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Deforestation in the Ayeyarwady Delta and the conservation implications of an internationally-engaged Myanmar

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ABSTRACT

Myanmar is a country of huge biodiversity importance that is undergoing major political change, bringing with it new international engagement. This includes access to international markets, which will likely spur investment in export-oriented agriculture, leading to increased pressures on already threatened ecosystems. This scenario is illustrated in the Ayeyarwady Delta, the country's agricultural heartland sustaining high deforestation rates. Using the Delta as a model system, we use an integrated approach to inquire about whether and how imminent agricultural reforms associated with an internationally-engaged Myanmar could introduce new actors and incentives to invest in agricultural expansion that could affect deforestation rates. We use a novel remote sensing analysis to quantify deforestation rates for the Delta from 1978 to 2011, develop business-as-usual deforestation scenarios, and contextualize those results with an analysis of contemporary policy changes within Myanmar that are expected to alter the principal drivers of land-cover change. We show that mangrove systems of Myanmar are under greater threat than previously recognized, and that agriculture has been the principle driver of deforestation on the Delta. The centrality of agriculture to the Myanmar economy indicates that emerging policies are likely to tip the scales towards agricultural expansion, agro-industrial investment and potentially greater rates of deforestation due to the introduction of well-funded investors, insufficient land tenure agreements, and low governance effectiveness. The broad national challenge is to initiate environmental governance reforms (including safeguards) in the face of significant pressures for land grabbing and opportunistic resource extraction.

1. Introduction

Myanmar is a heavily forested country (~48% forest cover; FAO, 2010) that retains among the largest remaining tracts of forest in Southeast Asia and some of the world's 'hottest hotspots' for species diversity and endemism (Myers et al., 2000). Despite retaining expansive forests, there is concern over Myanmar's long-term forest conservation: very little of its area is protected (6.3% of the total land area; World Bank, 2013a), and certain parts of the country have experienced high rates of deforestation (Leimgruber et al., 2005). Of particular concern is the Ayeyarwady Delta, an expansive alluvial floodplain originally home to the largest tract of mangroves in Myanmar, but which has sustained the highest deforestation rate in the country (Leimgruber et al., 2005).

Myanmar's mangrove forests support critical natural resources and rural livelihoods (e.g. Barbier et al., 2008). Mangroves support in- and offshore fishing industries that are critical sources of protein and rural income for many communities (e.g. Loneragan et al., 2005) and have potential to support export-oriented coastal aquaculture and fisheries (Fabrikant, 2013). The Ayeyarwady Delta system provides coastal protection and water regulation services (e.g. Koch et al., 2009) to a region with poor drainage/water infrastructure and high vulnerability to seasonal flooding (Than, 2001) and extreme weather events. Notably, the Delta is also one of Myanmar's key biodiversity areas (Tordoff et al., 2005; World Wide Fund for Nature, 2008), hosting some of the most floristically-diverse mangroves in the world (Spalding et al., 2010) and more than 30 species of 'endangered' fauna (IUCN, 2011) including the Ayeryawady dolphin (*Orcaella brevirostris*) (IUCN, 2011), estuarine crocodile (*Crocodylus porosus*), which

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numbers only ~100 individuals in the lower Ayeyarwady Delta (Thorbjarnarson et al., 2008), mangrove terrapin (*Batagur baska*), sarus crane (*Grus antigone*) (Tordoff et al., 2005), and numerous migratory bird species, including the critically endangered spoon-billed sandpiper (*Eurynorhynchus pygmeus*) (World Wide Fund for Nature, 2008). Moreover, the Delta's mangroves represent a substantial store of belowground carbon of interest to global climate change mitigation (Donato et al., 2011).

Mangrove forests are recognized as one of the most threatened ecosystems globally (Duke et al., 2007), and the Ayeyarwady Delta deserves attention as one of the most threatened mangrove deltas in the world. The Delta is heavily populated (7.7 million people, 13.7% of the nation's population; Central Statistics Organization, 2007) and a center of agricultural processing and production (Than, 2001; Xiao et al., 2006), responsible for ~35% of the country's rice production (FAO, 2013). As a result, the Delta has been heavily impacted and most of its biodiversity is severely threatened (World Wide Fund for Nature, 2008); mangrove deforestation is recognized as a critical environmental issue for the country (Phyu, 2012). Previous analyses have suggested agricultural expansion—largely for subsistence, limited domestic markets or redistribution during the decades of military rule—and fuelwood extraction as the principle drivers of mangrove loss (Oo, 2002; Leimgruber et al., 2005; Giri et al., 2008).

Recent and unprecedented political reforms in Myanmar since 2010 portend a potentially significant shift in the social, political and economic context of the country. These reforms, following 50 years of economic and political isolation, are catalyzing Myanmar's return to the international community, and have prompted high-level foreign visits along with efforts to re-establish political ties (e.g. Baker, 2012), increase international aid (e.g., AusAID, 2013), ease sanctions (e.g. Barta, 2012) and increase international trade and investment (e.g, Japan Times, 2012). These initiatives have the potential to deliver profound social, humanitarian and economic changes for Myanmar (e.g., Asian Development Bank, 2011), which has some of the lowest development indicators in the world (United Nations Development Program, 2011; World Bank, 2012), and one of the lowest Purchasing Power Parity GDPs (US$1300, ranking 200/225; Central Intelligence Agency, 2010). Yet these changes may also bring environmental conservation challenges across Myanmar, as both small and industrial-scale producers within and outside Myanmar respond to new policies and opportunities (Schmidt, 2012; Webb et al., 2012).

A large literature demonstrates an agricultural expansion-deforestation link globally and within Myanmar (e.g., Geist and Lambin, 2002; Lambin et al., 2003; Rudel et al., 2009; Songer et al., 2009), and Myanmar's agricultural sector contributes one of the highest percentages of national GDP in the world (World Bank, 2013a). Therefore, it is justifiable to inquire about whether and how imminent agricultural reforms associated with an internationally-engaged Myanmar could introduce new actors and incentives to invest in agricultural expansion that could affect the remaining natural systems. And further, whether current policy instruments are sufficient to both promote agricultural innovation while protecting local landholders and remaining natural systems. Indeed, concerns over the potential environmental and humanitarian impacts in Myanmar resulting from greater international engagement are already mounting (Burma Environmental Working Group, 2011; Webb et al., 2012; Chong, 2012; Schmidt, 2012; Wang et al., 2013).

In this study, we explore the historical trend of deforestation in the Ayeyarwady Delta, as a model system to Myanmar, and subsequently consider the potential ramifications of recent policy developments designed to increase access to international markets, on Myanmar's broader environment. We first use a novel remote sensing analysis to document historical changes in land-cover in the Ayeyarwady Delta, demonstrating that almost all deforestation in the Delta has been for rice agriculture and that the Delta mangroves have been lost at a substantially greater rate than previously thought. We then contextualize our results with an analysis of recent policy changes within Myanmar. Our analysis suggests that pressure on natural forests in Myanmar is expected to increase as a result of policy developments favoring export-oriented agriculture, improvements in technology and infrastructure, and the introduction of actors (investors) who may benefit from land expropriation under insufficient land laws. We use this discussion to frame the environmental policy and governance challenges going forward in a rapidly changing context. This integrated approach (Mattison and Norris, 2005) is instrumental to providing a framework to predict the salient, large-scale land use change drivers that are expected on the Delta, and more broadly, Myanmar.

2. Methods

2.1. Data collection

We quantified mangrove cover on the Ayeyarwady Delta at four times over a 33-year period: 1978, 1989, 2000 and 2011. Spectral data were acquired from Landsat multispectral scanner (MSS), thematic mapper (TM) and enhanced thematic mapper (ETM+) imagery for 1978, 1989, 2000, 2008, 2009 and 2011 (Table 1, available from the USGS Earth Resources Observation and Science Center, http://eros.usgs.gov). A minimum of two images were used for each time period to fill data gaps in imagery from 2008, 2009 and 2011, and to increase model accuracy (Table 1). Images from 2008 and 2009 were used to test for an impact of Cyclone Nargis on mangrove cover. Elevation data were acquired from the ASTER GDEM Version 2 (available from the Earth Remote Sensing Data Analysis Center, http://www.ersdac.or.jp), and were averaged using a 9×9 pixel neighborhood filter to correct any gross errors in elevation.

Four regions of the Delta, in proximity of the settlements of Saluzeik, Yegyawgyi, Mayan and Kyaiklat in the Ayeyarwady region, were selected for extensive ground-data collection (Fig. 1). The zones ranged in size from 270 to 460 km^2. A total of 240 points were randomly selected within the four zones with the GRASS

Table 1
Summary of images and model traits.

Model year	# Classes	Factors	Imagery dates	Training dataset (or "Model")
1978	3	MSS imagery	1974 Jan 6 1978 Nov 5	H
1989	3	TM imagery	1989 Jan 16 1989 Feb 1	H
2000	3	TM imagery	2000 Jan 31 2000 Apr 4	H
2008	3	ETM+ imagery	2007 Dec 4 2008 Jan 21 2008 Feb 6	H
2009	3	ETM+ imagery	2008 Dec 6 2009 Jan 7 2009 Mar 28	H
2011	5	ETM+ imagery TM imagery MSS imagery Distance to 0-m contour Distance to 5-m contour Distance to large water body	2010 Jan 10 2011 Apr 3 2000 Jan 31 2000 Apr 4 1989 Jan 16 1989 Feb 1 1974 Jan 6 1978 Nov 5	C

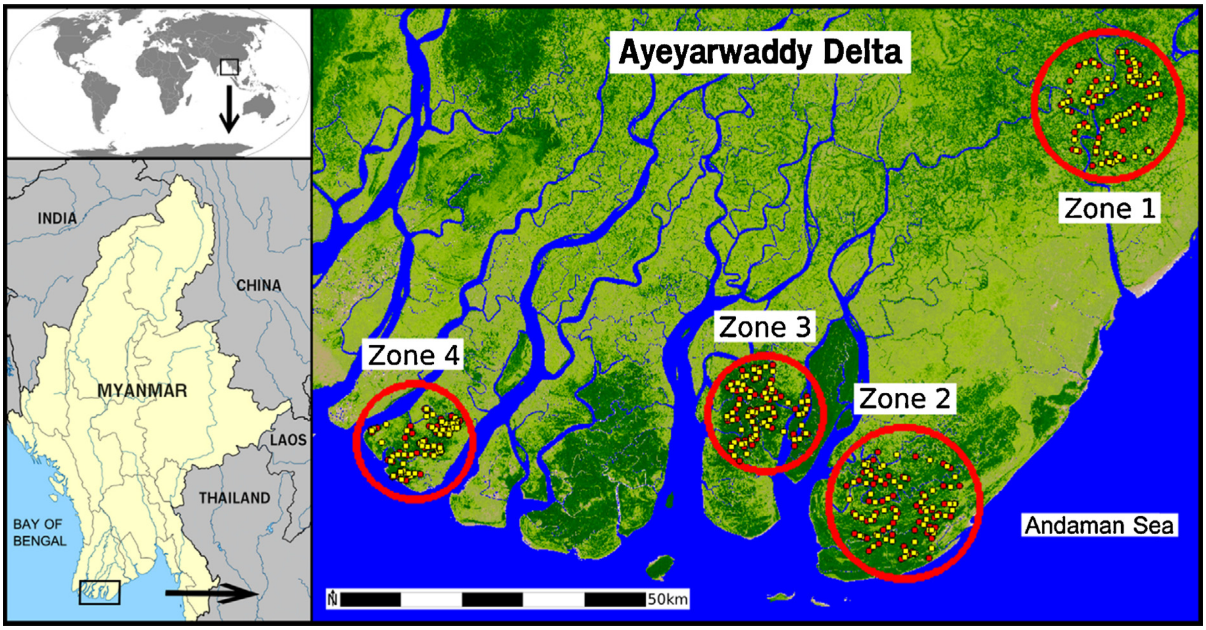

Fig. 1. Map of study area showing the Ayeyarwady delta of Myanmar and the ground data collection points. Red points indicate random points, while yellow points indicate half-way points where additional ground data were collected. 239 points were sampled in total with approximately 60 red and 60 yellow points in each zone. The areas of each zone are: Zone 1 = 437 km^2, Zone 2 = 460 km^2, Zone 3 = 270 km^2, Zone 4 = 270 km^2.

(2011) Geographic Information System. During a field campaign conducted between 16 March–19 April 2011, four teams of researchers (including author MMT) travelled to the assigned points to determine the dominant land-cover type at a resolution of 30 m × 30 m. Positions were recorded on a handheld geographical positioning system (GPS) with an accuracy of <15 m; this positional error was less than the size of the Landsat pixel of 30 m × 30 m (National Aeronautics and Space Administration, 2011). Four photographs, one in each cardinal direction, were taken for data screening and standardization (Fig. 2). A total of 239 additional points were collected at random while travelling to an assigned GPS location, increasing the total number of ground reference points to 479. Land cover was classified as mangrove, degraded mangrove, agriculture, water or other (Fig. 2). Data were screened and classifications standardized among the four teams.

2.2. Model construction

A 5-class contemporary model (Model C) was produced for 2011 and a 3-class historical model (Model H) was produced for 1978, 1989 and 2000. Model construction began with developing the necessary training datasets. To produce both contemporary as well as historical mangrove models, two different training datasets were required: a historically valid training data set for 3-class analysis (Model H) and a contemporary training data set for 5-class analysis (Model C). This distinction was necessary because 5-class data could not be accurately inferred for the historical time periods. The training datasets were compiled from the ground-collected and remotely-collected data (described in Section 3.1).

Table 2
Descriptions of training datasets used for model derivations.

Historical Training Dataset (H)	Contemporary Training Dataset (C)
168 Historical mangrove points[a]	479 Ground collected points
168 Historical non-mangrove points	168 Water points
168 Historical water points	

[a] Subset of Model C ground collected points; the non-mangrove and water points were extracted from satellite images.

The training dataset for Model C consisted of 647 points: 479 ground-collected points collected in 2011 (described previously), and 168 remotely-collected water points (Table 2). The 168 remotely-collected water points were selected randomly from large water bodies (>100 ha) determined from a normalized difference vegetation index (NDVI) map derived from the Landsat satellite imagery. Additional water points were collected in order to better represent this class in the final training dataset.

Training dataset H consisted of 504 points distributed equally (168 each) among the three classes: mangrove, non-mangrove and water. The non-mangrove and water points were remotely collected and the mangrove data points were ground-collected during the 2011 field excursion (Table 2). This dataset was deemed historically valid based on two key biological and environmental assumptions: (1) given the 33-year time period of this study, water body and elevation variables do not change significantly and (2) if a dense mangrove without evidence of human degradation exists today it likely existed over the past 33 years. As we go further back in time the accuracy of these assumptions will decrease, so we would expect to see a similar decline in model prediction accuracy. The water and non-mangrove training points were randomly selected in the GIS from water bodies and non-tidal land areas that were unlikely to support mangroves (Table 2, Fig. A1). Water points were selected randomly from large water bodies (>100 ha) determined from a normalized difference vegetation index (NDVI) map derived from the Landsat satellite imagery. Non-mangrove terrestrial points were selected randomly from land areas situated more than 10-km inland from the 5-m elevation contour determined from the ASTER GDEM Version 2 digital elevation model; thus ensuring that points were chosen in areas where it would be physiologically impossible for mangroves to be present, to minimize class confusion (Table 2, Fig. A1). The mangrove training points corresponded to the ground-collected points classified as mangrove. Ground-collected points classified as degraded mangrove were not included as it was uncertain whether these areas would have been mangrove over the entire study period.

An algorithmic approach to model development was chosen over traditional data modeling approaches due to their superior predictive ability (Breiman, 2001). The approach used three modeling methods—multilayer perception, rotation forest and sequential minimal optimization—which were combined using a majority-voting algorithm. The rotation forest method split the training set into N random subsets and then performed a principal component analysis on each subset (Rodriguez et al., 2006). The principal components were then classified using decision trees. The multilayer perceptron method is a type of neural network that uses back-propagation to model classes (Ware, 2000). The sequential minimal optimization method is a time-optimized way to train support vector classifiers (Platt, 1998).

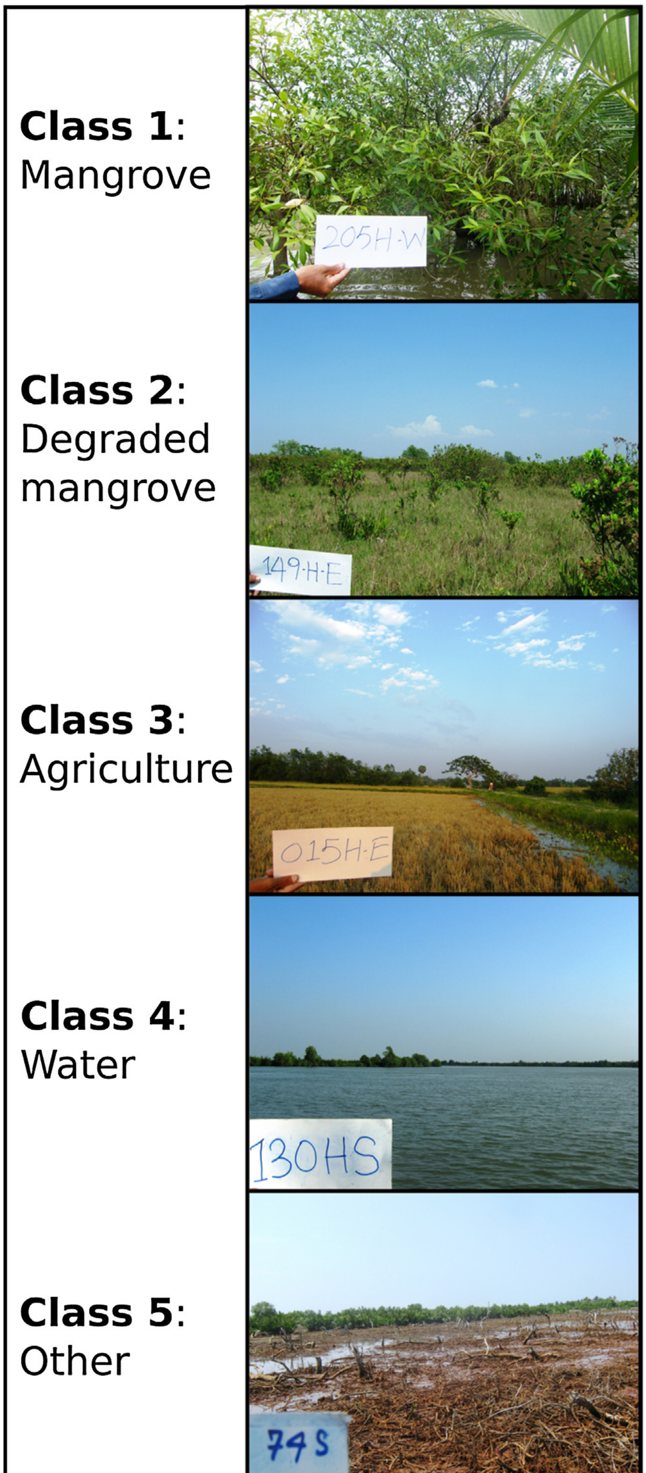

Fig. 2. Examples of ground data collection photos of the five land cover classes in this study.

Modeling was performed using Weka, a machine learning software (Hall et al., 2009). Modeling was conducted using a 10-fold cross-validation, which produced robust accuracy assessments involving confusion matrices, user accuracies, producer accuracies, overall classification accuracies and Cohen Kappa coefficients (see Congalton, 1991). A unique model was trained for each time period using the input variables and training datasets summarized in Tables 1 and 2.

Congruence between estimates derived using the two models (validation) was accomplished by comparing the estimated mangrove area (derived by applying the 3-class Model H to the 2011 image) with the area of dense mangrove estimated according to Model C (also on the 2011 image). Because Model C was used to report land cover for 2011 (owing to a higher number of classes that were ground-referenced), the Model H estimation for 2011 was only used as a validation procedure and not included in the land cover time-series.

2.3. Accuracy assessment

Accuracies were estimated using a 10-fold cross validation method in which the training datasets were split randomly into 10 equal subsets; 90% of the data were used to build a model, which was then tested on the remaining 10%. Ten models were built and tested using this method, and the classification accuracies were averaged to develop a robust estimate of the generalization accuracy of each model (Kohavi, 1995). Classification accuracy for the 3-class models for each year ranged between 89.9% and 95.6% (Table A1). The non-mangrove class was most frequently misclassified with an average producer accuracy over the four time periods of 0.894, compared to 0.909 and 0.972 for the mangrove and water classes, respectively. This is because the 'non-mangrove' training points included multiple land uses, such as bare ground, upland forest, urban, and agriculture. Thus, the spectral variability was greatest in the non-mangrove class.

The 5-class model for 2011 had lower accuracy—as is expected of higher order models—with an overall accuracy of 81.6% and a kappa coefficient of 0.749 (Table A2). The mangrove, agriculture and water classes had the highest accuracies, while the degraded mangrove and other classes had significantly lower accuracies. The degraded mangrove class likely had low accuracy, as its spectral reflectance would be intermediate of mangrove and agriculture. The "other" class likely had low accuracy because it was a 'catch-all' class for a broad range of land-cover types that did not fit into the other classes, and thus, did not have a constant spectral

Table 3
Mangrove area statistics for the Ayeyarwady Delta, Myanmar. The range was calculated using producer and user accuracies. Model H for years 1978–2000 was trained using 2011 dense mangroves from ground collected points. Mangrove estimates for the year 2011 are dense mangroves only. The 2011 Mangrove areal statistics using models trained on datasets H and C overlap, validating the use of models based on dataset H for historical time periods for which more nuanced field data were not available. The model based on Training Dataset H gives a slightly higher predicted range of mangrove areas likely due the fact that it is less able to distinguish dense and degraded mangrove, as degraded mangrove training points were not available in the past.

Model year	Area (km^2)	Range
1978	2623	2329–3030
1989	2138	1990–2228
2000	1198	1114–1256
2008 (pre-Nargis)	933	805–1060
2009 (post-Nargis)	918	820–973
2011 (Model H)	1096	937–1226
2011 (Model C)	938	705–1061

Table 4
Comparison of classification accuracy of the current study with other recent mangrove remote sensing studies.

Study	Location	Imagery type	# of classes	Classification accuracy %	Kappa coefficient (3dp)
This study	Myanmar	Landsat + ASTER GDEM, Model H	3	89.9–95.6	0.848–0.935
This study	Myanmar	Landsat + ASTER GDEM, Model C	5	81.6	0.749
Fatoyinbo et al. (2008)	Mozambique	Landsat + satellite altimetry	8	93.9	0.870
Fatoyinbo et al. (2008)	Mozambique	Landsat	8	71.0	N/R
Ruiz-Luna et al. (2010)	NW Mexico	Landsat	2	>85.0	>0.810
Alatorre et al. (2011)	NW Mexico	Landsat	7	84.0	N/R
Rakotomavo and Fromard (2010)	Madagascar	Landsat	11	84.4	N/R

N/R, not reported.

identity. Also, there were relatively few "other" points in the training dataset used to train the model, decreasing the ability of the model to accurately predict that class.

A high congruence was observed between Model H and Model C for the 2011 estimates (Table 3). Whereas the mangrove area predicted by the 5-class and 3-class 2011 models differed by 185 km^2, the range of possible mangrove areas overlapped substantially, providing validation for the models using Training Dataset H (Table 3). Overall, the level of accuracy obtained through this novel classification method was comparable to, or greater than, other studies utilizing Landsat imagery for mangrove classification (Table 4).

2.4. Deforestation scenarios

We developed deforestation projections that were based on the quantified deforestation rates: i.e. business-as-usual (BAU) conditions (Sloan and Pelletier, 2012). As our models produced value ranges for each year of analysis, we produced four deforestation scenarios: (1) a best-case scenario (lowest possible 33-year deforestation rate), where the deforestation rate was calculated based on the lowest value of the 1979 mangrove cover range and the highest value of the 2011 mangrove cover range; (2) a mean deforestation rate, calculated as the regression line through estimates of 1978, 1989, 2000 and 2011; (3) a worst-case based on the highest 1979 mangrove cover range and lowest 2011 mangrove cover range; and (4) the most recent deforestation trend of 2000–2011. The calculations excluded the Meinmahla Kyun Wildlife Sanctuary and remote offshore islands (~137 km^2) because our analysis indicated that the protection of those areas has been effective in preventing deforestation over the 33-year period, which was assumed to continue going forward. Thus, the scenarios relate only to unprotected mangroves—i.e. 95% of the 1978 mangrove cover. The BAU scenarios had three assumptions. First, it was assumed that the remaining mangroves were situated on land suitable for rice cultivation. Second, future mangrove conversion to agriculture would not be prohibited by costs of site treatment related to the prevention of soil salinization. Lastly, underlying drivers of deforestation remained constant.

2.5. Contextualizing the case study

We undertook a literature review to contextualize this case study. We focused a review on the deforestation literature, specifically in terms of linking market access and agricultural production with forest transitions. Given the assumption that the political transition in Myanmar is corresponding with the development of policies to facilitate access to international agricultural markets, we evaluated how deforestation pressures may be shaped by greater investment in export-oriented agriculture. We also inquired as to who might be the agents of change, given that the (gradual) integration of Myanmar into the international enterprise networks will introduce new actors into the agricultural sector.

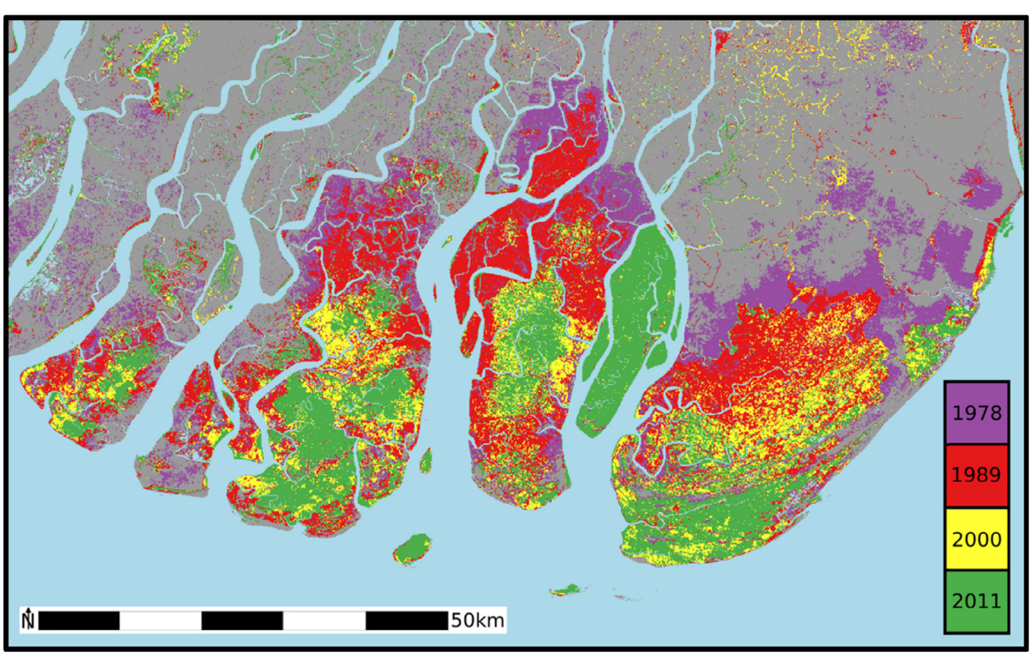

Fig. 3. Map showing mangrove land cover in the Ayeyarwady Delta, Myanmar, in 1978, 1989, 2000 and 2011. The large island that has remained completely forested is the Meinmahla Kyun Wildlife Sanctuary.

Table 5
Mangrove transitions in the Ayeyarwady Delta, Myanmar. Land cover classes in 2011 that were mangrove in 1978.

Land class 2011	Area (km^2)	Area (%)
Degraded mangrove	277.8	13.1
Agriculture	1727.6	81.2
Water	3.4	0.2
Other	118.9	5.6
Total	2127.7	100

3. Results and discussion

3.1. Rapid, agriculture-driven deforestation in the Delta

Mangrove area cover has changed dramatically in the Ayeyarwady Delta since 1978 (Fig. 3). In 1978, mangroves covered 2623 km^2 (range of estimate 2329–3030 km^2, Table 1). Over the 33-year study period, mangrove cover declined by 64.2%, at an average rate of 51 km^2 (3.1%) per year, to an area of 938 km^2 (range 705–1061 km^2) in 2011. Deforestation rate varied substantially over the three periods, from 44.1 km^2 per yr in 1978–1989, to 85.5 km^2 per year in 1989–2000, to 23.6 km^2 per year from 2000 to 2011 (Table 3). During the 1989–2000 period, 44% of remaining mangrove area was lost. The only area of the mangrove not sustaining a precipitous decline was the 137 km^2 Meinmahla Kyun Wildlife Sanctuary and small, remote offshore islands (Fig. 3). It is notable that we report higher levels of confidence in estimates for both historical and present day land-cover estimates, than with previous studies that used traditional land-cover analyses (Leimgruber et al., 2005; Giri et al., 2008). The results also returned high classification accuracies (*cf.* Leimgruber et al., 2005), and which included error estimates (range per land cover type). Notably, our estimate of mangrove loss between 1989 and 2000 (44% of remaining forest cover) is more than double that of the only other previous study (20% loss; Leimgruber et al., 2005).

Cyclone Nargis did not result in immediate reduction of mangrove areal extent (Table 3). Extensive flooding occurred during Cyclone Nargis, and on-the-ground observations and permanent plots noted extensive damage to some mangrove species, particularly in low-lying sites (Aung et al., 2011) or areas that had already been severely degraded owing to fuelwood harvest and conversion to rice paddies (Fritz et al., 2009). In addition, some mangrove species were able to recover rapidly after the disturbance event (Aung et al., 2011, 2013).

The vast majority (81%) of dense mangrove loss was caused by conversion to rain-fed rice paddy, some of which has likely been abandoned and subsequently regenerated to degraded mangrove (13%) (Table 5, Fig. 4). Mangrove patches >100 km^2, comprising nearly 60% of the total mangrove area in 1978, accounted for only 25% of total area by 2011 (Fig. 5). Moreover, by 2011 the mangrove landscape was highly fragmented and consisted of no patches >300 km^2. Most of these remaining fragmented mangroves are expected to support significantly reduced marine and terrestrial resources (Barbier, 2003; Polidoro et al., 2010) as well as reduced coastal defense functions (Barbier et al., 2011). Indeed, deforestation in the Delta has substantially impacted biodiversity (World Wide Fund for Nature, 2008; IUCN, 2011) and potentially the well-being of rural communities. For example, anecdotal evidence (described by Feagin et al., 2010) suggests that the loss and degradation of the Ayeyarwady mangroves may have increased population risk to the impacts of Cyclone Nargis.

The mean 33-year deforestation rate BAU scenario suggested that Ayeyarwady mangroves (outside Meinmahla Kyun) could be completely deforested by about 2026 (Fig. 6). Using worst- and best-case BAU scenarios, the forecast to depletion ranged from 2019 to 2035, respectively, and the 2000–2011 deforestation rates projected mangrove depletion by 2044. Business-as-usual deforestation scenarios suggest that most, if not all of the unprotected Ayeyarwady mangroves will be lost in the next few decades at a rate faster than other mangrove deforestation hotspots in the region, such as the Mekong Delta from 1965–1995 (prior to major investment in shrimp aquaculture, Thu and Populus, 2007). However, the BAU scenarios should be viewed with caution because deforestation may decelerate as the system vanishes; yet it is noteworthy that our analysis shows a fairly rapid deforestation rate from 2000 to 2011.

Rigorous, quantitative historical analysis of deforestation drivers from 1978 to 2011 was not possible given the lack of robust, reliable socioeconomic data for Ayeyarwady (see Woods and Canby, 2011; Bissinger, 2012), limiting our ability to quantitatively evaluate specific drivers (*cf.* Geist and Lambin, 2002) or to make spatially-explicit predictive deforestation scenarios (*cf.* Sloan and Pelletier, 2012). Despite this caveat, our analysis clearly indicates that rice agriculture has been the dominant proximal driver of deforestation in the Delta, likely alongside firewood extraction (see Oo, 2002; Fritz et al., 2009). This assessment concurs with all previous assessments of land transformations in the Delta, which highlight the role of rice agriculture and associated agrarian policies in shaping historical land-use transformations the Delta (e.g. Than, 2001; Kurosaki et al.,

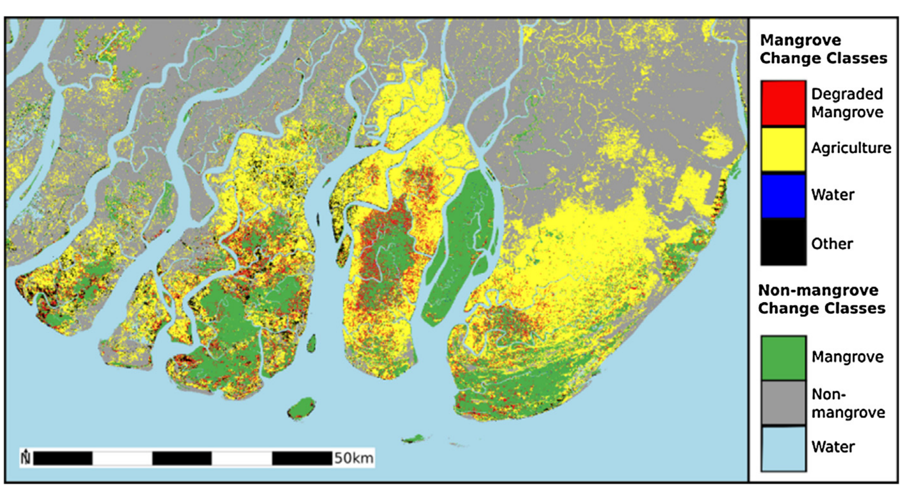

Fig. 4. Mangrove land cover change map showing 2011 mangrove land cover (green) and transitions into other land uses by 2011 ("Mangrove Change Classes"). Grey and light blue areas were never mangrove over the time periods modeled in this study.

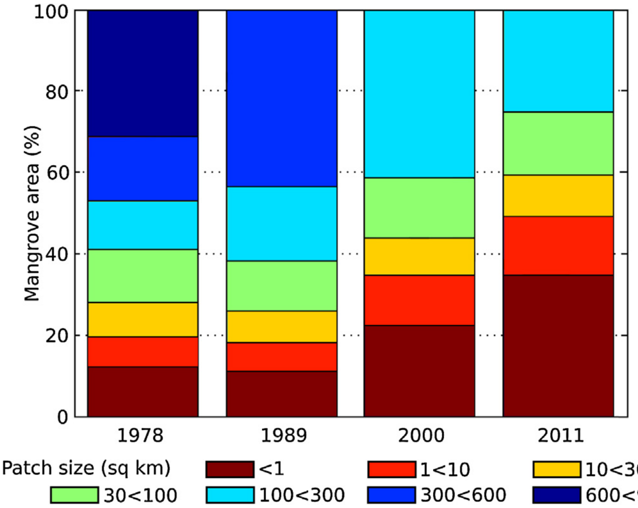

Fig. 5. Bar chart showing the relative area comprising mangrove patches of different areas, across a 33-year study period in the Ayeyarwady Delta, Myanmar.

2004; Leimgruber et al., 2005; Okamoto, 2005; Giri et al., 2008; Matsuda, 2009; Okamoto, 2009). The literature suggests that rice agricultural expansion in the Delta region—and in other parts of Myanmar—was largely for smallholder paddy, facilitated by the State through assistance with land preparation, irrigation and agricultural extension services (Matsuda, 2009). State-facilitated agricultural expansion has been seen in other tropical countries, where deforestation prior to the 1990s was driven largely by state-supported activities (Rudel, 2007; Rudel et al., 2009). In addition, farmers in the Delta and across Myanmar experience severe land tenure insecurity, which has important implications for agricultural development in an environment that may facilitate large-scale agro-industrial investment (see below).

3.2. Agriculture expansion and land use change: A look forward for Myanmar

Given that the Delta is one of Myanmar's key rice growing regions (Xiao et al., 2006), future agricultural investment and expansion in response to new access to international markets, are likely to affect the Delta. At the national scale, agriculture is considered central to Myanmar's economic reform, has great potential for growth (Dapice et al., 2010) and is a development priority (see President U Thein Sein's inaugural address at http://www.burmalibrary.org/docs11/NLM2011-03-31.pdf). The government of Myanmar recognizes the need to reshape agricultural production towards export-oriented markets. The Ministry of Agriculture is promoting expansion of rubber, jute, cotton, sugarcane and palm oil industries (Ministry of Agriculture and Irrigation, 2010), which are attracting foreign investment (Burma Environmental Working Group, 2011; Montlake, 2013). The Delta is experiencing expansion of higher-value and export-oriented agricultural products such as oilseed crops, pulses and vegetables (see Aung, 2011; Zaw et al., 2011). Moreover, there is emerging interest in developing Myanmar's coastal aquaculture industry, particularly cultured shrimp for export (Fabrikant, 2013). Although our results show that less than 2% of Delta mangroves were supplanted by active aquaculture since 1978 (see also Giri et al., 2008), pond aquaculture represents major future potential for both small-scale and commercial income generation, as has occurred in neighboring Thailand (Flaherty et al., 1999; Goss et al., 2000) and Vietnam (Thu and Populus, 2007). These developments strongly suggest that as Myanmar increases its access to international markets, it will emphasize export-oriented crops, potentially leading to "crop booms" (Hall, 2011), which have important implications for an understanding of the actors driving land use change and potentially deforestation.

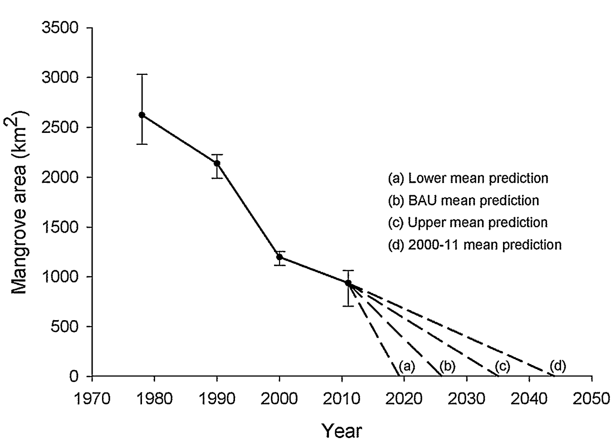

Fig. 6. Area cover of mangroves in the Ayeyarwady Delta, Myanmar from 1978 to 2011 (with error bars), and four deforestation projections. Scenarios a–c are based on the 33-year deforestation rate, with (a) being the best-case, (b) the regression line through all points (i.e., the mean) and (c) being the worst-case. Scenario (d) is a BAU scenario based on the 2000–2011 deforestation rate. The calculations exclude the Meinmahla Kyun Wildlife Sanctuary and remote offshore islands (~137 km^2).

Specific policies reflect efforts to improve access to international markets, including in the agricultural sector. For example, Myanmar is signatory to the China-ASEAN Free Trade Agreement that will remove tariffs on 90% of goods by 2015 (http://fta.mofcom.gov.cn/topic/chinaasean.shtml). Myanmar has also increased cooperation with Thailand, which plans to triple bilateral trade by 2015 (Pratruangkrai, 2012). The government has broadened the banking sector, increasing the number of sanctioned private banks, increasing local credit access, and introducing swift international monetary transfers that will facilitate remittances and investment (Asian Development Bank, 2011, 2012; Kyaw, 2012a). Facilitated by these policies, Myanmar reported a 28% increase in foreign trade during the first 9 months of the 2011–2012 fiscal year (Xinhua, 2012), as well as a substantial increase in Asian investment (Kate and Kubota, 2012) including plans for increased trade with India, Bangladesh and China (Mirdha, 2011; Te Te, 2011).

The agriculture sector of Myanmar currently employs ~70% of the labor force and contributes >40% of GDP (Central Intelligence Agency, 2010), yet is currently characterized by inefficiency, low quality and high levels of farmer debt. Investments into updated farming technologies, improved varieties, crop diversification, education, and increased credit access could revitalize the sector (Kurosaki et al., 2004; Aung, 2011; Dapice et al., 2011, 2012). The Myanmar Agricultural Bank recently doubled credit available to farmers (Asian Development Bank, 2011), and a new agricultural bank was established in 2012 (Szep, 2012). Access to credit along with increased efficiencies and technology could help stimulate agricultural production, potentially doubling rice exports by 2017 (Chanjaroen, 2012).

Both small- and industrial-scale agriculture and aquaculture remains heavily limited by infrastructure (Dapice et al., 2010; Ministry of Agriculture and Irrigation, 2010; Asian Development Bank, 2012), particularly in the Delta following Cyclone Nargis (Fritz et al., 2009) but there is evidence that infrastructure development is a domestic priority. Thailand and Myanmar are developing a major seaport and industrial complex (see http://www.daweiport.com/), and are improving a transportation network that will extend to neighboring countries (Boot, 2010). The Japanese government has recently agreed to absolve approximately $3.36 billion in Myanmar debt, coupled with major loans and investment in infrastructure (Fuller, 2012; Kyaw, 2013), and the World Bank is providing a $165 million interest-free loan to support priority needs, including infrastructure (World Bank, 2013b).

The trends in Myanmar we detail above—improved market access, technologies and infrastructure—mirror those in other tropical countries since the 1990s, with important effects on land use and forest cover (Angelsen and Kaimowitz, 1999; Geist and Lambin, 2002; Abdullah and Hezri, 2008; Brando et al., 2013). Notably, export-oriented agricultural expansion such as plantations, and agricultural trade are the principal forces underlying deforestation in Asia since the 1990s, having usurped smallholder expansion as the principle driver in the decades prior (Rudel, 2007; Rudel et al., 2009; Hall, 2011; DeFries et al., 2013). Because Myanmar has been largely sidelined from the international markets since the 1950s, improved market access suggests that an expansion of export-oriented agriculture (e.g., rubber and oil palm) is likely to hold going forward in Myanmar.

Thus, the expectation is that the policy developments designed to improve international market access, combined with improvements to technology and infrastructure, will result in greater pressure being placed on natural systems across Myanmar, potentially leading to greater deforestation rates (Angelsen and Kaimowitz, 1999; Geist and Lambin, 2002). Neighboring countries across continental Southeast Asia also offer salient examples. For example, conversion of upland forest to oil palm is a major driver of deforestation in both Malaysia and Indonesia (Koh and Wilcove, 2008). Vietnamese aquaculture increased production from 168,000 tons in 1990 to 2,700,000 tons in 2010 (FAO, 2006-2013) in response to greater market access; aquaculture expansion has been implicated as the principle driving force of increased mangrove deforestation rates (De Graaf and Xuan, 1998), especially in the northeast Mekong delta from 1995 to 2001 (687 ha/year or 13.1% annual rate; Thu and Populus, 2007). In addition, improved infrastructure has been associated with road-facilitated deforestation in the highlands of northern Thailand (Delang, 2005), and expansion of rubber at the expense of forest in Xishuangbanna, southern China (Li et al., 2007). However, roads combined with capital investment in urban areas, may also facilitate rural-to-urban migration, which may reduce pressure on forests as marginal lands are abandoned (e.g. Rudel et al., 2005; Izquierdo et al., 2011).

3.3. Agents of change transforming or protecting the landscape

Based on the case study of the Ayeyarwady Delta, and in line with previous findings across the region, we anticipate that new market incentives for export-oriented agriculture will likely result in broad and increased future deforestation (Rudel et al., 2009; DeFries et al., 2010). However the mechanisms and actors responsible for future transformations are evolving. While historically deforestation in the Delta was principally driven by small-holder rice farmers receiving government support, these patterns will not necessarily hold true into the future. Based on experiences across the region and emerging evidence from within Myanmar, it is likely that powerful interest groups, both domestic and foreign, will play an increasingly significant role in enterprise-driven deforestation. The behavior of these elites, in conjunction with government agencies and often in contest with other local actors, will be key in decisions over how Myanmar's landscape is transformed and/or protected.

First, it is likely that a significant portion of capital investment for agriculture will come internationally. Although foreign direct investment (FDI) to agriculture in Myanmar is low (Bissinger, 2012), the lifting of sanctions has already increased investment, with Myanmar now seen as one of the world's biggest "agricultural investment frontiers" (Osborne, 2013). This suggests that well-financed international elites will be entering Myanmar, with levels of capital much greater than available locally. For example, despite the banking reforms, farmer access to credit and capital for investment will be greatly overshadowed by foreign investment given the low levels of smallholder capital (low incomes) and collateral (insecure land tenure for leveraging). Further, foreign capital is a "necessary condition" for economic growth of developing countries (Zoomers, 2010)—especially in countries such as Myanmar where FDI is seen as a critical element of kick-starting the economy. Finally, the Foreign Investment Law passed in November 2012 provides numerous incentives to increase FDI, including tax breaks, a guarantee against nationalization of the investment, ability to repatriate investment gains, and land leases of 50 years with two 10 year extensions (which contravenes the Vacant, Fallow and Virgin Lands Management Law of 2012 stipulating 30 year leases) (Mayer Brown JSM, 2012; Buchanan et al., 2013). Thus, foreign investors are expected to be important actors in the "control and use of land" (Zoomers, 2010).

Second, although land tenure and land reform are considered critical to equitable economic growth, agricultural output, improved food security and environmental sustainability in Myanmar (Food Security Working Group, 2012; Kyaw, 2012b), rural and farmland tenure in Myanmar remains insufficient. Two relevant laws recently passed in Myanmar, the Farmland Law (2012) and the Vacant, Fallow and Virgin Lands Management Law (2012), have made strides toward improved land tenure security (English translations of both laws available online at http://www.burmalibrary.org/show.php?-cat=1200). These laws have established a land use certificate and registration system for cultivated land (the Farmland Law), and an application system to lease State land for lawful purposes, including agricultural development (The VFV Law; Oberndorf, 2012). Nevertheless, these laws lack sufficient provisions for secure tenure to rural farmers: the State retains ownership of all land (any changes in cropping require permission, and the State can confiscate land if "conditions of use are not met"); the definition of 'famer' is so broad as to include investors and management personnel, who can receive confiscated land or apply for land leases under the VFV Law; disputes involving allocation or use are not heard by a court of law; women do not enjoy explicit equal landholding rights; customary law is not sufficiently recognized; and there is a lack of free, prior and informed consent for leasing of VFV lands that might interfere with existing land claims of any groups (Human Rights Foundation of Monland, 2012; Oberndorf, 2012).

The combination of rapidly expanding export-oriented agriculture ("crop booms", Hall, 2011), increasing FDI and insecure land tenure are likely to create conditions that facilitate land grabbing by elites, both national and domestic (Zoomers, 2010; Borras and Franco, 2010). Indeed, more than 750 cases of land disputes and confiscations were reported in the first year of the Farmland and VFV laws (New Light of Myanmar, 2013), indicating significant loopholes in the law that facilitate land disputes and open the door for land grabbing, with significant advantages to well-funded and well-connected elites (Osborne, 2013). Certainly, land seizures in Myanmar have been and continue to be commonly associated with the military (Zaw and Khaing, 2013); however there is evidence of non-state actors obtaining land through extralegal means, e.g. agro-industrial plantation development without regard for terms of lease agreement under the VFV Law (Oberndorf, 2012), and land confiscation for Chinese investment in agribusiness, particularly in northern Myanmar (Buchanan et al., 2013). In the Ayeyarwady Delta, farmers are seeking reparations or the return of land that may have been seized by the government (Zaw and Khaing, 2013). Nevertheless, potentially massive influxes of investment for agroindustry, such as Wilmar International's interest in expanding the sugar industry to the Ayeyarwady Delta (Montlake, 2013), will likely serve as a test of whether private industry will successfully exploit current land tenure insecurity to gain government approval to acquire and develop large-scale agroindustry on contested land.

Thus, as seen in other developing countries, Myanmar's policy objectives to promote private enterprise and increase FDI may also facilitate the transfer of control and use of land, leading to a "foreignisation of space" (Zoomers, 2010) to investors from China, Thailand, and Malaysia.

Third, Myanmar scores extremely low in all aspects of governance—including in rule of law and the control of governance—and in terms of providing an open and secure business and investment environment (www.govindicators.org; www.heritage.org). In emerging economies, corporate wealth tends to be highly concentrated (La Porta et al., 1999; Claessens et al., 2000), suggesting that elite actors are likely to work closely with the government to secure land leases, possibly exploiting loopholes in existing land laws. Given the recent analyses that strongly implicate industrial-scale, export-oriented agriculture in tropical deforestation (Rudel et al., 2009; DeFries et al., 2010), it therefore seems entirely possible that an Indonesian-style system of crony capitalism could emerge in Myanmar, with well-connected elite agro-industrial investors (palm oil, rubber) making significant land deals in the absence of a well-articulated, and enforced, land law and tenure system (Oberndorf, 2012).

Substantial on-the-ground work needs to be done to more deeply evaluate the behavior of actors, on-the-ground incentives and investment in agriculture and agro-industry, how actors are acquiring land and navigating/exploiting the current land tenure system, and the consequences for forest cover dynamics in Myanmar. Our study on the physical dimensions of land use change in the Delta incorporated on-the-ground data, however, we lack critical socioeconomic data that could advance our understanding of the political economy of increased focus on export-oriented agriculture, introduction of foreign actors and their interaction with the existing power structure in Myanmar, and the dynamics of emerging land law; all of which will affect forest cover in the future. A nuanced approach will be essential for well-informed policy (Borras and Franco, 2010). However, adequate and verifiable data on these critical components needed for a complete understanding of the current and potential drivers of land use change in Myanmar are largely absent, as noted by a recent study on Myanmar's forest law and policy (Woods and Canby, 2011).

3.4. Policy and governance challenges going forward

In this paper we have identified trends of forest loss in the Ayeyarwady Delta and the critical role of rice agriculture to deforestation. The opening up of Myanmar to international investment and enterprise promises to bring new actors, pressure on forest, and governance challenges. High rates of historical mangrove deforestation, and the growing tension between rapid economic development and mangrove conservation in the Ayeyarwady Delta illustrate the broader need for significant attention to be paid to numerous aspects of environmental governance to ensure "environment-friendly reform" that considers multiple objectives (Webb et al., 2012). The quality of environmental policy and governance may ultimately determine whether business-as-usual scenarios are maintained, improve, or worsen. Going forward, policymakers need to consider several policy dimensions to prevent significant increases in deforestation while focusing on greater agricultural production (e.g., Angelsen, 2010; Sayer et al., 2013).

There are mounting calls within Myanmar for unambiguous environmental safeguards and mainstreamed environmental and social impact assessments, improved land-use planning, a strengthened environment agency and training for government on how to deal with environmental issues, and mechanisms for public engagement and consultations (Rao et al., 2002; Burma Environmental Working Group, 2011). And, this analysis further highlights a critical need for significantly improved data collection and analysis to capture existing, on-the-ground land use patterns, as well as increased consideration for how contemporary policy reforms may shape the future environment.

Moreover, the need for an improved protected area system in Myanmar has been highlighted for over a decade (Rao et al., 2002, 2013). In the Ayeyarwady Delta, for example, the Meinmahla Kyun Wildlife Sanctuary has successfully protected both forest cover (our analysis) and the endangered estuarine crocodile (Thorbjarnarson et al., 2008). Especially given the comparatively small area currently under conservation, more financing could be provided to significantly expand the protected areas network (Rao et al., 2002). In the Delta, there is equally scope for community-based reforestation and forest management programs, which could rehabilitate mangroves and help to fulfill demand for fuelwood in the Delta (see Macintosh et al., 2012), and substantial investment is expected for direct conservation funding to conserve coastal species and habitats (e.g. Critical Ecosystems Partnership Fund, 2012; Wildlife Conservation Society, 2013).

To date, however, Myanmar's protected areas network has remained small, and environmental regulations in Myanmar have been largely absent (e.g. Li, 2008), and rarely or arbitrarily enforced (Burma Environmental Working Group, 2011; Rao et al., 2002). There are considerable challenges to developing and implementing environmental safeguards and environmental impact assessments in the context of Southeast Asia, where they are often viewed as disincentives to development, investment and short-term economic gains (Li, 2008). These challenges may be aggravated by the rapid arrival of foreign financial interests and new waves of agricultural land-grabbing that may conflict with efforts to increase environmental regulation; this may be particularly acute within Myanmar, given its complex socio-political landscape and extremely low governance capacity (World Bank, 2012). Moreover, Myanmar's largest foreign investors—China and Thailand—may view economic liberalization as an opportunity to export polluting industries (Boehler, 2012), extract raw materials (e.g., Yap, 2010; Asian Development Bank, 2012), and supply agricultural exports (e.g., Yunfei and Lingling, 2010). The fear is that these interests have little regard for environmental impacts (Casey, 2007; Burma Environmental Working Group, 2011; Fuller, 2011) and may influence both policymaking and enforcement. Moreover, leveraging foreign aid and technical support to encourage improved natural resource governance is largely considered ineffective (Carbonnier, 2011), especially in a region dominated by emerging donors (Woods, 2008; Reilly, 2012).

A high priority needs to be placed on land tenure reform, in order to promote equitable economic growth and improved agricultural output, mitigate against land grabbing, and promote environmental sustainability. Community-based conservation mechanisms and responsible local-level land management, for example, often depend heavily on secure land tenure, recognition of customary land use practices and rights to local stewardship (Mendelsohn, 1994; Angelsen and Kaimowitz, 1999). Policy analysis has already put forth a set of guidelines for improving the current Farmland Law and the Vacant, Fallow and Virgin Lands Management Law, including freedom to farm crops of farmers' choice, recognition of equal rights for women, recognition of customary laws governing land use, creation of independent bodies to hear and adjudicate land disputes, prioritization of land allocation for marginalized citizens, and adhering to the concepts of free, prior and informed consent (Oberndorf, 2012). Beyond amending current law, however, recommendations for a comprehensive Land Law have been made to explicitly safeguard smallholder rights, create secure land tenure (e.g. prevention of land foreclosures), and clarify both the land registration procedure and the land use classification system (Oberndorf, 2012). Land tenure reform would provide opportunity for smallholders to improve their long-term agricultural objectives, allow them to better access international markets, and prevent land seizures (Song, 2013), while at the same time clearly demarcating State managed lands such as production forests and protected areas. Such transparency could help reduce contestation over land and promote better land stewardship.

Environmental governance policy needs to advance alongside the development of policies designed to enhance international enterprise and agricultural output. Given that previous research has strongly implicated large, enterprise-oriented agroindustrial development in recent tropical deforestation in Asia, policy mechanisms to protect forests, both in the Delta and in upland areas, need emphasis. Given clear land use planning, agrotechnological changes could simultaneously facilitate intensification and land sparing for forest conservation (Lambin and Meyfroidt, 2011, but see Morton et al., 2006). Policy could require conservation set-aside programs funded by large-scale agroindustry, to not only enhance the current protected area system but also to require large-scale farming to occur on limited land (Rudel, 2007). Such policies will likely only occur through efforts by coalitions of local, national and international conservation interests that "pressure for institutional safeguards for natural forests and contest growth coalition plans for expanding agricultural enterprises at the expense of tropical forests" (Rudel, 2007). Such grassroots farmer coalitions appear to be forming (e.g. Lwin and Ei, 2013). However, such a protectionist agenda needs to be undertaken carefully so that it does not result in "green grabbing", which could end up excluding local people from forests (e.g. Fairhead et al., 2012).

4. Conclusion

Understanding future prospects for conservation in a dynamic environment characterized by shifting policies and economic drivers requires an integrated approach (Mattison and Norris, 2005). Our quantitative analysis demonstrates that Myanmar's Ayeyarwady Delta mangroves are under considerably greater threat than previously documented. Further, there is an urgent need to revisit business-as-usual scenarios such as the one we present for the Ayeyarwady Delta, and to reconsider conservation priority-setting and threat analyses, and to anticipate future drivers of change. As Myanmar's government takes steps toward political and economic reform and is rewarded with increased international engagement, private investment and overseas aid, it also potentially faces increased environmental pressures. These necessitate proactive environmental safeguarding and precautionary management. However, given the current state of environmental governance and regional precedents, recent policy developments seem poised to deeply and negatively affect remaining natural ecosystems across Myanmar.

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Appendix A

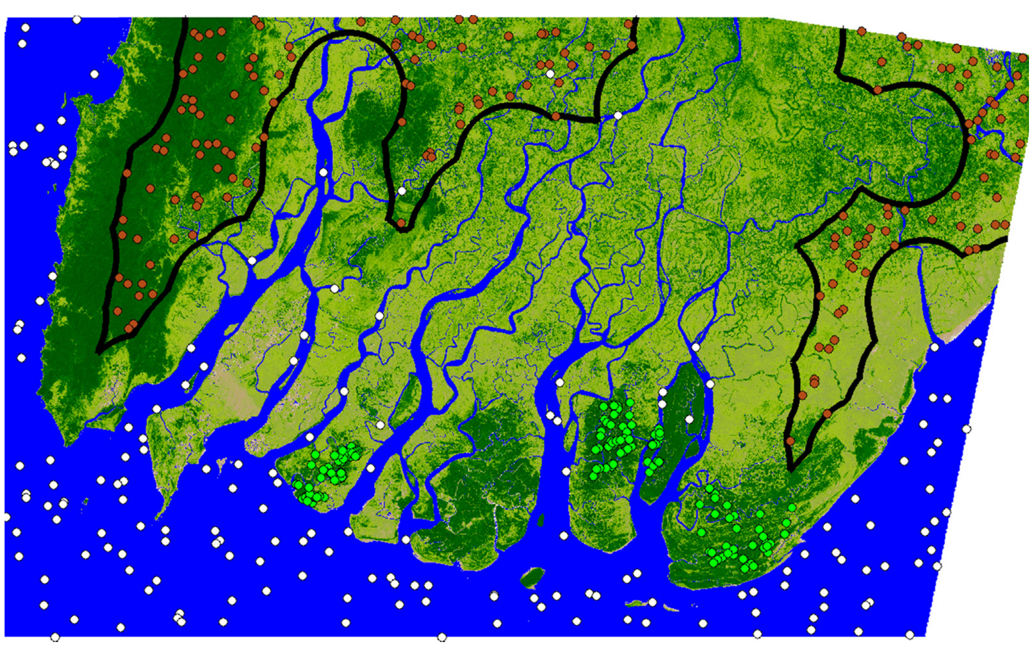

Fig. A1. Distribution of historical training points for Model H. There were 168 points of each class: mangrove (green dots, dense mangrove points taken from the ground surveys), non-mangrove (brown dots) and water (white dots). Water points were randomly selected from within the blue areas and non-mangrove terrestrial points were selected within the area delineated by the black line.

Table A1
Ten-fold cross-validation accuracy assessments of historical land-cover models based on Training Dataset H (historical).

Model	2009		2008		2000		1989		1978	
	PA	UA	PA	UA	PA	UA	PA	UA	PA	UA
Mangrove	0.940	0.893	0.863	0.863	0.952	0.930	0.958	0.931	0.845	0.888
Non-mangrove	0.988	0.965	0.994	0.994	0.917	0.951	0.929	0.929	0.899	0.839
Water	0.863	0.935	0.845	0.845	1.000	0.988	0.958	0.988	0.952	0.976
Overall accuracy	93.1%		90.1%		95.6%		94.8%		89.9%	
Cohen's Kappa	0.896		0.851		0.935		0.923		0.848	

PA, producer's accuracy; UA, user's accuracy.

Table A2
Ten-fold cross-validation accuracy assessments of 2011 Ayeyarwady land cover model based on Training Dataset C (contemporary).

	PA	UA
Mangrove	0.869	0.752
Degraded mangrove	0.333	0.500
Agriculture	0.840	0.866
Water	0.972	0.972
Other	0.529	0.563
Overall accuracy	81.6%	
Cohen's Kappa	0.749	

PA, producer's accuracy; UA, user's accuracy.

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