Research Progress Report for

NASA LCLUC Grant "Mapping industrial forest plantations in tropical monsoon Asia through integration of Landsat and PALSAR imagery"

(NNX14AD78G, 4/1/2014 – 3/31/2017, with no-cost extension to 3/31/2020)

The areas of industrial forest plantations have expanded enormously in recent years across tropical and subtropical regions, in particular tropical monsoon Asia. For example, there are ~10 million ha of rubber plantations in the world, and about 97% of global natural rubber supply comes from Southeast Asia. Since 1990, the harvested area of oil palm in Indonesia and Malaysia has expanded by 6.5 million ha and accounts for ~87% of global palm oil production. Forest plantations in tropical monsoon Asia are significant components of rural livelihoods and national economies. Conversion of natural forests, secondary regrowth and non-forested lands to monoculture forest plantations has a profound impact on water resources, carbon cycles, and biodiversity. The primary goal of this project is to identify and map the area, spatial distribution and temporal dynamics of industrial forest plantations in tropical monsoon Asia.

Here we briefly summarize the outcomes under the support of this project. We have developed a set of new approaches to identify and map the spatio-temporal dynamics of forest, evergreen forest, industrial plantations, and biomass in southeast Asia. We have published 24 peer review journal papers, including *Nature Sustainability*, *Nature Plants*, *Nature Communications*. The project trained three postdoc and support two students who completed graduate study with Ph.D. degree at the University of Oklahoma.

A. Algorithm development, application, and data products

Here we highlight three major outputs of this project: (1) forest maps: PALSAR + time series MODIS/Landsat-based forest mapping approach, (2) industrial forest maps: PALSAR + Sentinel-1 + time series Landsat-based industrial forest mapping approach, and (3) deciduous rubber plantation maps: PALSAR+Landsat plantation mapping approach.

A1. Improved forest maps.

<u>Algorithm development and products.</u> We developed a pixel-, phenology-based approach and generated PALSAR/MODIS forest map in monsoon Asia (Figure 1) through the integration of structure- and biomass-relevant information from active microwave remote sensing imagery (ALOS PALSAR) and greenness-relevant information from time series optical remote sensing imagery (MODIS) (Qin et al. 2016; Qin et al. 2015). This product reduces the uncertainties in forest maps, in comparison to those forest maps that were developed by using only optical or active microwave remote sensing images. We also carried out the area and spatio-temporal changes of forests during 2007-2015 using the PALSAR and Landsat images (Chen et al. 2018b).

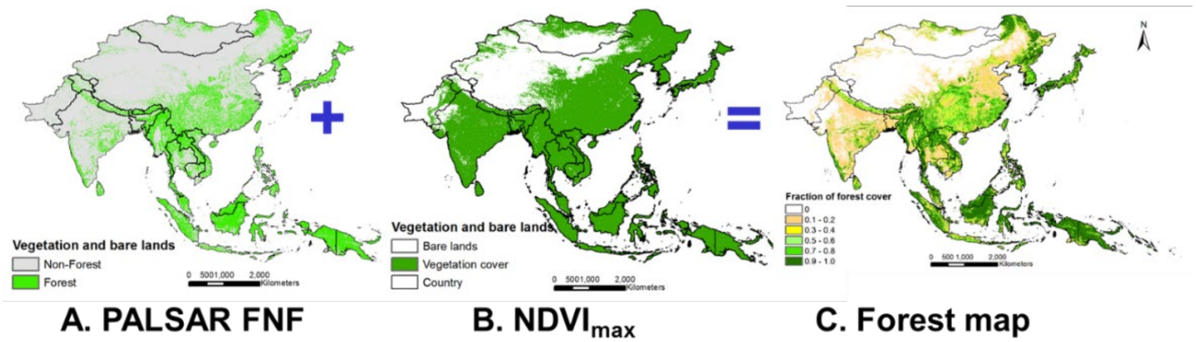


Figure 1. The PALSAR and time series MODIS imagery-based forest map in monsoon Asia.

Based on the PALSAR/MODIS forest map (50-m spatial resolution), we developed an evergreen forest mapping approach (Qin et al. 2016; Qin et al. 2019) based on the greenness-related Enhanced Vegetation Index (EVI) and water-related Land Surface Water Index (LSWI) derived from daily MOD09A1 (MODIS/Terra Surface Reflectance 8-Day L3 Global 500 m SIN Grid) observations. The evergreen forest mapping approach has been successfully applied in monsoon Asia (Figure 2), showing improvement to current evergreen forest maps (Qin et al. 2016). The PALSAR/MODIS forest mapping approach and the evergreen forest mapping approach provide robust forest mapping tools and high accuracy baseline maps to identify and map industrial forest plantation maps.

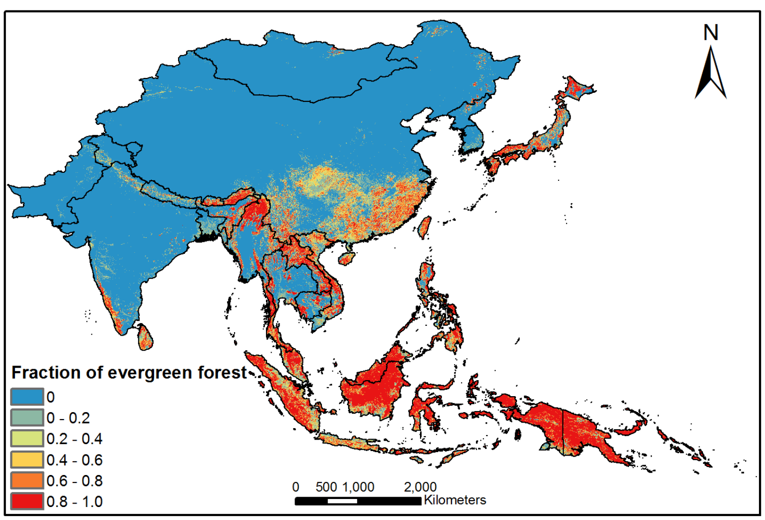


Figure 2. The area fraction of evergreen forests within individual gridcells in monsoon Asia.

Applications: Our PALSAR/MODIS forest mapping approach was further evaluated and successfully applied to map annual forests in South America (Figure 3) (Qin et al. 2017b). Our evergreen forest mapping approach was successfully applied to track the area and spatio-temporal dynamics of forests in the Brazilian Amazon during 2000-2017 (Figure 4), which is published in *Nature Sustainability* (Qin et al. 2019). The comparison between our PALSAR/MODIS forest maps and evergreen forest maps with several major forest cover maps clearly highlights the potential of our approaches in improving map accuracy and reducing map uncertainty in the tropical zone (Qin et al. 2019; Qin et al. 2017b).

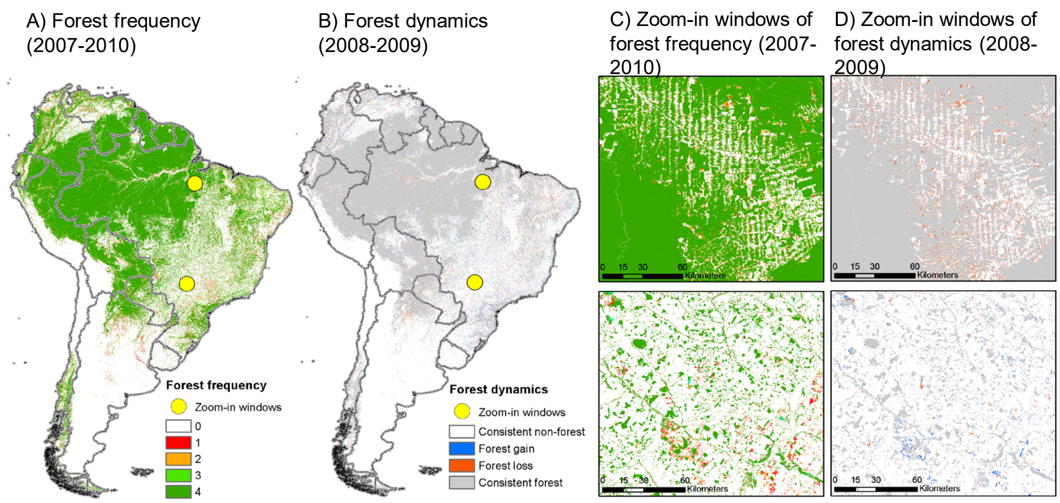


Figure 3. Forest frequency and dynamics of the PALSAR/MODIS forest maps in South America.

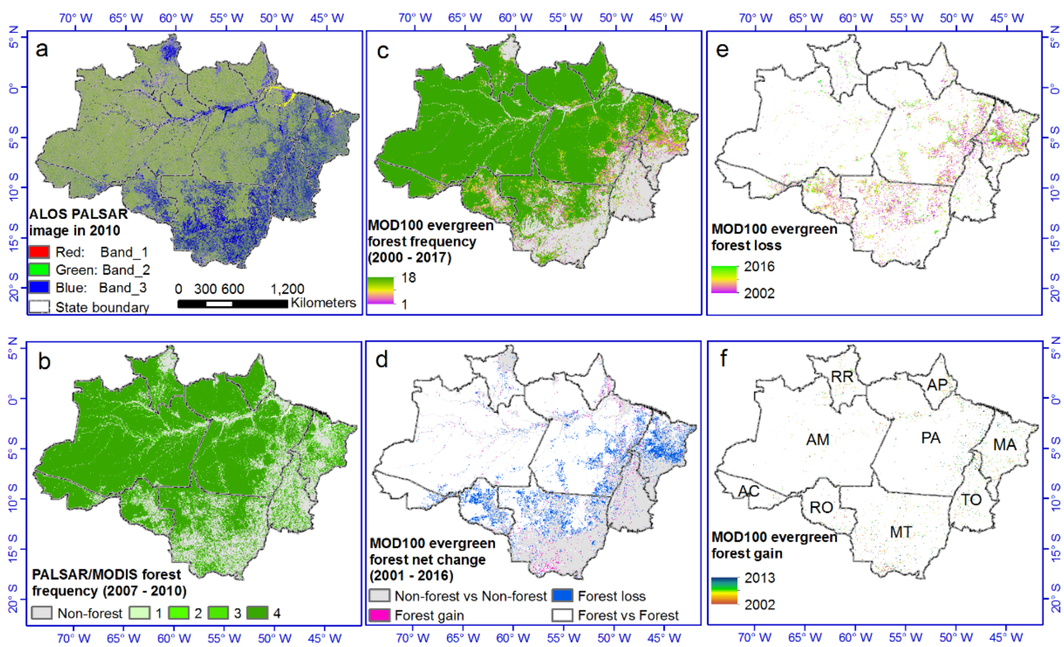


Figure 4. Spatial distributions of forests in the Brazilian Amazon during 2000–2017.

To improve the understanding of the tropical forest phenology and biomass changes, high accuracy forest maps are urgently needed. Our evergreen forest maps have been used to support another study that aimed to address the debate if Amazon forests greens up during the dry season, which was published in *PNAS* journal by our group (Doughty et al. 2019). Our evergreen forest maps have also been used to analyze the inter-annual relationship between tropical forest area change and biomass change, which was published in *Nature Plants* (Fan et al. 2019) and Drs. Xiao and Qin are co-authored in this paper.

Our PALSAR/MODIS forest maps have been used as the baseline map to identify and map industrial plantations in Southeast Asia. Please see details in section A2. Besides, the PALSAR/MODIS forest maps help the algorithm development for mapping urban areas (Qin et al. 2017a) and rice paddy (Zhang et al. 2020; Zhang et al. 2017) in monsoon Asia. The resultant paddy rice maps were published in a recent paper in *Nature Communications* (Zhang et al. 2020).

On-going studies. We have generated annual global PALSAR/MODIS forest maps at 50 m spatial resolution. We are working on the data analysis and manuscript writing (Qin et al., in preparation). We also completed an analysis of evergreen tropical forests in recent 20 years and are writing a manuscript (Qin et al., in preparation).

A2. Industrial forest plantation mapping.

Algorithm development and products. We developed an approach to identify and map industrial forests from Myanmar and Indonesia (Figure 5) using three new datasets, including PALSAR-2, Sentinel-1, and Landsat-8 (Torbick et al. 2016). We used over ten variables, including common ratios, vegetation indices, and texture indices, and then used the CART-Random Forest approach to map industrial forest plantations.

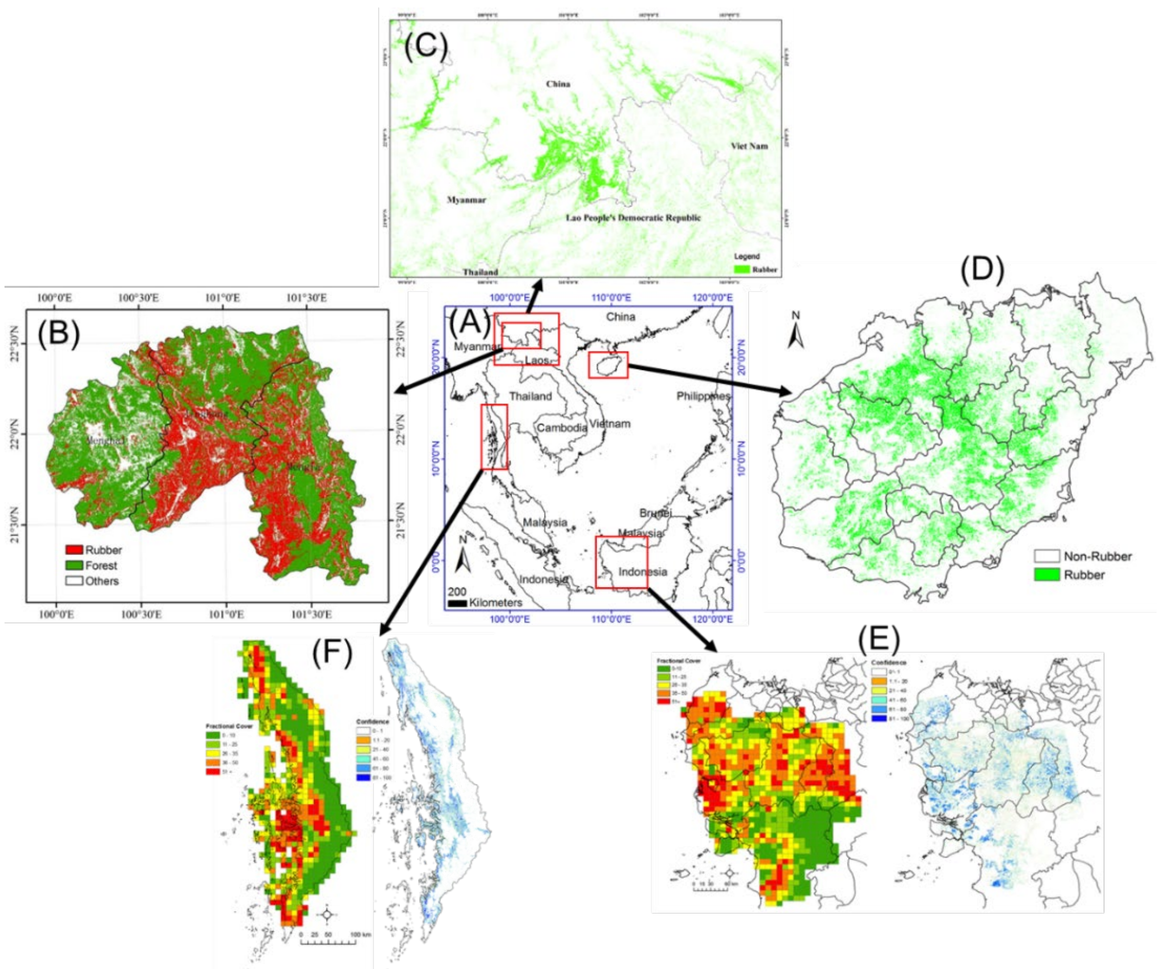
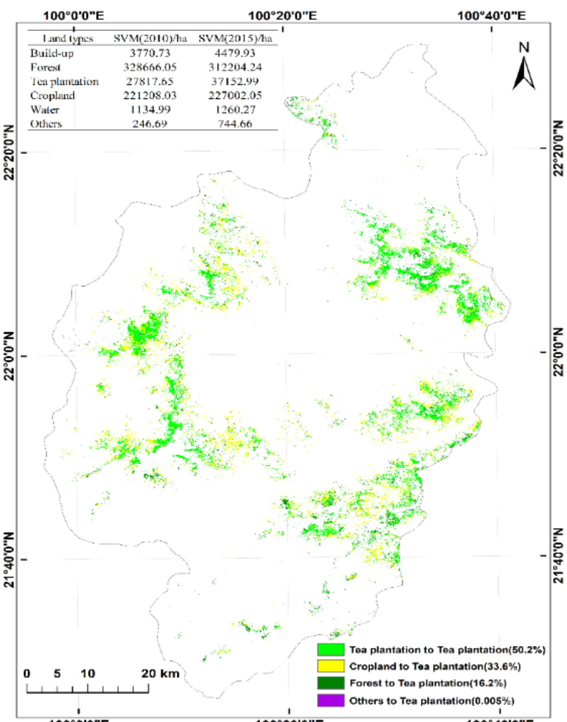


Figure 5. Industrial forest maps and deciduous rubber plantation maps in typical regions (A) in monsoon Asia. (B-D) are deciduous rubber plantation maps and (E-F) are industrial forest maps.

We developed annual maps of rubber plantation at specific years. We developed a PALSAR + time series Landsat-based approach to identify and map deciduous rubber plantation in China and southeast Asia (Figure 5) based on its unique phenology features (Chen et al. 2016; Dong et al. 2013). We used field photos to track the phenology of deciduous rubber plantation, which has a rapid defoliation and foliation process in January and February. We also analyzed the phenology of deciduous rubber plantation using the temporal profiles of time series Landsat NDVI, EVI, LSWI and Near-Infrared (NIR) reflectance. Compared with other types of natural forests, deciduous rubber plantation is distinguishable in the defoliation stage or rapid foliation stage, which was used to map deciduous rubber plantation.

We used the machine learning and developed an approach to identify tea plantations using the PALSAR and time series Landsat images. We then analyzed the area and spatio-temporal changes of tea plantation during 2010-2015(Figure 6).

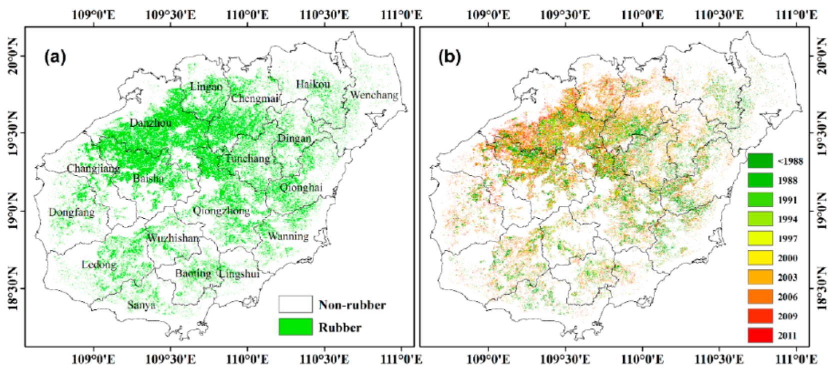
We also developed a new classification algorithm to map mangrove forests in 2015 using time series Landsat and Sentinel-1A images (Chen et al. 2017). More specifically, we map mangrove forests by identifying: (1) greenness, canopy coverage, and tidal inundation from time series Landsat data, and (2) elevation, slope, and intersection-with-sea criterion. The annual mean NDVI was found to be a key variable in determining the classification thresholds of greenness, canopy coverage, and tidal inundation of mangrove forests, which are greatly affected by tide dynamics. In addition, the integration of Sentinel-1A VH band and modified Normalized Difference Water Index (mNDWI) shows great potential in identifying yearlong tidal and freshwater bodies, which is related to mangrove forests.



Land types	SVM(2010)/ha	SVM(2015)/ha
Build-up	3770.73	4479.93
Forest	328666.05	312204.24
Tea plantation	27817.65	37152.99
Cropland	221208.03	227002.05
Water	1134.99	1260.27
Others	246.69	744.66

Figure 6. map of change in tea plantation area from 2010 to 2015 at 30-m spatial resolution.

Applications: Based on the approach to identify deciduous rubber plantations, we developed an approach to identify the establishment years of rubber plantations, as plantation stand (establishment) age is an important factor in management and production. It is also important to identify the pre-conversion land cover types for new rubber plantations (e.g., from older rubber plantations, forests, croplands). We have developed Landsat-based approach (Landsat 5/7/8, TM/ETM+/OLI) to identify and map both establishment years (Figure 7) (Kou et al. 2015) (Chen et al. 2018a; Kou et al. 2018) and pre-conversion land cover types of rubber plantations (Chen et al. 2018a).



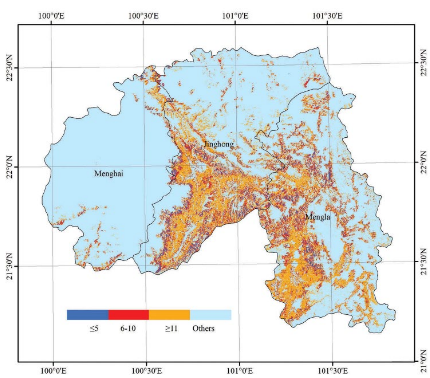


Figure 7. (**a**) rubber plantations in 2015 and (**b**) their establishment year on Hainan Island. (c) The establishment year of rubber plantations in Xishuangbanna.

On-going studies. We have generated deciduous rubber plantation maps in monsoon Asia, and we are writing the manuscript (Chen et al., in preparation). We have developed robust models (Figure 8) to estimate the biomass of rubber plantations in southeast Asia and are ready to submit it to *Remote Sensing of Environment* (Chen et al. in preparation).

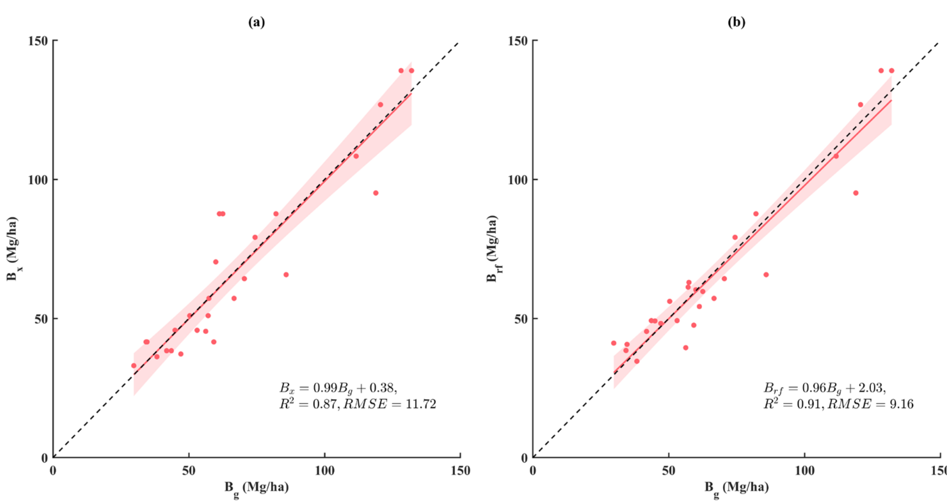


Figure 8. Biomass of rubber plantation in Hainan Island estimated by (a) allometric equation with stand age, (b) random forest model.

C. Service and contribution to the remote sensing community

We have organized several successful activities to communicate with worldwide researchers and promote and deepen the studies in mapping industrial forest plantations. We have organized a special issue "Mapping the Dynamics of Forest Plantations in Tropical and Subtropical Regions from Multi-Source Remote Sensing" in Remote Sensing journal, American Geographical Union (AGU) sessions in 2015-2019, and have published fifteen papers that document the classification methodologies and data products of forests and industrial plantations in tropical and subtropical regions. We have collected 25,000+ geo-referenced field photos as the training and validation ground reference from crowdsourcing and local citizen scientists in tropical monsoon Asia (http://www.eomf.ou.edu/photos/map/).

Publications from the project

Chen, B.Q., Li, X.P., Xiao, X.M., Zhao, B., Dong, J.W., Kou, W.L., Qin, Y.W., Yang, C., Wu, Z.X., Sun, R., Lan, G.Y., & Xie, G.S. (2016). Mapping tropical forests and deciduous rubber plantations in Hainan Island, China by integrating PALSAR 25-m and multi-temporal Landsat images. *International Journal of Applied Earth Observation and Geoinformation, 50*, 117-130

Chen, B.Q., Xiao, X.M., Li, X.P., Pan, L.H., Doughty, R., Ma, J., Dong, J.W., Qin, Y.W., Zhao, B., Wu, Z.X., Sun, R., Lan, G.Y., Xie, G.S., Clinton, N., & Giri, C. (2017). A mangrove forest map of China in 2015: Analysis of time series Landsat 7/8 and Sentinel-1A imagery in Google Earth Engine cloud computing platform. *Isprs Journal of Photogrammetry and Remote Sensing, 131*, 104-120

Chen, B.Q., Xiao, X.M., Wu, Z.X., Yun, T., Kou, W.L., Ye, H.C., Lin, Q.H., Doughty, R., Dong, J.W., Ma, J., Luo, W., Xie, G.S., & Cao, J.H. (2018a). Identifying Establishment Year and Pre-Conversion Land Cover of Rubber Plantations on Hainan Island, China Using Landsat Data during 1987-2015. *Remote Sensing, 10*

Chen, B.Q., Xiao, X.M., Ye, H.C., Ma, J., Doughty, R., Li, X.P., Zhao, B., Wu, Z.X., Sun, R., Dong, J.W., Qin, Y.W., & Xie, G.S. (2018b). Mapping Forest and Their Spatial-Temporal Changes From 2007 to 2015 in Tropical Hainan Island by Integrating ALOS/ALOS-2 L-Band SAR and Landsat Optical Images. *Ieee Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 11*, 852-867

Dong, J.W., Xiao, X.M., Chen, B.Q., Torbick, N., Jin, C., Zhang, G.L., & Biradar, C. (2013). Mapping deciduous rubber plantations through integration of PALSAR and multi-temporal Landsat imagery. *Remote Sensing of Environment, 134*, 392-402

Doughty, R., Kohler, P., Frankenberg, C., Magney, T.S., Xiao, X., Qin, Y., Wu, X., & Moore, B., 3rd (2019). TROPOMI reveals dry-season increase of solar-induced chlorophyll fluorescence in the Amazon forest. *Proc Natl Acad Sci U S A, 116*, 22393-22398

Fan, L., Wigneron, J.P., Ciais, P., Chave, J., Brandt, M., Fensholt, R., Saatchi, S.S., Bastos, A., Al-Yaari, A., Hufkens, K., Qin, Y., Xiao, X., Chen, C., Myneni, R.B., Fernandez-Moran, R., Mialon, A., Rodriguez-Fernandez, N.J., Kerr, Y., Tian, F., & Penuelas, J. (2019). Satellite-observed pantropical carbon dynamics. *Nat Plants, 5*, 944-951

Kou, W.L., Dong, J.W., Xiao, X.M., Hernandez, A.J., Qin, Y.W., Zhang, G.L., Chen, B.Q., Lu, N., & Doughty, R. (2018). Expansion dynamics of deciduous rubber plantations in Xishuangbanna, China during 2000-2010. *Giscience & Remote Sensing, 55*, 905-925

Kou, W.L., Xiao, X.M., Dong, J.W., Gan, S., Zhai, D.L., Zhang, G.L., Qin, Y.W., & Li, L. (2015). Mapping Deciduous Rubber Plantation Areas and Stand Ages with PALSAR and Landsat Images. *Remote Sensing, 7*, 1048-1073

Qin, Y.W., Xiao, X.M., Dong, J.W., Chen, B.Q., Liu, F., Zhang, G.L., Zhang, Y., Wang, J., & Wu, X.C. (2017a). Quantifying annual changes in built-up area in complex urban-rural landscapes from analyses of PALSAR and Landsat images. *Isprs Journal of Photogrammetry and Remote Sensing, 124*, 89-105

Qin, Y.W., Xiao, X.M., Dong, J.W., Zhang, G.L., Roy, P.S., Joshi, P.K., Gilani, H., Murthy, M.S.R., Jin, C., Wang, J., Zhang, Y., Chen, B.Q., Menarguez, M.A., Biradar, C.M., Bajgain, R., Li, X.P., Dai, S.Q., Hou, Y., Xin, F.F., & Moore, B. (2016). Mapping forests in monsoon Asia with ALOS PALSAR 50-m mosaic images and MODIS imagery in 2010. *Scientific Reports, 6*

Qin, Y.W., Xiao, X.M., Dong, J.W., Zhang, G.L., Shimada, M., Liu, J.Y., Li, C.G., Kou, W.L., & Moore, B. (2015). Forest cover maps of China in 2010 from multiple approaches and data sources: PALSAR, Landsat, MODIS, FRA, and NFI. *Isprs Journal of Photogrammetry and Remote Sensing, 109*, 1-16

Qin, Y.W., Xiao, X.M., Dong, J.W., Zhang, Y., Wu, X.C., Shimabukuro, Y., Arai, E., Biradar, C., Wang, J., Zou, Z.H., Liu, F., Shi, Z., Doughty, R., & Moore, B. (2019). Improved estimates of forest cover and loss in the Brazilian Amazon in 2000-2017. *Nature Sustainability, 2*, 764-772

Qin, Y.W., Xiao, X.M., Dong, J.W., Zhou, Y.T., Wang, J., Doughty, R.B., Chen, Y., Zou, Z.H., & Moore, B. (2017b). Annual dynamics of forest areas in South America during 2007-2010 at 50m spatial resolution. *Remote Sensing of Environment, 201*, 73-87

Torbick, N., Ledoux, L., Salas, W., & Zhao, M. (2016). Regional Mapping of Plantation Extent Using Multisensor Imagery. *Remote Sensing, 8*

Zhang, G., Xiao, X., Dong, J., Xin, F., Zhang, Y., Qin, Y., Doughty, R.B., & Moore, B. (2020). Fingerprint of rice paddies in spatial–temporal dynamics of atmospheric methane concentration in monsoon Asia. *Nature Communications, 11*, 554

Zhang, G.L., Xiao, X.M., Biradar, C.M., Dong, J.W., Qin, Y.W., Menarguez, M.A., Zhou, Y.T., Zhang, Y., Jin, C., Wang, J., Doughty, R.B., Ding, M.J., & Moore, B. (2017). Spatiotemporal patterns of paddy rice croplands in China and India from 2000 to 2015. *Science of the Total Environment, 579*, 82-92