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Extreme Development of Dragon Fruit Agriculture with Nighttime Lighting in Southern Vietnam

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Abstract

Dragon fruit is widely grown in Southeast Asia and other tropical or subtropical regions. As a high-value cash crop ideal for exportation, dragon fruit cultivation has boomed during the past decade in the southern Vietnam. Light supplementing during the winter months using artificial lighting sources is a widely adopted cultivation technique to boost the productivity in the major dragon fruit planting regions of Vietnam. The application of the electric lighting at night leads to a significant increase of nighttime light (NTL) observable by satellite sensors. The strong seasonality signal of NTL in the area of dragon fruit cultivation enables the identification of dragon fruit plantations using NTL images. We employed Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB) monthly nighttime imagery from 2012 to 2019 to extract the growing area of dragon fruit in Bình Thuận Province, the largest dragon fruit growing region of Vietnam. Breakpoint for Additive Seasonal Trend (B-FAST) analysis was applied to calculate the seasonality of NTL inside the dragon fruit plantations and distinguish them from the background. The results indicated that the dragon fruit cultivation strongly increased after 2014 and reached a plateau after 2017. In recent years, the area of dragon fruit cultivation has experienced a slight decrease due to market fluctuations. We applied a buffer analysis over the largest dragon fruit cultivation area in Bình Thuận to analyze the spatial trend of the expansion of dragon fruit planting. Our results suggest that the dragon fruit cultivation of Bình Thuận has expanded to cover most inter-hill plains, reaching a spatial extent capacity due to the topographical constraints, and thus has begun to encroach into the low-elevation foothill area. In the case of emergency lock-down orders in February 2020 during the COVID-19 pandemic, NTL used for dragon fruit cultivation changed heterogeneously in time and space driven by market price and shipping limitations far away from the local restrictions. Under the dual rural-urban hot spot situation with strong and contemporaneous developments of both dragon fruit agriculture together with urban tourism industry, building structures were detected densely in city and gradually dispersed well into the rural landscape of the Dragon Kingdom in Bình Thuận. The outcomes of this study will be valuable for local policymakers to obtain a better understanding of the available area for dragon fruit cultivation and achieve a better-coordinated cultivation planning against future fluctuations of global market, while providing insights and new understanding into the dual hot-spot developments valuable for planning rural-urban change strategies.

Keywords: Dragon fruit agriculture, urbanization, dual hot spot, COVID-19, nighttime light, radar
1. Introduction

Dragon fruit, also known as pitahaya or pitaya (*Hylocereus undatus*), is the fruit of several different cactus species (*Cactaceae* family) indigenous to the Americas and is widely grown in Southeast Asia and other tropical or subtropical regions. As a high-value cash crop ideal for exportation, dragon fruit cultivation has boomed during the past decade in southern part of Vietnam, where the fruit production in 2016 reached one million metric tons valued toward a billion USD (Paull and Chen, 2019).

Currently, the development of pitaya plantations has been a haphazard process with an array of uncoordinated personal efforts by farmers who are self-driven by market fluctuations (Nguyen et al., 2019). A complete and systematic regional mapping is needed to serve as the first full reference of the dragon fruit agriculture in Vietnam. Yet the existing global land cover/land use (LCLU) products are insufficient as there have been limited mapping initiatives targeting Vietnam and the nearby Southeast Asian countries to discern especially pitaya plantations among multiple agricultural land types such as rice paddies, orchards, and others.

Recently, the Japan Aerospace Exploration Agency (JAXA) Earth Observation Research Center (EORC) has published an annual LCLU mapping product for Vietnam at 10-m resolution from 2015 to 2018 (JAXA, 2020), extracted from Advanced Land Observing Satellite-2 (ALOS-2) Phased Array type L-band Synthetic Aperture Radar (PALSAR-2). Although this product separates orchard from other agricultural land types, the orchard class may mix multiple types of tropical fruit plantations. Obtaining a specialized mapping product for dragon fruit is still much needed and can be achieved by utilizing the unique nighttime light (NTL) radiance and its seasonality signal, which are distinctively different from urban NTL characteristics (Krauser, 2020).

This study seeks to delineate the dragon fruit plantations in southern Vietnam with NTL variability. Unlike consistently lit regions such as cities, the NTL radiance of dragon fruit plantations fluctuates with growing seasons, as growers of dragon fruit apply turn on light bulbs during the winter months to supplement daytime solar radiation with artificial lighting to sustain the production of dragon fruit plants. This unique seasonal pattern of NTL can be applied to distinguish dragon fruit plantations from other lit-up regions. Conducted on a yearly basis, we can extract the boundaries of dragon fruit plantations of Vietnam and conduct an inter-annual change of dragon fruit growth in Vietnam’s most prominent dragon fruit growing region.

This research presented here advances Earth Observation analysis specific to LULC mapping to explore the temporal trends for an important cash crop that recently soared as an agricultural hot spot in Vietnam. Moreover, the case of the COVID-19 pandemic in 2020 is examined to assess disaster impacts on the pitaya production physically and economically. The research results will provide crucial information for local governments to plan for a better coordinated planting strategy against global market fluctuations.
2. Study area

Vietnam is the largest pitaya supplier to the world (Luong and Nguyen, 2015), where the extensive pitaya plantations have been developed in the provinces of Bình Thuận, Long An, and Tien Giang. The three southern provinces account for 92% of the total land area of dragon fruit cultivation and 96% of dragon fruit output for Vietnam. Bình Thuận Province accounts for 63.2% of the land area and 68.4% of the output of dragon fruit, and is known as the “Dragon Kingdom.” Located in the south-central coastal zone of Vietnam with arid desert-like conditions on the flat landscape, the province is particularly suitable to grow the pitaya cactus (Hoat et al., 2018). In contrast, Long An Province has a low and flat landscape in the Mekong Delta region of southern Vietnam that is subject to flooding in the rainy season (Long An Province Government, 2020), where the local agriculture has been converted into pitaya cultivation due to the high cash return.

![Figure 1](image1.png)

**Figure 1.** Lighting at night in a plantation of dragon fruit in Bình Thuận Province. The upward shining nightlight can be observed with a high intensity in satellite NTL imagery. The inset shows freshly harvested dragon fruits with a red skin. Photos by S. V. Nghiem, February 2020.

![Figure 2](image2.png)

**Figure 2.** VIIRS DNB image in February 2020. Lighting in the dragon fruit plantation regions in Bình Thuận and Long An is much more intense than that in Hồ Chí Minh City, the most populous city in Vietnam with extensive lighting at night. Inset is the city photo at night taken by S. V. Nghiem.
The latest planting techniques of dragon fruit use a nighttime light supplement (Figure 1) to drive the photoconversion process of phytochromes in order to stimulate flowering on plants and enhance fruit yield (Rockwell and Lagarias, 2006). The wide adoption of these techniques across the Vietnamese agricultural landscape has led to a unique NTL seasonal signal detectable from space. During the peak of the growing season for dragon fruit, the NTL radiance from dragon fruit plantations is intense and even dwarfs the night light radiance signal emitted from Hồ Chí Minh City, the largest and most populous city in Vietnam (Figure 2).

3. Data and analysis methods

Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB) nighttime imagery was utilized as a source of NTL images of this study. Specifically, we used the 750-m monthly composite product of VIIRS DNB with the maximum stray light corrected brightness from 2012 to 2019. This VIIRS NTL dataset filters stray light contamination depending on the position of the satellite and a contrast ratio based on moonless nights (Lee and Cao, 2016).

Compared with the previous generation of NTL products from the Operational Linescan System flown on the Defense Meteorological Satellite Program (DMSP-OLS) satellites, VIIRS DNB images are better validated and calibrated across years, making the inter-annual comparison much easier. So far, VIIRS DNB images have been adopted to map the boundaries of built-up area in cities and document the change of human activities (Elvidge et al., 1999; Nghiem et al., 2014; Small and Sousa, 2016). The application of VIIRS DNB images in mapping other human-induced land cover types such as agricultural land is scarce, particularly for use in dragon fruit agriculture.

![Figure 3. NTL variations: (a) Average NTL of dry season (winter, from October to December) and wet season (summer, from April to July), and (b) B-FAST NTL interannual analysis of monthly VIIRS NTL at a pitaya location in Bình Thuận, with Yt for observed data values in time (t), St for seasonal component, Tt for trend component, and et for residual variation not explained by Tt and St.](image)
In contrast to nighttime lit-up areas from cities persistently maintained without a significant seasonality signal, NTL radiance in dragon fruit plantations changes month by month with a strong seasonal cycle, peaking during the winter months (dry season and reaching the lowest around summer (wet season) as shown in Figure 3a. During the winter months, NTL radiance from dragon fruit plantations is also higher than stable, built-up areas in cities. As such, we derived the seasonal signature of monthly NTL from 2012 to 2019 to separate highly NTL bright pixels covering dragon fruit plantations that are distinguished from cities, whose NTL remain relatively stable across months and are lower than dragon fruit plantations during the winter months. The high level of NTL radiance areas can serve as a proxy of dragon fruit cultivation in the study area.

However, the extraordinarily high NTL radiance from the dragon fruit plantations can cause a prominent light blooming effect, leading to an overestimation of dragon fruit planting area if the effect is not accounted for during analysis. The Breakpoint for Additive Seasonal Trend (B-FAST) analysis (Verbesselt et al., 2010) is applied to monthly VIIRS DNB NTL images (e.g., Figure 3b for a pitaya location in Bình Thuận) in order to distinguish the over-glow area from the dragon fruit planting area and the city lights. This method considers the seasonality of NTL in dragon fruit plantations and the different levels of NTL radiance for unlit areas, city light, blooming effect, and dragon fruit plantations. For these types, the classification is based on the decision-tree approach utilizing thresholds for NTL characterization from B-FAST including seasonal range, a 6-month autocorrelation coefficient, slope and mean values of each break interval, and the Normalized Difference Light Index (Krauser, 2020). Boundaries of dragon fruit plantation extracted using the NTL DNB images were validated (Krauser, 2020) with ground truth from field surveys and compared with a high resolution LULC map generated using PALSAR-2 LCLU data products from JAXA (2020).

To further understand the spatial pattern and change of dragon fruit cultivation, we calculated a series of buffer rings expanding around the geographic center in the largest dragon fruit cultivation region in Bình Thuận Province. The geographic center was selected as the origin of buffer rings as it coincides with the center of the traditional dragon fruit cultivation land of Bình Thuận. Each buffer ring has an incremental width of 1.5 km, with a total number of 25 spreading out from the center to cover the extensive landscape of Bình Thuận. The total area of dragon fruit cultivation and the average NTL radiance was calculated inside each buffer to obtain the spatial pattern of dragon fruit cultivation in Bình Thuận’s largest dragon fruit cultivation area. This analysis helps identify the area where the dragon fruit signal was strongest and suggests potential environmental constraints that dragon fruit cultivation in Bình Thuận has faced while expanding. A series of profiles were also derived for each year of analysis to compare the inter-annual change of the spatial pattern.

Moreover, as a dual rural-urban hot spot, the contemporaneous development of both dragon fruit agriculture and urban tourism industry in Bình Thuận necessitates the use of high-resolution synthetic aperture radar (SAR ) such as Sentinel-1 SAR with a 10-m posting to identify building structures and determine the rural-urban change pattern, not only in urban clusters but also in rural reclusions. The algorithm utilizes strong radar backscatter from man-made building
structures (Nghiem et al., 2014; Mathews and Nghiem, 2021) together with time-series data to
detect the persistent targets (Ngo et al., 2021). Moreover, the concept of geomorphons
(Jasiewicz and Stepinski, 2013) enables the algorithm to overcome the misclassification in areas
with complex mountainous topography, while the Normalized Difference Vegetation Index
accounts for errors due to water-tree interactions is radar signatures (Ngo et al., 2021). The
results will provide insights into the regional rural-urban transformation.

4. Results

4.1. Dragon fruit planting area extracted using NTL images

The decision-tree classifier, leveraging seasonal dynamics of NTL, produced estimates for
the classes of “Unlit,” “Dragon Fruit,” “City Lights,” and “Light Bloom” across the Bình Thuận
province (Figure 4a). Overall accuracy was 68.89% and the Kappa statistic was 53.5%. The lowest
error of commission was found in the city lights class (17.7%), while the lowest error of omission
was found in the unlit class (11.1%). The classes with the most significant error percentages
occurred between Dragon Fruit and Light Bloom classes (Krauser, 2020).

![Figure 4. (a) Left panel: Dragon fruit cultivation (green), light bloom (blue), and city lights
(yellow) detected by B-FAST analysis over monthly NTL images of 2018 overlaid on a 2018 Google
Earth image of Bình Thuận Province (white boundary). (b) Right panel: The latest land-cover
classification of the Bình Thuận province in Vietnam for the year 2018 from the Japan Aerospace
Exploration Agency (JAXA).]

The results from the decision-tree classifier vary considerably from the fine-scale land-
cover classification produced by JAXA. Classes for the JAXA product (Figure 4b) were determined
using a Bayesian classifier with kernel density estimation (JAXA, 2020). While accuracy
assessments for high-resolution JAXA products are better than those associated with the low-
resolution NTL classification attempt in this study, there are several key differences between the
products. The orchard category (light green in Figure 4b) listed in JAXA LULC products seems to
be associated with dragon fruit cultivation (green in Figure 4a), but misrepresents dragon fruit
production in the area near the eastern most sector of Bình Thuận. Additionally, the NTL-
produced land-cover, with a larger pixel size, may exhibit less discretion among discrete land-
cover as a function of the continuous NTL data. Also, of note, the JAXA’s term “orchard” did not seem to be used widely among dragon fruit producers in the region. As a unique agricultural product that requires trellising as support for many plants, a dragon fruit “tree” is actually four or more dragon fruit cactus plants supported by one central post, rather than a typical tree (like an orange tree) usually found in a fruit orchard.

4.2 Light intensity change in dragon fruit planting area

The annual trend of NTL radiance from 2012 to 2019 in Bình Thuận Province, Vietnam’s most prominent dragon fruit planting area, indicated a significant increase of dragon fruit cultivation began around 2014 and reached a plateau after 2017 (Figure 5a). The increasing use of night lighting for dragon fruit cultivation was the most prominent driver behind the significant increase of average NTL radiance from 2012 to 2019. We carried out linear regression analyses between VIIRS NTL with actual statistical data (Binh Thuan Statistics Office, 2019) for planted area (in Ha), gathering area (in Ha), and fruit production (in ton) of dragon fruits. The results shows that the correlation of determination R² = 0.95 between NTL and planted area, R² = 0.91 between NTL and gathering area, and R² = 0.90 between NTL and fruit production across the lighting years of 2013-2019. In fact, R² values based on lighting years (June to May of the following year) are the highest compared to those based on calendar years and on monsoon water years (April to March of the following year).

Change of seasonality in NTL radiance of Bình Thuận also reflected a consistent pattern (Figure 5b). From 2012 to 2019, the average NTL during the winter months when the use of light supplementing technique was at its peak greatly increased, while the average of NTL radiance was relatively stable during the summer months when the artificial light treatment was absent. However, the average NTL radiance of November and December 2019 dropped to a lower level than the two precedent years (2017 and 2018). November and December are the peak months of light supplementing technique usage. Such drop, along with the fact that the average NTL radiance fluctuated around 45 nanoW/cm²/sr from 2017 to 2019, can be a signal of saturation for the cultivation of dragon fruit in Bình Thuận.

![Graph](image1.png)

(a) Change of annual average NTL radiance  (b) NTL radiance from 2012 to 2019 by months

**Figure 5.** Change of NTL radiance from 2012 to 2019 in Bình Thuận Province and Long An Province.
4.3 Expansion of dragon fruit planting area

A spatially spreading trend of seasonal NTL radiance signal implies an expansion of dragon fruit farming and/or an increase in land use conversion to dragon fruit farms. To fully substantiate those changes, additional field work is needed. However, we further compared the observed inter-annual change of dragon fruit planting area in Bình Thuận Province to examine the pattern of change in planting area. Figure 6 shows that from 2013 to 2019, the seasonally consistent pattern of lit-up area in Bình Thuận expanded from the traditional dragon fruit planting area in the coastal plain towards the foothill area in the northwest. Furthermore, the gaps inside the stable, lit-up area also grew smaller, indicating the dragon fruit planting area expanded to cover the remaining flat area near the hills, where the elevation and slope conditions hindered the spatial extension of dragon fruit farming.

**Figure 6.** Expansion of stably lit-up area detected by VIIRS DNB NTL from 2013 to 2019 in a major dragon fruit planting region of Bình Thuận. The black contour represents the dragon fruit cultivation area derived from NTL (corresponding to green area in Figure 4a). The big circle indicates the largest buffer among all buffers (see inset in Figure 7) from the geographical center of the entire lit-up area.

Results from the buffer and profile analysis further documented the spatial expansion of dragon fruit cultivation, especially the expansion beyond the traditional planting regions after 2015. In the largest lit-up area of Bình Thuận, we found there are two peaks of dragon fruit planting areas at the start of the study period, located near 7 km and 22 km apart from the geographic center of the area of dragon fruit farming (Figure 7). Compared with the baseline (2012-2013), we found the total area of dragon fruit planting increased from 2013 to 2019, while
the location of peaks moved further away from the center. The first peak moved from 7 km from the center to 10.5 km from the center, while the second peak moved from 20 km from the center to 22 km from the center. The increase of planting area of each buffer zone and the migration of peak both revealed the increase of planting area inside each buffer zone and the spatial expansion of the planting area.

Figure 7. Area of dragon fruit planting from the geographical center point to the most distant 1.5 km buffer of the largest lit-up area in Bình Thuận Province.

While the year-to-year increase of dragon fruit planting area continued from 2012 to 2019, the region near the first peak of dragon fruit planting area may have reached its capacity to accommodate further expansion of dragon fruit plantation. The profile for 2017-2018 and 2018-2019 are almost identical from 0 to 20 km away from the center (Figure 7). This pattern indicated there was little room for dragon fruit plantation to grow in the traditional dragon fruit planting area after years of expansion. After 2017, the increase of dragon fruit plantation mostly happened in the area beyond 20 km way from the center, indicating the encroachment into the foothill region where the last available flat area for dragon fruit planting is located.

The spatial expansion of dragon fruit planting area pushed the boundary of prominent dragon fruit planting area towards regions where the dragon fruit plantation was scarce or nonexistent before 2013. Profiles showed that the traditional dragon fruit planting was constrained within 30 km from the geographical center of the stably lit-up area in Bình Thuận (red and orange profiles in Figure 6). Although expanded a little around 2014-2015, the lit-area did not surpass the 30 km buffer. However, in 2016, the boundary of planting area expanded beyond this spatial...
constraint with a great leap from 30 km to 40 km away from the center. This newly established region for dragon fruit planting experienced a significant hump of planting after 2017 and became stable around 2019.

We can categorize the profiles into three groups based on the area and the spatial extent of dragon fruit planting, reflecting three stages in the expansion of dragon fruit cultivation in Bình Thuận from 2012 to 2019. The first stage is 2012 to 2014, when the increase of dragon fruit plantation mostly occurred near the established central region and a spatial expansion did not happen. The second stage is 2014 to 2017, when the location of both area peaks started to move further from the center and the growth of dragon fruit planting area was significantly higher than the cross-year incrementing from 2012 to 2014. The third stage is 2017 to 2019, when the planting area increased with a great leap from the previous stage and the newly established planting area beyond 30 km from the center became stable. The third stage is also when the planting area of dragon fruit may have reached a limitation in this region due to the topographic constraints in mountainous areas.

4.4 Increase of dragon fruit planting intensity

The level of NTL radiance and the lit-up area for dragon fruit planting inside each buffer zone has a positive relationship (Figure 8), indicating the brightest area is often where the dragon fruit planting is the largest in size. Such relationship is the most significant in 2012-2013, 2013-2014, and 2014-2015 (Figure 8). During these years, the average NTL radiance inside a buffer increased in parallel to the size of lit-up area in this buffer. Buffers with the lowest NTL radiance near the outskirt of the entire study area often had the smallest lit-up area.

![Figure 8. Lit-up area inside each buffer and the average NTL radiance of the lit-area area.](image)

This relationship became significantly weaker after 2015. Since then, the size of dragon fruit planting area increased near the outskirt of the entire buffer zone (20-30 km from the center,
light blue dots in Figure 8), while the NTL radiance remained at the same level (< 200 nano W/cm²/sr), indicating the existence of a vast region with relatively low plant density near the boundary of the dragon fruit planting area. After 2016, the expansion of lit-up area between 20 and 30 km from the center also continued, with limited increase of NTL radiance (< 250 nano W/cm²/sr). Meanwhile, the traditional dragon fruit planting area near the geographic center of lit-up area did not undergo an increase of size and experienced a hike in the average NTL radiance (red and orange dots, Figure 8). This indicates that the increase of brightness was contributed by the increase of plant density, not the expansion of lit-up area. These two processes added together to cause the weakening of the positive relationship between the size of lit-up area and the average NTL radiance.

4.5. The 2020 COVID-19 Case

The on-going COVID-19 pandemic has inflicted profound impacts on people lives, the economy, and the environment across the world, including Vietnam. In Vietnam, the emergency lock-down orders were implemented in February 2020 during the first wave of the pandemic when touristic centers were shut down, hotels and resorts were deserted, and urban and rural activities were minimized. In particular, we investigate the case of the dragon fruit agriculture regarding NTL change corresponding to the COVID case over the Dragon Kingdom in Bình Thuận.

![Figure 9. Red(2/13/2020)-Green(2/16/2019)-Blue(2/21/2018) composite map of VIIRS NTL over the Dragon Kingdom in Bình Thuận Province.](image)

The map over the Dragon Kingdom in Figure 9 shows the temporal composition of VIIRS NTL with red for 13 February 2020 (time of COVID emergency orders), green for 16 February 2019,
and blue for 21 February 2018 with clear-sky conditions in all cases. In Hầm Thuận Bắc District located in the northern region of the Dragon Kingdom (red ellipse in Figure 9), NTL appeared stronger in 2019 (greenish areas) and in 2018 (bluish areas), indicating that the night lighting for the dragon fruit cultivation was reduced around the similar time in 2020. However, the reduction of NTL did not appear all over Bình Thuận. NTL appeared whitish in the RGB composite using three years around the central region of Hầm Thuận Nam District (blue ellipse in Figure 9), indicating there was no significant change in Feb. 2020 and the radiance remained relatively stable across 2018, 2019, and 2020.

Moreover, the comparison of VIIRS NTL around mid-February (13 February 2020) and in late February (29 February 2020, also clear sky) reveals that the NTL gained intensity and become brighter in the later part of February in 2020. Overall, the NTL change during the COVID case was spatially and temporally heterogenous across various areas in the Dragon Kingdom.

4.6 Dual Rural-Urban Hot Spot

Figure 10. Dual rural-urban hot-spot conditions by the extreme development of dragon fruit plantation (in translucent green) co-existing with the extreme tourism development and urbanization of Phan Thiết City (capital of Bình Thuận Province), where building structures (in orange with black contour) are observed densely in the urban area (in translucent yellow, from NTL analysis) and found sparsely dispersed far into the rural area of dragon fruit farming. The over-glow area due to Nightlight blooming (in translucent blue).

While the rural region of Bình Thuận has undergone a transformative change from rags in an arid desert environment to riches from the extreme development of the dragon fruit agriculture, urban areas such as the capital Phan Thiết City have transformed under rapid urbanization and the intensive development of the prolific tourism industry at the same time. In contrast to the case of urban expansion at the expense of rural demise or vice versa, the situation
of dual rural-urban hot spot contemporaneously has created a rare encounter where the rural-urban pattern needs to be examined to reveal and understand how the rural-urban interface and transition zone may have occurred.

Results from building structures mapping from Sentinel-1 SAR 10-m time-series data acquired in 2018 are presented in Figure 10. Validated with in-situ data and field observations, results of building structures obtained from SAR data were found accurate within an overall root-mean-square error of 10.6% accounting for buildings misclassified as other types and for others misclassified as building in both rural and urban areas (Ngo et al., 2021). In Phan Thiết City, the capital of Bình Thuận Province, a pattern of densely distributed buildings was found in clusters occupying the area identified as city from VIIRS NTL data (yellow area in Figure 4a) and from the ALOS LCLU city product (red area in Figure 4b). Transitioned further away from Phan Thiết City, building structures distributed less densely and became more separated in smaller isolated reclusions dispersedly and reaching deeply into the rural landscape identified as the dragon fruit cultivation region (green area in Figure 4a) extending far inland toward the mountains in the west.

5. Discussions and Conclusions

The unique nighttime lighting technique adopted by dragon fruit growers in Vietnam and several Asian countries provided a chance to use NTL images to identify the plantations of dragon fruit. Such technique is also very flexible, allowing growers to conveniently adjust the amount of production by turning on and off the lights at night. With better regional coordination from the government of Vietnam, such flexible adjustments toward the global market fluctuation can be bolstered. As the spatial expansion of dragon fruit areas may have reached a plateau in some areas of Vietnam due to the topographical constraints and available arable land for dragon fruit, the local growers may use the lighting adjustments more often to change the amount of production. Researchers should focus more on the change of light brightness to estimate the amount of dragon fruit production.

In the core area of dragon fruit cultivation in the Dragon Kingdom where such agriculture has a long history, growers have tried to expand the cultivation by converting land on the level and easily accessible terrain to dragon fruit plantations. Such expansion may become saturated as the amount of non-dragon fruit land available for such conversion is limited. Therefore, in recent years, more and more dragon fruit cultivation were found in the outer circle of the planting area extending toward the mountains. These newly claimed dragon fruit cultivation areas usually have a lower plant density than the traditional cultivation area, reflected as a dimmer area in the NTL images.

The B-FAST method has been demonstrated to be effective in separating seasonal, scattering, and stable NTL radiance to distinguish between seasonal planting, light bloom, and city lights. The workflow using B-FAST over NTL images is robust and can open up new possibilities in generating monthly and more accurate land cover/land use map for certain land cover/land use types that show a distinguishable pattern in NTL images. Such product can be valuable supplemental data to further correct the estimation of greenhouse gas (GHG) emission that
currently relies on NTL data products that may not represent cities with high GHG emissions and may actually associated rural regions with much lower emissions (Gaughan et al., 2019).

The tourism industry in urban areas and the dragon fruit agriculture in Bình Thuận draw potential growers to purchase land, with some leaving stable income and “...betting their life on dragon fruit,” (Krauser, 2020). Some farmers included former medical professionals moving onto cassava plantations in order to convert it to dragon fruit production. The financially compelling nature of dragon fruit production even drew a doctor and nurse out of their city home for a new livelihood in Bình Thuận Province. Another farmer anecdote included a large family that settled onto a new plot of land in 2018 after leaving Hồ Chí Minh City and their real-estate careers to pursue growing organic dragon fruit. These scenarios speak to the power of the dragon fruit market as one healthy enough to draw people against the greater trend of urbanization to rural areas for smallholder agricultural production.

NTL change presented in the COVID-19 case might not be consistent with the local restrictions from the emergency lock-down orders across Bình Thuận in February 2020. From interviews with farmers during our field verification excursions, the dragon fruit demand and thus the market price decreased in early February 2020, and at the same time the fruit transportation across the Vietnam-China border was largely restricted due to COVID-19 problems. As such, factors impacted the NTL were driven by market and transportation issues thousands of km away and were not controlled by the local inactivity under local COVID-19 lock-down orders. In late February 2020, dragon fruit processing and distribution centers could export dragon fruits by marine commercial ships to different markets in multiple countries, and thus NTL was increased to enhance the fruit production. Night lighting for dragon fruit cultivation decreased in Hàm Thuận Bắc District where the dragon fruit agriculture was recently developed, in contrast to the stable lighting in Hàm Thuận Nam District where dragon fruit farming and market connectivity were stably established. Such differences suggested that responses to COVID-19 effects were heterogenous and haphazard in different regions.

The dual rural-urban hot spot situation results in contemporaneous developments of large hotels and resorts in the capital Phan Thiết City and real estates along the coast to support the prolific tourism industry while dragon fruit farmers in Bình Thuận become rich and build substantial processing centers and/or residential complexes in the rural areas seen in the distribution pattern of building structures (Figure 10). Nevertheless, the dual hot spot may lead to a competition in labor work force between the rural and urban sectors. Future research is necessary to examine various possibilities such as the collaborative scenario with agritourism that benefits both dragon fruit farmers and tourism investors, or the competitive scenario with higher labor costs to attack the work force to each sector, or the hostile scenario with different sectors fighting for land and labor. Understanding driving factors of land cover and land use change will contribute effective strategies to enhance collaboration and minimize hostility among the different rural-urban sectors.

This present study is constrained by the low resolution of NTL data. At a resolution of 750 m, the VIIRS NTL images can only serve as a data source to roughly extract the general area where
the cultivation of dragon fruit is the highest possible, though it can distinguish dragon fruit plantations from other agricultural types. Although produced at a much higher resolution than the NTL radiance product, LULC maps developed using ALOS-2 (JAXA, 2020), Landsat (Liu et al., 2020), or Sentinel surface reflectance (Chen et al., 2019) could not produce a significantly better result, as these images often have a prominent misclassification issue in the area where dragon fruit and other agricultural types are mixed. In order to distinguish the dragon fruit plantations from the background, the rough delineation of dragon fruit planting area using NTL images need to be combined with very-high-resolution images, whose spatial resolution is sufficient to identify the unique checkboard texture for dragon fruit plantations as the cactus plats are grown in a regular grid with specific spacings for the most effective dragon fruit production. Such regular pattern can be effectively achieved with convolutional neural network methods (Lettry et al., 2017). Moreover, in synergy with high-resolution SAR data, buildings and other LCLUC types can be mapped and monitored in complex and mix-used terrains in high detail and fidelity across the landscape in future research.

A notable conclusion from this study on the extreme development of dragon fruit agriculture in Vietnam, using extensive electric lighting at night to achieve the commercially prolific fruit production, is that NTL from satellite observations is really associated with agriculture activities in rural environments. This case highlights that NTL may not represent human inactivity due to local emergency orders amid a pandemic such as the COVID-19, and therefore NTL must be interpreted carefully to avoid misinformation. Moreover, the intensive and extensive NTL seen in satellite data products across the landscape dominated by dragon fruit agriculture in Bình Thuận and Long An Provinces is irrelevant to human activity in an urban environment causing fossil fuel CO₂ (FFCO2) emission, and thus a correct use of NTL is crucial to accurately estimate FFCO2 to support the implementation of the Paris Agreement within the United Nations Framework Convention on Climate Change (UNFCCC).

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7. References


Figure Captions

**Figure 1.** Lighting at night in a plantation of dragon fruit in Bình Thuận Province. The upward shining nightlight can be observed with a high intensity in satellite NTL imagery. The inset shows freshly harvested dragon fruits with a red skin. Photos by S. V. Nghiem, February 2020.

**Figure 2.** VIIRS DNB image in February 2020. Lighting in the dragon fruit plantation regions in Bình Thuận and Long An is much more intense than that in Hồ Chí Minh City, the most populous city in Vietnam with extensive lighting at night. Inset is the city photo at night taken by S. V. Nghiem.

**Figure 3.** NTL variations: (a) Average NTL of dry season (winter, from October to December) and wet season (summer, from April to July), and (b) B-FAST NTL interannual analysis of monthly VIIRS NTL at a pitaya location in Bình Thuận, with Yt for observed data values in time (t), St for seasonal component, Tt for trend component, and et for residual variation not explained by Tt and St.

**Figure 4.** (a) Left panel: Dragon fruit cultivation (green), light bloom (blue), and city lights (yellow) detected by B-FAST analysis over monthly NTL images of 2018 overlaid on a 2018 Google Earth image of Bình Thuận Province (white boundary). (b) Right panel: The latest land-cover classification of the Bình Thuận province in Vietnam for the year 2018 from the Japan Aerospace Exploration Agency (JAXA).

**Figure 5.** Change of NTL radiance from 2012 to 2019 in Bình Thuận Province and Long An Province.

**Figure 6.** Expansion of stably lit-up area detected by VIIRS DNB NTL from 2013 to 2019 in a major dragon fruit planting region of Bình Thuận. The black contour represents the dragon fruit cultivation area derived from NTL (corresponding to green area in Figure 4a). The big circle indicates the largest buffer among all buffers (see inset in Figure 7) from the geographical center of the entire lit-up area.

**Figure 7.** Area of dragon fruit planting from the geographical center point to the most distant 1.5 km buffer of the largest lit-up area in Bình Thuận Province.

**Figure 8.** Lit-up area inside each buffer and the average NTL radiance of the lit-area area.

**Figure 9.** Red(2/13/2020)-Green(2/16/2019)-Blue(2/21/2018) composite map of VIIRS NTL over the Dragon Kingdom in Bình Thuận Province.

**Figure 10.** Dual rural-urban hot-spot conditions by the extreme development of dragon fruit plantation (in translucent green) co-existing with the extreme tourism development and urbanization of Phan Thiết City (capital of Bình Thuận Province), where building structures (in orange with black contour) are observed densely in the urban area (in translucent yellow, from NTL analysis) and found sparsely dispersed far into the rural area of dragon fruit farming. The over-glow area due to nightlight blooming (in translucent blue).