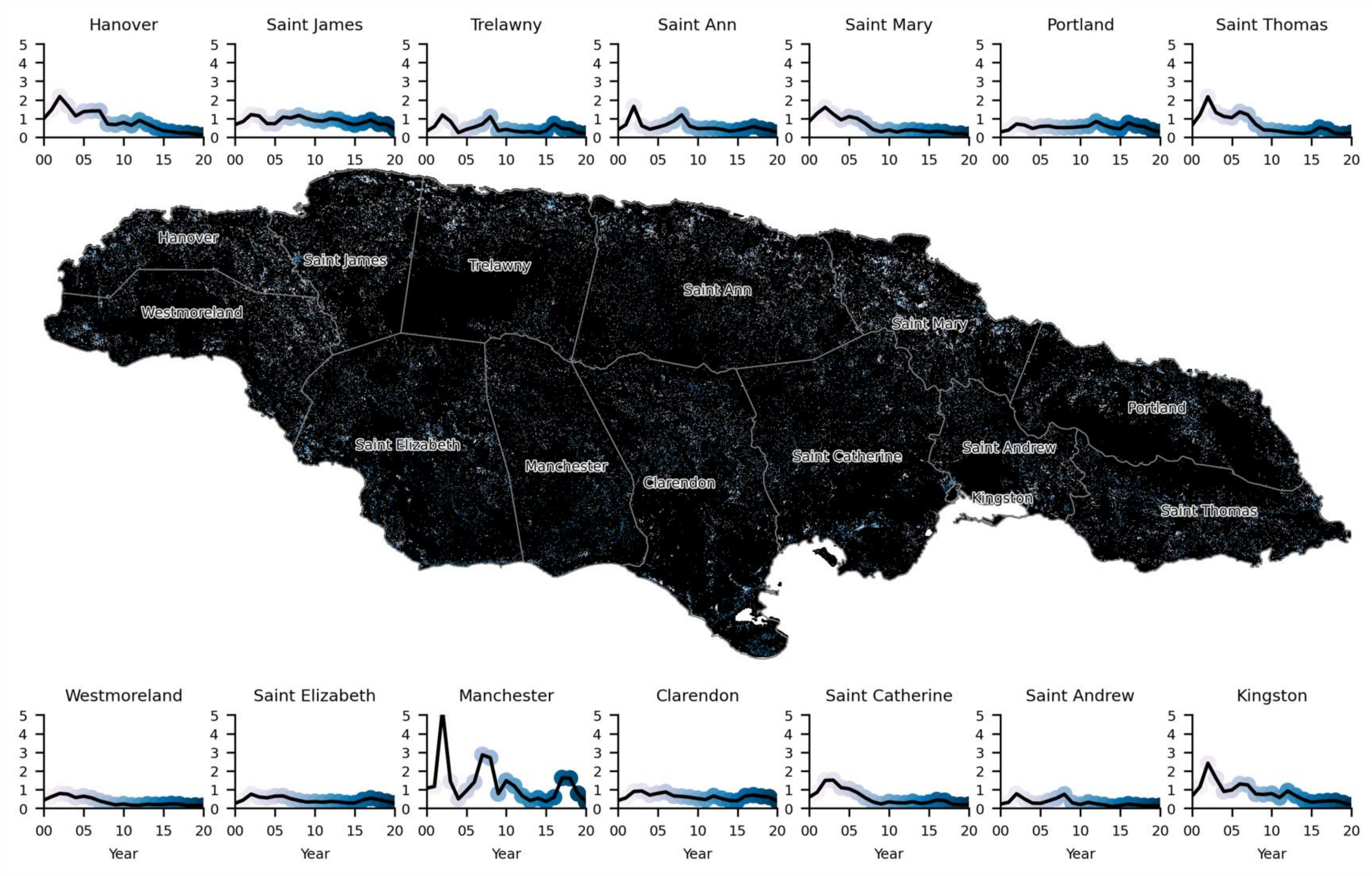
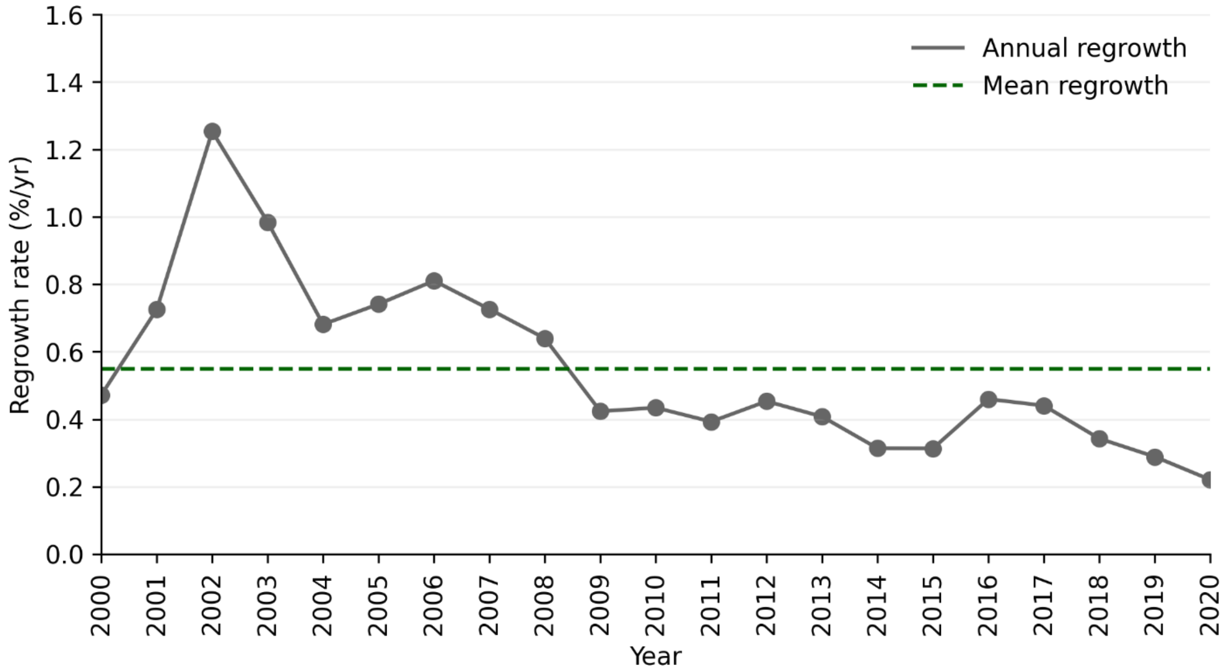


Figure 13 Locations of forest (re)growth detected from 2000 – 2020 in the land cover time series. Pixels are colours by date, with darker blues showing more recent changes. Graphs show the trend of change in each province as a percentage.



Converting regrowth to a proportional change indicates an annual increase in forest area 0.55 %/yr for the period 2000 – 2020 (Figure 12). Rates of forest area increase are higher earlier in the time series, with a gradual reduction in regrowth across the time series. As with deforestation there may be edge effects at the end of the satellite time series that artificially suppress changes in the most recent maps.

Validation

Map outputs were validated qualitatively and quantitatively by the geospatial working group. Validation has to this point focussed on land cover estimates, but in future it is planned to also consider the accuracy of the change outputs.

Qualitative validation

Attendees of the geospatial working group reviewed map outputs. The following known issues were identified in the spatial distribution and extent of land cover types:

- Misclassification between settlements, bare land, and mining
- Misclassification between forest classes, in particular the dry forest class also contains many examples of very sparse tree cover in agricultural regions. Dry forest is more frequently mis-classified towards to the start of the time series.
- Forest cover dominates is higher than existing estimates. This may result from a different representation of forest in these land cover maps than existing land cover time series.
- Bauxite mining areas are well-delineated, although these can also include agricultural areas following the extraction of bauxite.
- There may be edge effects in change estimates associated with the end of the satellite data time series, with declines in rates of deforestation and regrowth in the most recent land cover maps.

Quantitative validation

Exemplar locations of each of the major land cover types of interest were identified by members of the geospatial working group. Locations were selected for stability throughout the time series (1984 – 2020), such that each year's map output could be tested against the same validation dataset. Validation was conducted at two levels: (i) for consistency with IPCC classes (level 1 outputs) and (ii) for consistency against the national classification scheme (level 2 output) (see Table 3).

Overall map accuracy varied between 90–95% (level 1) and 80-90% (level 2), with a general trend of increasing map accuracy through time (Figure 14). Increasing accuracy may be associated with improved data availability from the Landsat data archive since 2000. This observation prompted the reporting of change data only for the period 2000 – 2020.

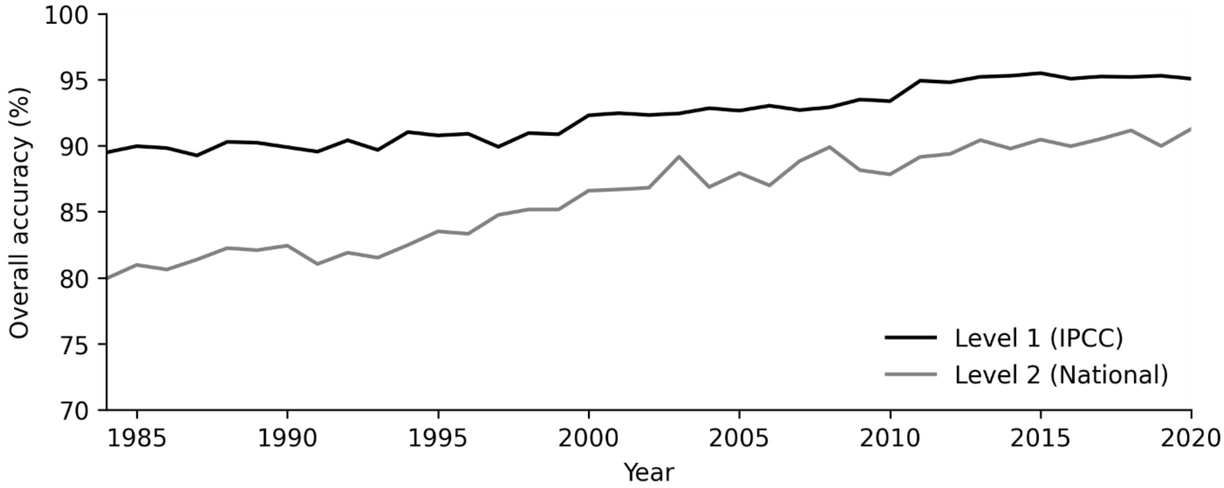


Figure 14 Overall map accuracy for each year's map output.

Accuracies for each map class show a similar pattern to overall accuracy, with generally better perfomance for the latter part of the time series (Figure 15). The best performing map classes were consistently the dense and secondary forest classes and croplands, indicating that the largest classes were captured effectively and increasing confidence in change estimates.

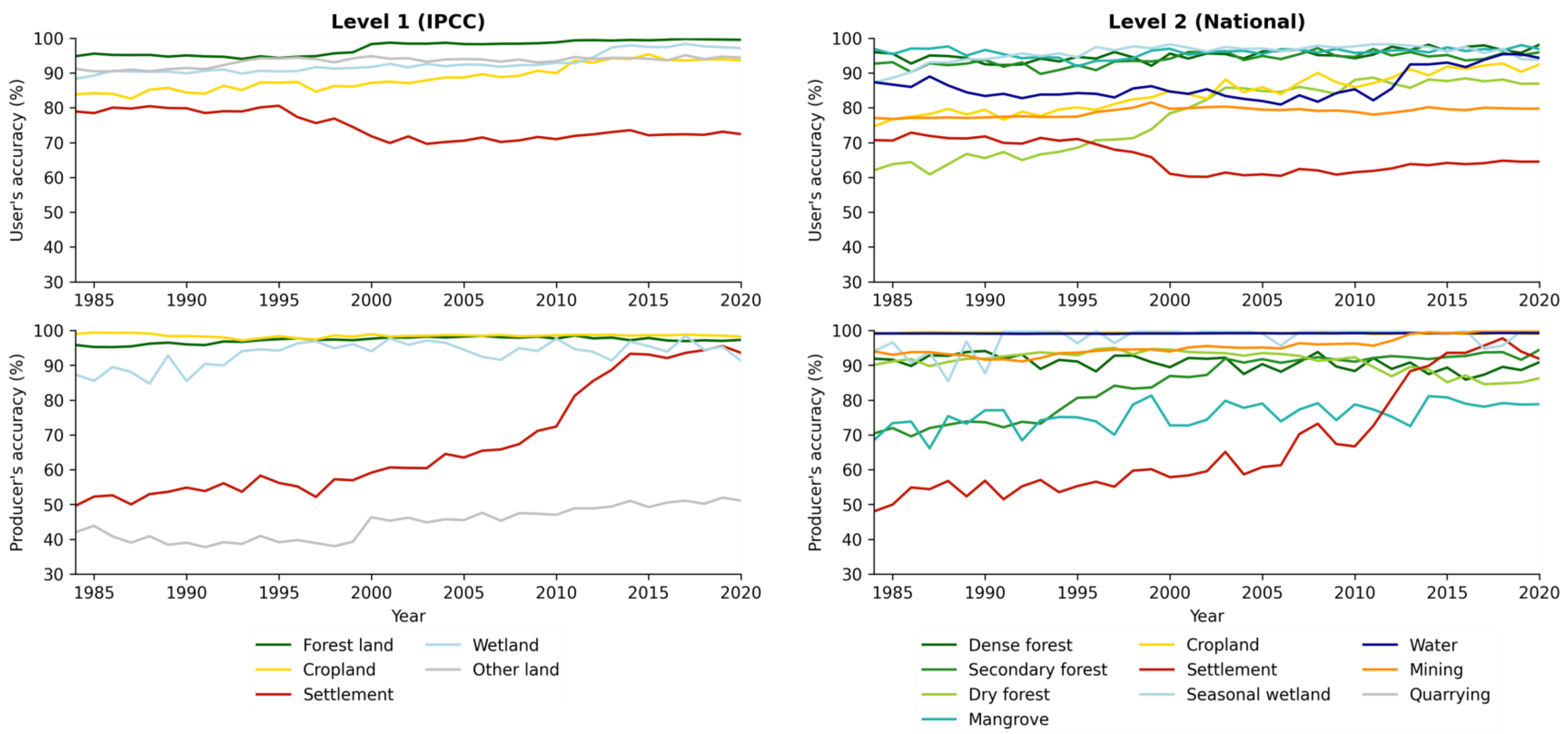


Figure 15 Reported map class accuracy through time at level 1 (left) and level 2 (right). Accuracy for each class is reported as a User's accuracy (the probability of a mapped pixel representing it's correct class on the ground) and Producer's accuracy (the probability of a location on the ground being correctly classified by the map).

4 Discussion and next steps

Main findings

The outputs presented in this report provide a consistent record of historical land cover, giving new insights into the state and change of land cover in Jamaica. Key emergent results for the purposes of the REDD+ strategy are:

- Forest cover is the largest land cover in Jamaica, with the majority of this area consisting of low density or secondary forest. High carbon density primary forests are largely limited to protected and high elevation areas.
- Rates of deforestation are probably low, averaging 0.46 %/yr since 2000. Deforestation is associated with infrastructure development, settlement expansion, bauxite mining and agriculture.
- Regrowth of forest is widespread, matching or exceeding rates of deforestation. This will be harder to accurately quantify, but is of central importance to REDD+.
- The results from this analysis present a picture of net stability or increasing forest cover in Jamaica.

Planned developments

The outputs presented in this report are the latest map outputs, and while results are more stable than in previous iterations, maps remain subject to updates. The following priorities for future work have been identified in collaboration with the geospatial working group.

Benchmarking

Multiple alternative datasets exist for measuring land cover change in Jamaica, offering a possibility for comparison. Where estimates are similar to other predictions the data can be treated with greater confidence, and where they differ, we can learn about weaknesses in the approach. Proposed benchmark comparisons are:

- **Existing land cover maps** The Forestry Department's existing land cover maps provide estimates of land cover and land cover change for the period 1998 – 2013. See section 0 for a description of this dataset.
- **Global Forest Change** This dataset provides a global view of forest cover, deforestation and forest regrowth[7], also based on Landsat time series. It is the leading global source of deforestation data and should be expected to show similar spatial patterns to our predictions.
- **MODIS NDVI** MODIS is a moderate resolution sensor (250 m) with a consistent time series dating back to 2001. The temporal trend of vegetation greenness is expected to reflect the spatial distribution of forest losses and gains observed here, and will provide a particularly important independent assessment of our observation of widespread forest regrowth.

Further mapping developments

Map outputs can at this stage be considered ready for use, although work will continue to improve map products where feasible. With the geospatial working group, two priority areas have been identified:

- **Improvements to problematic map classes** Reported map accuracies remain sub-par for dry forest and settlement map classes. Work will focus on improvements to training

[7] Global Forest Change data can be visualised here: http://earthenginepartners.appspot.com/science-2013-global-forest.

and validation data for these classes, and inclusion of new image features to better discriminate these classes. This work is of particular importance for the dry forest class, which were mis-classified as a non-forest class early in the time series leading to inflated deforestation estimates.

- **Edge effects** Declines in rates of deforestation in the most recent images from the satellite time series may represent a real trend but might also be attributed to edge effects associated with low confidence in map classification or transition probabilities being too stringent. Further testing will be performed to identify if there is a problem and implement suitable solutions.

Collect Earth Survey

While remote sensing analyses can provide useful information on the spatial patterns of forest change, most REDD+ countries derive quantitative estimates of change from sample-based area estimation. This method uses augmented manual interpretation of high-resolution imagery[8], an approach that promotes consistency in definitions of forest cover, and allows for the generation of bias-corrected area estimates with quantified uncertainty information. These methods are most frequently implemented in the open source Collect Earth software (Figure

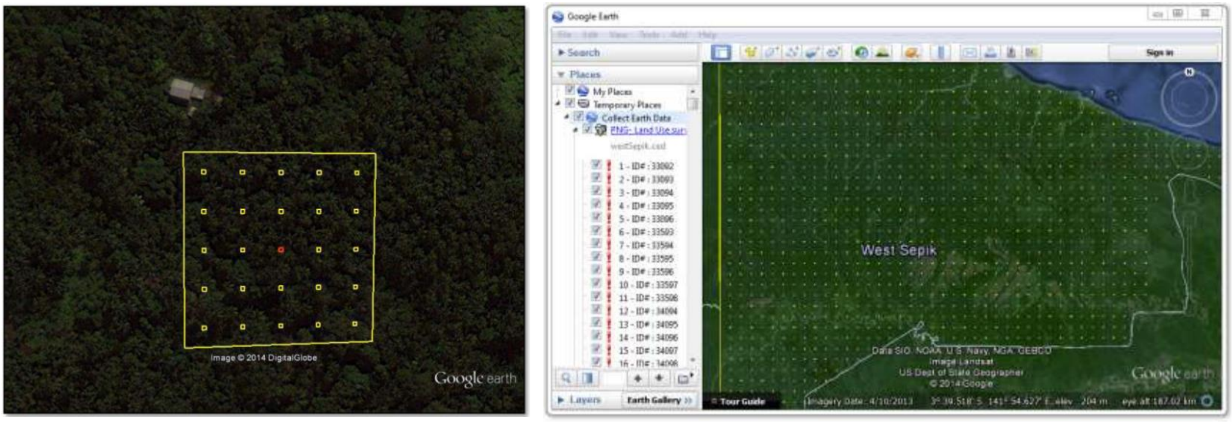


Figure 16 Example of a Collect Earth survey, where sample points (left) are manually surveyed across a regular grid to produce estimates of forest cover and change (source: Collect Earth manual).

16).

Design of an island-wide Collect Earth survey is proposed for the robust quantification of deforestation and regrowth rates in Jamaica. Such surveys have the advantages of not requiring fieldwork, but will necessitate a substantial commitment of staff time at the Forestry Department to be conducted effectively. The output will be a method for the consistent estimate of rates of deforestation and regrowth with quantified uncertainties, and the testing of an approach that can be adapted for a future Forest Reference Emissions Level (FREL) submission.

Quantification of drivers of change

Map outputs have currently offered a qualitative estimate of the drivers of change in Jamaica, but the relative importance of each driver has not yet been quantified. In the absence of fieldwork being possible, two methods are proposed to generate an estimate of the main causes of change:

[8] From Reference levels to result reporting: REDD+ under the United Nations Framework Convention on Climate Change, FAO 2020. http://www.fao.org/3/cb1635en/cb1635en.pdf

- **The association between land cover change and land ownership** High-quality cadastral data exist in Jamaica, held by the National Land Agency[9]. These data include a classification of land ownership in Jamaica (e.g. private ownership, crown lands, mining concessions), which may be used to identify the activities associated with deforestation and forest regrowth. The Forestry Department currently have access to part of these data; for an un-biased analysis the full dataset will need to be made available. Access to this data is subject to ongoing discission with the Forestry Department.
- **Collect Earth survey** The causes of forest change can often be identified in remote sensing imagery (see section 5). This may be formalised into a Collect Earth survey, allowing a quantitative assessment of the dominant drivers of change. As described in section 0, such a survey would require a large commitment of staff time to be conducted, so feasibility will depend on staff availability.

[9] See https://elandjamaica.nla.gov.jm/elandjamaica/interactivemap.aspx

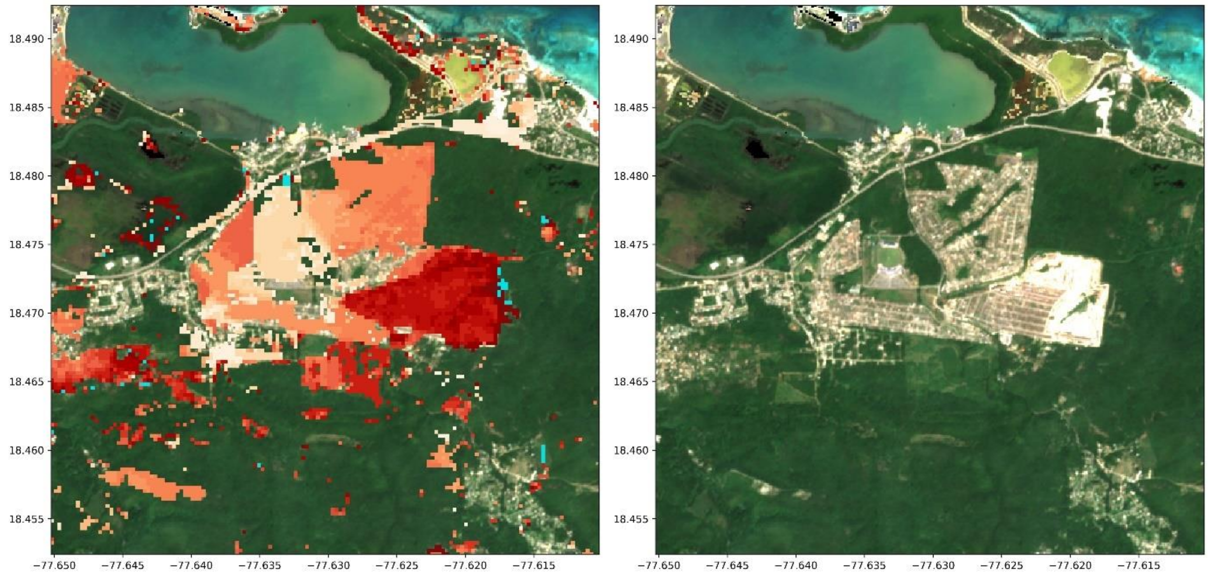
5 Drivers of change

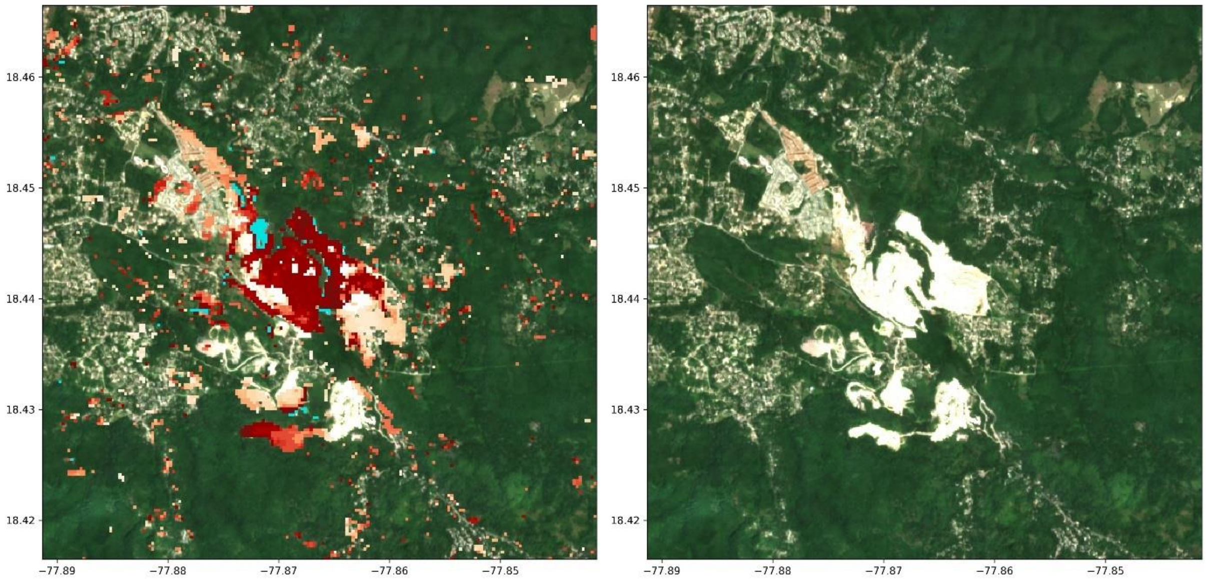
In consultation with the geospatial working group of the National REDD+ steering committee, map outputs were used to identify the primary activities resulting in forest cover change in Jamaica. The following is a qualitative assessment of the causes of forest change derived from map products, with the aim of identification of all important drivers of change in advance of an effort to quantify their relative impact. Further work will focus on identifying the relative importance of these drivers of change to inform Jamaica's REDD+ strategy.

In this section examples of each form of change are overlaid on a satellite image from 2020. Darker colours are used to represent more recent changes ranging from 2000 – 2020.

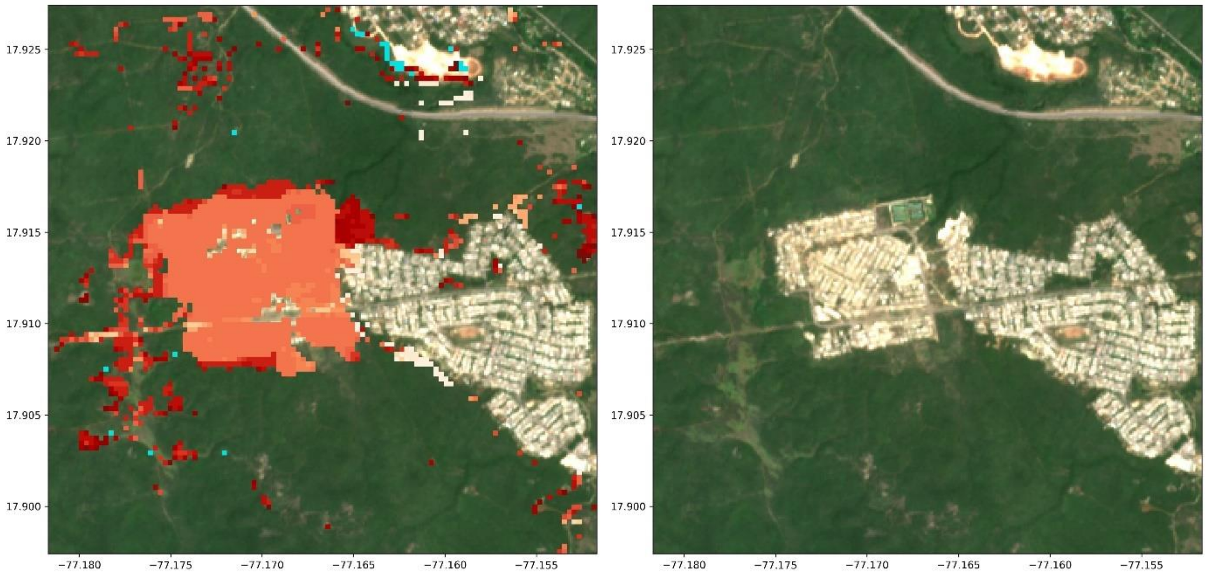
Settlement expansion

Settlement refers to buildings and other construction features such as airstrips, roads, and bridges. Urban expansion is a clear driver of forest change in Jamaica, taking the form of large housing estates and small-scale informal settlements. Large housing schemes and new hotels were identified along the north coast of the island, particularly in the parishes of St James, Trelawny, and St Ann:

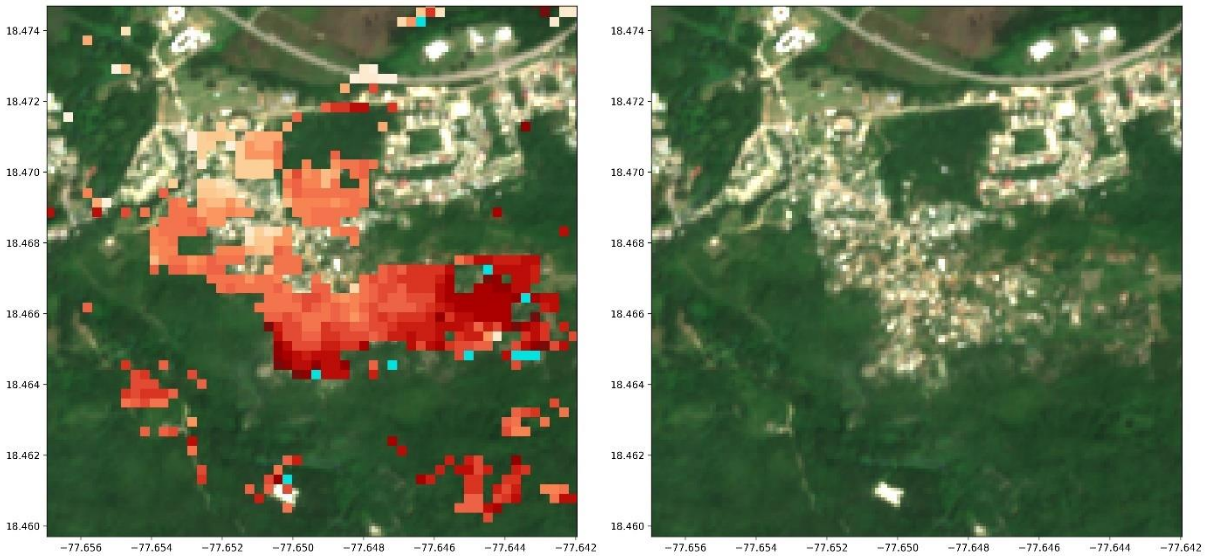




Also apparent were new housing on the south coast, particularly in the vicinity of Kingston and in St Catherine parish:

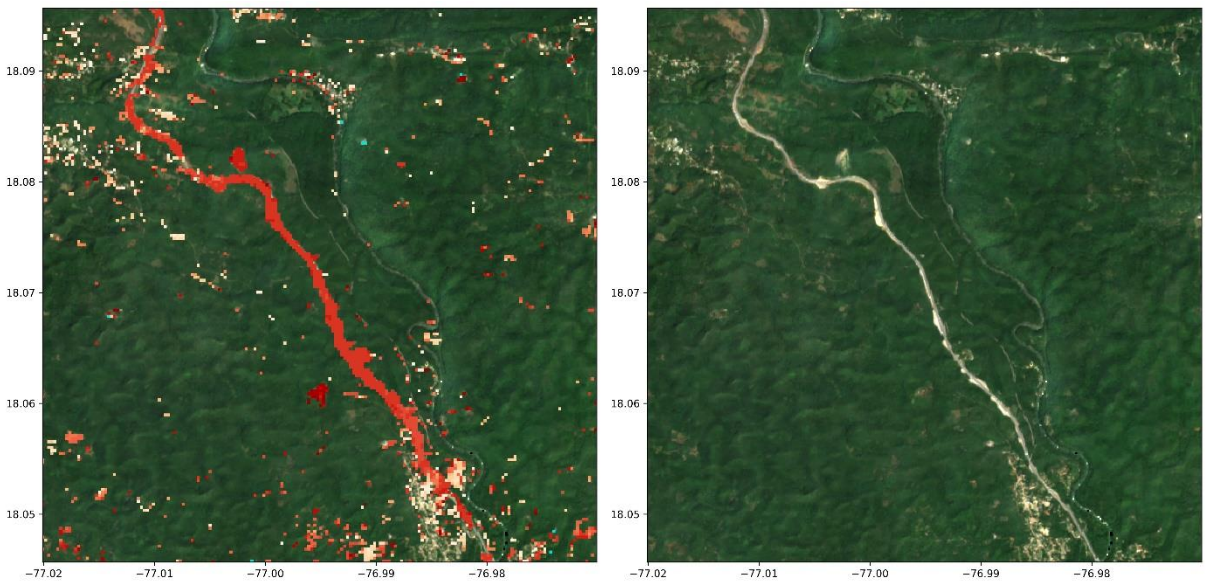


Less apparent in the change data, but also present, were examples of expansion of informal settlements. These tended to cover smaller areas and be more dispersed:



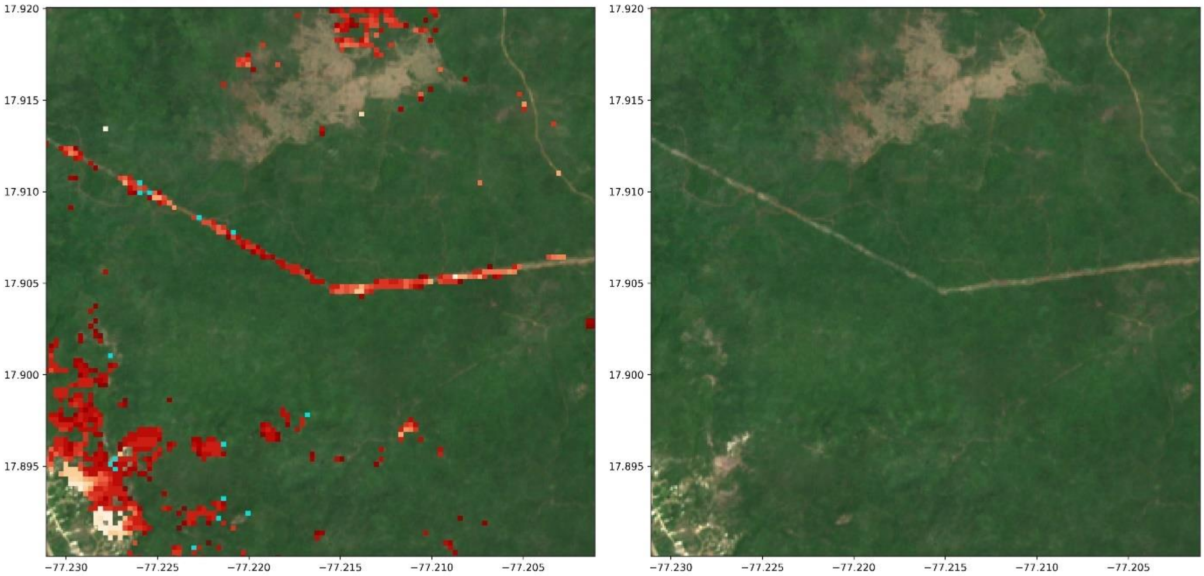
Infrastructure development

Construction of roads has resulted in losses of forest areas across Jamaica, with several road construction projects apparent in the time series. Most prominent is the phased construction of Highway 2000, a north-south highway connecting Kingston and Ocho Rios in St Ann:

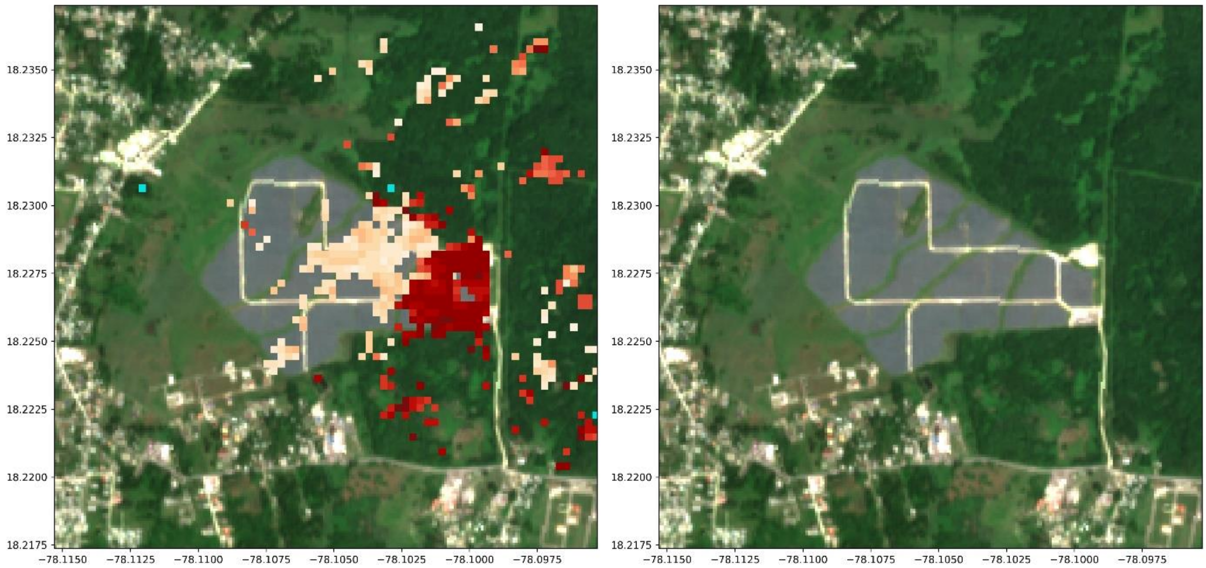


Road development eases access to agricultural land and settlements and may be a driver of larger changes to forest cover in locations where access is improved. A possible example of this is large housing developments on the north coast of the island following construction of Highway 2000.

Other changes were associated with powerline construction, such as in the dry forests of Clarendon:

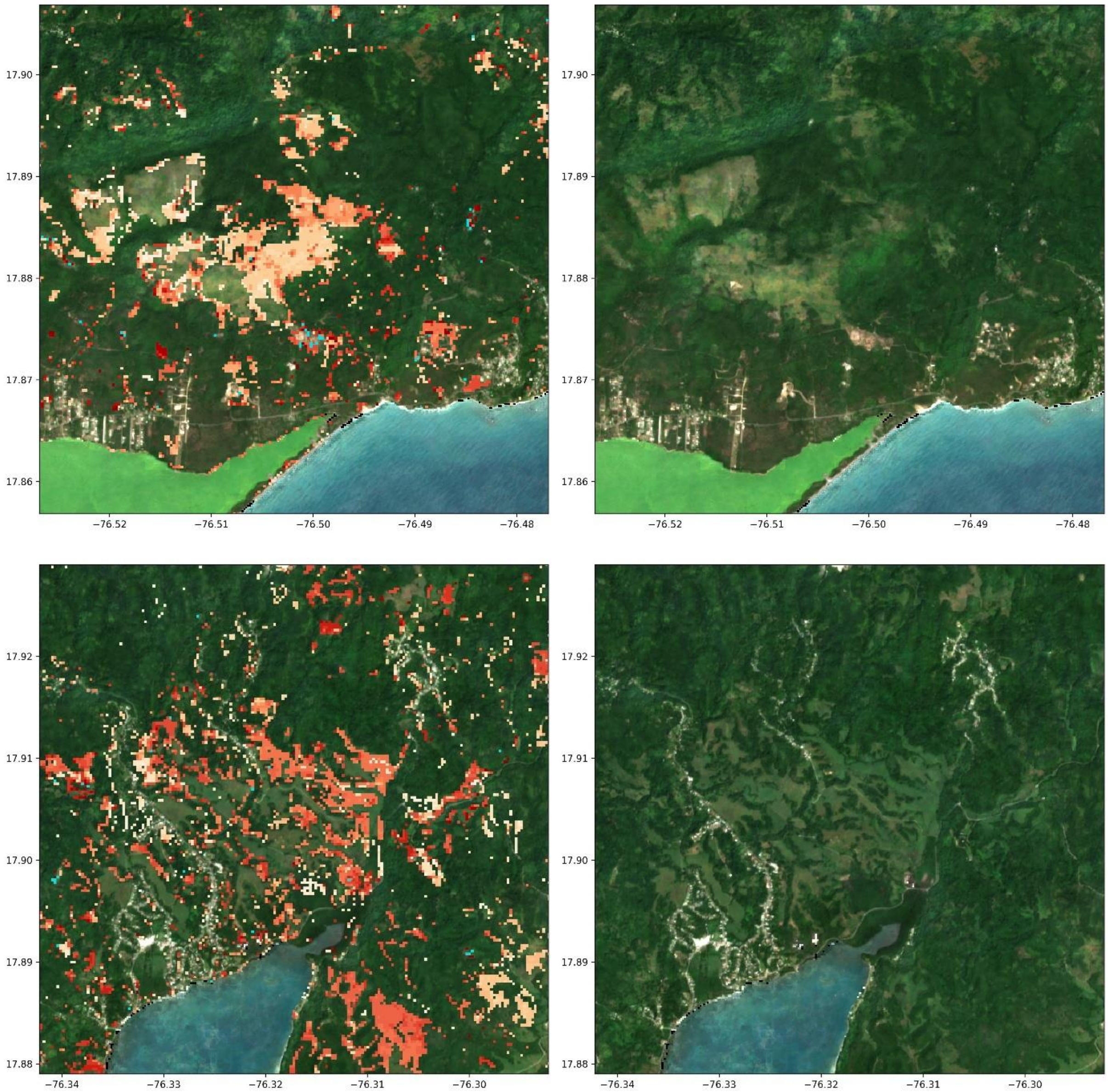


and the recent construction of a solar farm in Westmoreland:

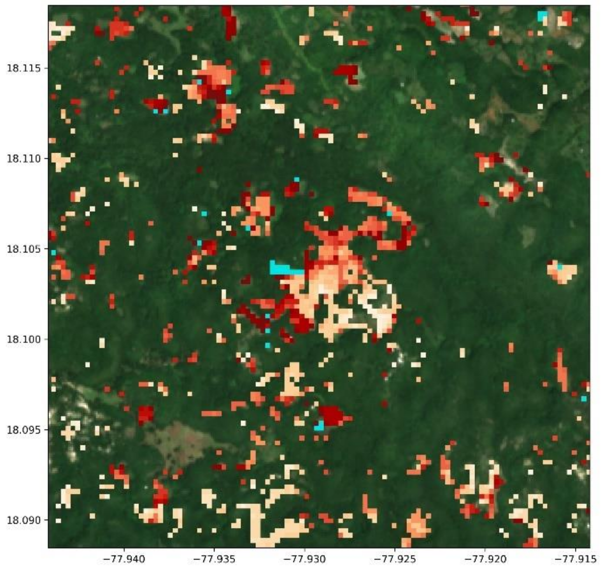


Agriculture

Agricultural lands were associated with both losses and gains of forest cover across the island. Clearance of vegetation for agriculture is associated both with large land holdings and small-scale agriculture. Large-scale (commercial) agricultural clearance has a characteristic appearance, covering large contiguous areas, presumably associated with a single land user:

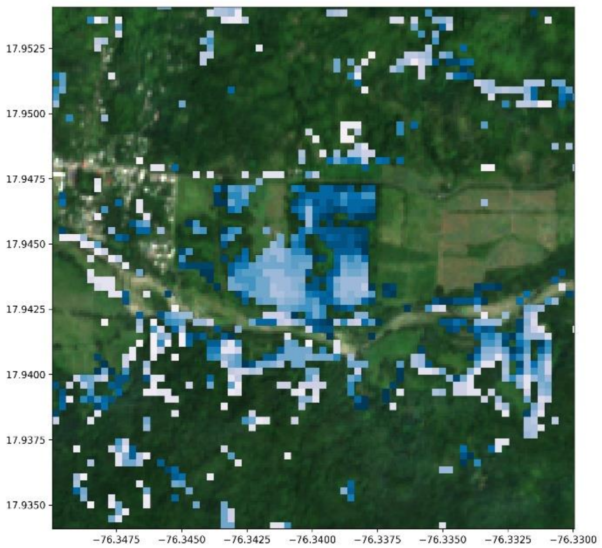


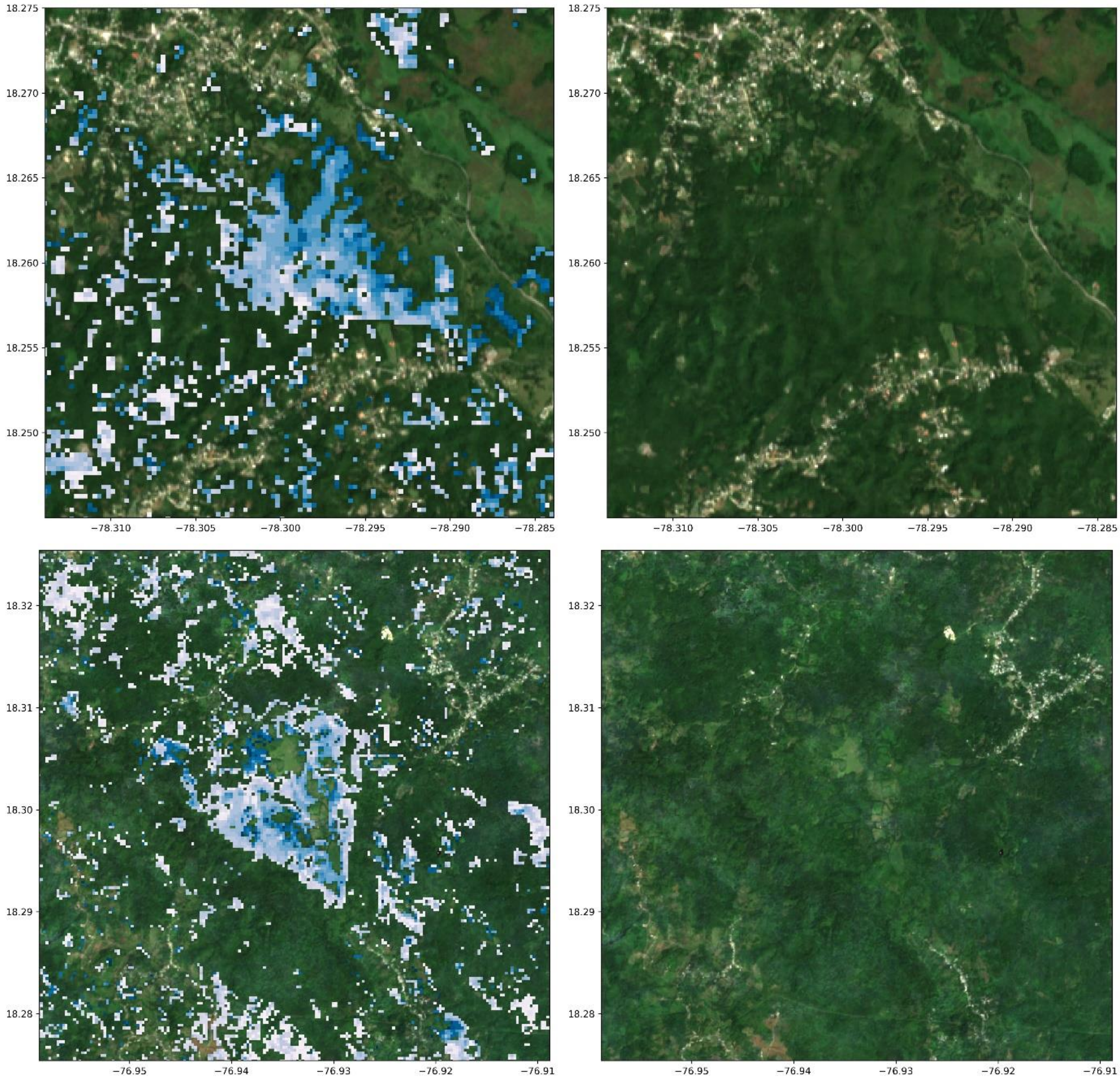
Smallholder farming is also associated with clearance, although the changes are of smaller scale and more dispersed:



There does not appear to be an agricultural frontier in Jamaica as can be common in other regions. Instead, changes are spread widely across the island. Changes were mostly identified in secondary forests, with little evidence of widespread expansion of agricultural lands into other forests.

Agricultural abandonment has been common in Jamaica over the past two decades, a pattern associated with reductions in agricultural profitability and migration to urban areas. Where cultivation ceases regeneration of tree cover occurs rapidly, either through assisted or natural regeneration. Forest regrowth was very widespread, and may represent a larger area than the total area of all activities associated with deforestation. Examples include both large landholdings and small-scale land abandonment, and is likely associated with an increase in secondary forest cover on the island over the past two decades:

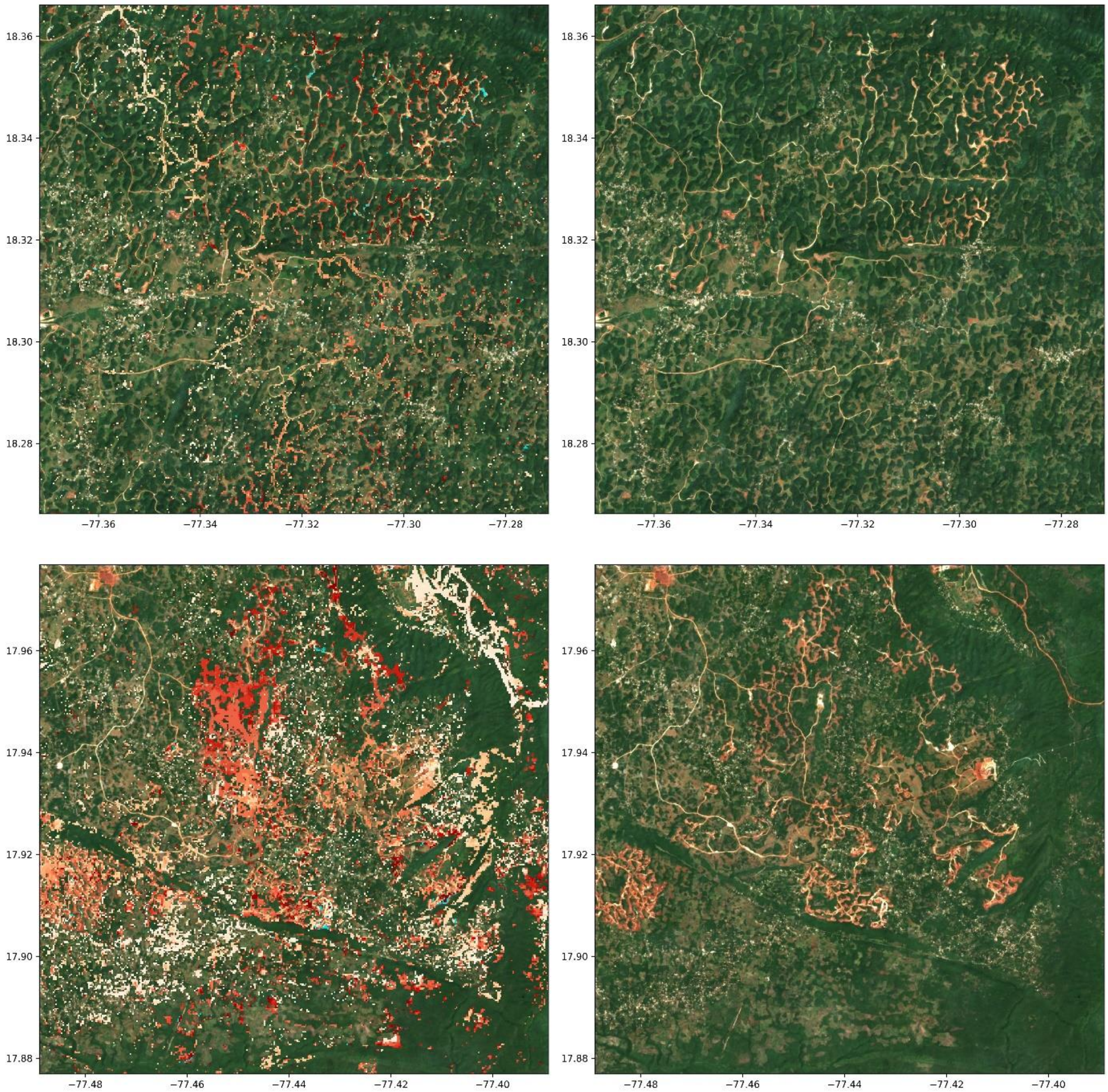




It is noted that much of this change may be temporary, and a change in commodity market conditions could see these areas rapidly revert to agricultural production.

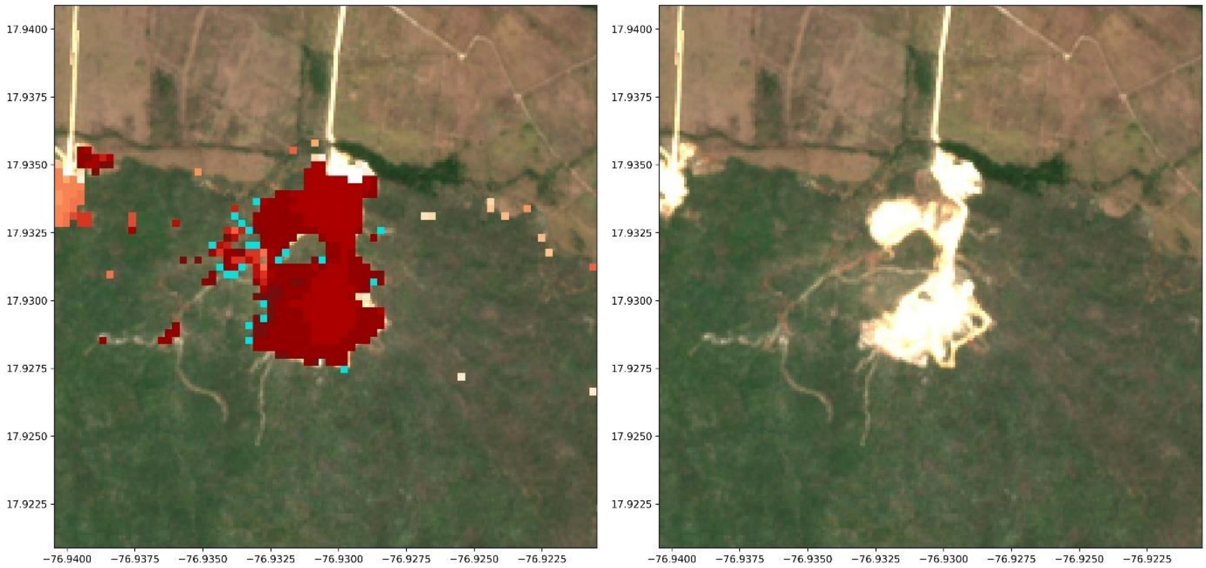
Bauxite mining

Bauxite is an important export for Jamaica, produced in large mines in Clarendon, Manchester, St Elizabeth and St Ann parishes. Bauxite extraction over the past 20 years has resulted in notable losses of forest cover, forming a distinctive pattern of road construction and forest fragmentation that spreads along access roads. Areal changes to forest cover associated with the bauxite industry were extensive, and there was little evidence in the satellite data time series of recovery of forest cover following bauxite extraction.

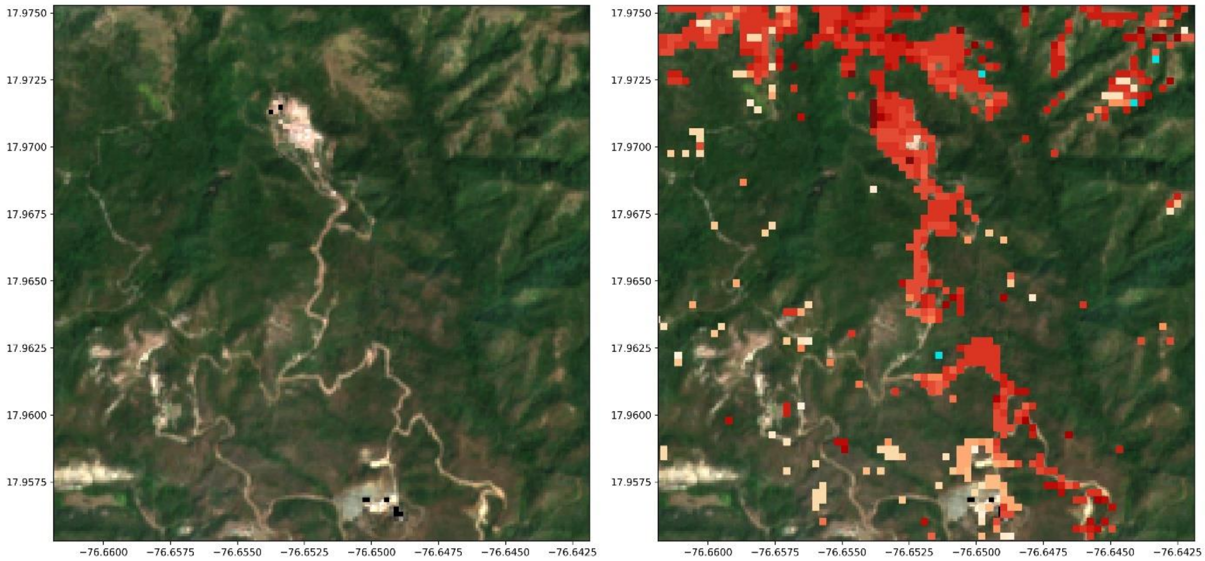


Quarrying

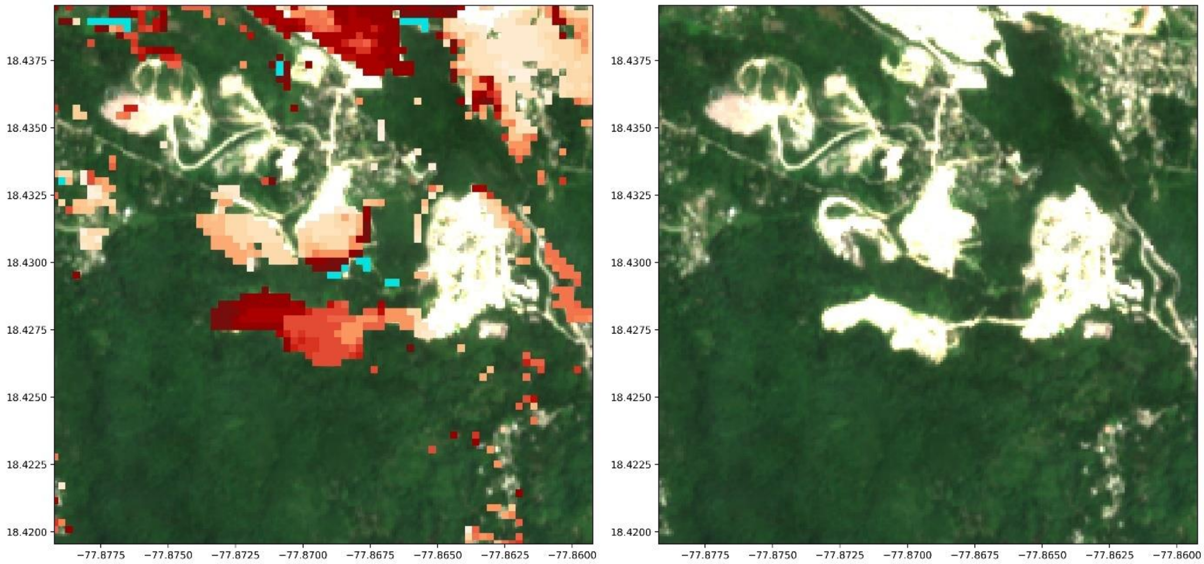
Quarries were identified across the island, most commonly producing limestone for domestic use and export. Forest changes associated with the opening of quarries were clearly apparent, with locations identified in St Catherine, Hanover, St James, St Elizabeth, Westmoreland and Portland. Quarries have a distinctive pattern that is clearly apparent in satellite data:



In addition to the direct forest cover losses associated with the quarry itself, in several locations access roads had resulted in additional forest losses:

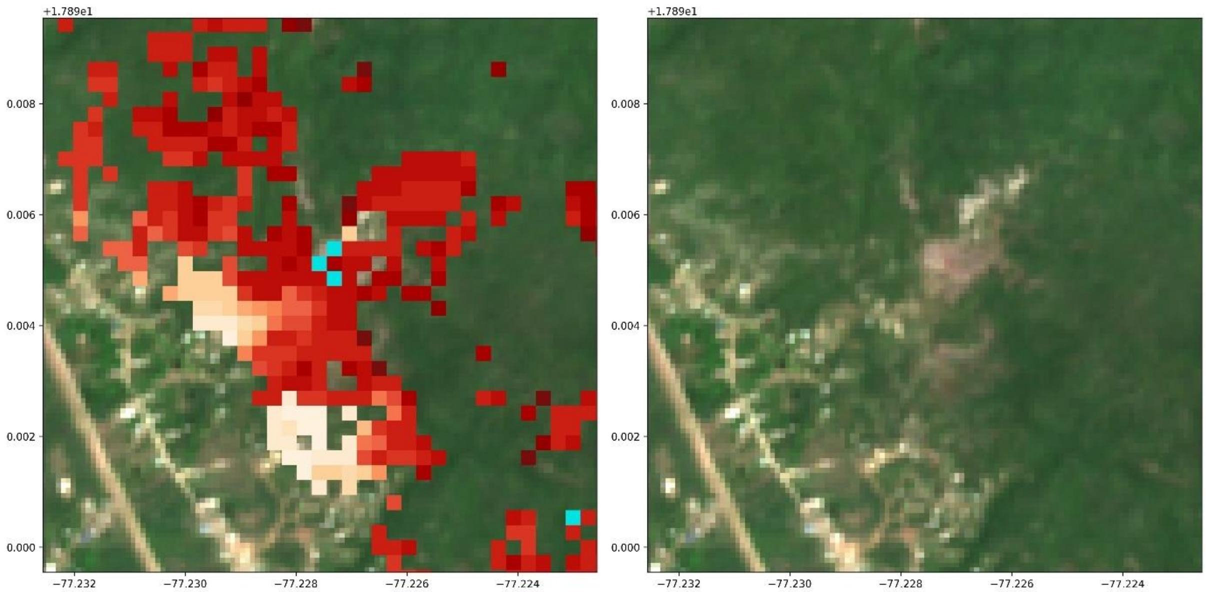


Some quarries appeared to have been established in the vicinity of new housing construction, and the two may be associated:



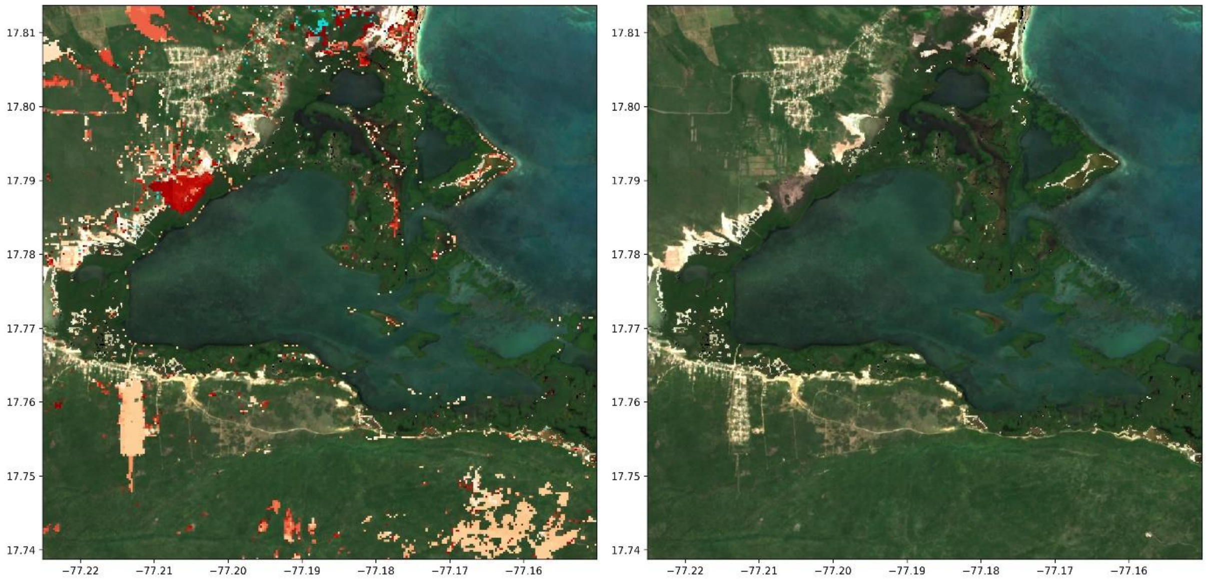
Charcoal

Charcoal is produced for domestic consumption in Jamaica. Areas of charcoal production are typically small-scale, and thus coarse map outputs are not well suited to identifying charcoal production. One known location of larger-scale production was detected in the Braziletto Mountains, an area of dry forest in Clarendon. It is likely that some of the small-scale changes detected on the map are also associated with charcoal, but this activity it not readily identified even in high resolution satellite images so its importance may need to be assessed with other methods.

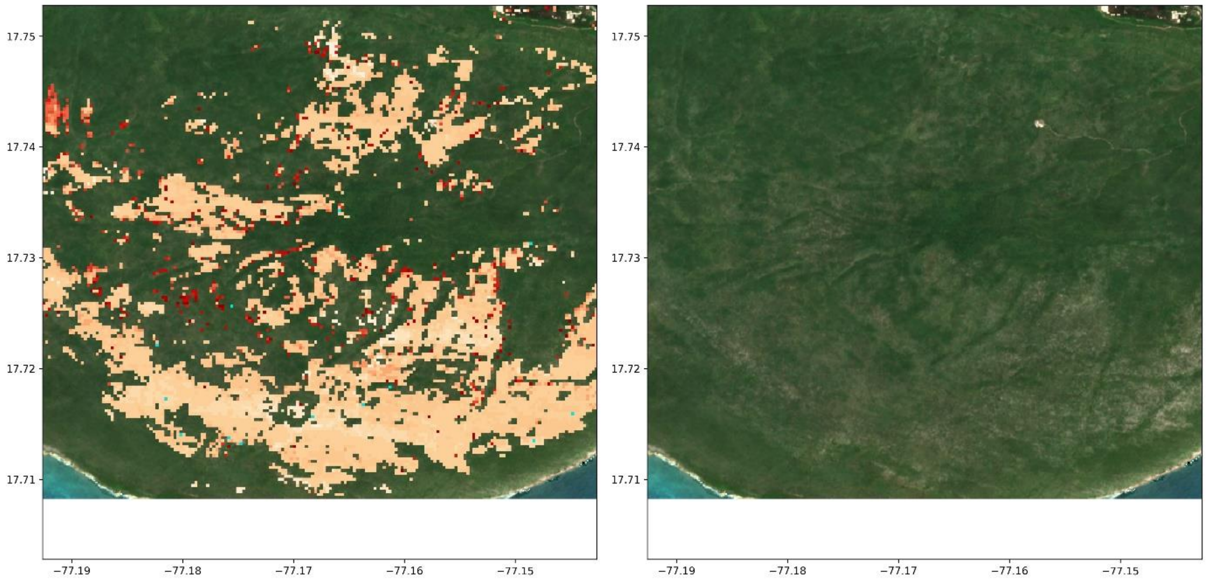


Natural hazards

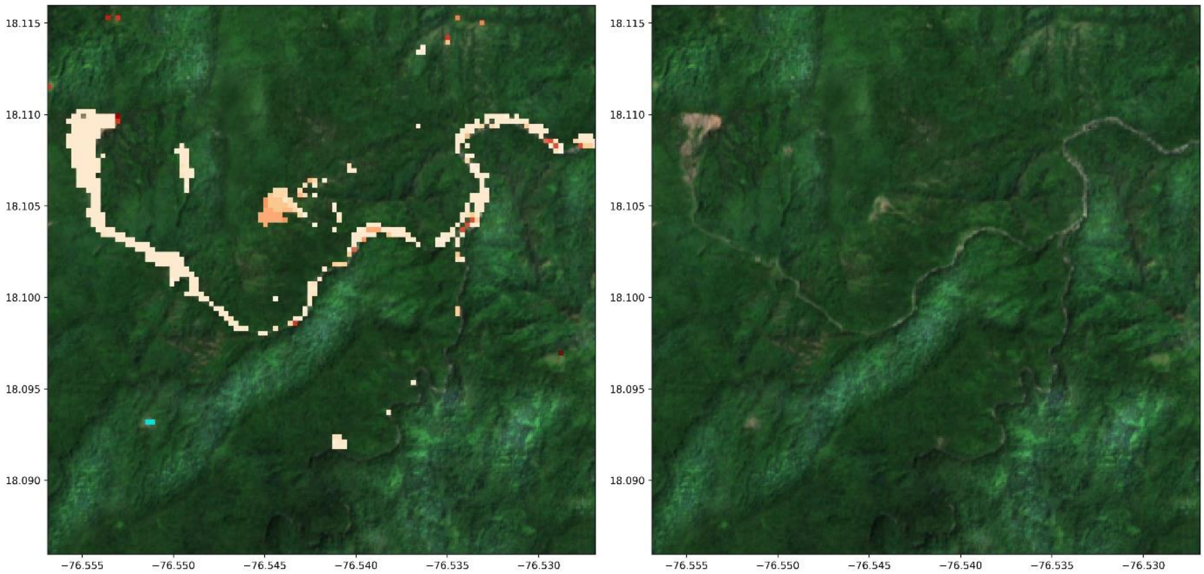
Hurricanes and storm surges are two major influences of large-scale agriculture loss in Jamaica, but also have resulted in changes to forest cover. For example, losses of mangrove cover were observed in Clarendon parish, coincident with Hurricane Ivan in 2004:



Forest cover changes were identified from a large wildfire in Portland Bight in Clarendon:



In addition losses of tree cover around some mountain rivers was observed, presumed to result from flooding: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