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ISSUE BRIEF

SATELLITE-BASED FOREST CLEARING DETECTION IN THE BRAZILIAN AMAZON: FORMA, DETER, AND PRODES

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SUMMARY

The advent of near-real-time forest monitoring can dramatically strengthen efforts by governments, businesses, and communities to conserve and sustainably manage the world's forests. This issue brief introduces a system called FORest Monitoring for Action (FORMA), which provides near-real-time information on new forest clearing in the humid tropical forests of Asia, Africa, and Latin America. To assess FORMA's performance, we compare its spatial and temporal accuracy against PRODES *(Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite)* and DETER *(Sistema de Detecção do Desmatamento em Tempo Real na Amazônia)*, two well-established systems that monitor forest clearing in the Brazilian Amazon.

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I. SUMMARY

This issue brief introduces a system called FORest Monitoring for Action (FORMA), which provides near-real-time information on new forest clearing in the humid tropical forests of Asia, Africa, and Latin America.[1] To assess FORMA's performance, we compare its spatial and temporal accuracy against PRODES (*Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite*) and DETER (*Sistema de Detecção do Desmatamento em Tempo Real na Amazônia*), two well-established systems that monitor forest clearing in the Brazilian Amazon. Our assessment focuses on a rapidly deforesting area that overlaps Manicoré and Novo Aripuanã municipalities, located in the southeastern portion of the Brazilian state of Amazonas (Figure 1).

FORMA and DETER are both designed to identify new forest clearing at medium spatial resolution, while PRODES identifies cleared areas with higher precision on an annual basis. Our assessment examines: (1) the relative spatial accuracy of FORMA and DETER against the higher-resolution annual data provided by PRODES; (2) the spatial and temporal correlation of information provided by FORMA and DETER; and (3) the possible complementarity of FORMA and DETER in predicting PRODES-identified cleared areas.

By "spatial accuracy" we mean the accuracy with which FORMA and DETER detect forest clearing in areas where clearing has been identified by the higher-resolution PRODES system. By "temporal accuracy" we mean the relative timeliness of forest clearing detection by the three systems.

FIGURE 1

MANICORÉ AND NOVO ARIPUANÃ MUNICIPIOS, AMAZONAS STATE, BRAZIL

In terms of spatial accuracy:

- Forest clearing areas identified by FORMA and PRODES are highly correlated. This result is consistent and stable when several statistical methods are applied.
- In the comparison of identified clearing areas, FORMA's correlation with PRODES is significantly higher than DETER's.
- FORMA and DETER appear to be complements rather than substitutes. A combination of DETER and FORMA identifies PRODES cleared areas more accurately than FORMA alone, although FORMA's contribution to identification is greater.

In terms of temporal accuracy:

- FORMA-identified areas of new clearing consistently appear in cleared areas identified by PRODES in its next annual review.
- Temporal identifications of cleared areas by FORMA and DETER are highly correlated.
- In the identification of newly cleared areas, FORMA actually leads DETER by about half a year.

> This issue brief introduces a system called FORest Monitoring for Action (FORMA), which provides near-real-time information on new forest clearing in the humid tropical forests of Asia, Africa, and Latin America.

II. FOREST COVER CHANGE MONITORING

The world's forests are a vital foundation for human livelihoods, climate stability, and biodiversity conservation. The capability to detect forest clearing where and when it happens can empower governments, businesses, and communities to take timely action to curtail illegal and unsustainable forest clearing. Past clearing often went unchallenged, in part because it occurred in remote locations. It was out of sight, so it was out of mind. The advent in the 1990s of remote sensing technologies—such as high-resolution satellite imagery to monitor forests—was a major step forward in challenging illegal or unsustainable forest clearing. For the first time, people could literally see what was happening across often remote and vast areas of forest landscape.

But even today, by the time high-resolution satellite imagery of forests is available, analyzed, and shared, forest clearing is too often long done. The loggers have moved on; cattle are already grazing amid stumps; and an oil palm plantation has been established. One simply finds out about forest clearing too late. What the world needs is monitoring that identifies forest clearing activity very soon after it has started; that is, in near-real time.

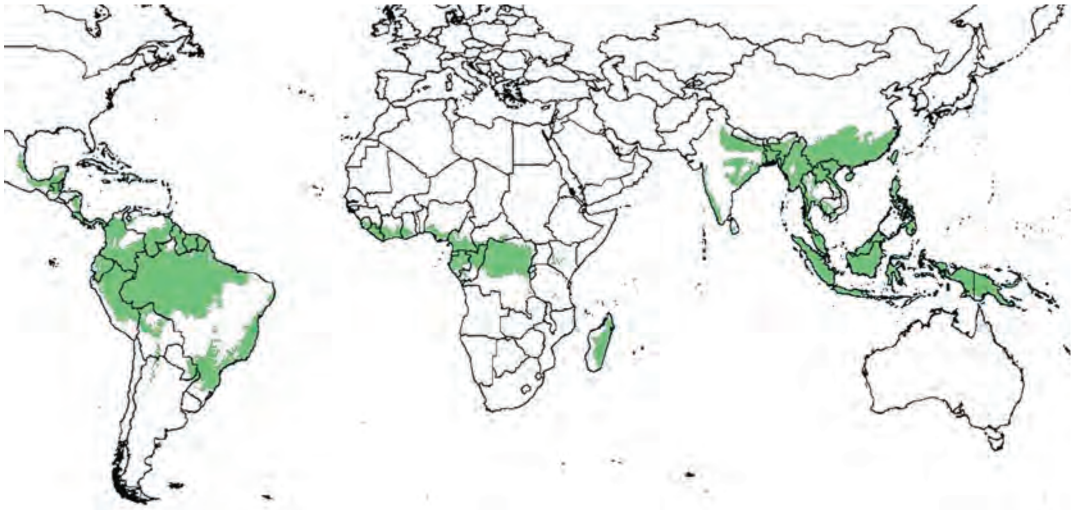
Recent research on Brazil underscores the importance and potential efficacy of near-real-time forest monitoring, although controversy continues about the drivers of reduced deforestation in the Brazilian Amazon during the 2000s. Assunção et al. (2013) find that the main drivers were implementation of the Real Time System for Detection of Deforestation (DETER) and more active law enforcement. DETER is a satellite-based system that enables quick identification of new forest clearing in the Amazon. The information coming from DETER has greatly enhanced forest monitoring and enforcement targeting capacity, making it easier for government agencies to act quickly in areas where illegal deforestation is occurring.

Having this capacity for other forests around the world, and for other parts of Brazil, could go a long way toward improving forest conservation and sustainable management of forests.

In this issue brief, we introduce FORest Monitoring for Action (FORMA), a near-real-time system that identifies new clearing in the humid tropical forest regions[2] of

FIGURE 2

FORMA'S COVERAGE OF HUMID TROPICAL FOREST REGIONS



Asia, Africa, and Latin America (Figure 2). The advent of systems like FORMA has the potential to provide rapid identification of new clearing, thereby dramatically strengthening efforts to conserve and sustainably manage these important ecosystems.

We begin by describing FORMA, its purpose, and how it works. We continue with brief descriptions of two well-established forest monitoring systems used in the Brazilian Amazon, DETER and PRODES. Through a series of regression analyses, we then assess the spatial and temporal performance of FORMA relative to DETER and PRODES in portions of the municipalities of Manicoré and Novo Aripuanã, Brazil.[3] We conclude with some observations about FORMA's performance based on this comparative analysis.

III. ABOUT FORMA

FORMA is a near-real-time forest clearing alert system. It uses a cloud computing algorithm to combine frequently updated satellite imagery with complementary information on factors that affect forest cover loss, such as fires and precipitation. The system generates twice-monthly "alerts" for humid tropical forests that identify 500 x 500 meter areas where new, large-scale clearing is likely to have occurred.

FORMA is designed for quick identification of new forest clearing. This allows for rapid response and prioritization of scarce financial and human resources dedicated to forest conservation or sustainable forest management. The twice-monthly alerts essentially tell stakeholders, "Significant forest clearing is very likely to have occurred at location X during time period Y." Armed with this information, stakeholders can use complementary methods such as on-the-ground visits or aerial inspection to investigate suspected forest clearing and curtail it if that is appropriate. This rapid response capability can empower law enforcement officials, government agencies responsible for protecting forests, nongovernmental organizations, companies committed to sustainable forest management practices and supply chains, and indigenous groups and forest-dependent communities. In addition, FORMA alerts are of value to researchers who study temporal and spatial patterns of forest clearing.

FORMA uses an automated statistical algorithm that relates spatially formatted data on forest clearing to information on (a) vegetation reflectance (provided by imagery from NASA's Moderate Resolution Imaging Spectroradiometer satellite, or MODIS)[4]; (b) active fires (provided by NASA's Fire Information for

Resource Management, or FIRMS);[5] and (c) rainfall (provided by Precipitation Reconstruction Over Land, or PREC/L).[6] The algorithm employs parallel processing in a distributed server system—"the cloud"—that enables rapid analysis of very large data sets. It employs statistical techniques to achieve the best fit to data on forest clearing published by Hansen et al. (2008a) in the *Proceedings of the National Academy of Sciences*.[7] These data identify 500 x 500 meter areas in humid tropical forests where clearing at "agro-industrial scale" (the authors' term) was highly likely during the period 2000–05. FORMA's parameters are refitted to the Hansen data for each of the terrestrial ecoregions defined by WWF International for the pantropics,[8] which span 89 countries.[9] On a twice-monthly basis, the system estimates the probability that large-scale clearing has occurred since 2005 for each 500 x 500 meter area in humid tropical forests. FORMA's probabilities are measures of "signal strength" provided by the multiple indicators of forest-clearing activity.

To illustrate, Figure 3 portrays FORMA's probability calculations, superimposed on recent satellite imagery for Brazil's Manicoré region in southeastern Amazonas state. We display relative signal strength by coloring each 500 x 500 meter area according to the probability that it has been the site of large-scale clearing between 2005 and 2012: yellow for 21–49 percent, red for 50–79 percent, and purple for 80–100 percent. Areas with probabilities lower than 21 percent are not colored. The probabilities in Figure 3 clearly show the pattern of axial clearing that has occurred along spurs from the main highway during the period in question. Lower (yellow) probabilities generally indicate areas where new forest clearing has begun at the margins of previously cleared areas.

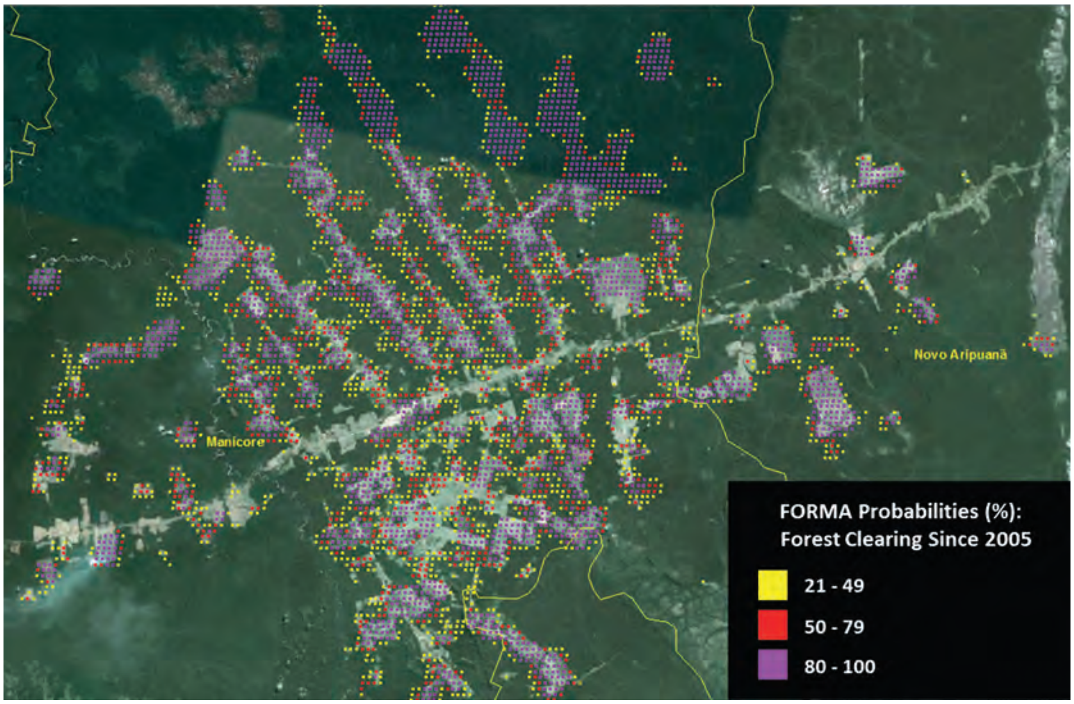
FORMA alerts are designed to indicate where and when a likely forest clearing event has occurred, but not the areal extent (i.e., hectares) of the area cleared. Higher resolution satellite imagery provided by Landsat and other sources is required for more accurate quantification of cleared areas. However, our validation research indicates that FORMA's signal strength is strongly associated with clearing extent. Figure 4 summarizes the results of a study for West Kalimantan, Indonesia, that shows a strong relationship between FORMA clearing probabilities for 500 x 500 meter areas and clearing extent in 60 x 60 meter areas identified from Landsat imagery. To summarize, average clearing grows as the FORMA probability increases.

FORMA was developed in collaboration with a number of institutions. The authors developed FORMA-1000 while working at the Center for Global Development (Hammer, Kraft, and Wheeler 2009). It provided monthly probabilities for 1000 x 1000 meter areas in Indonesia and Brazil. With support from the World Resources Institute (WRI), the authors developed FORMA-500 for twice-monthly coverage of 500 x 500 meter areas in all of the world's humid tropical forests. FORMA-500 provides the information for this issue brief. FORMA-250 is being developed by the authors with support from Google and WRI. It will have the same temporal resolution and geographic coverage but 250 x 250 meter spatial resolution, the highest possible using MODIS satellite imagery.

FORMA uses a cloud computing algorithm to combine frequently updated satellite imagery with complementary information on factors that affect forest cover loss, such as fires and precipitation.

FIGURE 3

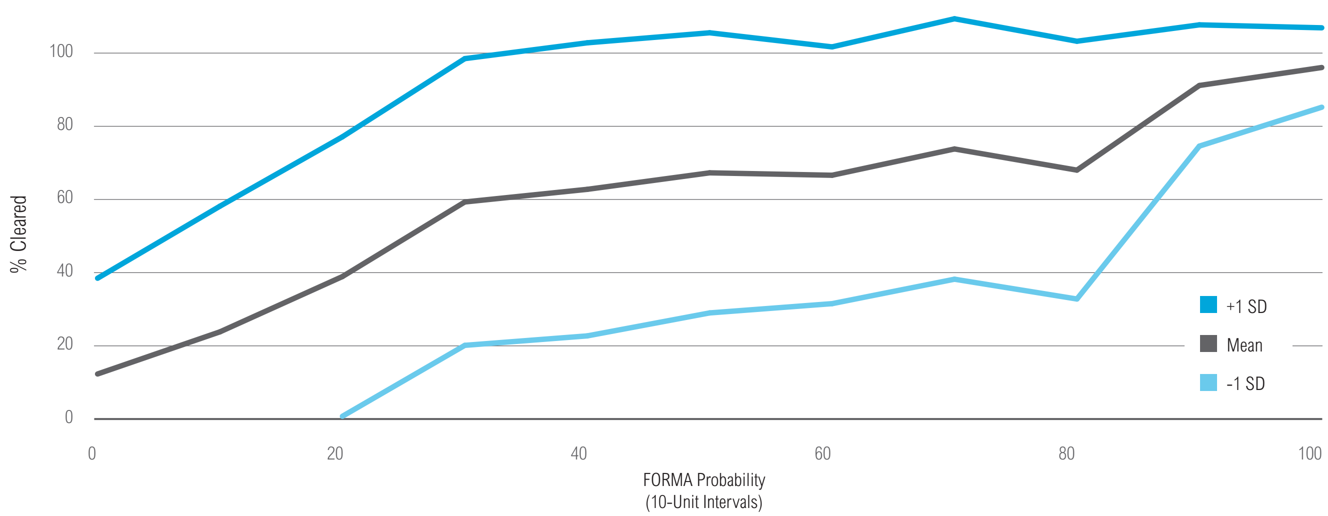
FORMA PROBABILITIES FOR THE MANICORÉ REGION, BRAZIL, 2005–12



Note: Background: Google Earth composite: various clear Landsat images from the period 2005–13.

FIGURE 4

MEAN PERCENT CLEARED BY FORMA PROBABILITY INTERVAL, KABUPATEN SAMBAS, WEST KALIMANTAN PROVINCE, INDONESIA



Note: Vertical axis measures derived from Landsat imagery. Figure 4 plots mean percent cleared (in gray), one standard deviation (SD) above the mean (dark blue) and one SD below (light blue). The three lines reveal substantial variation in the midrange: The upper SD line reaches 100 percent clearing at a FORMA probability around 30 percent, while the lower SD line rapidly converges to the mean beyond a FORMA probability of 80 percent.

IV. COMPARISON WITH BRAZILIAN SYSTEMS

To gauge how well FORMA identifies forest clearing spatially and temporally, we have compared it with two well-recognized forest clearing detection systems for the Brazilian Amazon, a region known for its highly sophisticated forest monitoring.

> FORMA and DETER are primarily intended to provide frequent and regular updates from relatively coarse-resolution satellite imagery. PRODES provides a more precise answer to the question: "Where did forest clearing occur during the past year, and how much clearing was there?"

The Real Time System for Detection of Deforestation (*Sistema de Detecção do Desmatamento em Tempo Real na Amazônia*, or DETER) provides monthly alerts so that law enforcement officials can quickly identify and inspect new forest clearing areas in the Amazon. DETER uses imagery from the MODIS satellite at a spatial resolution of 250 x 250 meters. It produces alerts in three steps: (1) automated, algorithm-based production of land cover maps using data from MODIS and AWIFS-ResourceSat; (2) post-processing validation (inspection and adjustment) of the results by interpreters; and (3) visual interpretation of validated maps to identify forest clearing.[10] Although DETER employs continuously measured variables, it applies a cutoff criterion to identify areas for public alerts.[11] DETER is a project of the Brazilian National Institute for Space Research (INPE).[12]

The Amazon Deforestation Monitoring Project (*Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite*, or PRODES) uses high-resolution data from Landsat, CBERS (China–Brazil Earth Resources Satellite program) and DMC (Disaster Monitoring Constellation) to provide annual identification of newly cleared Amazonian areas that are larger than 6.25 hectares. Brazilian experts produce PRODES maps by examining high-resolution Landsat imagery for changes in forested areas (Shimabukuro et al. 2000). The system identifies areas that have been cleared between September of the previous year and August of the current year; for example, PRODES 2006 reports clearing for September 2005 through August 2006. PRODES is the "gold standard" for annual deforestation estimates in the Brazilian Amazon because it incorporates higher-resolution imagery and more intensive scrutiny by skilled interpreters. Its status as the reference standard has been confirmed in peer-reviewed journals such as *Remote Sensing of Environment* (Hansen et al. 2008b). Like DETER, PRODES is a project of INPE, Brazil's National Institute for Space Research.

Although they are all forest monitoring systems, FORMA, DETER, and PRODES differ in a variety of ways (Table 1). For instance, FORMA and DETER are primarily intended to provide frequent and regular updates from relatively coarse-resolution satellite imagery. In effect, they provide answers to the question: "Where has forest clearing occurred recently?" In contrast, PRODES provides a more precise answer to the question: "Where did forest clearing occur during the past year, and how much clearing was there?" While DETER and PRODES both include expert human interpretation, FORMA's predictions are completely automated. And whereas DETER and PRODES focus on the Brazilian Amazon, FORMA spans the humid tropical forest biome from the Americas to Africa and Asia.

TABLE 1

COMPARISON OF THREE FOREST CLEARING DETECTION SYSTEMS

Feature	PRODES	DETER	FORMA
Spatial resolution	30 m	250 m	500 m (soon 250 m)
Temporal resolution	Annual	Twice-monthly	Twice-monthly
Geographic coverage	Brazilian Amazon	Brazilian Amazon	Tropical humid forests worldwide
Satellite	Landsat	MODIS	MODIS
Processing method	Involves expert interpretation	Involves a computer algorithm and expert interpretation	Fully automated
What it does	Identifies forest clearing during the previous year	Identifies new clearing as it emerges to guide preventive measures	Identifies new clearing as it emerges to guide preventive measures

V. COMPARATIVE ASSESSMENT

In our comparison against PRODES and DETER, we assessed the spatial and temporal performance of FORMA in a multi-step analysis that included:

- Selection of a test location with a large number of forest clearing detections by FORMA, PRODES, and DETER.
- Establishment of a benchmark: annual forest clearing identified by PRODES within the test area for the period September 2005 through August 2012.
- Construction of the database required for comparing FORMA and DETER with PRODES, and for comparing FORMA with DETER.
- Formal statistical performance comparisons for FORMA and DETER against PRODES to assess spatial accuracy, since PRODES has higher spatial resolution.
- Visual assessment of the match between the location of FORMA alerts and PRODES cleared areas.
- Formal statistical comparisons of FORMA and DETER to better assess temporal performance, since DETER provides monthly updates.

It is important to note that because FORMA, DETER, and PRODES use different data sets and methods, they will not necessarily produce identical maps of forest clearing in each period. What counts is not whether the three systems always align pixel-by-pixel, but whether they identify the same contiguous areas of clearing (or “hot spots”) for effective and timely intervention. Our standard of reference for hot spot identification is PRODES, since it uses higher resolution data.

1. Selecting the test area

We selected a portion of Manicoré municipality,[13] located in the southeastern portion of the Brazilian state of Amazonas (Figure 1), as the area for our comparison. It straddles the Trans-Amazon highway and has experienced significant deforestation during the past 20 years (Figure 5). The observation area is roughly 100 kilometers east-to-west and 60 kilometers north-to-south. Boundary coordinates in decimal degrees are longitude (61.85W, 61.05W) and latitude (8.15S, 7.65S).

FIGURE 5

FOREST CLEARING IN MANICORÉ, 1990–2012

Source: Google Earth Engine, Landsat 30-meter imagery.

Figure 5 shows that, by 2000, parallel deforestation tracks extended north from the Trans-Amazon highway, while a deforestation cluster had emerged south of the road. Rapid growth of the northern tracks and southern cluster continued after 2005, accompanied by clearing in several large, roughly rectangular areas in the north and east.

2. Setting the PRODES benchmark

We located the boundaries of forest clearing within the test area as identified by PRODES for the period September 2005 through August 2012. To illustrate, Figure 6 provides (a) a Landsat image of the test area in 2004 (prior to the testing period);(b) a Landsat image of the test area in 2012 (at the end of the testing period); and (c) PRODES-identified areas (in purple) cleared between September 2005 and August 2012, overlaid with a Google Earth composite image of the area. Recall that PRODES identifies forest clearing on an annual basis ending in August. Thus the 2006 data consist of clearing from September 2005 through August 2006.

Inspection of Figure 6 indicates that PRODES provides an accurate view of cleared areas. It captures the lengthening and widening of the northern tracks; intensive clearing in the southern cluster; and the appearance of large, regularly shaped blocks in peripheral areas.

FIGURE 6

PRODES COVERAGE OF TEST AREA

Google Earth Engine, 2004

Google Earth Engine, 2012

PRODES 2005–12 Over Google Earth Composite 2003–07

Source: Google Earth Engine, Landsat 30-meter imagery.

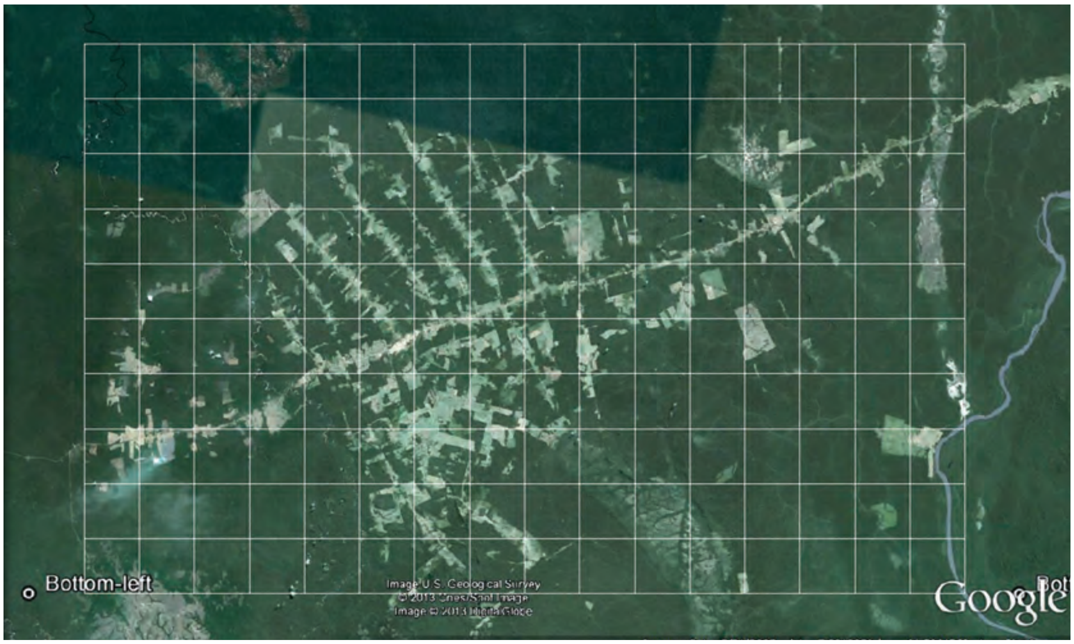
3. Comparing performance: FORMA and DETER relative to PRODES

We defined the area for analysis using the 0.05 degree grid that is overlaid on Manicoré in Figure 7. The grid contains 160 square cells whose sides measure approximately 5.5 kilometers (3,025 ha), bounded by longitude (61.85W, 61.05W) and latitude (8.15S, 7.65S). We chose a grid cell size that was large enough for meaningful aggregation within cells, and small enough to permit identification of forest clearing hot spots. We built the database from INPE's monthly shapefiles for DETER; INPE's annual shapefiles for PRODES; and FORMA's twice-monthly, pixel-level clearing probability estimates. The database includes 22,146 pixels gridded at .0042 decimal degrees. In each case, our measure for the core analysis is the year-to-year change in the variable described. Database elements were produced as follows, using ArcGIS 10.0 and Python 2.6:

- **PRODES, 2006–12.** We calculated all intersections of the 160 grid cells with PRODES-identified areas in each year. We added intersection areas within grid cells, producing a PRODES-based estimate of clearing intensity for each cell and year. Following INPE's specification, we assumed that cell totals for each PRODES year reflected clearing for 12 months through August of the observation year.

FIGURE 7

MANICORÉ GRID OVERLAY



Note: Background: Google Earth composite: various clear Landsat images from the period 2005–13.

- **DETER, 2006–12.** We calculated all intersections of the 160 grid cells with DETER-identified areas in each month. We added intersection areas within grid cells, producing a DETER-based estimate of clearing intensity for each cell and month. Then we added monthly intersection area totals for 12-month periods through August of each year. The result is an annual, DETER-based measure of clearing intensity within each cell that matches the PRODES measure described above.
- **FORMA, 2006–12.** We constructed a pixel-level categorical variable whose value is 1 when a pixel's FORMA probability exceeds 50 percent and 0 otherwise. We added pixel values within cells to produce an estimate of clearing intensity for each cell and month. We then added monthly totals for 12-month periods through August of each year. The result is an annual, FORMA-based measure of clearing intensity within each cell that matches the PRODES and DETER measures.

We used regression analysis to compare the performance of FORMA and DETER against the PRODES benchmark. The analysis was designed to answer the question, "Across grid squares and over time, how well are PRODES-identified deforestation hot spots tracked by DETER and FORMA?" Before settling on the final regression specification, we performed two standard tests (Breusch-Pagan and Cook-Weisberg) that revealed gross heteroskedasticity when the raw intensity measures are used in our regressions. Among the standard transformations used to correct for heteroskedasticity, we chose cell ranks in each year for two reasons. First, rank regressions provide very robust estimates in cases where outlier observations can distort results.[14] Second, rank regressions align with our analytical objective: assessing the ability of the two frequently updated systems to identify contiguous areas of new clearing (hot spots) that are assigned high priority or "high rank" by PRODES.

Although there are many overlaps, DETER's coverage is much sparser and more scattered than FORMA's coverage, missing both large and small PRODES-identified areas in significant numbers, while FORMA appears to miss very few.

We used Stata 13 to estimate the rank regressions.[15] Table 2 provides estimation results for three techniques, in ascending order of sophistication: ordinary least squares (OLS), panel estimation (Panel),[16] and panel estimation with adjustment for spatial autocorrelation (Spatial Panel).[17] The results, reported in columns 1–6, have three striking features:

1. *FORMA and DETER ranks* are positively associated with PRODES ranks with very high statistical significance.
2. *FORMA and DETER are stable.* For both FORMA and DETER, parameter estimates are basically stable across OLS, Panel, and Spatial Panel.
3. *FORMA predicts hot spots more accurately than DETER.* All regression R^2 estimates indicate that FORMA predicts PRODES hot spots more accurately than DETER predicts these hot spots.[18] In pairs by estimation method, the comparative adjusted R^2 estimates are:
   - OLS: FORMA 0.49 and DETER 0.17
   - Panel: FORMA 0.49 and DETER 0.17
   - Spatial Panel: FORMA 0.80 and DETER 0.37

Figures 8 and 9 provide visual support for the statistical assessment of prediction accuracy in Table 2. Figure 8 overlays all PRODES-identified areas since 2005 with FORMA pixels that meet the 50 percent probability threshold for 2006–12. The visual "fit" is quite good, with accurately aligned coverage for almost all major PRODES areas. Figure 9 overlays the PRODES areas with DETER-identified areas for 2006–12. Although there are many overlaps, DETER's coverage is much sparser and more scattered than FORMA's coverage. DETER appears to miss both large and small PRODES-identified areas in significant numbers, while FORMA appears to miss very few. Figures 8 and 9 provide an intuitive, visual demonstration of why FORMA's rank regression R^2 measurements are much higher than DETER's.

TABLE 2

RANK REGRESSION ANALYSIS OF FORMA, DETER, AND PRODES

Comparison	PRODES fit: FORMA vs. DETER						DETER fit: FORMA		
Technique	OLS	OLS	Panel	Panel	Spatial Panel	Spatial Panel	OLS	Panel	Spatial Panel
Dependent variable rank	PRODES	PRODES	PRODES	PRODES	PRODES	PRODES	DETER	DETER	DETER
FORMA rank	0.613		0.572		0.59		0.179	0.179	0.173
■ Absolute value of T statistic	30.11*		25.49*		27.79*		11.30*	11.30*	12.79*
DETER rank		0.699		0.5		0.662			
■ Absolute value of T statistic		14.11*		11.38*		13.66*			
Regression constant	19.974	33.878	22.319	39.866	21.301	35.375	19.843	19.843	20.16
■ Absolute value of T statistic	15.76*	20.86*	15.81*	25.88*	13.59*	11.06*	20.15*	20.15*	22.68*
Observations	960	960	960	960	960	960	960	960	960
R-squared	0.49	0.17	0.49	0.17	0.8	0.37	0.12	0.12	0.83
Cells			160	160	160	160		160	160

Note: All variables are annual ranks among 160 cells
* Significant at 1 percent

FIGURE 8

FORMA VS. PRODES

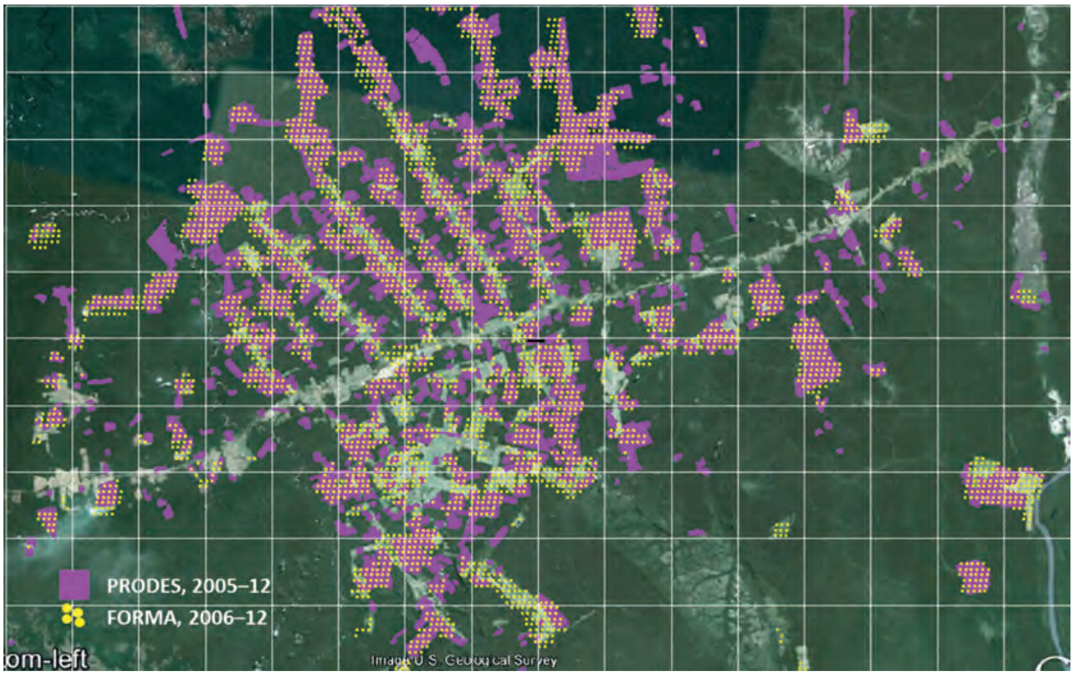
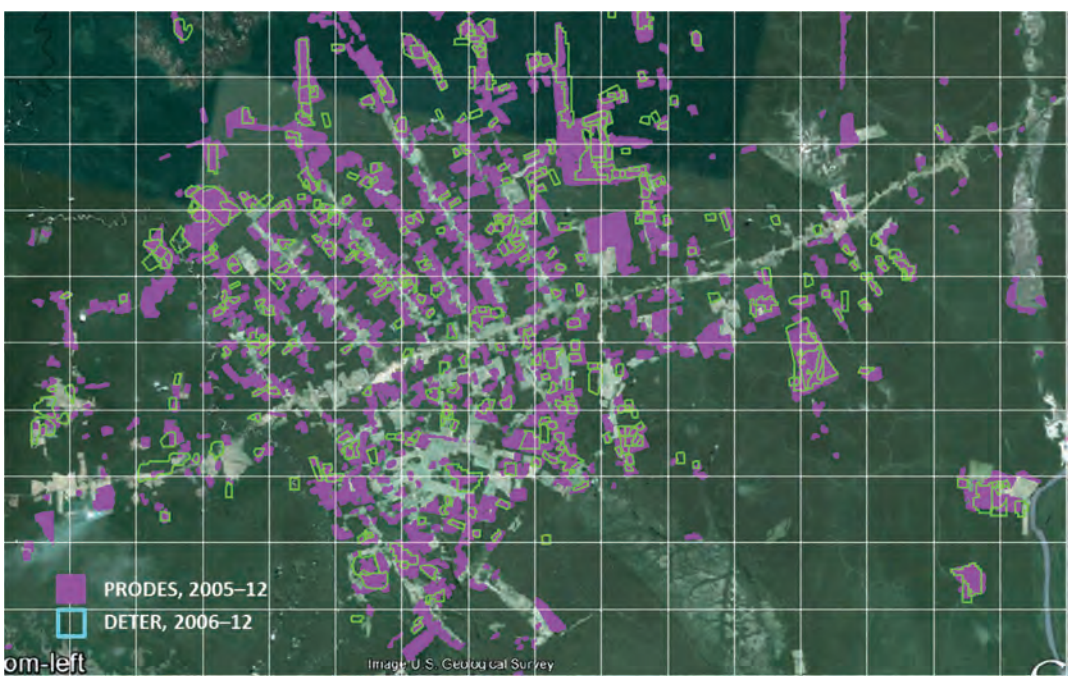


FIGURE 9

DETER VS. PRODES



4. Conducting a visual check: FORMA and PRODES

The statistical evidence indicates that FORMA estimates are strongly associated with PRODES hot spots. A visual display of imagery over time reinforces the statistical insights. Slideshow 1 (available at: <http://goo.gl/sWZK7t>) overlays PRODES-cleared areas and FORMA pixels on the high-resolution map of Manicoré. Since FORMA probabilities are updated twice-monthly while PRODES areas are updated annually, we begin each year of the animation with end-of-year PRODES updates, making it easier to watch the FORMA pixels "fill in" areas that PRODES will ultimately identify. We color the FORMA pixels to reflect probability ranges of 21–49 percent (yellow), 50–79 percent (orange), and >80 percent (red). Pixels with probabilities below 21 percent are not shown.

Slideshow 1 plays automatically in presentation mode, with each slide showing for one second. The first frame presents the Google Earth image of Manicoré, drawn from composite Landsat data for 2005–13. The second frame presents PRODES-cleared areas for September 2005 to August 2006. FORMA pixels then appear for January 2006, followed by monthly pixel updates through August 2006. Then the PRODES areas jump ahead to August 2007, and FORMA pixels update monthly for the intervening 12 months. This process continues through October 2012.

The animation creates three visual impressions. First, the evolving "fit" between FORMA predictions and PRODES outcomes per year is extremely good. Second, in this rapidly deforesting area at least, FORMA pixels in the 20–49 percent probability range (yellow pixels) are important as lead indicators of clearing that is to come in future time periods. Third, in the few areas where there are FORMA pixels but no PRODES identification, the consistent clustering and color evolution over time of the FORMA pixels suggest that clearing activity has occurred, even if it does not cross the area extent threshold for PRODES cleared status.

5. Comparing performance: FORMA vs. DETER

Columns 7–9 in Table 2 present results for regressions of DETER ranks on FORMA ranks. All the results indicate highly significant annual associations between their hot spot predictions. To investigate their lead/lag relationship in months, we constructed aggregate time series for Manicoré from the monthly database. Then we performed formal tests of the lead/lag relationship in Stata 13, using the Granger technique incorporated in the Stata package gcause.

Table 3 reports the results for monthly structures that vary from 3- to 10-month lags. The first column reports "Granger causation" tests for the null hypothesis: "FORMA does not lead (Granger-cause) DETER." The null hypothesis is strongly rejected for monthly lags of length 5, 6, 7, and 8, with the strongest result for a 7-month lag. In contrast, the results for column 2 show uniform failure to reject the null hypothesis of "DETER does not lead (Granger-cause) FORMA." By implication, the evidence suggests that on average FORMA estimates lead DETER estimates by about 7 months or—more roughly—half a year. We suspect that FORMA's use of rapidly available information on active fires explains its temporal advantage. In contrast, DETER identifies clearing only after satellite imagery has confirmed a change in forest cover.

The statistical evidence indicates that FORMA estimates are strongly associated with PRODES hot spots. A visual display of imagery over time reinforces the statistical insights.

TABLE 3

GRANGER TEST RESULTS FOR FORMA AND DETER

Monthly lags	H_0: FORMA does not lead DETER[a]	H_0: DETER does not lead FORMA[b]
3	F(3, 61) = 1.54	F(3, 61) = 0.85
	Prob> F = 0.2140	Prob> F = 0.4716
4	F(4, 53) = 1.50	F(4, 53) = 0.40
	Prob> F = 0.2144	Prob> F = 0.8053
5	F(5, 45) = 3.15	F(5, 45) = 0.63
	Prob> F = 0.0159	Prob> F = 0.6771
6	F(6, 38) = 4.05	F(6, 38) = 1.20
	Prob> F = 0.0031	Prob> F = 0.3297
7	F(7, 32) = 5.39	F(7, 32) = 1.80
	Prob> F = 0.0004	Prob> F = 0.1210
8	F(8, 26) = 4.23	F(8, 26) = 0.84
	Prob> F = 0.0024	Prob> F = 0.5763
9	F(9, 21) = 1.57	F(9, 21) = 0.74
	Prob> F = 0.1887	Prob> F = 0.6657
10	F(10, 16) = 1.11	F(10, 16) = 0.81
	Prob> F = 0.4099	Prob> F = 0.6251

Notes: [a] Formally expressed as "FORMA does not Granger-cause DETER"
[b] Formally expressed as "DETER does not Granger-cause FORMA"

We then considered the possibility that FORMA and DETER are actually complements rather than strict substitutes, because they use different methodologies to identify new forest clearing (see Sections III and IV). Table 4 reports the relevant rank regressions. As in Table 2, the parameter estimates are essentially invariant to regression technique. In all three cases, FORMA and DETER ranks play highly significant, independent roles in predicting PRODES ranks. At the same time, the results indicate that FORMA plays a much stronger predictive role: OLS Beta coefficients (standard measures of relative explanatory importance) for FORMA and DETER are 0.629 and 0.199, respectively. Regression t-statistics also provide indicators of relative importance. As with the Beta coefficients, they have an approximately 3:1 ratio for all techniques reported.

6. Why FORMA performs better than DETER

As we noted in Sections III and IV, FORMA and DETER use very different methods and data sets to identify forest clearing hot spots. These differences may well account for part of the performance gap in our results. However, our findings may also reflect differences in the treatment of uncertainty. To explore this possibility, we conducted a pixel-level comparison at varying probability thresholds for FORMA. In the Manicoré area, for each year, 22,146 pixels (.0042 decimal degrees) are assigned clearing probabilities by FORMA and dichotomous clearing status (cleared=1/not cleared=0) by PRODES and DETER. For our assessment, we converted each FORMA probability to six dichotomous variables (cleared=1/not cleared=0) using probability thresholds of 10, 30, 50, 70, 90, and 95 percent. To illustrate, the first variable is 1 for FORMA probabilities greater than 10 percent and 0 otherwise.

For each year in the period 2008–12, we computed percentages of correctly identified cleared and uncleared PRODES pixels for FORMA and DETER. We also computed their precision, or accuracy rate, for pixels identified as cleared. This measure has particular significance for rapid response systems like FORMA and DETER, since their alerts could prompt costly supervision or enforcement actions. We summarized the results by computing mean annual values, which are presented in Table 5. They corroborate our grid-level results for the 50 percent probability threshold reported in Table 2. At this threshold, FORMA is much more accurate than DETER in predicting PRODES-identified cleared pixels (63.3 percent vs. 33.2 percent) and slightly less accurate in predicting uncleared pixels (91.9 percent vs. 97.4 percent). Overall, Table 5 shows that increasing the probability threshold sharply decreases FORMA's predictive accuracy for cleared pixels (from 88.0 percent at 10 to 33.5 percent at 95) while moderately increasing its accuracy for uncleared pixels (from 81.4 percent at 10 to 97 percent at 95). For threshold probabilities in the range 30–70 percent, FORMA clearly outperforms DETER. Only at 90 percent does FORMA's performance begin to resemble DETER's.

These results are consistent with extreme aversion to false-positive errors (mistaken identification of uncleared areas as cleared) in the implementation of DETER. If this interpretation is correct, our results highlight the size of the price that is paid: When compared with FORMA at the 50 percent threshold, DETER accepts a loss of 30.1 percent (33.2 percent – 63.3 percent) in identification of cleared areas for a 5.5 percent gain (97.4 percent – 91.9 percent) in identification of uncleared areas. For the FORMA estimates, raising the threshold to 90 percent would produce a loss of 24.1 percent in identification of cleared areas for a 4.3 percent gain in identification of uncleared areas.

At first glance, these results suggest that lower FORMA thresholds provide a better balance between the two types of uncertainty. Indeed, as

TABLE 4

FORMA AND DETER AS JOINT PREDICTORS OF PRODES

Technique	OLS	Panel	Spatial Panel
Dependent variable rank	PRODES	PRODES	PRODES
FORMA rank	0.553	0.548	0.529
■ Absolute value of T statistic	26.42*	25.78*	24.97*
■ Beta coefficient	0.629		
DETER rank	0.336	0.331	0.387
■ Absolute value of T statistic	8.36*	8.29*	9.47*
■ Beta coefficient	0.199		
Regression constant	13.312	13.764	13.154
■ Absolute value of T statistic	9.12*	9.30*	7.49*
Observations	960	960	960
R-squared	0.52	0.52	0.8
Cells		160	160

Note: All variables are annual ranks among 160 cells
* Significant at 1 percent

Figure 3 indicates, FORMA probabilities in the range 21–49 percent play a significant predictive role in the Manicoré region. However, this simple prescription ignores the potential cost of unnecessary actions prompted by false-positive alerts. Table 5 shows that FORMA's precision (46.9 percent) is comparable to DETER's (49.9 percent) at a probability threshold of 95, but declines to 38.4 percent at 50 and 27.3 percent at 10. When the threshold is lowered to 10, FORMA correctly identifies 88 percent of the pixels that PRODES identifies as cleared, but its low precision (27.3 percent) means that 72.7 percent of its alerts identify uncleared pixels. This tradeoff provides a clear economic rationale for DETER's apparent aversion to false-positive errors that may prompt costly but unnecessary monitoring and enforcement actions.

The last two columns of Table 5 also provide insight into the direct relationship between FORMA and DETER. At the 50 percent threshold, FORMA correctly identifies 63.3 percent of cleared pixels in DETER and 90.5 percent of uncleared pixels. As before, raising the probability threshold to 90 percent produces a modest (4.9 percent) improvement in identification of uncleared pixels in DETER, but at the cost of a 20 percent decrease in identification of cleared pixels. Conversely, reducing the probability threshold to 10 percent compensates a loss of 11 percent in identification of uncleared pixels with a gain of 22.5 percent in identification of cleared pixels. These results suggest that FORMA may lead DETER (Table 3) because FORMA's 50 percent probability threshold permits detection of early clearing signals from active fires that must strengthen for several months before they become "visible" to DETER.

TABLE 5

MEAN PERCENT OF PIXELS CORRECTLY IDENTIFIED, 2008–12

FORMA Probability Threshold	PRODES Pixels		PRODES (Correctly Predicted by DETER)			PRODES (Correctly Predicted by FORMA)			DETER (Correctly Predicted by FORMA)	
	Cleared	Not Cleared	Cleared	Not Cleared	Precision	Cleared	Not Cleared	Precision	Cleared	Not Cleared
10	7.4	92.6	33.2	97.4	49.9	88	81.4	27.3	85.8	79.5
30						73.9	89.1	35	72.1	87.3
50						63.3	91.9	38.4	63.3	90.5
70						53	94	41.5	55.3	92.9
90						39.2	96.2	45	43.3	95.4
95						33.5	97	46.9	38.3	96.4

7. FORMA vs. DETER in areas with high and low forest clearing intensity

As Figure 5 shows, parts of the Manicoré region exhibit the “fishbone” pattern of deforestation along main and feeder roads that characterizes many parts of Brazil. This strong pattern lends itself to detection by PRODES, DETER, and FORMA. But FORMA and DETER, with their relatively coarse resolution, may not be as sensitive as PRODES in detecting smaller scale deforestation. FORMA also operates from a different baseline than PRODES and DETER, because the latter two exclude secondary forest (Hansen et al. 2008b), while FORMA does not.

In a more complete exercise, we would have compared FORMA and DETER with PRODES in a diverse set of Amazonian regions. However, the Manicoré region itself covers roughly 6,000 square kilometers. To assess variation in forest clearing intensity within the region, we computed the cleared area identified by PRODES in each of our 160 grid cells. We ranked the cells by cleared area (largest first) and computed the cumulative percent of total area cleared. Table 6 presents the results by decile for cells ranked from 1 to 100. It reveals a highly concentrated pattern, with 27.0 percent of total clearing in the top 10 cells and 75.7 percent in the top 40.

We exploited this highly skewed distribution to investigate the relative performance of FORMA and DETER in areas of high and low forest clearing intensity. We divided the 160 cells into the top 22, which account for 50 percent of total clearing during 2007–12, and the remaining 138. Then we replicated the OLS and Panel regressions reported in Table 2 for the high- and low-intensity cases. Our cell assignment procedure created within-group spatial gaps between cells that prevented comparable Spatial Panel estimation. By the same token, however, the spatial gaps probably reduce spatial autocorrelation from geographic contiguity of cells. In any case, the similarity of the Spatial Panel results to the others in Table 2 bolsters our confidence in the OLS and Panel results reported in Table 7.

TABLE 6

CONCENTRATION OF PRODES-IDENTIFIED CLEARING, 2007–12

Cell Rank	Cumulative Percent: Total PRODES
10	27.0
20	47.0
30	63.2
40	75.7
50	85.3
60	92.0
70	95.7
80	97.7
90	98.9
100	99.8

TABLE 7

RANK REGRESSION ANALYSIS OF FORMA, DETER, AND PRODES FOR CELLS WITH HIGH AND LOW FOREST CLEARING INTENSITY

Comparison	PRODES fit: FORMA vs. DETER							
Technique	OLS				Panel			
Forest Clearing Intensity	High		Low		High		Low	
Dependent variable rank	PRODES	PRODES	PRODES	PRODES	PRODES	PRODES	PRODES	PRODES
FORMA rank	0.475		0.526		0.475		0.499	0.386
■ Absolute value of T statistic	6.05*		23.75*		6.05*		20.97*	8.40*
DETER rank		0.802		0.474		0.819		
■ Absolute value of T statistic		6.73*		9.67*		7.38*		
Regression constant	13.53	9.272	26.964	44.493	13.53	8.893	28.65	47.25
■ Absolute value of T statistic	4.82*	2.97*	18.59*	26.94*	4.82*	2.62*	18.29*	29.70*
Observations	132	132	828	828	132	132	828	828
R-squared	0.22	0.26	0.41	0.1	0.22	0.26	0.41	0.1
Cells					22	22	138	138

Note: All variables are annual ranks among 160 cells
* Significant at 1 percent

Table 7 resembles Table 2 in displaying consistently high significance for FORMA and DETER. However, the separation into clearing intensity groups reveals an important difference that helps explain FORMA's superior overall performance. In both the OLS and Panel estimates, the regression R^2 values and parameter significance levels for the high-intensity group are nearly identical for FORMA and DETER. For the low-intensity group, however, FORMA's R^2 values and significance levels are much higher than DETER's.

These results are far from conclusive, because they are drawn from cells that lie within the same area in one region of Amazonia. However, they do suggest that FORMA's main advantage over DETER may lie in areas where large-scale, clustered forest clearing has not yet occurred. In Manicoré grid cells where clearing has been more intense, FORMA's performance is nearly identical to DETER's.

VI. CONCLUSIONS

Our assessment highlights the strong performance of FORMA as a forest clearing detection system in a rapidly deforesting part of Manicoré municipality, Brazil. The comparison of FORMA with two long-standing systems—PRODES and DETER—found that:

- FORMA identifies PRODES hot-spot areas with significantly higher overall accuracy than DETER.
- FORMA does significantly better than DETER in lightly cleared areas, and matches DETER's performance in heavily cleared areas.
- FORMA and DETER appear to be complements rather than substitutes. A combination of DETER and FORMA identifies PRODES hot spots more accurately than FORMA alone, although FORMA's contribution to identification is greater.
- FORMA predicts year-to-year changes in PRODES-identified hot spots very well. In the statistical analysis, newly identified FORMA hot spots predict newly emerging PRODES hot spots with very high statistical significance.
- Temporal identifications of emerging hot-spot areas by FORMA and DETER are highly correlated.
- In the identification of new hotspots, FORMA actually leads DETER by about half a year. Our results suggest that FORMA's 50 percent probability threshold permits earlier detection of deforestation signals.
- The comparative performance of FORMA and DETER is significantly affected by the choice of probability threshold for FORMA. Our results suggest that the next version of FORMA may benefit from a probability threshold lower than 50 percent, the current standard.

Limitations and next steps

Our comparative assessment was limited in scope. We considered just one 6,000 square kilometer region of the Brazilian Amazon and did not assess performance in other parts of that biome. We also did not assess performance in other humid tropical forests. The primary reason for the latter was the absence of other publicly reported forest monitoring or clearing alert systems with periodicities less than a year. Comparative analysis akin to our Manicoré assessment was therefore not possible.

With these limitations in mind, future research priorities are clear. Comparative assessments should be performed in more Amazonian locations to broaden our findings. Similarly, alternative assessment methods should be applied to comparisons of FORMA data with available information for other humid tropical regions with different deforestation patterns. Such analyses could, for example, use time series of high-resolution satellite imagery from sensors such as Landsat, Rapid Eye, or SPOT. They could be complemented by on-the-ground observations by researchers using equipment such as mobile phones with photographic and GPS capabilities.

Concluding thoughts

The world's forests are a vital foundation for human livelihoods, climate stability, and biodiversity conservation. The capability to detect forest clearing where and when it happens can empower governments, businesses, and communities to take timely action to curtail illegal and unsustainable forest clearing. The advent of near-real-time forest monitoring systems like FORMA has the potential to provide this capability, thereby dramatically strengthening efforts to conserve and sustainably manage these important ecosystems.

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ENDNOTES

1. FORMA is updated twice-monthly at <www.globalforestwatch.org>.
2. FORMA covers pixels classified as forested in 2000, using a threshold value of 25 for the vegetation continuous field (VCF) index, based on Hansen et al. (2003).
3. Although we refer to Manicoré for expositional convenience in the remainder of the brief, our assessment area overlaps slightly with the municipality of Novo Aripuanã.
4. MODIS data are available at <http://modis.gsfc.nasa.gov/data/>.
5. FIRMS data are available at <https://earthdata.nasa.gov/data/near-real-time-data/firms/active-fire-data>.
6. PREC/L data are available at <http://www.esrl.noaa.gov/psd/data/gridded/data.precl.html>.
7. See Hammer, Kraft, and Wheeler (2009) for a complete discussion of the rationale for selection of FORMA variables and the modeling approach.
8. The shapefile for WWF ecoregions is available at <http://worldwildlife.org/publications/terrestrial-ecoregions-of-the-world>.
9. The Hansen study does not use data from PRODES to produce its estimates for Brazil.
10. For a lucid explanation of the DETER approach, see Butler (2011).
11. Formally, these are published as shapefiles.
12. Another MODIS-based detection system for the Amazon, Sistema de Alerta de Desmatamento (SAD) has been developed by Imazon, a Brazilian nonprofit research institution (http://www.imazon.org.br/). A comparison with PRODES published by INPE (Escada et al. 2011) indicates that DETER performs significantly better than SAD. We are therefore applying a higher reference standard by comparing FORMA with DETER rather than SAD.
13. We refer to Manicoré for expositional convenience, although our assessment area overlaps slightly with the municipality of Novo Aripuanã.
14. Formally, robust estimation methods like rank regression address the violation of classical error variance assumptions by heteroskedasticity associated with variables that are skew-distributed.
15. As a check on robustness, we estimated the same rank regressions using variables derived from two other FORMA measures: (1) a pixel-level categorical variable whose value is 1 when a pixel's FORMA probability exceeds 20 percent and 0 otherwise; (2) the pixel-level FORMA probabilities. In both cases, the patterns revealed by our results are identical to the patterns reported in this paper.
16. We used random effects estimation for direct comparison with the spatial panel estimates. The estimates are produced by xtreg in Stata 13.
17. We estimated the spatial weights matrix from grid cell centroids using spmat in Stata 13. The spatial estimates are produced by spglsxt in Stata 13. This panel estimator uses the generalized method of moments suggested by Kapoor et al. (2007) to adjust for error components that are both spatially and temporally correlated.
18. R^2 is the square of the simple correlation coefficient for our bivariate regressions of PRODES ranks on FORMA ranks and DETER ranks. For example, in columns 1 and 2 of Table 2, the R^2 values and corresponding correlation coefficients are (.49, .70) and (.17, .41), respectively.

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