Simulating National-scale Deforestation in the Philippines Using Land Cover Change Models

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After the year 2010, a century of rapid decline in Philippine forest cover was reversed due to a deliberate National Greening Program (NGP). Drivers that can sustain or counter this increase can be better investigated through the help of land change models. However, such models are not yet in mainstream use for planning in the Philippines. Hence, this study used two models – FOREST-SAGE and GEOMOD – to simulate forest conditions based on anthropogenic drivers and to evaluate model applicability in the Philippines. The performance of each model was assessed using the root-mean-square error (RMSE), mean absolute error (MAE), Kappa, national average tree cover percentage, and common deforestation hotspots with reference datasets. Validation with Climate Change Initiative Land Cover dataset (CCI-LC) yielded similar results between the models: 2015 tree cover maps with RMSE of 22–25% tree cover, MAE of 10–12% tree cover, and moderate agreement with reference map based on Kappa (0.4–0.6); and 2010–2015 change maps with RMSE of 8–9% tree cover, MAE of 1–2% tree cover, and agreement due to chance based on Kappa (0.01–0.03). Validation with MODerate Resolution Imaging Spectroradiometer-Vegetation Continuous Field (MODIS-VCF) maps yielded similar MAE results (10% tree cover) between the models. Validating FOREST-SAGE end-time and change maps with MODIS-VCF yielded better RMSE results than GEOMOD (RMSE of 13% tree cover for FOREST-SAGE; 22% tree cover for GEOMOD). However, GEOMOD tree cover maps yielded better Kappa than FOREST-SAGE (0.60 for GEOMOD; 0.01 for FOREST-SAGE). Results suggest that FOREST-SAGE is more applicable in the Philippines for provincial extent studies that aim to quantitatively track forest cover change, while GEOMOD is more applicable for national extent studies that use categorical data. Results also suggest that input parameter settings must be improved to simulate spatial distribution of forest cover.

Keywords: deforestation, FOREST-SAGE, GEOMOD, land cover change, model calibration, model validation

INTRODUCTION
Changes within tropical forests in the past decades have received considerable attention due to the rapid rate of deforestation, affecting regional and global changes in biodiversity and climate (Mas et al. 2007, Li et al. 2016). One of the countries that underwent such rapid deforestation is the Philippines – from 70% of the country’s total land area in 1900 to 50% in 1950 and to less than 19% by 1990 (Kummer 1992). Although the decline in forest cover lessened in 2003 to 2010 (FMB, pers. comm., 13 Oct 2015), it was only after 2010 that a 3.29% annual increase in forest cover was observed (FAO 2015). The reported increase in Philippine forest cover has been
attributed to the implementation of the NGP in 2011. The NGP was a deliberate attempt to increase forest cover by planting 1.5 billion trees covering about 15,000 km² from 2011 to 2015. The program has been extended to 2028, through Executive Order No. 193 (Office of the President of the Philippines 2015), to cover an additional 71,000 km² of unproductive and denuded land for reforestation and to sustain the forest cover increase from the initial NGP. Land use and land cover change (LULCC) models may be useful in attaining the goal to sustain forest cover by providing a cost-effective means of studying forests over massive spatial extents.

Mathematical modeling techniques are useful in evaluating environmental transformation and finding solutions to environmental problems (Aral 2010). LULCC models may present information that can help evaluate strategies to mitigate negative impacts of anthropogenic activities to forest resources. However, models must be based on reality to be useful and reliable for decision-makers. Validating models and comparing simulations produced by different models are essential, considering that models differ from one another in terms of functionality and complexity, and have advantages and disadvantages depending on research objectives (Agarwal et al. 2002). Noszczyk (2018) and Agarwal et al. (2002) present a comprehensive review of different land use change models based on advantages and limitations, research objectives, and functionality.

Unfortunately, only a few models with regional scale projection capabilities have been applied in the Philippines (e.g., Verburg and Veldkamp 2004, Verburg et al. 2004). At the same time, scant literature exists on regional scale projections in the Philippines. Literature describing validation methods and usability of LULCC models at the national scale in the Philippines is also lacking.

Most of the currently published LULCC studies in the Philippines focus on specific provinces or local watersheds (e.g., Briones et al. 2016, Abino et al. 2015, Malahie et al. 2012, Pati 2014, Santillan et al. 2011). One of the few published studies on LULCC modeling at the national scale in the Philippines was conducted by Verburg and Veldkamp (2004) using CLUE-S (the Conversion of Land Use and its Effects at Small regional extent) to simulate land use change based on spatial policies, land use types, and location characteristics as factors of deforestation. Their study simulated land cover change at both a national coarse-scale and a detailed local scale in the Philippines, showing that coarse-scale simulations are useful to identify ‘hot zones’ of deforestation and overall land pattern of the country.

This study intends to strengthen research on LULCC modeling in the Philippines at the national scale. Specifically, the study aims to use two models – FOREST-SAGE (deFOREStation ScenArio GEnerator) (Tompkins et al. 2015) and GEOMOD (Pontius et al. 2001) – and evaluate their performance on simulating national-scale deforestation between 2010 and 2015. FOREST-SAGE was chosen as it has been applied in a large regional extent in South Africa (Tompkins et al. 2015) but is relatively new. Moreover, challenges in LULCC modeling concerning incorporating data of different dimensions (e.g., line and polygon) and interoperability among vector and raster data formats (Liu and Yang 2015) is addressed in this model. GEOMOD was chosen due to having been widely used for studies that cover both large and small spatial scales (Pontius and Chen 2006). GEOMOD is also available through the TerrSet Software with a graphic user interface that could facilitate ease of use. Both models have not yet been used for national scale simulations in the Philippines; hence, this study evaluates the applicability of the models for such simulations.

MATERIALS AND METHODS

The Models
FOREST-SAGE is a flexible deforestation model that disaggregates macro-scale rates of tree cover loss over space based on local-scale drivers of deforestation – specifically logging concessions, mining concessions, road networks, river systems, population, forest fragmentation, protected areas (PAs), and reforestation. FOREST-SAGE uses continuous maps or maps in which each pixel is assigned a range of tree cover percentage values ranging from 1 to 99. The model multiplicatively combines risks due to driver datasets to calculate each pixel’s risk for deforestation (Tompkins et al. 2015).

GEOMOD is a land cover change model that uses raster maps of land change drivers and existing land use maps to extrapolate the pattern of land use from one point in time to another (Pontius et al. 2001). The model uses categorical raster maps or maps in which pixels are assigned only one integer representing forests or non-forest areas. The overall land cover change risk of each pixel is determined by taking the weighted sum of suitability based on driver images (Pontius and Chen 2006).

Datasets and Input Parameter Values
Datasets obtained for this study cover the entire country for years 2000, 2005, 2010, and 2015. The study uses freely available datasets, most of which are accessible from online repositories that provide retrospective data at the national scale for the specified years. Constants assigned to input parameter values are based on existing literature on deforestation drivers in the Philippine and
Asian context – including government documents, peer-reviewed articles, and previous model applications.

Collection 5 of MODIS-VCF (DiMiceli et al. 2011) datasets were used as beginning-time images. These were obtained from the Land Processes Distributed Active Archive Center of the National Aeronautics and Space Administration (NASA). The datasets were resampled from 250 m to 1 km and 5 km using the nearest neighbor method through ArcGIS Resample Tool as part of the calibration process. MODIS-VCF was created through a regression tree algorithm to derive global vegetation continuous fields based on surface reflectance composites, with 30 m resolution Landsat data classified into four relative percent tree cover (0, 25, 50, 80+) as training data (Townshend et al. 2013, Hansen et al. 2002). The high-resolution training data were then aggregated to a coarse scale to derive continuous fields (Hansen et al. 2002). VCF Collection 5 has been validated in Maryland (RMSE = 9.47%) and Brazil (RMSE = 10.46%) (Townshend et al. 2013). The quality of the VCF Collection 5 product is one of the limitations of this study.

To create categorical raster, which is required for beginning-time images in GEOMOD, continuous MODIS-VCF datasets were reclassified into tree cover percentage thresholds (Appendix I). Four reclassified maps were produced, each with non-forest or forest pixels based on the definition of forest by the Philippine Forest Management Bureau (≥ 10% tree cover) or land cover class description of United Nations Land Cover Classification System used in CCI-LC datasets (≥ 15%, ≥ 40%, or ≥ 50% tree cover) (Poulter et al. 2015).

Legal and illegal commercial logging and mining are the main drivers of deforestation in the Philippines (Matthews et al. 2010). A cutout extraction rates could be placed at 200% of the annual allowable cut since overcutting is a standard practice in timber concessions in the Philippines (Van Den Top 1998). Logging and mining concessions were inputted in the models as factors that increase deforestation risk in areas where these are located. One of the limitations of the study is that input maps on logging and mining concessions do not show the exact location of these features. Instead, data from the Forest Management Bureau (FM B) and Mines and Geosciences Bureau (MGB) of the Philippine Department of Environment and Natural Resources (DENR) were translated into maps showing cities and municipalities where these concessions are located (Appendix II). Data on logging concessions obtained from FM B (2016a) include existing Forest Land Use Agreements, Forest Land Use Agreement for Tourism Purposes, Special Land Use Permit, Special Land Use Lease Agreement, Integrated Forest Management Agreement, and Socialized Industrial Forest Management Agreement. Data on mining permits and contracts obtained from MGB (2016) include Exploration Permits, Financial or Technical Assistance Agreements, Industrial Sand and Gravel Permits, Mining Lease Contracts, Mineral Processing Permits, and Mineral Production Sharing Agreement.

Roads are the second to third most important driver of deforestation in the Philippines (Carandang et al. 2012). Roads and rivers also encourage deforestation by making forests more accessible and serving as transport channels especially for illegally logged wood (Verburg et al. 2004). Forests nearer roads are more accessible and are thus more prone to deforestation. As such, more forest loss is observed in areas closer to roads (Liu et al. 1993). Lands nearer roads are more prized, with land value decreasing by at least 2% for every 3 km increment from roads (BLGF 2010). In terms of distribution of deforestation as a function of distance from rivers, Timber License Agreement holders in the country are required to maintain forest cover within a 20-m strip along the banks (Van Den Top 2003). Hence, deforestation should supposedly not occur within this buffer. Data on transport networks and population centers serve as drivers in the models that increase deforestation risk in areas proximate to these features. Road datasets were obtained from NASA’s Socioeconomic Data and Applications Center (SEDAC) (CIESIN and ITOS 2013) while water body datasets were obtained from DIVA-GIS (2011). The Euclidean distance tool in ArcGIS was used to create maps of distance from roads and rivers. Forest-SAGE automatically calculates distance from road features; hence, no additional distance maps were inputted into the model.

Urban expansion also ranks as the third most important cause of deforestation in Asia and in the Philippines (Carandang et al. 2012). This was the basis for assigning weights to population density in the models. Deforestation is often driven by access to local markets and the population density that influences the market (Tompkins et al. 2015). Data on deforestation as a function of distance from population centers are lacking in the Philippines, while for Asia, only data from Thailand (Panayotou and Sungswan 1989) is currently available. The Gridded Population of the World version 4 from SEDAC (CIESIN 2016) was used for the population dataset. The Euclidean distance tool in ArcGIS was used to create maps of distances from population centers for GEOMOD. A population center was limited to ≥ 500 persons/km² based on the definition of urban lands in the Philippines under Presidential Decree 1517 s. 1978.

Forest fragmentation can result from the impacts of other drivers, most especially logging and mining activities. In the Philippines, forests with large perimeter-to-area ratio were readily cleared within a span of 50 years (Liu et al. 1993). This indicates a relatively high risk for deforestation in fragmented forests.
VCF datasets were used for forest fragmentation, which increases the risk for deforestation by allowing more accessibility to forest areas. The datasets were inputted as raster maps in FOREST-SAGE and GEOMOD.

The presence of PAs and reforestation sites offset deforestation in the models. However, PAs in the Philippines are studied to be only about 2.3% more effective than non-PAs in curbing forest loss (Heino et al. 2015). Moreover, reforestation projects may not provide the full benefits of a forest until trees mature 30–80 years later (Lasco et al. 2001). PA dataset was obtained from the World Database on Protected Areas (IUCN and UNEP-WCMC 2016). Data from the FM B (2016b) on the NGP sites, Industrial Forest Management Agreement grantee, and Socialized Industrial Forest Management Agreement grantees were used to extract data for reforestation sites that were translated into vector maps showing cities and municipalities where reforestation sites are found. The PA and reforestation shapefiles were merged into one input dataset. Additional information about driver images is found in Appendix III.

Model Runs
The source code of Tompkins et al. (2015) was used for FOREST-SAGE runs carried out through terminal emulator Konsol in a Linux-operated machine with Fortran libraries. GEOMOD runs were carried out using TerrSet Geospatial Monitoring and Modeling Software by Clark Labs installed in a computer running on Windows 7.

There were two general sets of simulation runs: calibration and validation. Calibration determines the optimal set of parameter values and weights for input maps (Rykiel 1996), whereas validation assesses the model’s goodness of fit with an independent dataset (Van Vliet 2009). All simulations were carried out with a “business-as-usual” scenario only, which uses historical forest cover change rates. The macro-deforestation rates used were based on calculations from the MODIS-VCF datasets for timesteps 2000–2005, 2005–2010 and 2010–2015. The output maps of both models are in raster format with pixels carrying tree cover percentage values. The national average forest cover percentage was calculated based on the mean of all the tree cover percentage values in the pixels.

Calibration runs were carried out to determine the optimal set of input parameter values that yield the best simulation maps in comparison with MODIS-VCF reference dataset. A total of 95 FOREST-SAGE and 141 GEOMOD calibration runs were carried out to find the optimal set of input parameter values that yield the best simulation maps based on comparison with the reference dataset. The agreement of simulation maps with reference datasets was determined using RMSE, MAE, and Kappa. The criteria of Singh et al. (2004) was adopted for RMSE and that of Landis and Koch (1977) for Kappa (Appendix IV).

The resulting 2015 maps from the validation runs were compared to 2015 MODIS-VCF and European Space Agency CCI-LC datasets (Defourny 2016). The simulated change in forest cover (referred to in this study as change maps) from 2010 to 2015 were also compared to the reference datasets. Model performance was also assessed in terms of accuracy of the national average tree cover percentage and common deforestation hotspots with reference maps. Two types of validation runs were carried out for 2010–2015 to gain insight on model error propagation: Validation A used MODIS-VCF as the beginning-time image and Validation B used the resulting map from the 2005–2010 simulation as the beginning-time image.

RESULTS AND DISCUSSION
Calibration
Optimal set of input parameter values in FOREST-SAGE. The optimal set of input parameters in FOREST-SAGE that yielded the lowest RMSE and MAE, and highest Kappa indicates forest fragmentation as the most important driver of forest cover change – followed by roads, then population density, and rivers with equal weights. FOREST-SAGE does not include reforestation sites and PAs in the weighted drivers but asks for constant denoting afforestation rate and how effective PAs are in curbing forest loss. Afforestation in the optimal set is 80 years, while PAs have only minimal impact in reducing forest loss. The constant value for logging and mining as a driver denotes how likely deforestation is to occur within logging and mining concession compared to surrounding areas, in which optimal set of parameters shows that there is no difference in deforestation risk between concession and non-concession areas. However, the optimal set of input parameter values show that highly fragmented forests are at risk of deforestation, denoted by the p-q beta parameter in which a p and q equal 1 means the equal probability of deforestation at different percentages of forest cover. Moreover, based on the optimal set of input parameters, forest areas within 4.5 km from roads, 0.2 km from rivers, and 70 km from population centers more marketable and are hence more at risk of deforestation. A summary of the optimal set of input parameter values in FOREST-SAGE is found in Appendix V.

Optimal set of input parameter values in GEOMOD. The optimal set of input parameter values in GEOMOD indicates that logging and mining concessions are the most important factors of land cover change, along with PAs and
reforestation sites. It is essential to note that the calibration runs were carried out with the business as usual scenario, which uses forest cover change rates. Based on historical data using MODIS-VCF, Philippine forest cover increased between 2000 and 2010, although at a much slower rate compared to 2010–2015. This could explain why the most important factors in simulating forest cover change are PAs and reforestation sites, along with logging and mining concessions, in the optimal set of input parameter values in GEOMOD. Population density, distance from urban centers, and distance from roads are equally the second most important drivers for forest cover change. The least important driver based on optimal set of input parameter values is distance to water bodies, including rivers. Forest fragmentation is incorporated into the model through the neighborhood constraint setting, in which land conversion from forested to deforested can only happen around deforested cells. A summary of the optimal set of input parameter values is found in Appendix V.

Agreement with reference maps. FOREST-SAGE calibration runs using the optimal set of input parameter values produced a map that yielded an acceptable error value based on RMSE. Based on Kappa (0.0169–0.0247), however, the agreement of the maps with the reference dataset is only by chance. The 50% tree cover threshold maps of GEOMOD performed relatively better than other threshold maps. Using the optimal set of input parameter values with 50% tree cover threshold maps as beginning time images, the spatial agreement of GEOMOD calibration output maps with reference maps was moderate to substantial based on Kappa (0.5487–0.6056). None of the maps, however, yielded acceptable RMSE values. Calibration results are summarized in Tables 1 and 2.

Model performance with low and high-resolution maps. For both models, the 5-km resolution maps yielded better results than runs using 1-km resolution maps of the same input parameter values. Heterogeneity, which renders "noise" in a dataset, is greater in higher resolution datasets (Hu et al. 2015, Doubkova et al. 2014). This was the case for higher resolution simulation maps produced in this study. Using higher resolution maps are desirable for studies that are more localized and require more details within a smaller extent. Despite having less detail than a 1-km resolution map, a 5-km resolution is sufficient for this study given the national extent covered. Since the 5-km resolution runs yielded the best results, this resolution was used for the validation runs.

Validation

FOREST-SAGE validation with MODIS-VCF. FOREST-SAGE 2015 simulations validated against the 2015 MODIS-VCF dataset (Figure 1) yielded an RMSE of 12.80%, MAE of 10.30%, and Kappa of 0.0134 (Table 3). The RMSE was less than the ideal value of half the standard deviation of MODIS reference dataset (10.63%), while the Kappa result indicates agreement by chance. The national average tree cover percentage in the 2015 FOREST-SAGE simulation map is 35.19%. This is less than the value in the 2015 MODIS dataset at 36.33%, but quantitatively correct by 97%. Spatially, however, the accuracy needs to be improved considering how the percent tree values are distributed across the non-water pixels. Figure 2 shows that the model underestimated the maximum tree cover percentage value in the reference dataset (i.e., maximum of 74% in FOREST-SAGE and 80% in MODIS-VCF) and, in some areas, overestimated the minimum value (i.e., minimum of 14% in FOREST-SAGE and 1% in MODIS-VCF). Areas where the model underestimated percent tree cover correspond to areas situated within logging and mining concessions and far from roads and population centers. However, correlating the calibration results in FOREST-SAGE with the input parameter values show that the tau parameter has a strong negative correlation (r

<table>
<thead>
<tr>
<th>Output map</th>
<th>RMSE (% tree cover)</th>
<th>MAE (% tree cover)</th>
<th>%SD of reference Image</th>
<th>RMSE less than %SD?</th>
<th>Kappa</th>
<th>Kappa interpretation (agreement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>10.23</td>
<td>7.44</td>
<td>10.61</td>
<td>Yes</td>
<td>0.0247</td>
<td>By chance</td>
</tr>
<tr>
<td>2010-A</td>
<td>10.39</td>
<td>7.77</td>
<td>10.36</td>
<td>No</td>
<td>0.0238</td>
<td>By chance</td>
</tr>
<tr>
<td>2010-B</td>
<td>11.66</td>
<td>9.34</td>
<td>10.36</td>
<td>No</td>
<td>0.0169</td>
<td>By chance</td>
</tr>
</tbody>
</table>

Table 2. Most acceptable GEOMOD calibration run results.

<table>
<thead>
<tr>
<th>Output map</th>
<th>RMSE (% tree cover)</th>
<th>MAE (% tree cover)</th>
<th>%SD of reference Image</th>
<th>RMSE less than %SD?</th>
<th>Kappa</th>
<th>Kappa interpretation (agreement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>21.33</td>
<td>9.10</td>
<td>12.01</td>
<td>No</td>
<td>0.6056</td>
<td>Substantial</td>
</tr>
<tr>
<td>2010-A</td>
<td>23.14</td>
<td>10.71</td>
<td>12.18</td>
<td>No</td>
<td>0.5487</td>
<td>Moderate</td>
</tr>
<tr>
<td>2010-B</td>
<td>23.14</td>
<td>10.71</td>
<td>12.18</td>
<td>No</td>
<td>0.5487</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
In GEOMOD, the input parameter values for population density and logging and mining concessions had a strong positive correlation ($r = 0.91$ and $0.99$, respectively) with the RMSE results, while the values for distance from water bodies and roads had a strong negative correlation ($r = -0.99$ and $-0.95$, respectively) with RMSE (Appendix VI). These results for GEOMOD indicate that the low accuracy could be attributed to input parameter values for population density and concessions.

Cross-validating 2010–2015 FOREST-SAGE change maps with MODIS-VCF reference map yielded an RMSE of 10.92%, MAE of 7.86%, and Kappa of $0.0152$ (Table 4). Zonal statistics analysis in ArcGIS was used to identify deforestation hotspots, which are areas with the highest tree cover loss between the years 2010–2015 at the city/municipality and provincial level, for both FOREST-SAGE and MODIS-VCF change maps. The common deforestation hotspot identified between the model simulation and MODIS-VCF dataset is the province of Zamboanga del Norte. This result agrees with the data from FMB, indicating that Zamboanga del Norte experienced the highest rate of deforestation between 2003 to 2010 (FMB, pers. comm., 13 Oct 2015).

The model consistently underestimated the magnitude of change relative to the MODIS-VCF change map. The underestimation of decrease in tree cover (i.e., deforestation) in the change maps may be attributed to the driver weights and the value used for $\tau_f$ parameter (the forest regrowth rate used in the simulations).
Figure 2. Difference between (a) 2015-A FOREST-SAGE and 2015 MODIS-VCF maps and (b) 2015-B FOREST-SAGE and 2015 MODIS-VCF maps.

Table 4. RMSE, MAE, and Kappa results for 2010–2015 change map validation.

<table>
<thead>
<tr>
<th>Reference map</th>
<th>Simulation map</th>
<th>RMSE (% tree cover)</th>
<th>MAE (% tree cover)</th>
<th>½SD of reference Image</th>
<th>Kappa</th>
<th>Kappa interpretation (agreement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS-VCF (continuous)</td>
<td>FOREST-SAGE (continuous)</td>
<td>A</td>
<td>10.44</td>
<td>7.68</td>
<td>-0.0091</td>
<td>No agreement</td>
</tr>
<tr>
<td></td>
<td>FOREST-SAGE (continuous)</td>
<td>B</td>
<td>10.92</td>
<td>7.86</td>
<td>-0.0152</td>
<td>No agreement</td>
</tr>
<tr>
<td>MODIS-VCF (50% threshold)</td>
<td>GEOMOD A (50% threshold)</td>
<td></td>
<td>22.03</td>
<td>9.71</td>
<td>0.0423</td>
<td>By chance</td>
</tr>
<tr>
<td></td>
<td>GEOMOD B (50% threshold)</td>
<td></td>
<td>22.73</td>
<td>10.19</td>
<td>0.0018</td>
<td>By chance</td>
</tr>
<tr>
<td>CCI-LC</td>
<td>FOREST-SAGE A (50% threshold)</td>
<td></td>
<td>9.56</td>
<td>1.82</td>
<td>-0.0079</td>
<td>No agreement</td>
</tr>
<tr>
<td></td>
<td>FOREST-SAGE B (50% threshold)</td>
<td></td>
<td>8.21</td>
<td>1.32</td>
<td>0.0292</td>
<td>By chance</td>
</tr>
<tr>
<td></td>
<td>GEOMOD A (50% threshold)</td>
<td></td>
<td>7.90</td>
<td>1.24</td>
<td>0.0021</td>
<td>By chance</td>
</tr>
<tr>
<td></td>
<td>GEOMOD B (50% threshold)</td>
<td></td>
<td>7.93</td>
<td>1.24</td>
<td>0.0069</td>
<td>By chance</td>
</tr>
</tbody>
</table>
the driver weights for population, roads, rivers, and fragmentation increases the risk associated with these drivers, which could result in decreased tree cover in the end-time map. Increasing the \( \tau_f \) could lead to decreased tree cover in the end-time maps since the time it takes to increase tree cover is lengthened. In terms of tree cover increase (i.e., reforestation) in the change maps, underestimation could be attributed to PAs, reforestation sites, and the \( \tau_f \) parameter. Increasing the impact of PAs and reforestation sites and decreasing \( \tau_f \) could result in increased tree cover in the change maps. However, considering that the model multiplicatively combines the risk factors calculated from the drivers, further tests and sensitivity analyses are needed to systematically ascertain which input parameters contribute to the underestimated change in tree cover in FOREST-SAGE simulations.

**FOREST-SAGE validation with CCI-LC.** FOREST-SAGE simulation maps were reclassified to validate these with CCI-LC reference maps (presented in Appendix VII), which contain categorical data. The same reclassification rules and thresholds for GEOMOD were used for this step. Based on RMSE, MAE, and Kappa, the map with the 50% tree cover threshold yielded the best result from the validation of the reclassified 2015 FOREST-SAGE map with CCI-LC reference map. The Kappa for this result is 0.4094, indicating moderate agreement with the CCI-LC reference map. Moreover, only the change map using 50% tree cover threshold yielded a Kappa value that is non-negative and greater than 0 at 0.0292 (agreement with the change map of CCI-LC by chance). The national average tree cover percentage computed from CCI-LC map was 35.74%. This value is closer to the average percentage computed from the continuous 2015 FOREST-SAGE simulation map at 35.19% (98% correct). However, if the 50% tree cover threshold FOREST-SAGE map is used, the average tree cover percentage is only 16.16% (45% correct).

The 50% tree cover threshold FOREST-SAGE change map (presented in Appendix VII) was used to locate specific areas at risk for deforestation (areas with the highest loss in percent tree cover) using zonal statistics analysis for comparison with CCI change map. The common hotspot province between the FOREST-SAGE 50% threshold change map and the CCI-LC change map is Basilan, an island province in Mindanao.

**GEOMOD validation with MODIS-VCF using 50% tree cover threshold maps.** The 2015 GEOMOD 50% tree cover threshold end-time maps (Figure 3) have a moderate agreement with the 2015 MODIS-VCF 50% tree cover threshold map based on Kappa (0.5996). The corresponding GEOMOD change maps (presented in Appendix VII), however, only agree by chance with the MODIS-VCF change map for the same years (Table 3). The national average tree cover percentage calculated from the GEOMOD map at 39.18% is 90% correct with MODIS-VCF and CCI-LC datasets.

The 2010–2015 GEOMOD change maps of all thresholds show no areas of tree cover loss; hence, no municipalities/cities and provinces were identified as deforestation hotspots for these years. This could be attributed to the

![Figure 3. GEOMOD 50% tree cover threshold end-time validation maps: (a) 2015 GEOMOD 50% threshold map from the validation run A, (b) 2015 GEOMOD 50% threshold map from the validation run B, and (c) 2015 MODIS 50% threshold map.](image)
change rate used and how GEOMOD was designed to simulate a single transition from Category 1 to 2, in which there should be less Category 1 pixels in the end-time map than the beginning-time map. In terms of the change rate used, the Philippines was reported to have an increase in tree cover between 2010 and 2015. For GEOMOD simulations, this meant that there are less non-tree pixels in the end-time (2015) than the beginning-time (2010). Hence, with the single transition simulation, only reforestation was observed in GEOMOD change maps.

**GEOMOD 50% tree cover threshold map validation with CCI-LC.** The spatial agreement of 2015 GEOMOD 50% tree cover threshold maps with 2015 CCI-LC dataset is moderate based on Kappa (0.5716), while the agreement of 2010–2015 GEOMOD change maps with the CCI-LC change map (Kappa = 0.0069) is only by chance (Table 4). The GEOMOD change map has a poorer agreement with the CCI-LC dataset due to the non-simulation of deforestation areas in GEOMOD maps when deforestation was determined from the CCI-LC datasets. Testing GEOMOD with different scenarios could potentially improve model results.

**Error Propagation**
In Validation B runs, the resulting simulation map from the previous time step, which already bears certain degrees of errors based on the calibration results, was used as the initial time image. Hence, one may expect for Validation B runs to produce more errors compared to Validation A runs, which uses MODIS-VCF maps as beginning time image. This indeed is the case, except for validation results of FOREST-SAGE change maps against CCI-LC map, and GEOMOD end-time maps against both MODIS-VCF and CCI-LC reference maps. More runs are needed to provide conclusive results on model error propagation to further gauge the performance of the models when land cover datasets are not yet unavailable for beginning time images in subsequent time steps.

**CONCLUSION AND RECOMMENDATIONS**
Two models, FOREST-SAGE and GEOMOD, were used and assessed in simulating national-scale deforestation in the Philippines. The models were calibrated to find the optimal set of input parameter values based on available literature. The calibrated models were then used to simulate national tree cover percentage in 2015 and tree cover change between 2010 and 2015. The resulting simulated maps were validated against MODIS-VCF and CCI-LC datasets.

Validation results suggest both models have the capacity to simulate forest cover quantitatively at the national level. The average tree cover percentage simulated by the models were very close to the average tree cover percentage estimates from the reference datasets: at least 97% correct for FOREST-SAGE and 90% for GEOMOD. This demonstrates that the models are useful in predicting national average tree cover percentage in the Philippines. Given such, the models could be useful in planning national-level forest management, especially when figures are presented quantitatively at the country level in forest assessment reports. However, input parameter settings need to be improved to accurately simulate tree cover change and provide useful insights into the spatial distribution of forest cover.

In terms of scale and complexity, FOREST-SAGE is more applicable for research requiring higher resolution and more detailed information on the extent of forest cover, such as might be expected of provincial scale planning. FOREST-SAGE is more applicable for studies that have the objective of quantitatively tracking the change in forest cover since the model can more precisely quantify tree cover percentage per pixel. GEOMOD is more ideal for research covering a large area but requiring only determination of forest/non-forest pixels, such as might be needed at the national level. GEOMOD is more applicable for studies that need more categorical data on land cover, and studies that aim to know the location of different categories of land cover and the extent of the land cover change.

More localized literature is needed to optimally run FOREST-SAGE, which is currently lacking. More studies, such as sensitivity experiments, need to be carried out on a more local scale to ascertain how the drivers relate to forest cover change and to better guide model calibration and input parameter setting. Local-scale simulations may also provide insights on model accuracy since ground-truthing is more feasible at this scale. More local or regional studies are also necessary since driver weights may vary within the Philippines given the contextual differences of administrative divisions or island groups (e.g., conflict in Mindanao).

A challenge in the calibration process is the lack of quantitative literature on deforestation drivers in the Philippine setting, which is integral in setting input parameters values. To guide model calibration in future studies, it is recommended that information on the relation of deforestation drivers with forest cover be obtained through studies in the Philippines, as well as through in-depth key informant interviews at the local scale. Nonetheless, common provinces were identified as deforestation hotspots between FOREST-SAGE results and the reference datasets, which demonstrates
the potential of FOREST-SAGE to simulate forest cover change at the provincial level.

There are many factors that could contribute to the poor agreement of model results with the reference datasets. It should be noted that the drivers used in this study were limited to logging and mining concessions, population density, transport networks, PAs, and reforestation programs. Geophysical factors such as slope, soil types, and climate were not included in model simulations. Moreover, tree cover percentage estimates did not involve tree height and slope, which are part of the official definition of forestlands in the Philippines. Other socio-economic factors such as GDP, logging exports, and agricultural production were also not considered. Incorporating these other factors is currently not possible with FOREST-SAGE but is possible with GEOMOD. This study was limited to drivers that both models can incorporate, but the use of other factors is recommended for future GEOMOD runs.

Availability of datasets and their formats also served as one of the limitations of the study. The logging concessions, mining concession, and reforestation site maps used in this study were based on tabulated data on the location of these features that were translated into maps showing cities and municipalities where these concessionaires and reforestation sites are located. This could have led to overestimation or underestimation of tree cover in model outputs. It is recommended, hence, to run the models with driver maps showing the exact location of these features.

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NOTES ON APPENDICES

The complete appendices section of the study is accessible at http://bit.ly/jmckmal_appendices.

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