Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012

Daniel R. Richards[a,b,1] and Daniel A. Friess[a]

[a]Department of Geography, National University of Singapore, Singapore 117570 and [b]Department of Animal and Plant Sciences, The University of Sheffield, Sheffield S10 2AS, United Kingdom

Edited by Matthew C. Hansen, University of Maryland, College Park, MD, and accepted by the Editorial Board November 24, 2015 (received for review May 26, 2015)

The mangrove forests of Southeast Asia are highly biodiverse and provide multiple ecosystem services upon which millions of people depend. Mangroves enhance fisheries and coastal protection, and store among the highest densities of carbon of any ecosystem globally. Mangrove forests have experienced extensive deforestation owing to global demand for commodities, and previous studies have identified the expansion of aquaculture as largely responsible. The proportional conversion of mangroves to different land use types has not been systematically quantified across Southeast Asia, however, particularly in recent years. In this study we apply a combined geographic information system and remote sensing method to quantify the key proximate drivers (i.e., replacement land uses) of mangrove deforestation in Southeast Asia between 2000 and 2012. Mangrove forests were lost at an average rate of 0.18% per year, which is lower than previously published estimates. In total, more than 100,000 ha of mangroves were removed during the study period, with aquaculture accounting for 30% of this total forest change. The rapid expansion of rice agriculture in Myanmar, and the sustained conversion of mangroves to oil palm plantations in Malaysia and Indonesia, are identified as additional increasing and under-recognized threats to mangrove ecosystems. Our study highlights frontiers of mangrove deforestation in the border states of Myanmar, on Borneo, and in Indonesian Papua. To implement policies that conserve mangrove forests across Southeast Asia, it is essential to consider the national and subnational variation in the land uses that follow deforestation.

forest loss | aquaculture | oil palm | Myanmar | Indonesia

Global demand for food, biofuels, and raw materials continues to drive land use and land cover change (LULCC), particularly in the tropics (1, 2). Demands are expected to further intensify as populations and global affluence increase, and further LULCC is expected, given that future demand cannot be met by yield increases of currently cropped lands alone (3). LULCC enables large-scale commodity production, but can have substantial negative impacts on biodiversity (4) and the provision of ecosystem services (5). To manage LULCC-driven deforestation and conserve tropical forested landscapes in the future, it is important to understand spatial and temporal variation in the land uses that replace forests, both locally and at regional scales.

Coastal mangrove forests grow in the intertidal zone in tropical and subtropical regions (6). Southeast Asia contains the greatest diversity of mangrove species (7) and more than one-third of the world's mangrove forest extent (8). Estimates of historical mangrove deforestation are unreliable in many instances (9), but Asia may have lost more than one-third of its mangrove area between the 1980s and 1990s (10). Such deforestation has had substantial negative impacts on biodiversity, with 16% of the world's mangrove vegetation species now at an elevated risk of extinction (11). Mangrove deforestation also has implications for the provision of ecosystem services. For example, mangroves store disproportionately high densities of carbon compared with other ecosystems (12), so LULCC in mangroves may result in carbon emissions equal to 2–8% of emissions from terrestrial deforestation, despite the fact that this ecosystem represents only 0.7% of the global tropical forest area (13, 14).

The aquaculture industry has been held primarily responsible for mangrove deforestation in Southeast Asia over the past 30 y (10, 15). Agriculture, forestry, and urbanization were generally considered less important drivers at the regional scale (10, 16), but rice agriculture and urbanization have recently been shown to be locally important (17, 18). The demand for alternative land uses, such as oil palm plantations, is a major driver of terrestrial deforestation in the region (19, 20), but oil palm has been considered in tropical coastal habitats only rarely. In general, the current importance of different drivers of mangrove conversion is not clear, in part because previous analyses focused on longer-term changes over several decades (10, 16, 21), hindering assessment of recent and contemporary trends. In addition, several previous studies used national-level government statistics (10, 15, 16), but these data may be unreliable (9, 22), and do not allow analysis of spatial variation in drivers within countries.

Different policy interventions may be needed to combat mangrove deforestation in Southeast Asia, depending on the proximate drivers that are responsible. For example, legislation may be led by different government ministries depending on whether the replacement land use is urban, forestry, agriculture, or aquaculture, especially because mangrove management is commonly spread over multiple agencies in Southeast Asian countries (23). Improvements in remote sensing technology and image analysis have allowed us to systematically monitor changes in the distribution of forests at regional and global scales (6, 8, 24), annually and at a high spatial resolution (24). Comparable approaches have not been applied to identify the land uses that replace forests, however, making it difficult to quantify the major proximate drivers of

Significance

This study quantifies the proximate drivers (i.e., replacement land uses) of mangrove deforestation across Southeast Asia between 2000 and 2012. Mangrove forests in the region were lost at an average rate of 0.18% per year. Aquaculture was a major pressure on mangrove systems during this period, but its dominance was lower than expected, contrary to popular development narratives. Rice agriculture has been a major driver of mangrove loss in Myanmar, and oil palm expansion is a key but under-recognized threat in Malaysia and Indonesia. The threat of oil palm to mangroves is likely to increase in the future as new frontiers open up in Papua, Indonesia. Future research and policy responses must consider the diversity of drivers of mangrove deforestation.

Author contributions: D.R.R. and D.A.F. designed research; D.R.R. performed research; D.R.R. analyzed data; and D.R.R. and D.A.F. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. M.C.H. is a guest editor invited by the Editorial Board.

[1]To whom correspondence should be addressed. Email: d.r.richards@nus.edu.sg.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1510272113/-/DCSupplemental.

Table 1. Mangrove area and loss statistics for Southeast Asian countries between 2000 and 2012

Country	Total mangrove in 2000, ha	Mangrove deforestation, ha	Mangrove habitat area lost, ha	Percentage mangrove loss 2000–2012, %
Indonesia	2,788,683	60,906	48,025	1.72
Myanmar	502,466	27,957	27,770	5.53
Malaysia	557,805	18,836	15,809	2.83
Thailand	245,179	3,504	3,344	1.36
Philippines	257,575	1,423	1,296	0.50
Cambodia	47,563	1,218	1,086	2.28
Vietnam	215,154	531	528	0.25
Brunei	11,054	48	41	0.37
Timor-Leste	1,066	2	2	0.19
Singapore	583	0	0	0
Southeast Asia	4,626,545	114,424	97,901	2.12

Countries are ordered by total mangrove lost. Mangrove habitat lost takes into account mangrove regrowth in deforested areas during the period.

deforestation over large areas. Some previous studies of LULCC at global and regional scales have used intermediate-resolution remote sensing imagery and, correspondingly, have analyzed broad land cover categories, such as "plantation" or "lowland forest" (25). Such broad land cover categories do not allow us to identify the particular commodities being produced. Remote sensing LULCC studies using finer-resolution imagery are typically geographically restricted to smaller case studies (18, 26), making it difficult to identify general patterns and compare the relative importance of different replacement land uses across countries.

In this study, we applied a systematic remote sensing method across Southeast Asia to quantify the LULCC that occurred in mangrove forests annually between 2000 and 2012, within all deforested patches larger than 0.5 ha. We identified the replacement land uses that followed deforestation by classifying patches into categories linked to proximate drivers: aquaculture, rice-dominated arable, oil palm plantation, urban, and other terrestrial forest (including possible rubber plantations). We also classified categories for mangrove regrowth, coastal erosion, and recently deforested mangrove with no clear replacement land use. We analyzed national and subnational variation in the rates and drivers of mangrove deforestation across Southeast Asia, and compared temporal trends in the three major replacement land uses between 2000 and 2012.

Results

Mangrove deforestation remains substantial across Southeast Asia, with more than 100,000 ha of mangrove forest lost between 2000 and 2012 (Table 1). Approximately 2% of the mangroves present in Southeast Asia in 2000 were lost during the study period, at an average rate of 0.18% per year. There is considerable spatial variation in the degree of deforestation, with hotspots in Myanmar, particularly in Rakhine state, in Indonesian Sumatra and Borneo, and in Malaysia (Fig. 1 and Table 1). The rate of mangrove deforestation was higher in these regions and was considerably lower in Thailand, Vietnam, and the Philippines (Table 1).

There were three main mangrove replacement land use types identified during the study period: aquaculture, rice, and oil palm

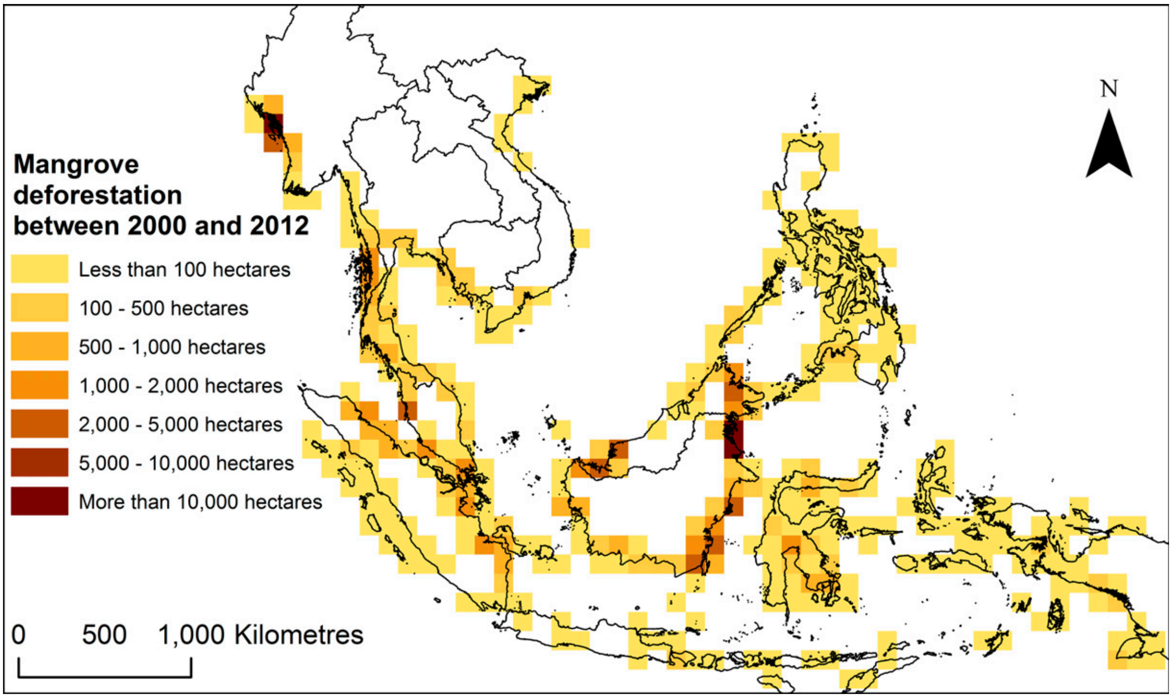

Fig. 1. Mangrove deforestation between 2000 and 2012. Deforestation is summarized within each 1 decimal degree square.

Table 2. Percentage of the total deforested mangrove (2000–2012) converted to different land uses

Country	Aquaculture	Rice	Oil palm	Mangrove forest	Urban	Other category
Indonesia	48.6	0.1	15.7	22.6	1.9	11.2
Myanmar	1.6	87.6	1.1	0.5	1.6	7.6
Malaysia	14.7	0.1	38.2	17.6	12.8	16.7
Thailand	10.8	5.6	40.0	5.1	14.4	24.1
Philippines	36.7	0.9	11.1	7.3	2.7	41.3
Cambodia	27.7	1.5	8.9	9.8	4.6	47.6
Vietnam	21.0	10.4	0.5	0.6	62.5	4.9
Brunei	29.2	0	27.7	12.5	15.9	14.8
Timor-Leste	0	26.1	0	0	0	73.9*
Singapore	0	0	0	0	0	0
Total	29.9	21.7	16.3	15.4	4.2	12.3

Countries are ordered by total mangrove lost. Percentages might not sum to 100 owing to rounding.
*The small amount of mangrove deforestation in Timor-Leste is due mainly to shoreline erosion.

(Table 2). Over the entire study period, the single most important replacement land use was aquaculture (30% of total area; SE, 2%), which was particularly dominant in Indonesia, Cambodia, and the Philippines (Fig. 2 and Table 2). Conversion to rice agriculture was important at the regional scale (22% of total area; SE, 1.5%), but this figure is skewed heavily by rice expansion in Myanmar (Fig. 2 and Table 2). Oil palm plantations also accounted for a considerable area (16% of total area; SE, 1.6%), particularly in Malaysia and Indonesia (Fig. 2 and Table 2). Urbanization had a small regional impact on mangrove extent, but locally important impacts in the Bangkok region, southern Malaysia and Vietnam (Fig. 2 and Table 2). Approximately 15% (SE, 1.5%) of the mangrove lost during the study period was classified as mangrove regrowth in 2012. Mangrove regrowth was particularly apparent in Indonesia (Table 2) and northwest Malaysia (Fig. 2).

Land use conversion did not occur at a constant rate between 2000 and 2012, and the relative importance of the different drivers varied temporally (Fig. 3). The percentage conversion to aquaculture ponds declined from 2000, before rising to the 2000 level in 2010 and 2011 (Fig. 3*A*). The percentage of mangrove converted to rice fields increased steadily between 2000 and 2009, before falling rapidly during 2010 (Fig. 3*B*). The rate of conversion to oil palm showed a sustained increase throughout the study period (Fig. 3*C*).

Discussion

Deforestation Rates Are Lower Than Previously Thought. The rate at which mangroves present in 2000 were deforested up to 2012 (average 0.18% per year) is lower than that of previous estimates across Asia (10) and insular Southeast Asia (25), which have estimated rates of at least 1% per year. It is possible that the rate of mangrove conversion has slowed since the 1990s, but the

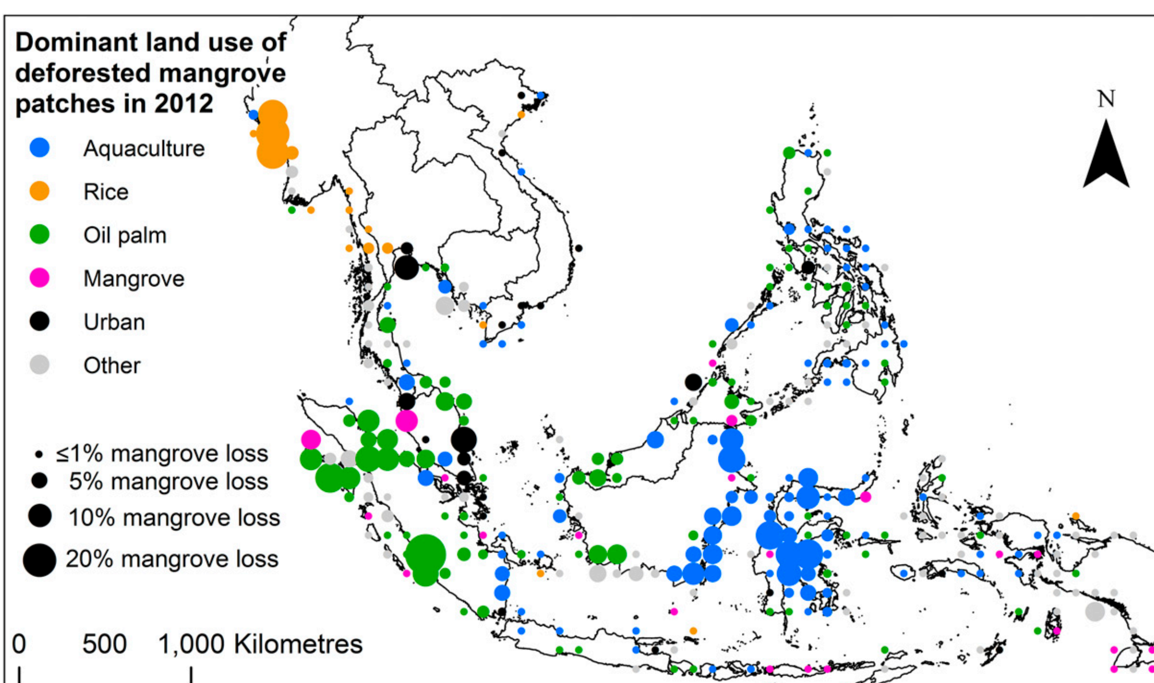

Fig. 2. Percentage mangrove deforestation between 2000 and 2012, and dominant land uses of deforested areas in 2012. Land uses are summarized as the converted land use with the greatest area within each 1 decimal degree grid square. Circles are located in the center of each grid square, and circle size represents the percentage of the mangrove area in 2000 that has been lost.

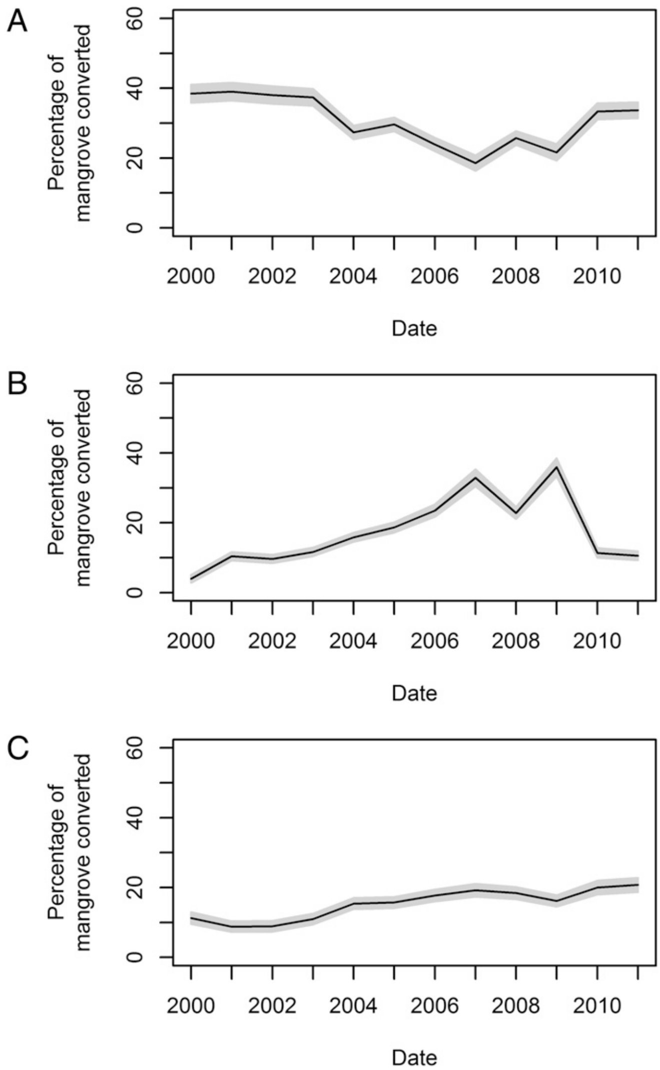

Fig. 3. Temporal trends in the conversion of mangrove habitats to aquaculture (*A*), rice agriculture (*B*), and oil palm plantation (*C*), between 2000 and 2012. Black lines indicate error-corrected estimates of the proportional coverage of each land use. Gray shading indicates the SE of the areal estimates.

discrepancy may also be related to methodological differences, given that the higher estimates of mangrove deforestation were based on analyses of national-level government statistics or literature reviews (10, 16) or on satellite imagery with relatively coarse resolution (25). The rates of mangrove loss in Southeast Asia reported in this study are lower than previously thought, but nonetheless a substantial area of mangrove (on average 9,535 ha $year^{-1}$) is lost annually. Continued mangrove deforestation will have further negative impacts on biodiversity and ecosystem service supply.

There was substantial spatial variation in the rate of mangrove forest change between 2000 and 2012, with >10% of mangrove forest lost per 1° grid square in parts of Rakhine state in Myanmar and in Sumatra, Borneo, and Sulawesi in Indonesia. In contrast, several countries that once were considered hotspots of mangrove deforestation, such as Vietnam and Thailand, showed relatively slower rates of deforestation between 2000 and 2012. The history of commodity production in these areas means that their coastlines have long been heavily managed, and the smaller areas of mangrove that remain may be more strongly protected (27).

Although most deforested mangrove was replaced with agriculture or aquaculture, a considerable deforested area was classified as mangrove in 2012, particularly in Malaysia and Indonesia. This regrowth may occur after illegal logging of mangrove wood, or after tree removal in sustainably managed mangrove forestry schemes, such as the Matang Mangrove Forest Reserve in northwest Malaysia. The Matang Reserve is largely managed as a sustainable monoculture of one mangrove tree species (*Rhizophora apiculata*) to provide mangrove charcoal (28). It is likely that mangrove forest has established in areas where it was not present in 2000, but such expansions would not be recorded using our method. The rate of mangrove forest expansion is considerable in South Asia (6), so it is possible that the percentage net loss in mangrove forest area in Southeast Asia between 2000 and 2012 may be less than 2%.

Aquaculture as a Driver of Mangrove Loss. Previous studies in Southeast Asia and globally have focused on the role of aquaculture in driving mangrove deforestation (10, 15, 29). Although aquaculture was still the dominant driver of mangrove deforestation between 2000 and 2012, the percentage converted to fish or shrimp ponds was approximately one-half that estimated during the 1980s–1990s (10), a period of rapid expansion of tropical coastal aquaculture. During the 1980s–1990s, aquaculture accounted for as much as 54% of all mangrove deforestation in a survey of eight major aquaculture-producing countries (29). The percentage converted annually to aquaculture was lower during most of the second half of our study period compared with the first half (although the percentage rose during 2010 and 2011). Since the 1960s and 1970s, conversion of mangrove forests to aquaculture ponds has been encouraged by the governments of Thailand, Indonesia, Vietnam, and the Philippines to enhance food security and improve livelihood (27, 30). These countries are now some of the largest aquaculture producers in the world (31). However, policies that encouraged expansion rather than intensification have now been reversed, and there are increased environmental regulations for new aquaculture development (27). Intensive production now accounts for the majority of production in Thailand (32).

Mangrove conversion to aquaculture now occurs mainly in Kalimantan and Sulawesi, Indonesia. Aquacultural expansion in these provinces largely drove the regional increase in mangrove conversion to aquaculture observed in 2010 and 2011. Aquacultural expansion has been driven in part by the recent Indonesian Government Regulation Per.06/MEN/2010, a policy that aims to position Indonesia as the world's largest aquacultural producer by 2015 (33). Thus, while Indonesia's aquacultural production was only slightly higher than other regional producers in 2006 (at 2.48 million tons), in 2012 Indonesia's production (9.6 million tons) was almost threefold larger than that of other regional aquaculture producers, such as Vietnam (3.3 million tons) (34). Indonesian government departments continue to encourage growth in the industry as a means of improving livelihood, generating foreign currency, and providing protein (30), so further mangrove conversion may be expected in the future.

Rice Expansion in Myanmar. Agricultural expansion for rice production, primarily in Myanmar, accounted for more than 20% of the total mangrove change in Southeast Asia over the study period. The local impact of rapid rice expansion on mangrove extent in the Ayeyarwady Delta has been described previously (18), but the present study shows that the expansion of rice agriculture across the whole of Myanmar is responsible for driving the fastest rate of mangrove deforestation of any country in Southeast Asia. Furthermore, our findings indicate that the rate of mangrove replacement with rice agriculture was lower in the agricultural hotspot of the Ayeyarwady Delta, and that recent rice expansion into mangroves has largely occurred in the state of Rakhine, an outlying region of the country with poor connections to the center (35). The government of Myanmar has historically aimed to increase rice production through engineering assistance and village-level expansion targets to enhance national food security (36). Reforms of the rice market in 2003, and accompanying suggestions of further liberalization by the government, might have stimulated some increased activity in the private market owing to price increases (18, 35).

Increasing rice production is considered critical for national food security (35), and it is likely that economic diversification from rice to such products as shrimp and oil palm will occur as export restrictions are eased in the future (18). The Myanmar government provides few environmental safeguards for mangrove forests; for example, the current protected area network is poorly enforced and covers little mangrove forest (37). As a result of the lack of environmental safeguards and continuing economic transformation in Myanmar, we may expect mangrove conversion to rice and other agriculture to continue to displace large areas of mangrove in this country in the future.

The Rise of Oil Palm as a Proximate Driver of Mangrove Deforestation. The development of oil palm plantations is a major driver of terrestrial forest and peat swamp deforestation in Malaysia and Indonesia (19, 38). That only a limited number of local or anecdotal case studies have identified oil palm cultivation as a potential driver of mangrove loss (39, 40) is surprising, given that our study highlights the large scale of oil palm production in former mangrove forests, particularly in Malaysia and Sumatra and Borneo in Indonesia. This is in keeping with the status of these countries as the top palm oil producers in the region; together they produce 85% of the world's palm oil (41). Palm oil production is encouraged by governments in Southeast Asia to enable energy security and economic development, with most plantations run by larger private enterprises or by smallholders who sell to large private enterprises (40, 42). The responsibility for intertidal habitats, such as mangroves, commonly falls between marine and terrestrial government agencies, which can lead to neglect of monitoring and management (43). Thus, in the past, conversion of mangrove forest to oil palm plantations might have been unnoticed or underreported, because oil palm expansion is generally considered a terrestrial issue (19, 38), and because plantations that replace mangrove forests may look similar to those that replace terrestrial and freshwater peat swamp forests.

Palm oil production in Indonesia is expected to continue to increase by almost 30% above 2012 levels by 2019 (44), owing to increasing global demand for foodstuffs and national targets to ensure energy security (41). It is likely that a large proportion of Indonesia's future oil palm expansion may occur in Papua. Papua has already granted large areas of terrestrial oil palm concessions (45), with a recent report showing an increasing rate of concession granting in the region (46). In May 2015, Indonesian President Joko Widodo announced the development of 1.5 million ha of new agricultural land in Papua within the next 3 y, as part of the Merauke Integrated Food and Energy Estate. This mixed agricultural development project is designed to increase food and energy security and stimulate economic growth in Papua (47, 48). Although our analysis showed a low deforestation rate in the mangrove-rich Indonesian province of Papua between 2000 and 2012 (Fig. 1), developments such as the Merauke project will bring substantial environmental and social impacts in the future (48).

Conclusions

Mangrove forests—a tropical coastal ecosystem on which millions of people depend—continued to be lost in Southeast Asia at an average rate of 0.18% per year between 2000 and 2012. Across Southeast Asia, mangrove forests are converted to alternative land uses to provide commodities, but the motivating factors for this conversion vary according to location and target commodity. In Myanmar, rice production is considered critical for national food security (35), whereas in Indonesia, Thailand, and the Philippines aquaculture is commonly presented as a means to develop the economy (27, 30). Palm oil production in Malaysia, Indonesia, and Thailand is promoted to enhance the economy and improve national energy security (41). Land use changes are performed by different demographic groups of people in different circumstances; in Myanmar, rice is farmed mainly by smallholders (36), whereas oil palm and aquaculture operations are commonly owned or managed by larger corporations (30, 40). This study provides quantitative data on the land uses that replace mangrove forests, at a high spatial resolution and annual frequency. This detailed information is required for decision makers to implement appropriate, evidence-based conservation. Thus, policy interventions must be targeted to address national and subnational variations in the drivers of mangrove loss.

Methods

Our analysis builds on two high-quality existing datasets: the global forest change dataset provided by Hansen et al. (24), which maps global deforestation annually between 2000 and 2012 at a detailed spatial resolution (pixel size = 0.09 ha), and the global distribution of mangrove forests in 2000/01 provided by Giri et al. (8). We performed a supervised land use classification of satellite imagery for each >0.5-ha deforested mangrove patch in Southeast Asia.

We cross-referenced the global forest change dataset (24) with the global distribution of mangrove forests in 2000/01 (8), and with the boundaries of the ASEAN states and Timor-Leste, to map the distribution of deforested mangrove pixels in Southeast Asia. We identified continuous patches of mangroves (i.e., pixels continuously connected in at least one of eight directions) that were deforested in the same year and that were larger than 0.5 ha, a total of 45,540 patches. Landsat satellite imagery was extracted for each deforested patch from the preprocessed 2012 Landsat image (24). We also calculated four other geographical predictor variables for each deforested patch: the Normalized Difference Vegetation Index in the surrounding 25 ha, the distance from the nearest major road at the center of the patch, and the United Nations Food and Agriculture Organization indices of climatic suitability for oil palm cultivation and rice agriculture (Table S1).

We used Google Earth Pro to view 3,091 deforested patches, and inferred the land use of 1,500 of these patches, which (*i*) were deforested before the date of the most recent imagery available and (*ii*) were clearly visible in the available imagery. We categorized the deforested patches into one of eight land use classes: aquaculture, rice field, oil palm plantation, urban, mangrove regrowth, terrestrial forest, coastal erosion, and recent mangrove deforestation with no observable replacement land use (Fig. S1). The majority of patches were sampled at random (n = 1,008), with additional targeted sampling done to increase the representation of less common categories (Fig. S2 and Table S2).

The training dataset of 1,500 deforested patches was used within a series of random forest classification models. Our classification problem was slightly different from the majority described in the remote sensing literature, which commonly classify at the level of single pixels within an image. In contrast, each area of interest in our study was a patch of variable size that contained a number of pixels. To prevent pseudoreplication caused by sampling multiple pixels from each patch, and to keep large deforested patches from having a disproportionate influence on the classification model, we sampled one pixel from each patch at random each time the classification was performed. This classification process was repeated 12 times, because the mean size of the deforested patches was 12 pixels. Each classification model was used to classify the 45,540 deforested mangrove patches, and the most commonly assigned category was assumed to be 2012 land use.

To assess the accuracy of the classification procedure, we carried out 100 cross-validations by randomly splitting the training dataset. In each cross-validation, we used 80% of our data to train a model, and compared the predictions from the model for the remaining 20% against their actual classification. Only randomly selected training data were used to test the classification accuracy. The median Cohen κ value of the 100 bootstrap models was 0.62, and the median accuracy of the whole classification was 68% (Table S3). To assess the potential impacts of systematic errors on the conclusions of the study, we calculated error-corrected estimates of the areal coverage of each land use and SEs for these estimates following recommended guidelines (49) for the overall and annual percentages of mangrove converted to each alternative land use (Fig. S3 and Table S4). More detailed descriptions of the methods and accuracy assessment are provided in *SI Methods*.

ACKNOWLEDGMENTS. We thank M. Hansen (University of Maryland), C. Giri (US Geological Survey), and their colleagues for their freely available and well-documented datasets. Deforestation data are available from Global

Forest Change (earthenginepartners.appspot.com/science-2013-global-forest), and the 2001 mangrove layer is hosted by the United Nations World Conservation Monitoring Centre (www.unep-wcmc.org/resources-and-data). We also thank J. Bramante (Woods Hole Institute) for his comments on this study. This study was supported by the Ministry of Education, Government of Singapore (Grant R-109-000-147-112).

1. DeFries RS, Rudel T, Uriarte M, Hansen M (2010) Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nat Geosci* 3(3): 178–181.
2. Gibbs HK, et al. (2010) Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proc Natl Acad Sci USA* 107(38):16732–16737.
3. Ray DK, Mueller ND, West PC, Foley JA (2013) Yield trends are insufficient to double global crop production by 2050. *PLoS One* 8(6):e66428.
4. Gibson L, et al. (2011) Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature* 478(7369):378–381.
5. Foley JA, et al. (2014) Amazonia revealed: Forest degradation and loss of ecosystem goods and services in the Amazon basin. *Front Ecol Environ* 5(1):25–32.
6. Giri C, et al. (2015) Distribution and dynamics of mangrove forests of South Asia. *J Environ Manage* 148:101–111.
7. Spalding M, Kainuma M, Collins L (2010) *World Atlas of Mangroves* (Earthscan, London).
8. Giri C, et al. (2011) Status and distribution of mangrove forests of the world using earth observation satellite data. *Glob Ecol Biogeogr* 20:154–159.
9. Friess DA, Webb EL (2014) Variability in mangrove change estimates and implications for the assessment of ecosystem service provision. *Glob Ecol Biogeogr* 23(7):715–725.
10. Valiela I, Bowen JL, York JK (2001) Mangrove forests: One of the world's threatened major tropical environments. *Bioscience* 51(10):807815.
11. Polidoro BA, et al. (2010) The loss of species: Mangrove extinction risk and geographic areas of global concern. *PLoS One* 5(4):e10095.
12. Donato DC, et al. (2011) Mangroves among the most carbon-rich forests in the tropics. *Nat Geosci* 4(5):293–297.
13. Pendleton L, et al. (2012) Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS One* 7(9):e43542.
14. Siikamäki J, Sanchirico JN, Jardine SL (2012) Global economic potential for reducing carbon dioxide emissions from mangrove loss. *Proc Natl Acad Sci USA* 109(36): 14369–14374.
15. Primavera JH (2000) Development and conservation of Philippine mangroves: Institutional issues. *Ecol Econ* 35(1):91–106.
16. Food and Agriculture Organization of the United Nations (2007) *The World's Mangroves, 1980–2005.* Forestry Paper 153 (FAO, Rome).
17. Lai S, Loke LHL, Hilton MJ, Bouma TJ, Todd PA (2015) The effects of urbanisation on coastal habitats and the potential for ecological engineering: A Singapore case study. *Ocean Coast Manage* 103:78–85.
18. Webb EL, et al. (2014) Deforestation in the Ayeyarwady Delta and the conservation implications of an internationally-engaged Myanmar. *Glob Environ Change* 24: 321–333.
19. Koh LP, Wilcove DS (2008) Is oil palm agriculture really destroying tropical biodiversity? *Conserv Lett* 1(2):60–64.
20. Fox J, Vogler JB (2005) Land-use and land-cover change in montane mainland southeast Asia. *Environ Manage* 36(3):394–403.
21. Giri C, et al. (2008) Mangrove forest distributions and dynamics (1975–2005) of the tsunami-affected region of Asia. *J Biogeogr* 35(3):519–528.
22. Friess DA, Webb EL (2011) Bad data equals bad policy: How to trust estimates of ecosystem loss when there is so much uncertainty? *Environ Conserv* 38(1):1–5.
23. Wever L, Glaser M, Gorris P, Ferrol-Schulte D (2012) Decentralization and participation in integrated coastal management: Policy lessons from Brazil and Indonesia. *Ocean Coast Manage* 66:63–72.
24. Hansen MC, et al. (2013) High-resolution global maps of 21st century forest cover change. *Science* 342(6160):850–853.
25. Miettinen J, Shi C, Liew SC (2011) Deforestation rates in insular Southeast Asia between 2000 and 2010. *Glob Change Biol* 17(7):2261–2270.
26. Tran H, Tran T, Kervyn M (2015) Dynamics of land cover/land use changes in the Mekong Delta, 1973–2011: A remote sensing analysis of the Tran Van Thoi District, Ca Mau Province, Vietnam. *Remote Sens* 7(3):2899–2925.
27. Hishamunda N, Ridler NB, Bueno P, Yap WG (2009) Commercial aquaculture in Southeast Asia: Some policy lessons. *Food Policy* 34(1):102–107.
28. Goessens A, et al. (2014) Is Matang Mangrove Forest in Malaysia sustainably rejuvenating after more than a century of conservation and harvesting management? *PLoS One* 9(8):e105069.
29. Hamilton S (2013) Assessing the role of commercial aquaculture in displacing mangrove forest. *Bull Mar Sci* 89(2):585–601.
30. Armitage D (2002) Socio-institutional dynamics and the political ecology of mangrove forest conservation in Central Sulawesi, Indonesia. *Glob Environ Change* 12(3):203–217.
31. Food and Agriculture Organization of the United Nations (2014) *The State of World Fisheries and Aquaculture* (FAO, Rome).
32. Lebel L, et al. (2002) Industrial transformation and shrimp aquaculture in Thailand and Vietnam: Pathways to ecological, social, and economic sustainability? *Ambio* 31(4):311–323.
33. Rimmer MA, et al. (2013) A review and SWOT analysis of aquaculture development in Indonesia. *Rev Aquac* 5(4):255–279.
34. Food and Agriculture Organization of the United Nations (2015) Global aquaculture production. Fishery Statistical Collections. Available at www.fao.org/fishery/statistics/global-aquaculture-production/en. Accessed October 27, 2015.
35. Okamoto I (2007) Transforming Myanmar's rice marketing. *Myanmar: The State, Community, and the Environment*, eds Skidmore M, Wilson T (Australian National Univ Press, Canberra), pp 135–158.
36. Matsuda M (2009) Dynamics of rice production in Myanmar: Growth centers, technological changes, and driving forces. *Trop Agric Dev* 53(1):14–27.
37. Myint Aung U (2007) Policy and practice in Myanmar's protected area system. *J Environ Manage* 84(2):188–203.
38. Koh LP, Miettinen J, Liew SC, Ghazoul J (2011) Remotely sensed evidence of tropical peatland conversion to oil palm. *Proc Natl Acad Sci USA* 108(12):5127–5132.
39. Bennett EL, Reynolds CJ (1993) The value of a mangrove area in Sarawak. *Biodivers Conserv* 2(4):359–375.
40. Lee JSH, et al. (2014) Environmental impacts of large-scale oil palm enterprises exceed that of small holdings in Indonesia. *Conserv Lett* 7(1):25–33.
41. Mukherjee I, Sovacool BK (2014) Palm oil-based biofuels and sustainability in southeast Asia: A review of Indonesia, Malaysia, and Thailand. *Renew Sustain Energy Rev* 37:1–12.
42. Wicke B, Sikkema R, Dornburg V, Faaij A (2011) Exploring land use changes and the role of palm oil production in Indonesia and Malaysia. *Land Use Policy* 28(1):193–206.
43. Ruttenberg BI, Granek EF (2011) Bridging the marine–terrestrial disconnect to improve marine coastal zone science and management. *Mar Ecol Prog Ser* 434:203–212.
44. Agricultural Ministry of Indonesia (2014) Commodities outlook reports: Palm oil (Outlook komoditi kelapa sawit). Available at epublikasi.setjen.pertanian.go.id/download/file/111-outlook-kelapasawit-2014. Accessed December 11, 2015.
45. McCarthy JF, Cramb RA (2009) Policy narratives, landholder engagement, and oil palm expansion on the Malaysian and Indonesian frontiers. *Geogr J* 175(2):112–123.
46. Franky YL, Morgan S (2015) West Papua oil palm atlas. Available at https://awasmifee.potager.org/uploads/2015/04/atlas-sawit-en.pdf. Accessed December 11, 2015.
47. Obidzinski K, Andriani R, Komarudin H, Andrianto A (2012) Environmental and social impacts of oil palm plantations and their implications for biofuel production in Indonesia. *Ecol Soc* 17(1):25.
48. Ito T, Rachman NF, Savitri LA (2014) Power to make land dispossession acceptable: a policy discourse analysis of the Merauke Integrated Food and Energy Estate (MIFEE), Papua, Indonesia. *J Peasant Stud* 41:29–50.
49. Olofsson P, et al. (2014) Good practices for estimating area and assessing accuracy of land change. *Remote Sens Environ* 148:42–57.
50. Landis JR, Koch GG, Biometrics S, Mar N (1977) The measurement of observer agreement for categorical data. *Biometrics* 33(1):159–174.
51. Stibig HJ, et al. (2007) A land-cover map for South and Southeast Asia derived from SPOT-VEGETATION data. *J Biogeogr* 34:625–637.
52. Congalton R, Gu J, Yadav K, Thenkabail P, Ozdogan M (2014) Global land cover mapping: A review and uncertainty analysis. *Remote Sens* 6:12070–12093.
53. Gong P, et al. (2013) Finer resolution observation and monitoring of global land cover: First mapping results with Landsat TM and ETM+ data. *Int J Remote Sens* 34(7): 2607–2654.