Conservation Status of Forest Types Vary Greatly in Myanmar - the Most Forested Country in the Indo-burma Biodiversity Hotspot

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Abstract

Diverse forests with distinct forest types, harbor exceptional biodiversity and provide many ecosystem goods and services, making some forest types more economically valuable and prone to exploitation than others. The high rates of deforestation in Southeast Asia endanger the existence of such vulnerable forest types. Myanmar, the region's largest forest frontier provides a last opportunity to conserve these vulnerable forest types. However, the exact distribution and spatial extent of Myanmar's forest types has not been well characterized. To address this research gap, we developed a national scale Forest Type map of Myanmar at 20m resolution, using moderate resolution, multi-sensor satellite images (Sentinel-1, Sentinel-2 and ALOS-PALSAR), extensive field data, and a machine learning model (RandomForest). We mapped nine major forest types and developed a Conservation Status Score to evaluate the conservation status of the mapped forest types. Swamp, Mangrove, Dry Deciduous, Lowland Evergreen and Thorn forests were ranked as the five least conserved forest types. We also identified the largest remaining patch for each of the five least conserved forest types and determined their protection status to inform future forest conservation policy. In most cases, these patches lay outside protected areas indicating areas that may be prioritized for future conservation.

Introduction

The potential natural distribution of different forest types is determined by geographic location (latitude and longitude), climate [1] and local environmental factors, such as elevation [2], and soil [3]. Spatio-temporal variation in these factors have led to the evolution of a wide range of highly distinct forest types across the globe [4]. Often, these highly diverse forests with many distinct forest types form the core of global biodiversity hotspots and represent critical habitat to rare, endemic, and other plant and animal species [5]. In addition to biodiversity resources, these forest types critically influence ecosystem goods and services, with some forest types being more widely exploited for economic purposes than others. Over time natural variation modulated by anthropogenic factors via resource use (e.g., firewood, building materials), forest conversion (e.g., conversion to grazing land), targeted management and conservation of forest resources [6,7] result in some forest types becoming increasingly rare, while others expand. In addition, forest types naturally restricted to very specific ecosystems [8,9] (e.g., Mangroves, Dry Deciduous forests) are more vulnerable to destruction and exploitation.

Southeast Asia is a major global deforestation hotspot [10,11] where rare and vulnerable forest types such as Indo-Malayan Lowland Sundaic forest, Dry Deciduous Dipterocarp are at risk [9,10]. Often these forest types are not well-represented in protected area networks or are located in ineffective protected areas [12]. Myanmar, the largest forest frontier in the region [9,13,14] is expected to have the remaining large patches of these invaluable forest types.

Myanmar lies in the Indo-Burma biodiversity hotspot [5] and has a wide range of forest types across the country, including Mangroves in Ayeyarwady delta, Evergreen forests in Tanintharyi, and Thorn forests in central Mandalay [15]. Approximately, 70% of Myanmar's population reside in rural areas [16] and are dependent on forests for their livelihood [17,18]. Overexploitation of forest resources and conversion of forests to agriculture and urban development has resulted in high rates of deforestation in Myanmar [13,14,19]. Not surprisingly, in 2015, United Nations' Food and Agriculture Organization (UN-FAO) declared Myanmar as the country with third highest rate of deforestation in the world, after Brazil and Indonesia [20]. Although Myanmar has a fairly extensive network of protected areas it still has not achieved its declared goal of protecting 10% of the country [21]. It is challenging to assess if the existing network proportionally protect and represent Myanmar's diverse and critically important forest ecosystems, in part due to the lack of inventory information on forest type distribution. For example, there is only one relatively small, protected area

that secures Dry Deciduous Diperocarp Forests (i.e., Chatthin Wildlife Sanctuary) and very few protected areas were designed to conserve critical Mangrove forests except Meinmahla Kyun Wildlife Sanctuary and Lampi Marine National Park. Only a few studies have attempted to assess the conservation status of specific underrepresented forest types such as the Dry Deciduous Forest [9,22,23] or forests highly vulnerable to anthropogenic disturbances and climate change such as Mangroves [8]. At global and broader regional scales, very few detailed remote sensing maps exist that quantify and map the extent of different forest types. Such information is critically needed to inform forest management and biodiversity conservation.

Mapping forest types from satellite data is often confounded by technical difficulties in separating high biomass vegetation types based on spectral characteristics alone [24–26]. This may be especially the case when the forest type is characterized by a complex species composition or when different forest types have dominant species with similar spectral properties. For example, the spectral signatures for natural tropical forests and mature rubber plantations at individual pixel level often are very similar [27,28] making it challenging to separate them based on only pixel-level remote sensing data at one point in time. Moreover, tropical forests tend to be highly heterogeneous in species composition, resulting in mixed spectral signals [26]. Mapping diverse forest types in the tropics would benefit from satellite images with fine spatial and spectral resolution due to vast information retrieved from the large number of spectral bands at high resolution [24]. However, while there have been a few attempts to map forest types at finer spatial scales, such as the Tanintharyi landscape in southern Myanmar [29], country-wide mapping efforts are lacking. This is especially true for Myanmar where limited financial and technical resources have hampered the development of a spatially explicit and reliable nationwide forest type map.

To advance sustainable forest management and conservation at the national level in Myanmar, it is necessary to develop country-wide, spatially explicit maps of different forest types. The current forest type map [30] used for broad reference by the Forest Department is more than 90 years old, is in coarse scale and outdated. Forest type classifications in global land cover products like ESA Climate Change Initiative (CCI) Land Cover (LC) [31] provide some information about the national forest type, at a relatively coarse scale (e.g., ESA CCI LC product has 300m resolution). The general forest types in the global (ESA CCI LC) and regional maps [32] also do not provide the detailed thematic classification required for effective forest inventory and conservation analyses at national level. The absence of recent and accurate forest type maps is a primary challenge for the Myanmar Forest Department [33].

Recent advances in cloud computing technology such as Google Earth Engine (GEE) [34], the availability of new, free, mid-resolution optical and radar satellite imagery like the Sentinels (Sentinel-2 and Sentinel-1), and machine learning methods provide an unprecedented opportunity to develop customized forest type maps suitable for national scale applications. GEE is a cloud-based platform which integrates access to large volumes of satellite imagery and ancillary datasets available from their data catalogue with geospatial analysis. It can process the results of any analysis with large data volume in a short time compared to traditional computers. Among the large volume of satellite images available through GEE, a combination of Sentinel-1 and 2 images has shown to improve the accuracy of forest type mapping in Myanmar compared to using Landsat-8 or Sentinel-2 alone [33]. To collect a large number of reference data on local forest types and their distributions, we collaborated with experts in Myanmar forests within local Non-Governmental Organizations (NGOs), Government and International Organizations. By combining state of art remote sensing technologies, satellite data, and extensive reference data, we developed the first spatially explicit forest type map of Myanmar circa 2020, at 20m resolution.

We used this new map to determine the extent, distribution, and conservation status of the different forest types in Myanmar. We developed a Conservation Status Score, based on abundance, protection status, and representation of

the forest type within protected areas, to identify the five least conserved forest types and their largest remaining patches. The results from our study will be critical to inform biodiversity conservation planning and forest management in Myanmar and the broader Southeast Asian region. In addition, our methods could easily be transferred to expand forest type mapping into neighboring countries in the Mekong region.

Results

At the national level, we mapped 507,361 km^2 of forests (Table 1) including 475,403 km^2 of natural forest and 31,958 km^2 of plantation forest. Natural forests cover ~70% of Myanmar's total land area. The most abundant forest types are Upland Evergreen (38.17% of total forest area), Bamboo (22.65%), and Mixed Deciduous (17.86%) forests, which combined make up ~79% of the total forest area in Myanmar. All other forest types combined constitute less than a quarter (21%) of the total forest area. Many of these less common forest types (eg. Swamp and Thorn) are only found in small areas and are highly restricted in their geographic distribution.

Table 1
Status of different Forest Types in Myanmar

Forest Type	Area (km2)	Forest Type Area Protected (km2)	Percentage of total mapped area (%)	Percent Forest Type Protected (%)	Percent Protected Area covered by Forest Type (%)	Conservation Status Score (%)
Swamp	1,875	29	0.37	1.56	0.07	2.00
Mangrove	7,867	141	1.55	1.79	0.33	3.67
Dry Deciduous	30,175	819	5.95	2.71	1.93	10.59
Plantation	31,958	885	6.30	2.77	2.09	11.16
Lowland Evergreen	33,552	1,731	6.61	5.16	4.09	15.86
Thorn	2,722	487	0.54	17.89	1.15	19.57
Mixed Deciduous	90,634	2,266	17.86	2.50	5.35	25.72
Bamboo	114,917	7,814	22.65	6.80	18.46	47.91
Upland Evergreen	193,660	28,162	38.17	14.54	66.52	119.24
Total	507,361	42,334	100.00		100.00	

Forest Type Extent and Distribution

The Upland Evergreen forests are mainly found in the mountains of Kachin, Sagaing, Chin, Shan, Kayah, Kayin and Tanintharyi (Figure 1). Bamboo occurs either as large clusters of Bamboo brakes along the slopes of the Rakhine Yoma in Rakhine State or co-occurs with Evergreen and Mixed Deciduous forests countrywide. Mixed Deciduous Forests are chiefly distributed in the area surrounding the Central Dry Zone in Shan, Kayah, parts of Kayin, Bago, western Ayeyarwady, northern Rakhine, Chin, central Sagaing, Magway, Mandalay, and Nay Pyi Taw.

Forest types accounting for between 10% and 1% of the forested area (Table 1) include Lowland Evergreen with a total area of 33,552 km^2 (6.61%) followed by Dry Deciduous Forests including Indaing (30,175 km^2 or 5.95%) and Mangroves (7,867 km^2 or 1.55%). Lowland evergreen forests occur in lowland or coastal areas of Kachin, Sagaing, Chin, Shan, Kayin and Tanintharyi (Figure 1) while Dry Deciduous Forests occur in the Central Dry Zone. Mangroves are found along the Myanmar coast in Rakhine, Ayeyarwady, Yangon, Mon and Tanintharyi.

Forest types occupying less than 1% of forest area (Table 1) include Thorn and Swamp. Thorn forests occupy an extent of 2,722 km^2 or 0.54% of forest area and stretch along the northern edges of the central Dry Zone in lower Sagaing, north Mandalay and Magway (Figure 1). Swamp forests, also known as inundated forests, are found along the floodplains of the Chindwin and Irrawaddy rivers. They represent only 0.37% of the total forested area, covering 1,875 km^2.

Accuracy Assessment

The overall accuracy of the validated classes (Bamboo, Lowland Evergreen, Upland Evergreen, Mangrove, Mixed Deciduous and Plantation) was 78.5% (Table 2). Mangroves were the most accurately mapped forest type with the highest User's Accuracy (UA: 97.41%) and Producer's Accuracy (PA: 95.88%), followed by Mixed Deciduous forests (UA: 76.14%, PA: 75.56%). Bamboo (UA: 71.19%) was often confused with Mixed Deciduous, Lowland (UA: 65.63) or Upland Evergreen (66.13%) as it often co-occurs with Mixed Deciduous and Evergreen forests. Based on the ground data collected, Plantation was the least accurately mapped class (UA: 51.43%, PA: 45%).

Table 2
Error Matrix of the national forest type classification in Myanmar.

Map	Reference							
	Bamboo	Lowland Evergreen	Upland Evergreen	Mangrove	Mixed Deciduous	Plantation	Row Sum	User's Accuracy
Bamboo	42	5	8	1	1	2	59	71.19
Lowland Evergreen	7	147	39	11	0	20	224	65.63
Upland Evergreen	2	60	246	0	64	0	372	66.13
Mangrove	1	11	1	489	0	0	502	97.41
MDF	13	0	46	4	201	0	264	76.14
Plantation	0	11	1	5	0	18	35	51.43
Col Sum	65	234	341	510	266	40	1456	
Producer's Accuracy	64.62	62.82	72.14	95.88	75.56	45.00		
Overall	78.50							

Conservation Status of Forest Types

Our analysis of conservation status of forests showed that Swamp and Mangrove forests are least abundant, least protected, and least represented with Conservation Status Score below 5. Dry Deciduous and Lowland Evergreen which rank more than 5 but below 20, also have low abundance, low protection status and low representation. Thorn forests which also have Conservation Status Score just below 20 are relatively rare (0.54%) but relatively more remaining areas of this forest type are protected (i.e., 17.89%). Comparatively, Mixed Deciduous forests are relatively abundant and have favorable Conservation Status Ranking (25.72) while Upland Evergreen is the most abundant, most protected, and most represented forest type with the highest Conservation Status Score (119.24).

Among other classes, it is noteworthy to find that Bamboo and Plantation occupy a large extent within protected areas (7,814 km^2 and 885 km^2 respectively).

Largest Patches of Least Conserved Forest Types

We identified Swamp (2), Mangrove (3.67), Dry Deciduous (10.59), Lowland Evergreen (15.86) and Thorn (19.57) as the five least conserved forest types (Table 1). The largest remaining patch of Swamp (Table 3, Figure 2) lies in northern Myanmar, on the border of Kachin and Sagaing. It covers an area of 108 km^2. Tanintharyi has the largest remaining patches of Mangroves (126 km^2) and Lowland Evergreen (5,479 km^2) forests. The largest patches of Dry Deciduous (2,604 km^2) and Thorn (26 km^2) forests lie in north of Central Dry Zone near the border of Chin and Magway and Sagaing respectively. It is worth noting that most of the largest remaining patches currently lie outside protected areas. Only 99 km^2 of Lowland Evergreen forest is protected in Tanintharyi Nature Reserve.

Table 3
Location, Extent and Protection Status of five most vulnerable forest types.

Sl. No.	Forest Type	Location of largest patch	Area of largest patch (km^2)	Protection Status
1.	Swamp	On the border of Kachin and Sagaing	108	Not protected.
2.	Mangrove	On an island just off the coast of Tanintharyi	126	Not protected.
3.	Dry Deciduous	Near the border of Chin and Magway	2,604	Not protected.
4.	Lowland Evergreen	Tanintharyi	5,480	Very little (99 km^2) is protected in Tanintharyi Nature Reserve.
5.	Thorn	Sagaing	26	Not protected.

Discussion

We developed the first spatially explicit countrywide forest type map of Myanmar and mapped nine major forest types at 20m resolution. Our map represents a significant expansion beyond previous efforts in mapping forest types. These previous efforts

a) were restricted on smaller areas, such as the Tanintharyi region [29];

b) used single-class classifier to map a specific forest types, such as Dry Deciduous forest [9,23]; or

c) mapped general land use and land cover with the inclusion of fewer and more general forest types [35–37].

Our map provides a comprehensive, baseline estimate of major forest types within the country. This map may fill the existing knowledge gap created by the absence of national level forest type map. The estimates of forest type extent generated from our map may be used by agencies and stakeholders to:

- Identify vulnerable forest types for conservation and forest management purposes.
- Monitor forest-type-specific deforestation rate by using our estimate as a baseline extent.
- Estimate and understand past deforestation trends by forest type using previous maps of deforestation.
- Contribute to improving the estimates of emission factors and activity data for future Forest Reference Level (FRL) and Greenhouse Gas Inventories (GHG-I) through forest type specific estimates. These may be used for reporting to the United Nations Framework Convention on Climate Change (UNFCCC) as well as for reporting to the Forest Resource Assessment (FRA) of the Food and Agriculture Organization of the United Nations (FAO).

Our map shows improved forest cover/type mapping in Central Myanmar. Previous studies tended to misclassify Dry Deciduous forests as other land use types [35,36], or underestimate these forest types[9]. Our method of using region specific tree cover thresholds facilitated improved mapping of the Dry Deciduous in Central Myanmar compared to existing products (Figure 3). In our study we used a greater than 10% tree cover threshold identifying forested pixels in Central Myanmar. In addition, the 20m resolution of the Sentinel-2 imagery also helped us to include formerly excluded small fragmented Dry Deciduous forests thus improving our estimate of Dry Deciduous forest extent. To demonstrate the improvement of our methods over existing land cover products we selected a well-studied region of Dry Deciduous forests at Chatthin Wildlife Sanctuary (CWS) (Figure 3). CWS is located at the northern edge of the Myanmar's Central Dry Zone. It was created to protect the highly endangered Indaing forests ecosystem [23,38]—a specific type of Dry Deciduous forests—in addition to conserving one of the largest remaining populations of endangered Eld's deer (Rucervus eldii) [39]. At CWS, Dry Deciduous forest (e.g., Indaing) co-occurs with Mixed Deciduous forests [40]. We compared our forest type map of CWS to two existing national level land cover maps of Myanmar –

i) Land cover land use map for Myanmar at 30-m resolution for 2016 [35],

ii) Myanmar National Land Cover Monitoring System (LCMS) [36]

Figure 3. Comparing the detection of Dry Deciduous forests in Chatthin Wildlife Sanctuary among three maps. A. High resolution image of the Area of Interest (AOI) from Google Earth. B. This study, showing the dominant presence of Dry Deciduous forests within the AOI. C. Land cover land use map for Myanmar at 30-m resolution for 2016 [35] showing the Shrub and Grassland as the dominant land cover in the AOI. D. Myanmar National Land Cover Monitoring System (LCMS)[36], showing the dominant land cover within the AOI as Woody.

Our comparison shows that we correctly mapped the dominant forest type in CWS as a mixture of Dry and Mixed Deciduous forests (Figure 3B) while [35] mapped the dominant land cover of CWS as Shrub and Grass (Figure 3C) which is not considered as natural forests according to their own definition[37]. Further, Myanmar National LCMS [36] maps the dominant land cover in CWS as Woody (Other Wooded Land) (Figure 3D) which is not considered as Forest. Both studies [35,36] fail to classify the dominant vegetation of CWS as forest and instead classify it as Shrubs/Grass or Woody, indicating that the vegetation is less than 5m tall which is not true according to ground

conditions. Our forest type map can benefit both products by providing them with more accurate and detailed information on forest types.

Historically, deforestation patterns across Myanmar are not uniform but concentrated in some regions and often on specific forest types [9,13,14,23]. Different forest types have different economic and conservation values and are exposed to different levels of threat due to regional differences in the socio-economic, political factors driving deforestation [13,41]. For example, the Mixed Deciduous forests in Myanmar's Bago region used to be an important resource to support the hardwood industry in Myanmar, especially the globally renowned 'Burma Teak', but have been severely overexploited, resulting in significant forest degradation [42]. The dominant presence of Bamboo on the eastern side Bago Yoma, bears testimony to the degraded condition (Figure 1) as the presence of Bamboo in Evergreen and Mixed Deciduous forest is a sign of forest degradation. For the same reason, the presence of Bamboo within protected areas (Table 1) is concerning. However, within Rakhine, Bamboo is considered a part of the natural ecosystem and is an integral part of the local fire ecology [43,44]. The presence of Plantations in protected areas is another reason for concern as it is a sign of anthropogenic activity within protected areas leading to loss of habitat [45].

Swamps, Mangroves, Dry Deciduous, Lowland Evergreen and Thorn forests were identified as the five most vulnerable forest types in Myanmar (Table 1). All have low representation in Myanmar's protected area system. The largest patch of most of these forests lie mostly unprotected providing a last opportunity for conservation and improved representation of the vulnerable forest types within Myanmar's protected area system.

Swamp forests are the rarest and most vulnerable forest type in Myanmar. Very little is known about these forests though they provide essential ecosystem services and are critical in supporting local wetland biodiversity. They provide critical habitat for the Critically Endangered Burmese Roofed Turtle [46,47] and many other threatened freshwater species. The largest patch of Swamp lies unprotected on the Kachin and Sagaing near the Irrawaddy River, covering an area of 107.5 km^2.

Mangroves are highly threatened at a global and regional scales [8]. In Asia, Mangroves have been historically felled for agricultural expansion, aquaculture development, and charcoal production [14,41,48]. A recent study reports that, between 2000-2012, Myanmar had the fastest rate of Mangrove deforestation among countries in Southeast Asia [8]. It is known that between 1990-2000, Mangrove forests in Ayeyarwady Region had the highest countrywide rate (2.2-3.3%) of forest loss in Myanmar [14]. Recent studies confirm the continuing high rate of Mangrove conversion (3.60%–3.87%) and decreasing Mangrove extent [41,48]. In 2016, the national Mangroves extent in Myanmar was reported to be 6287 km^2 [48]. Our analysis found that currently only 7867 km^2 of Mangrove (Table 1) remains in Myanmar, a slightly higher estimate than the previous studies, possibly due to increased detection of small, fragmented Mangroves using Sentinel-2 imagery. Though our study reports a slightly higher extent, only 1.79 % (141 km^2) of total Mangrove extent is protected, and there is a poor representation (0.33%) of Mangroves in the protected area system of Myanmar. The Meinmahla Kyun Wildlife Sanctuary in Ayeyarwady and the Lampi Marine National Park in Tanintharyi are the last strong hold of remaining stretches of Mangroves in Myanmar. Given the high rate of deforestation and the low remaining extent of Mangroves (1.55% of total forest area), immediate effort should be made to conserve Mangroves currently lying outside protected areas. Though efforts have been made to regenerate Mangroves in Tanintharyi [49], more effective results can be achieved by bringing large, unprotected Mangrove patches under protection status. The largest patch of the remaining Mangrove forest lies unprotected on an island in Tanintharyi Region providing an immediate opportunity for conservation (Figure 2).

Dry Deciduous forests is the third most vulnerable forest type in our study with a Conservation Status Ranking of 10.59 (Table 1). Compared to the reported national extent of 79,000 km^2 in 2011 [9] we found only 30,175 km^2 of remaining Dry Deciduous forests in 2020. Thus, in the past nine years its national extent has been reduced by ~ 62%. The Indaing forests, included in our definition of Dry Deciduous forests, are known to experience intensive anthropogenic pressure for conversion to agriculture and hydroelectric development [14,23]. Between 1973 and 2005, 62% of Indaing forests was lost at an annual rate of 1.83% [50] at CWS, which is a relatively small, protected area in Central Myanmar. Moreover, the dry forests in northern Central Dry Zone had the second highest rate (0.7%) of annual deforestation in the country between 1990-2005[14]. In 2006, 24,000 km^2 of Indaing forests was estimated in and around CWS [23]. Such regional estimate accounts for 80% of the Dry Deciduous forests (30,175 km^2) estimated by our study. This indicates the extremely low extent of Dry Deciduous forests remaining countrywide. Myanmar has the highest Dry Deciduous forest coverage in Southeast Asia [9], so our estimates highlight the overall small extent of remaining Dry Deciduous forest in entire Southeast Asia.

Though Myanmar has the largest remaining Dry Deciduous forests in Southeast Asia, very little of its vulnerable forests is protected (2.71%). In 2005, 4% of Dry Deciduous forests was protected [23] which was reduced to only ~2% in 2011 [9] and 2.71% in our study. Forest loss within protected areas in dry forests has been reported to be the highest in of South and Southeast Asia [22] in early 2000s so the reduction in the extent of Dry Deciduous forests from 4% in 2006 to ~2 in 2011 is in agreement with broader regional trends. It is interesting is that the percentage of Dry Deciduous within protected areas remained constant between 2011 (~2%) [9] and 2020 (2.17%). Thus, we assume that the ~62 reduction in extent of Dry Deciduous forests between 2011-2020 occurred outside the protected areas highlighting the urgency of protection. Dry Deciduous forests are not well represented in Myanmar's current protected area network (1.93%) and continue to face significant deforestation risk. Opportunities to increase the protected extent and improve its representation within the protected areas system exist as the largest patch of Dry Deciduous forest remains unprotected on the border of Chin and Magway in northern Myanmar, which still has most of the remaining Dry Deciduous forests in the country [9].

The Lowland Evergreen forests across entire Southeast Asia are vulnerable to deforestation due to conversion pressure to plantations [51] . Most of similar forests in insular and continental Southeast Asia have already been converted [52], thus it is no surprise that it is the fourth most vulnerable forest type in Myanmar. The Lowland Evergreen forests in Tanintharyi are especially important from the conservation perspective as they constitute the Tanintharyi Sundaic Lowland Evergreen forests [53]. These forests are highly diverse in flora and fauna, being located between the transition zone of the Indochinese and Sundaic region [54] and are among the last large stretches of remaining lowland forests in the Indochinese and Sundaic region [52,54]. The forests in Tanintharyi were protected de facto until 2011, largely due to isolation caused by political instability in the region [52]. Post 2011, widespread forest conversion to plantations (oil palm and rubber) was reported in this region [55,56]. The largest Lowland Evergreen patch in Myanmar lies in Tanintharyi, covering an area of 5479.60 km^2, with only 1.8% of it being protected within Tanintharyi Nature Reserve.

Thorn forest is a rare forest type in Myanmar covering only 0.54% (2721.86 km^2) of forest area. Much of the remaining Thorn forest only persisted because it is located in protected areas or zones that are of cultural importance —as is the case with the slopes of Mount Popa in central Myanmar. This explains why the remaining forest appears to be relatively well-protected (17.89 %). This number can be misleading without discussing the context that this forest type is extremely rare and has low representation in Myanmar's protected area network (1.15%). Although there have been localized efforts to map Thorn forests, to our knowledge our map provides a first approximation of how much is

left and where the remaining Thorn forests can be found. Efforts to increase the representation of Thorn forests may include protecting the largest patch of currently unprotected Thorn forest in Sagaing.

According to our national level accuracy assessment, Plantation was the least accurately mapped class (UA: 51.43%, PA: 45%). In Myanmar, the type of plantations is different in the north and south. The plantations in the north are generally more challenging to separate because of the relatively small scale and diverse types of agroforestry [57] that are present. Because that our field teams were unable to collect large number of plantation points in Kachin and Shan States due to active armed conflicts, the accuracy of plantation in the northern part of the country was lower than the national average. We caution the use of plantation maps alone in northern Myanmar as it is often underestimated and confused with Lowland Evergreen forests.

  In the south, however, industrial scale oil palm and rubber plantations are widespread and account for majority of the plantation land cover type. They are relatively easy to identify based on their texture (Figure 6a) and are easily separated from the surrounding forest types found such as Mangroves, Lowland and Upland Evergreen. We estimated the user's accuracy of plantation maps in the south, particularly in Tanintharyi region to gauge a regional classification accuracy in the best case scenario. We generated 150 random points within the Plantation layer in Tanintharyi and assessed the user's accuracy of the points using high resolution images on Google Earth. Among the 150 points assessed, 111 points are identified as Plantation and 39 points are Evergreen. Thus, we mapped plantations with reasonable User's Accuracy of 74% in Tanintharyi, a significant increase from the national average. our results showed that in Tanintharyi, the plantation maps have relatively high accuracy and are generally reliable.

Future directions to improve this study include:

i) Input satellite images used-

a) The new Harmonized Landsat Sentinel-2 (HLS) dataset may be used to improve the temporal frequency of imagery available for phenological analysis. Denser phenological time series information will be helpful to avoid data loss due to clouds in cloudy regions in Myanmar.

b) Using high-resolution images (<5m) from commercial small satellites like Planetscope, RapidEye, Qucikbird, Worldview etc. will help to improve the detection of the low tree cover and small fragmented forest types, like Dry Deciduous forests and Thorn forests due to more spatial details captured. Using high-resolution images (<5m) may also help to map a few other, relatively rare, and localized forest types. These include pine, oak, and rhododendron forests which occur at higher elevations, often along ridge tops and which are no included in our Upland Evergreen forest category. these forests are of high importance for biodiversity conservation and there should be increased efforts at mapping and validating maps for these forest types.

ii) Open-source ground collected data- We collected extensive ground truth data during this project with the help of our own field team in Myanmar and through local (Myanmar Forest Department) and international (UN-FAO) collaborations. Despite our sincere efforts, some parts of the country were inaccessible due to conflict. Increasing the variation and volume of training/validation data is expected to improve the forest type classification. Creating open-access data sharing mechanisms for ground collected forest type data across local and international will be key to facilitating development of more accurate forest type products not only in Myanmar but around the globe.

iii) More research into the lesser-known ecosystems such as Swamp and Thorn forests are needed.

Conclusion

In this study we developed Myanmar's first spatially explicit national level forest type map using multi-sensor satellite imagery, ancillary datasets, extensive training data and machine learning methods. Our map provides a current, accurate status of forest type extent, distribution, and protection status. We also determined the conservation and protection status of all existing forest types and identified the five most vulnerable forest types. Our maps will be able to inform future forest conservation policies, especially those related to greenhouse gas emissions, biodiversity conservation and sustainable forest management.

Methods

Study Area

Myanmar lies at the junction of South and Southeast Asia between 9°32′N to 28°31′N and 92°10′E and 101°11′E (Figure 4). It shares international borders with Bangladesh, India, China, Laos, and Thailand. Occupying an area of 678,500 km^2, it is the largest country by area in continental Southeast Asia. Administratively, Myanmar is composed of 7 Regions (formerly called Divisions, Ayeyarwady, Bago, Magway, Mandalay, Sagaing, Tanintharyi, and Yangon), 7 States (Chin, Kachin, Kayah, Kayin, Mon, Rakhine and Shan) and 1 Union Territory (Nay Pyi Taw) (Figure 4).

Physiographically, Myanmar consists of a flat Central Dry Zone that is surrounded by hill regions that represent extensions of the Himalayas. Hill and mountain regions oriented towards the Bay of Bengal, such as the south-southwest facing slopes of the Rakhine Yoma, receive some of the highest monsoon precipitation in Asia [58]. The north/northeast facing slopes and particularly the Central Dry Zone are in the rain shadow of these mountains and experience pronounced dry seasons. The variation in topography from high mountains in the north to the Bay of Bengal, along with these rainfall patterns, have given rise to wide range of diverse forest types across the country [15].

Data

To map the forest types in Myanmar, we used optical (Sentinel-2) and radar (PALSAR, Sentinel-1) images, collected between 2015 and 2020, along with ancillary datasets (Global Forest Canopy Height, 2019, Myanmar percent tree cover map of the year 2018, SRTM DEM).

Satellite Data Sources

Sentinel-2 collects multispectral satellite images consisting of 13 bands and was chosen because of its higher resolution (20m vs 30m) and greater number of spectral bands (13 vs 8) compared to Landsat-8. In our previous analysis of forest types for a selected areas of Myanmar using Sentinel-2 images significantly improved map accuracy over using Landsat-8 images due to finer spatial resolution and the unique contributions of the vegetation red edge bands [33].

The Phased Array L-band Synthetic Aperture Radar (PALSAR) is a L-band radar system widely used in mapping forests [59]. The L band allows for better penetration of the forest canopy compared to C-band Sentinel-1 and consequently provides new and additional information on forest structure [60]. We used the 25m global PALSAR/PALSAR-2 mosaic developed by [59].

Sentinel-1 collected C- band radar data. We used the VV and VH bands which have 10m resolution. Sentinel-1 radar data had finer resolution than PALSAR (10m vs 25m), and the addition of Sentine-1 C-band also brought significant

accuracy improvement in forest type maps for central Myanmar [33]. We used both, L-band PALSAR and C-band Sentinel-1 images to maximize the structural information retrieved from the ground.

Ancillary Datasets

The Myanmar percent tree cover map of the year 2018 [61] available at https://smithsonian.figshare.com/articles/dataset/Myanmar_percent_tree_cover_map_of_the_year_2018/12772490 provides information on percent tree cover value at each 30m Landsat pixel. The percent tree cover values range from 0-100%. The dataset is derived by calibrating tree-cover estimates from Landsat Vegetation Continuous Fields (VCF) tree cover layer against high-resolution estimates derived from drone imagery and other sources. The product was developed by a collaboration between Smithsonian Conservation Biology Institute and terraPulse. We used this percent tree cover map to develop a non-forest mask, allowing us to focus our mapping on forested pixels only.

The Global Forest Canopy Height dataset [62] is available at https://glad.umd.edu/dataset/gedi and provides an estimate of the forest canopy height at 30m resolution. It was developed by integrating lidar-based forest structural metrics from the Global Ecosystem Dynamics Investigation (GEDI) sensor and surface phenology information from Landsat time-series [62]. The variable forest canopy height was expected to be a predictor forest types by differentiating between tall (Evergreen) and short (Thorn) forests.

Previous research has shown that elevation, slope and aspect are a strong predictor of forest types [63]. To better assess and predict different forest types we relied on elevation, slope and aspect data which we obtained from 90m resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation data, version 4 [64].

All the images and data products except the Myanmar percent tree cover map of the year 2018 are available in GEE (https://developers.google.com/earth-engine/datasets). The Myanmar percent tree cover map of the year 2018 is available at (https://smithsonian.figshare.com/articles/dataset/Myanmar_percent_tree_cover_map_of_the_year_2018/12772490). It was uploaded into GEE as a private asset. All images and datasets were accessed through GEE.

Forest Type Classification and Field Data Collection

We developed a countrywide forest type classification suitable for satellite-based forest type mapping for Myanmar (Table S1). This classification system was based on existing literature on Burmese forests and plants [65], forest types used and defined by the Forest Department, and consultation with country experts and foresters from the Myanmar Forest Department during a workshop conducted in November 2017. The objective of this classification was to focus on mapping the dominant forest types with unique remote sensing spectral and structural characteristics. Indaing forests, a distinct edaphic type of dry dipterocarp forest in Myanmar's Central Dry Zone was included in our definition of Dry Deciduous forests as they are spectrally similar. We mapped Mangroves, Lowland and Upland Evergreen forests, Mixed Deciduous forests, Dry Deciduous forests (including Indaing), Thorn forests, and Swamp. Bamboo, a commonly occurring well-known group of grass species such as *Arundinaria* sp., *Dendrocalamus sp.*, *Thyrsostachys* sp. were also mapped as well as Plantations. The plantations mapped include oil palm, rubber and others with clear texture and row like structures.

To verify our forest type classification in the field and to collect training data, we conducted field work at 12 locations across Myanmar during the dry season in late 2018 and early 2019 (Figure 4). Field work was conducted by three

teams, consisting of three members each. Each team member had a background in forestry and/or botany and was well versed in identifying the different forest types found in Myanmar. The teams recorded latitude, longitude, elevation, forest type and photos of location acquired for 10 directions (North, North-East, East, South-East, South, South-West, West, North-West, Above, and Ground). The entries were recorded in customized forms in the Collect Mobile app (http://www.openforis.org/newwebsite/tools/collect-mobile.html) available in the Open Foris platform. The collected data included 370 data points representing different forest types.

To validate our forest type map, we compiled a validation dataset by combining ground points collected by our team (127), with the ones collected by FAO (1329) (Figure 4). The validation dataset is independent of the training dataset and consisted of a total of 1456 ground points. Each of the ground points collected by our team had a specific forest type attributed to it. The ground points collected by the FAO followed a hierarchical forest type classification. The hierarchical FAO forest types were reclassified to match our forest type definition (Table S1). The validation dataset allowed us to validate the classes Bamboo, Lowland Evergreen, Upland Evergreen, Mangrove, Mixed Deciduous Forest and Plantation. We did not have sufficient points to validate the remaining classes, Dry Deciduous, Thorn and Swamps.

Methods

We developed an open-source method to map the broad forest types in Myanmar using freely available satellite images and machine learning algorithm in GEE. Forest type maps were developed for each level 1 administrative unit (State/Region/ Union Territory) and then mosaicked to form the national forest type map. The national forest type map developed is representative of the year 2020. The overall workflow (Figure 5) of the forest type map development consists of the following steps:

1. Satellite image processing
2. Masking non-interest areas
3. Training data creation
4. Model parameterization and selection of important variables
5. Map development
6. Accuracy assessment

Satellite Image Processing

Selection, processing, and classification of the satellite images was performed in GEE. For Sentinel-2, we selected dry season surface reflectance images collected between November–April to ensure low cloud cover (<50%) and best overall image quality because of reduced haze and blue band scatter. Remaining clouds were masked using the information from QA60 band (https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-2-msi/level-1c/cloud-masks). The QA60 is a bitmask band and contains information on cloud mask. After cloud masking the image, the collection was split into monthly composites using the median pixel value in each band at each location. Each monthly composite was used to calculate Vegetation Indices including Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Soil Adjusted Vegetation Index (SAVI), Water Ratio Index (WRI), Automated Water Extraction Index (AWEI), Canopy Chlorophyll Content Index (CCCI), Sentinel-2 Red-Edge Position (S2REP) and Inverted Red-Edge Chlorophyll Index (IRECI) (Table S2). Band ratios, Normalized Difference of bands, and texture

metrics [66] were also calculated for each band in every monthly composite. Texture metrics were computed using a 3 X 3 window.

The PALSAR and Sentinel-1 images were converted to decibels and a Refined Lee Filter was run to remove speckle in the images [67]. Since the PALSAR dataset was an annual dataset no monthly compositing was done. We used the HH and HV band of the PALSAR data. The Sentinel-1 images were available for the entire year, so it was split into monthly composites. We used the 10m VV and VH bands of the Sentinel-1 images. Texture metrics were computed from each radar band of both radar satellites in a 3 X 3 window.

Finally, all the satellite datasets were resampled and stacked to create a raster stack with 20m resolution.

Masking Non-Interest Areas

To focus our image classification on forest areas within administrative boundaries, we used masks to exclude areas that were not of interest. We developed three masks, a non-forest mask, a water mask, and an area mask to ensure that we select only the forested pixels within the level 1 administrative boundaries.

For the non-forest mask, we utilized two data sources, Sentinel-2 monthly NDVI composites and the Myanmar percent tree cover map of the year 2018 [61]. Sentinel-2 monthly NDVI composites were used to exclude all pixels that had NDVI values consistently below 0.5 during the dry season. For pixels which consistently had NDVI values above 0.5 during the dry season in the Sentinel-2 monthly NDVI composites, the Myanmar percent tree cover map of the year 2018 [61] was used to further select forested pixels. For areas in the Central Dry Zone (Magway, Mandalay, and Nay Pyi Taw) that typically include dry deciduous and thorn forests with low canopy cover, we used a threshold of >10%, for Kachin State we used >35% threshold to exclude areas with cloud contamination. For the remainder of Myanmar, we used a canopy cover >30% to exclude non-forest areas.

For the water mask we selected pixels which had NDVI less than 0 in any month of the dry season. These two masks combined allowed us to remove pixels with low biomass vegetation cover with clear trend in seasonality which may be confused for forests in the Myanmar percent tree cover map of the year 2018.

The third mask, an area mask, masked all pixels outside the level 1 administrative boundary.

Training Data Creation

Training data was collected for each distinct forest type by delineating polygons for homogeneous forest pixels based on field data and overlaying high resolution images available on GEE, and Google Earth. Training polygons for each forest type were identified in high resolution and satellite images based on their characteristic texture and seasonality (Figure 6a and 6b). For example, Bamboo has a characteristic thin star shaped canopy, mature oil palms have a thicker star shaped canopy, young oil palm, rubber, tea, coffee, or any other bush/shrub plantations are planted in rows leading to typical vegetation texture, evergreen forests have green cover and constantly high NDVI throughout the year, whereas the mixed and dry deciduous forests as well as thorns have progressively higher difference in NDVI between dry and wet seasons. Mangroves were found around coastal areas and near rivers and mostly inundated. Special care was taken to include training polygons around the boundaries of each study area to ensure a smooth blending of forest types when the units are mosaiced at country level.

Model Parameterization and Selection of Important Variables

We used a random forest [68] algorithm to develop the administrative level forest type map. The random forest algorithm was run with the number of trees equal to 500 and the number of variables/split set to square root of the number of input variables.

The random forest algorithm was run twice. In the first run we selected 30 pixels from each forest type class and used all the bands and metrics computed from satellite datasets to select the top 20-25 bands which contributed to our forest type classification based on their importance value, calculated from the random forest function.

Map Development

In the second run, we used the selected bands and all the training data created to develop the forest type map. Initially, a forest type map was created for each of the 15 Level 1 administrative units (States/Regions/Union Territory) and then the 15 units were mosaiced together to derive a countrywide map. This approach enabled us to adjust the tree cover threshold regionally to include low tree cover forested pixels in Central Dry Zone which would otherwise be missed if a single countrywide tree cover threshold is used to define forested pixels.

Accuracy Assessment

A national level accuracy assessment was conducted to calculate the user's, producer's, and overall accuracy.

Protected Area Dataset and Analysis.

To assess the conservation status for different forest types, we used a shapefile for the latest existing protected areas in Myanmar [69]. The dataset included 43 existing protected areas. We considered three factors to determine the conservation status:

1. Abundance determined as the percent area of all forest areas covered by a forest type;
2. Protection Status, calculated as the percent of each forest types that is protected;
3. Conservation Representation, computed as the percent of all protected areas covered by this forest types;

Finally, the Conservation Status Score for each forest type is calculated as the sum of the previous indices: a+b+c, representing the comprehensive degree of vulnerability. Since it is a sum of three indices in percentage, its value ranges from 0-300 and its unit is percentage.

Forests with low values for the Conservation Status Ranking are rare, less protected, and not well represented in Myanmar's protected area system, making them more vulnerable than forests with higher Conservation Status Ranking. To determine the five most vulnerable forest types, we ranked the Conservation Status Score of all forest types in ascending order and identified the first five forest types.

Identifying the Largest Remaining Patches by Forest Type

We were also interested in providing maps of the largest remaining forest patch for the five most vulnerable forest type. Such maps may provide guidance for the development of new protected areas. To identify the largest remaining patches of forest, we clumped connecting forested pixels together in ArcGIS[70] for each of three forest types using the regiongroup algorithm. Based on these clusters we then identified the largest remaining patch. For each of the vulnerable forest types identified, we determined the location, extent, and protection status of the largest remaining patch.

Declarations

Data Availability

The forest type map developed and associated metadata are available on Figshare at https://smithsonian.figshare.com/articles/figure/Myanmar_Forest_Type_Map_2020/16613818

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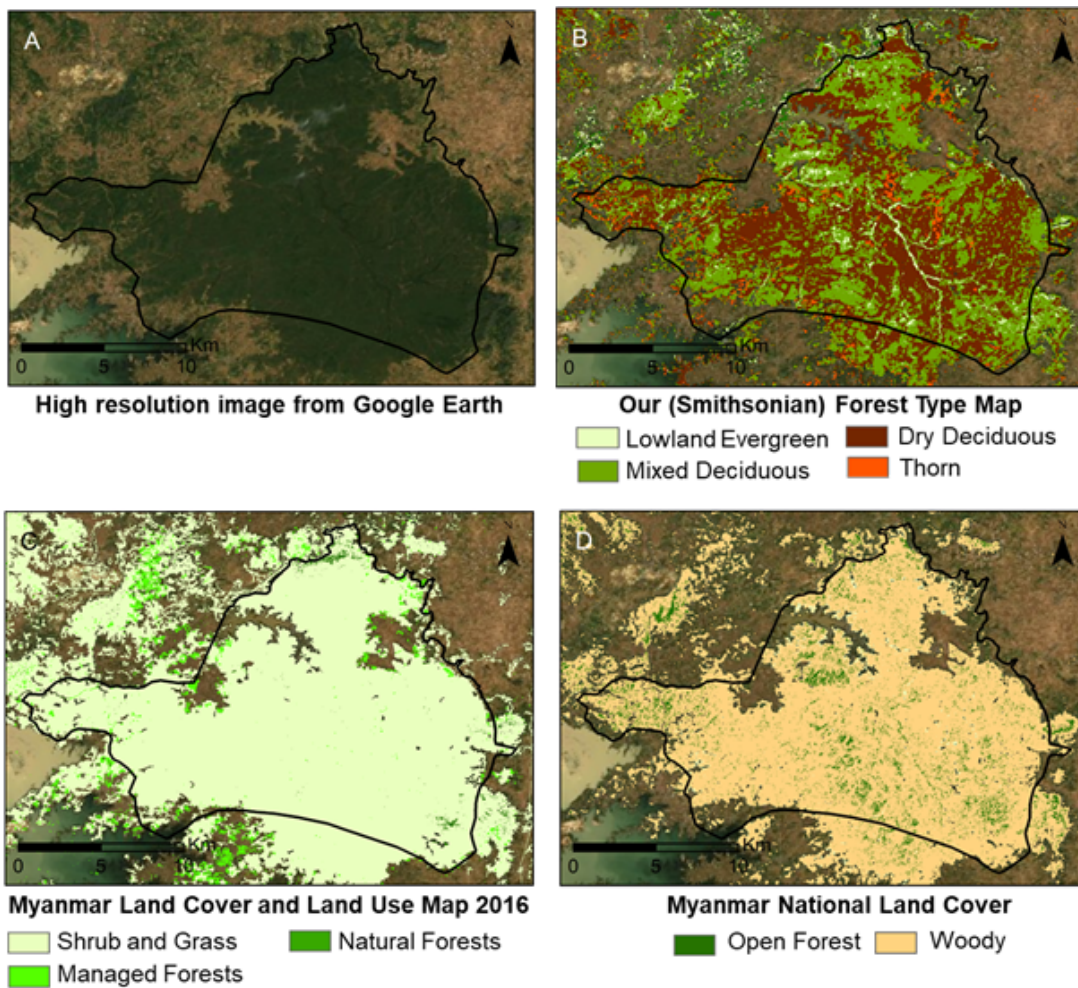
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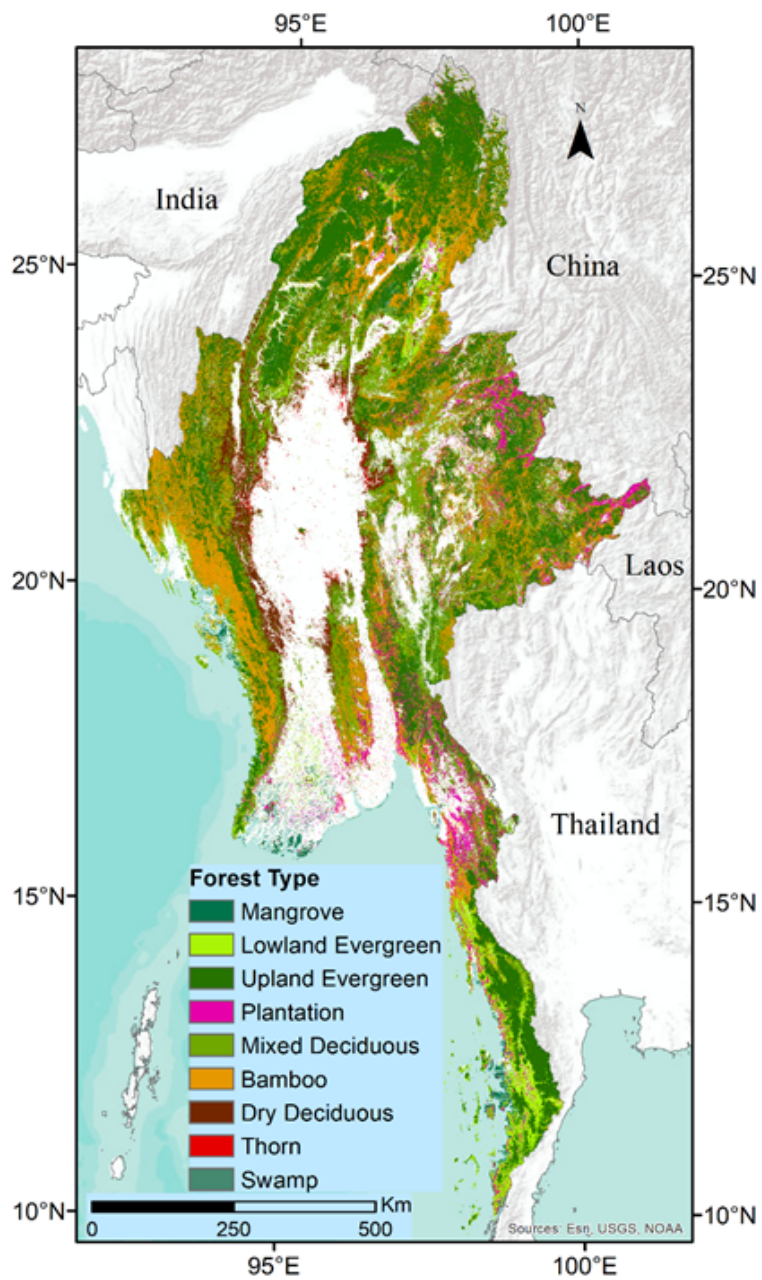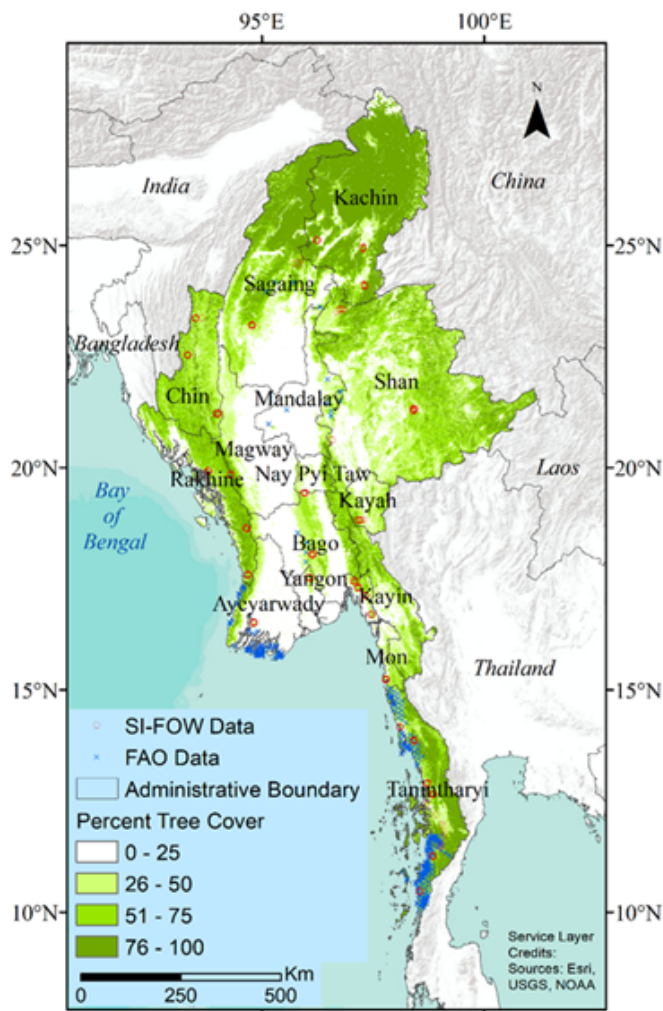
Figure 1

Forest Types of Myanmar
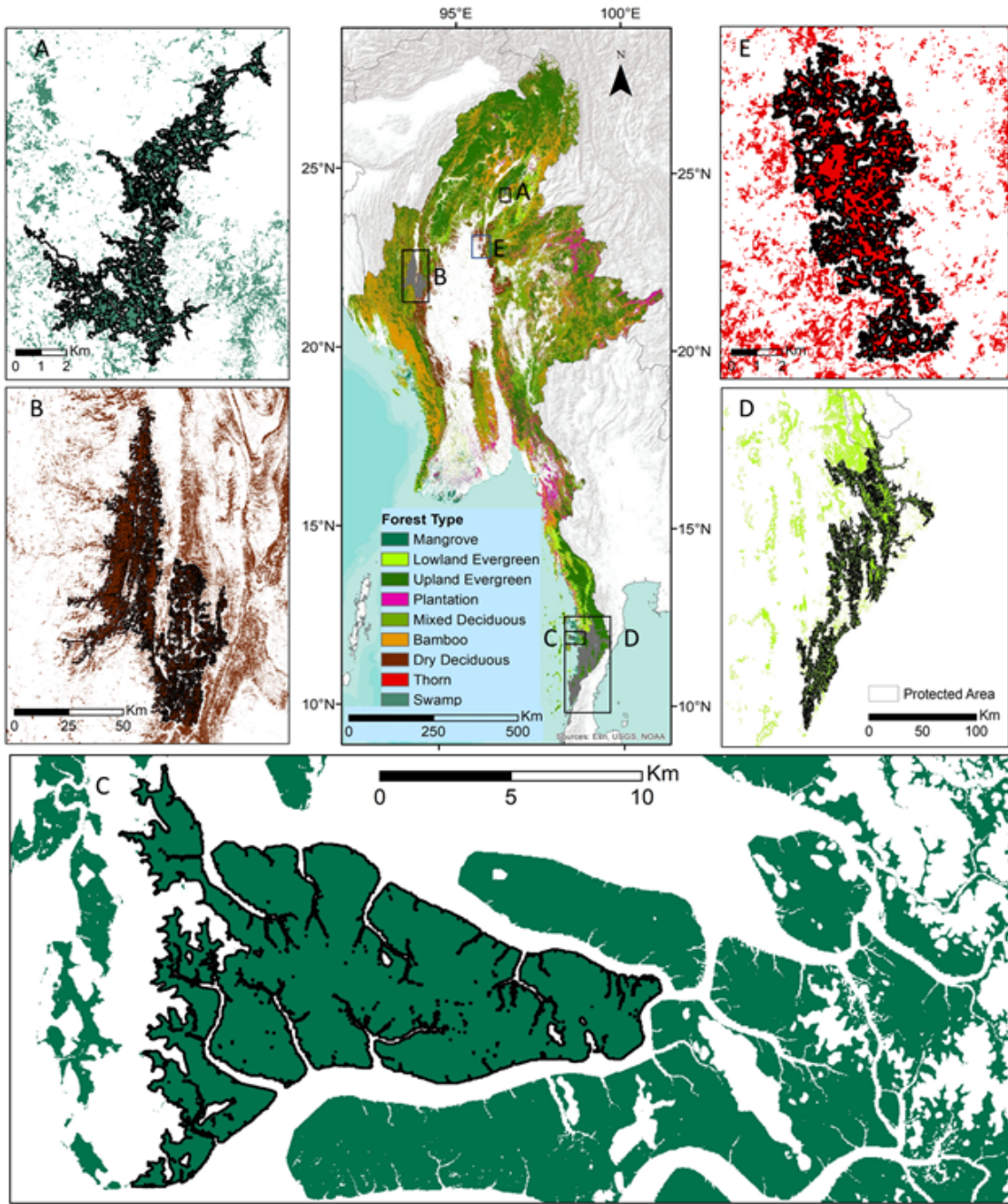
Figure 2

Location of the largest remaining patch for each of the four most vulnerable forest types. The largest identified patch is outlined in Black color. A. Location of the largest Swamp patch on the border of Kachin and Sagaing. B. Location of the largest Dry Deciduous forest patch near the border of Chin and Magway. C. Location of the largest Mangrove patch on an island just off the coast of Tanintharyi. D. Location of the largest Lowland Evergreen patch in Tanintharyi. E. Location of the largest patch of Thorn in Sagaing.
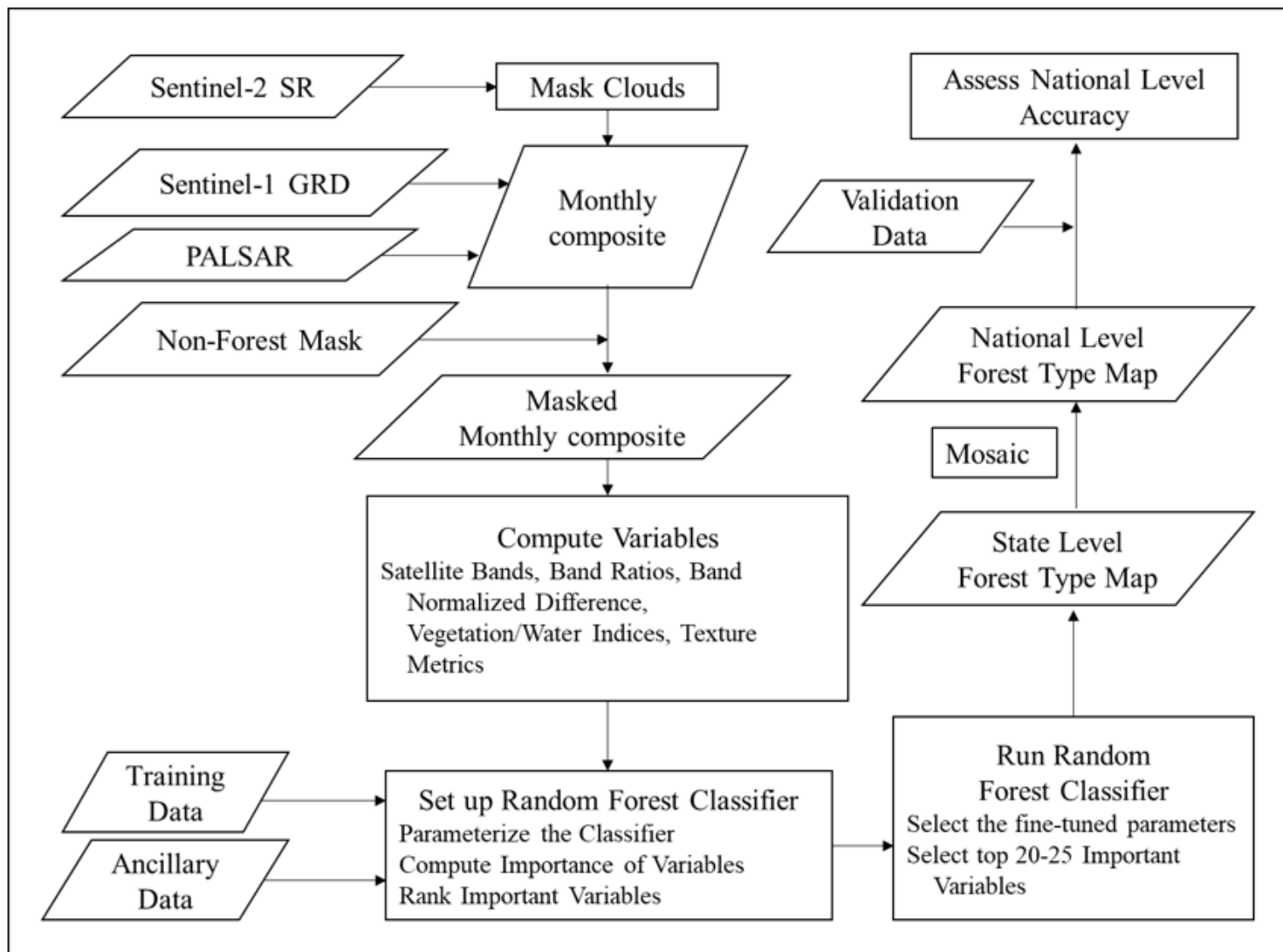
Figure 3

Comparing the detection of Dry Deciduous forests in Chatthin Wildlife Sanctuary among three maps. A. High resolution image of the Area of Interest (AOI) from Google Earth. B. This study, showing the dominant presence of Dry Deciduous forests within the AOI. C. Land cover land use map for Myanmar at 30-m resolution for 2016 [35] showing the Shrub and Grassland as the dominant land cover in the AOI. D. Myanmar National Land Cover Monitoring System (LCMS)[36], showing the dominant land cover within the AOI as Woody.
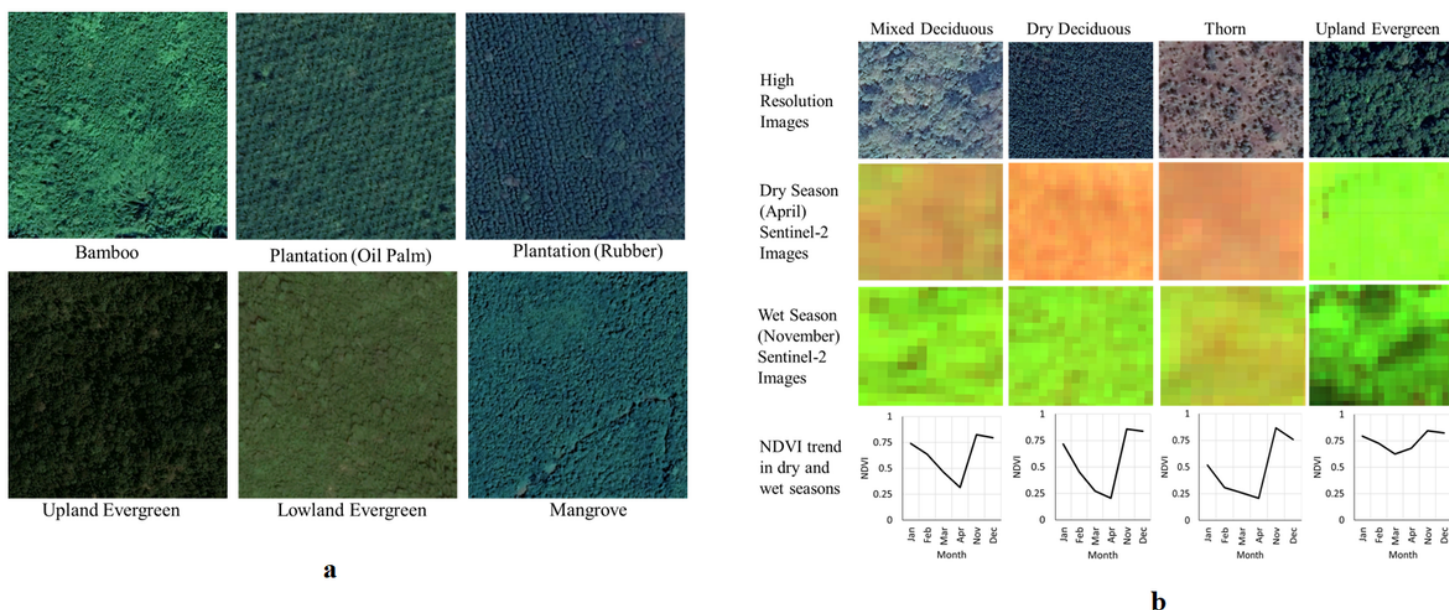
Figure 4

Map of Study Area. The background shows percent tree cover ranging from 0-100 (Wang et al., 2020). The red circle and blue cross show areas where field data collected by Smithsonian Institution-Friends of Wildlife (SI-FOW) and UN-FAO (FAO).

Figure 5

Diagram showing the outline of the adopted methodology.

Figure 6

a. Characteristic texture used to identify the different forest types and plantations.

b. Phenological information from Sentinel-2 used to identify the seasonal forests. False Color Composites for Dry (April) and Wet (November) season are displayed in band combinations B11, B8, B3 in Red, Green and Blue channels.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformationSR.docx