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Assessing the Impact of Land Use on Dew Yield Using Remote Sensing Data in Taiwan

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Abstract

Dew condensation plays a significant role in hydrological cycles and resource management, particularly in regions with diverse climatic and land use conditions. This study integrates the Nocturnal Condensation Potential Index (NCPI) with satellite-derived Leaf Area Index (LAI) and Land Use/Land Cover (LULC) data to evaluate dew condensation potential across Taiwan from May 2016 to April 2017. NCPI, based on air temperature, dew-point differences, and relative humidity. The integration of NCPI with LAI resulted in the LAI-derived Condensation Potential (LCP), capturing spatial and temporal variations in condensation potential. Key findings include higher NCPI values during the cold season, higher LCP values in dense forested areas, and greater variability in urban and riverine environments. Trees consistently exhibited the highest LAI and the lowest variability, while urban and riverine areas showed significant heterogeneity in condensation potential. Seasonal differences revealed higher dew condensation potential during the cold season, with implications for hydrology and resource management. This research enhances understanding of dew condensation dynamics and highlights its potential applications in agriculture, urban planning, and sustainable water resource management. The findings underscore the importance of integrating meteorological and satellite-derived indices to evaluate dew formation patterns in diverse landscapes. Future work should explore finer-scale microclimatic interactions and the viability of dew harvesting in water-scarce regions.

1. Introduction

Dew condensation occurs when atmospheric water vapor condenses on surfaces cooled below the dew point, typically during the night. Although dew constitutes only a minor component of the Earth's overall water budget, it plays an essential role in localized hydrological cycles. The efficiency of dew formation varies across different surface materials such as polyethylene foils, grass, soil, leaves, and sand particles. (Nilsson, 1996; Williams et al., 1998; Jacobs et al., 1999; Wilson et al., 1999; Li, 2002). Furthermore, several meteorological and geographical factors significantly influence dew yield, including high relative humidity, air-surface temperature differentials, reduced wind speeds, and clear skies (Nilsson, 1996; Kidron et al., 2002; Beysens et al., 2016).

In natural ecosystems, particularly forests and grasslands, dew plays a vital role in the hydrological cycle by supplying additional moisture during dry periods, contributing to overall ecosystem stability (Aguirre-Gutiérrez et al., 2019; Binks et al., 2021). This supplemental moisture can be absorbed directly through foliar uptake, sustaining plant life in otherwise arid conditions. In addition to providing moisture, dew influences the energy balance of vegetation by lowering leaf temperatures through evaporative cooling and altering the albedo and emissivity of plant surfaces (Paul and Pinter, 1986; GerleinSafdi et al., 2018; Li et al., 2023). Therefore, dew has broader implications for vegetation health and ecosystem function.

In agricultural settings, the role of dew is more complex, as it can be both beneficial and detrimental. Dew provides additional moisture, which supports plant growth, particularly in regions with low rainfall (Alnaser and Barakat, 2000; Kidron et al., 2002). However, this same moisture can create favorable conditions for fungal growth and the proliferation of plant pathogens, potentially leading to crop diseases (Duvdevani, 1953; Lhomme and Jimenez, 1992; Schmitz and Grant, 2009). Consequently, the presence of dew represents a double-edged sword in agricultural management, offering potential benefits for crop hydration but also increasing the risk of disease outbreaks that can negatively affect yields.

To comprehensively assess dew formation's spatial and temporal patterns, particularly concerning land-use practices, it is essential to integrate both in-situ and satellite-based observations. Previous studies have utilized leaf wetness sensors and remote sensing data to monitor dew's role in ecosystems and agriculture (Madeira et al., 2002;; Cosh et al., 2009; Schmitz and Grant, 2009). However, more research is needed to explore the relationships between meteorological factors and land-use indicators, such as the Normalized Difference Vegetation Index (NDVI) and Leaf Area Index (LAI), across different land types.

Taiwan offers a unique case study, with approximately twothirds of its land area covered by mountainous regions—key locations for tea plantations—while the remaining one-third consists of flatlands, ideal for general agriculture. Dew condensation significantly impacts both land-use types, with notable effects on tea plantations in the highlands and crop production in the lowlands. Despite this, there is a paucity of research investigating dew's role in Taiwan's agriculture and forestry, particularly concerning its spatial distribution and effects across diverse land-use categories. Given Taiwan's diverse topography and climatic conditions, it presents an ideal opportunity to study nocturnal condensation's role in hydrology and agriculture.

Therefore, this study aims to address these knowledge gaps by integrating in-situ data with satellite-based remote sensing to assess dew formation across various land-use types in Taiwan. By combining meteorological observations with remote sensing data, the study will analyze the spatiotemporal variation in dew formation between Taiwan's mountainous and agricultural regions. This research will provide crucial insights into how land use influences dew condensation potential, offering valuable

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implications for sustainable agriculture and water resource management.

2. Material and Methods

2.1 Study Area

The study area is located in Taiwan, where approximately twothirds of the terrain consists of mountainous regions oriented from northeast to southwest (Figure 1). The island spans elevations from sea level to 3,952 meters and measures 394 kilometers in length and 144 kilometers in width, with a total area of 35,873 square kilometers. Taiwan's central geographic coordinates are 23°58' N and 120°58' E. Between 1991 and 2020, the average annual precipitation was 2,422 mm, approximately 2.4 times the global average. The seasonal variation in temperature exhibited a symmetrical pattern, with the lowest monthly average temperature of 15.8°C occurring in January and the highest of 26.8°C in July. The average monthly relative humidity was 78.9%, with values exceeding this average from April to September.

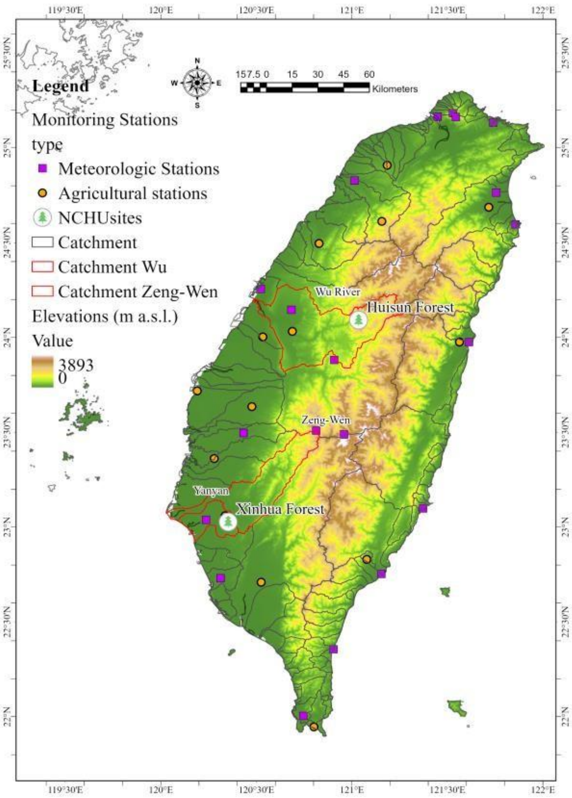


Figure 1. Map of the study area, showing the locations of monitoring stations, selected catchments, and topographic features.

To examine conditions at the catchment scale, we selected the Husin Forest and Xinhua Forest, which are academic experimental forest sites managed by National Chung Hsing University (NCHU). These sites are located within the Wu and Zeng-Wen catchments. The Wu catchment features a river length of 119 kilometers and a drainage area of 2,025 square kilometers. The basin’s farthest source originates on the southern side of Gengmeng Mountain, at an elevation of 2,532 meters. The Zeng-Wen catchment has a total river length of 139 kilometers, a drainage area of 1,177 square kilometers, and a source elevation of 2,440 meters.

2.2 Dew Measurement and Dew Model

To facilitate mobile and efficient nocturnal dew collection, we constructed a dew box in the shape of a triangular prism with a base of 20 cm x 20 cm and a height of 11.6 cm. The box was made from white polymethyl methacrylate (PMMA) with a thickness of 3 mm, and it was positioned on a 30-degree slope to maximize dew accumulation (Lin and Wu, 2024). In addition to physical dew measurements, we employed a dew formation model (Beysens, 2016; Tomaszkiewicz et al., 2017), which used meteorological data to estimate potential dew yield. The model inputs included key parameters such as temperature, humidity, and wind conditions, providing a comprehensive method for dew prediction alongside in-situ measurements.

2.3 Meteorological Data

In the field experiments, surface temperatures of the condensation plates were manually recorded using a surface thermometer (Model: TES-1310). A hygrometer and thermometer (Model: TES-1364) were installed 15 cm above the ground to automatically monitor meteorological conditions over time. In addition to local field data, we collected meteorological information from 49 monitoring stations across Taiwan, including meteorological stations and agricultural stations (Figure 1). These stations recorded a range of atmospheric parameters including air pressure, ambient air temperature, dew-point temperature, relative humidity, wind speed, wind direction, precipitation, and evaporation rates. This comprehensive dataset provided an accurate representation of the environmental factors influencing dew formation across diverse landscapes.

2.4 Remote Sensing and GIS Data

To extend the findings from field experiments to a broader regional scale, we incorporated remote sensing data (Figure 2 and Figure 3), including Leaf Area Index (LAI), Land Use/Land Cover (LULC), and the Normalized Difference Vegetation Index (NDVI). High-resolution (10-meter) GeoTIFF files from the ESA Sentinel-2 Land Use/Land Cover Map (2017–2021) were utilized, sourced from Esri, Microsoft, and Impact Observatory. Additionally, we integrated LAI and NDVI datasets (300-meter resolution) from the Copernicus Global Land Service’s Sentinel-3 product, spanning from January 2014 to the present. These datasets were used in combination with terrain and hydrological data to create detailed spatial maps and conduct GIS-based analyses, enabling a comprehensive assessment of dew formation across various land-use types and topographies in Taiwan.

3. Results and Discussion

3.1 Nocturnal Condensation Potential Index

The Nocturnal Condensation Potential Index (NCPI) was developed in this study to evaluate the potential for dew formation during nighttime hours. The NCPI is calculated using the regression slope between the differences in air temperature and dew-point temperature, combined with relative humidity measurements recorded during the critical dew-forming period from 22:00 to 06:00. This approach captures the interplay of meteorological factors influencing dew condensation, including temperature gradients and atmospheric moisture availability. The NCPI showed a statistically significant negative correlation (r = -0.62) with average daily dew yield, as determined using an established dew model (Lin and Wu, 2024). This relationship underscores the role of smaller temperature-dew point differentials and higher relative humidity in enhancing dew formation. Regions with higher NCPI values are associated with greater dew condensation potential, making it a valuable predictive metric for spatial and temporal dew yield estimation.

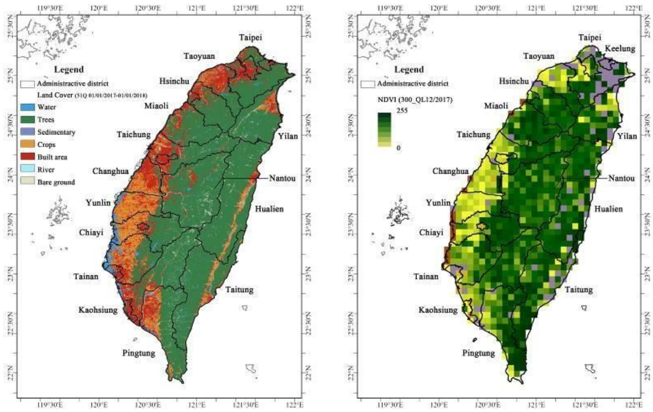
To standardize and facilitate the comparison of NCPI values across diverse geographic and temporal scales, the index was normalized to a range of 0 to 1. Higher normalized values indicate areas with greater nocturnal dew condensation potential. This normalization is particularly useful for identifying hotspots of dew activity and comparing seasonal variations. Data from 49 monitoring stations, collected from May 2016 to April 2017, were analyzed to identify seasonal variations in NCPI. The analysis revealed higher NCPI values during the cold season compared to the warm season, reflecting the influence of cooler temperatures and higher relative humidity on condensation potential during colder months. Figure 4 illustrates the spatial distribution of NCPI, highlighting regional variations across Taiwan.

3.2 LAI-derived Condensation Potential

Atmospheric vapor condenses on various surfaces, with vegetation being a prominent medium due to its extensive surface area. To quantify this potential, the LAI-derived Condensation Potential (LCP) was calculated by integrating the Leaf Area Index (LAI) with the Nocturnal Condensation Potential Index (NCPI). The LCP serves as an indicator of dew condensation potential on vegetative surfaces, where higher values correspond to greater likelihood and volume of dew formation.

The distribution of LCP across Taiwan and selected catchments, as shown in Figure 5 and Figure 6, reveals distinct seasonal and regional variations. During the warm season, areas with dense vegetation, such as forested regions and agricultural lands, exhibit higher LCP values due to the abundant surface area provided by leaves for dew condensation. Conversely, during the cold season, LCP values decrease in some areas, particularly along riverbeds and transitional zones between mountain foothills and plains, where vegetation density and LAI are reduced. From catchment-scale observations within the selected catchments, notable patterns emerge, it indicated the LAI and corresponding LCP values are significantly lower along riverbeds in the cold season compared to the warm season. This is likely due to seasonal vegetation dieback and reduced leaf coverage in these areas. Besides, transitional zones between foothills and plains show a marked decline in LCP from warm to cold seasons.

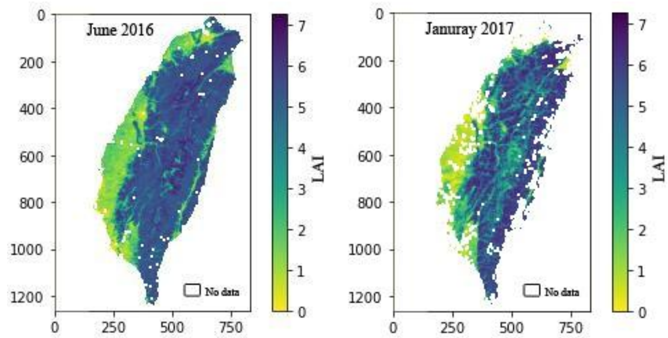
This decline highlights the sensitivity of vegetation in these regions to seasonal changes, potentially influenced by temperature and moisture availability. These findings underscore the importance of both vegetation density and meteorological factors in determining dew condensation potential. The integration of LCP with land use and climatic data provides valuable insights for understanding how seasonal dynamics affect dew formation, which could be critical for applications in agriculture, hydrology, and ecosystem management.



(a) Sentinel-2 Land Use/Land Cover in 2017

(b) Sentinel-3-based NDVI_QL_201712

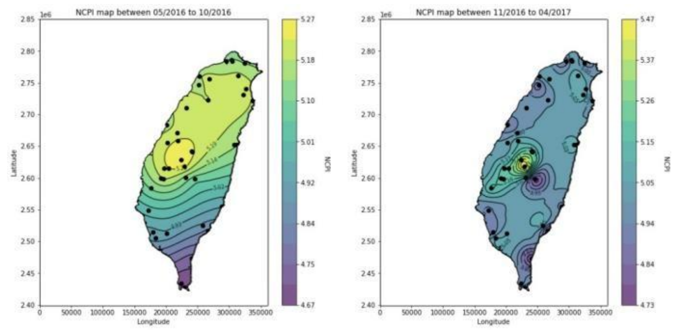
Figure 2. Spatial distribution of Land Use and Land Cover (LULC), Normalized Difference Vegetation Index (NDVI) within the study area.



(a) Sentinel-3-based LAI-201606

(b) Sentinel-3-based LAI-201712

Figure 3. Spatial distribution of Leaf Area Index (LAI) within the study area.



(a) NCPI in warm season derived from May 2016 to October 2016

(b) NCPI in cold season derived from November 2016 to April 2017

Figure 4. Seasonal distribution of the Nocturnal Condensation Potential Index (NCPI) across the study area.

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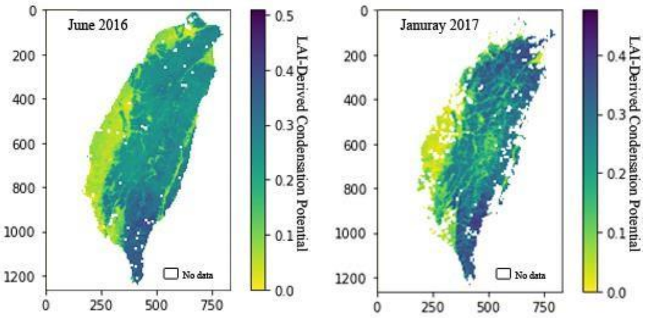
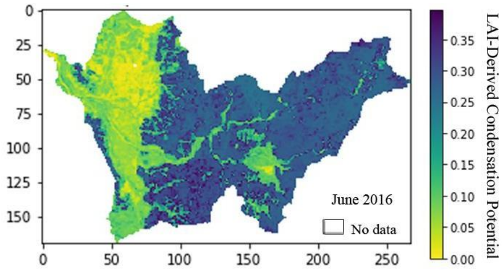


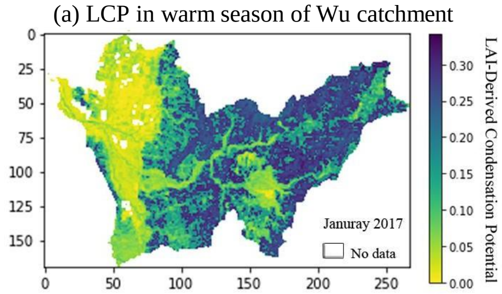
(a) LCP in warm season of Taiwan

(b) LCP in cold season of Taiwan

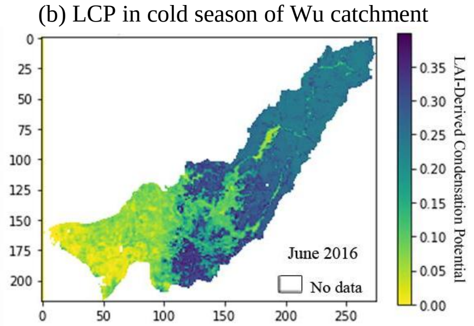
Figure 5. Spatial distribution of the LAI-derived Condensation Potential (LCP) across Taiwan during the warm and cold seasons.



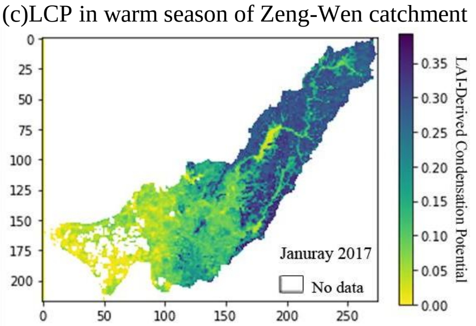
(a) LCP in warm season of Wu catchment



(b) LCP in cold season of Wu catchment



(c)LCP in warm season of Zeng-Wen catchment



(d) LCP in cold season of Zeng-Wen catchment

Figure 6. Spatial distribution of the LAI-derived Condensation Potential (LCP) across selected catchments during the warm and cold seasons.

3.3 Insights from Statistical Analysis of Key Parameters

3.3.1 LULC: Land use and land cover (LULC) in Taiwan were categorized into five simplified classes: built-up areas, rivers, trees, crops, and bare ground. Trees dominate the landscape, covering approximately 66% of the country, reflecting Taiwan's mountainous terrain (Figure 7). The two studied catchments also had higher proportions of tree coverage. However, built-up areas were relatively higher in the catchments compared to the national average, likely due to the presence of major cities within these regions.

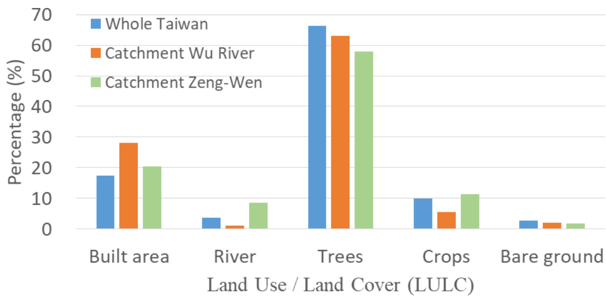


Figure 7. Land Use and Land Cover (LULC) classification and percentages across Taiwan and selected catchments.

3.3.2 NCPI: The NCPI values in Taiwan were generally higher during the cold season compared to the warm season, although the coefficient of variation (Cv) was greater in the warm season. When comparing the target catchments, the Zeng- Wen catchment exhibited higher NCPI Cv values in both seasons, reflecting greater variability in condensation potential. Regional variations in NCPI are depicted in Table 1 and Figure 4.

3.3.3 LAI: LAI values were higher during the warm season across both mountainous and plain areas (Figure 3). In contrast, the cold season showed lower LAI values, particularly in riverbeds and mountain peaks. Table 1 indicates that the mean LAI values were higher in the warm season, while the cold season had higher Cv values, reflecting increased variability in vegetation density.

3.3.4 LCP: Across Taiwan, the mean NCPI and LCP values were similar. However, the Cv of LCP was higher during the cold season, indicating significant spatial variability in LAI distribution across different terrains and LULC types. Pairwise correlations were conducted to further examine the relationships within each LULC class.

3.4 Pairwise Correlation of LULC

The statistical analysis of LAI, NCPI, and LCP across LULC categories revealed that NCPI values showed minimal variation across different LULC types. In contrast, the Trees category consistently demonstrated the highest mean LAI, reflecting dense vegetation coverage, and exhibited the lowest Cv, indicating stable vegetation density. Consequently, LCP values were also highest in the Trees category. On a catchment scale, higher LAI Cv values were observed in built-up areas and rivers within the Wu catchment, suggesting greater variability in vegetation or surface conditions compared to the Zeng-Wen catchment.

Pairwise correlations between LAI and LCP were lower for the Trees class due to the consistently high LAI values within this category (Table 2). In contrast, built-up areas and rivers exhibited higher correlations between LAI and LCP, likely influenced by urban microclimates or hydrological stability, which create uniform conditions affecting both indices.

3.5 Dew Condensation Potential Across Land Use Types

By integrating NCPI with satellite-derived LULC and LAI data, this study revealed seasonal patterns of dew yield potential across Taiwan. The distribution of higher dew yields is influenced by meteorological conditions and varies significantly across land use types. The lower pairwise correlation observed for trees suggests that factors such as canopy structure, evapotranspiration, or microclimatic conditions may disrupt the direct relationship between LAI and LCP. Conversely, built-up areas and rivers consistently showed high correlations, likely driven by urban and hydrological uniformity. These findings underscore the importance of considering temporal and spatial dynamics in dew condensation studies, with implications for urban planning and hydrology-focused research.

Item	Location	Season	Min	Max	Mean	Std	Cv
NCPI	Whole Taiwan	Warm season	0.27	0.49	0.35	0.05	**0.15**
		Cold season	0.16	0.55	**0.37**	0.04	0.11
	Wu	Warm season	0.28	0.34	0.31	1.20	3.87
		Cold season	0.29	0.39	0.33	1.23	3.73
	Zeng-Wen	Warm season	0.30	0.39	0.35	2.66	**7.60**
		Cold season	0.30	0.43	0.35	2.21	**6.31**
LAI	Whole Taiwan	Warm season	0.00	7.27	**4.20**	2.04	0.49
		Cold season	0.00	7.27	3.81	2.37	**0.62**
	Wu	Warm season	0.00	7.27	**4.10**	2.09	0.51
		Cold season	0.00	7.27	3.67	2.42	**0.66**
	Zeng-Wen	Warm season	0.00	7.27	**3.72**	2.17	0.58
		Cold season	0.00	7.27	3.33	2.34	**0.70**
LCP	Whole Taiwan	Warm season	0.00	0.51	0.21	0.11	0.51
		Cold season	0.00	0.48	0.20	0.13	**0.64**
	Wu	Warm season	0.00	0.34	0.18	0.09	0.51
		Cold season	0.00	0.40	0.18	0.12	**0.66**
	Zeng-Wen	Warm season	0.00	0.40	0.18	0.10	0.57
		Cold season	0.00	0.39	0.16	0.11	**0.67**

Table 1. Summary statistics for the Nocturnal Condensation Potential Index (NCPI)

No	LULC	LAI			NCPI			LCP			LAI&LCP
Items		Mean	Std	Cv	Mean	Std	Cv	Mean	Std	Cv	*r-value*
(a) Warm season in Taiwan											
1	Built area	1.79	1.36	**0.76**	0.34	0.05	0.15	0.09	0.07	**0.79**	**0.85**
2	River	1.52	1.69	**1.11**	0.36	0.05	0.14	0.08	0.09	**1.13**	**0.86**
3	Trees	**5.41**	1.02	0.19	0.35	0.05	0.15	**0.27**	0.06	0.24	0.54
4	Crops	1.83	0.81	0.44	0.34	0.05	0.15	0.09	0.05	0.55	**0.78**
5	Bare ground	3.12	1.93	**0.62**	0.35	0.06	0.17	0.16	0.10	**0.64**	**0.78**
(b) Cold season in Taiwan											
1	Built area	1.19	0.97	**0.82**	0.37	0.04	0.11	0.07	0.06	**0.89**	**0.86**
2	River	1.04	1.34	**1.28**	0.37	0.04	0.11	0.06	0.08	**1.33**	**0.85**
3	Trees	**5.12**	1.68	0.33	0.37	0.04	0.11	**0.27**	0.10	0.36	**0.75**
4	Crops	1.12	0.66	**0.59**	0.35	0.04	0.12	0.06	0.04	**0.65**	**0.86**
5	Bare ground	2.10	1.39	**0.66**	0.36	0.05	0.13	0.12	0.09	**0.73**	**0.77**
(c) Warm season in the Wu catchment											
1	Built area	1.81	1.53	**0.85**	0.30	0.01	0.03	0.08	0.07	**0.88**	**0.8**
2	River	1.74	1.54	**0.88**	0.30	0.01	0.03	0.08	0.07	**0.80**	**0.83**
3	Trees	**5.42**	0.98	0.18	0.31	0.01	0.04	**0.24**	0.05	0.20	0.48
4	Crops	1.88	0.76	0.41	0.30	0.01	0.04	0.08	0.04	0.53	0.67
5	Bare ground	2.80	1.91	0.68	0.30	0.01	0.03	0.13	0.09	**0.70**	**0.8**
(d) Cold season in the Wu catchment											
1	Built area	1.18	1.03	**0.87**	0.33	0.01	0.04	0.06	0.06	**0.98**	0.79
2	River	1.15	1.03	**0.89**	0.33	0.01	0.03	0.07	0.06	**0.94**	**0.81**
3	Trees	**5.08**	1.79	0.35	0.34	0.01	0.03	**0.24**	0.09	0.37	0.65
4	Crops	1.16	0.57	0.49	0.32	0.02	0.05	0.05	0.03	0.63	0.75
5	Bare ground	1.88	1.35	**0.72**	0.33	0.01	0.03	0.10	0.08	**0.82**	0.78
(e) Warm season in the Zeng-Wen catchment											
1	Built area	1.53	1.34	**0.88**	0.37	0.01	0.04	0.08	0.07	**0.87**	**0.93**
2	River	1.44	1.71	**1.19**	0.37	0.02	0.06	0.07	0.08	**1.13**	**0.92**
3	Trees	**5.24**	1.14	0.22	0.34	0.02	0.07	**0.25**	0.06	0.24	0.75
4	Crops	1.67	0.64	0.38	0.37	0.02	0.04	0.09	0.03	0.39	**0.84**
5	Bare ground	3.11	1.95	0.63	0.35	0.02	0.07	0.15	0.09	0.60	**0.91**
(f) Cold season in the Zeng-Wen catchment											
1	Built area	1.18	0.88	**0.75**	0.36	0.01	0.04	0.06	0.05	**0.76**	**0.93**
2	River	0.90	1.17	**1.29**	0.36	0.01	0.04	0.05	0.06	**1.22**	**0.87**
3	Trees	**4.74**	1.89	0.40	0.34	0.02	0.06	**0.22**	0.09	0.38	**0.87**
4	Crops	1.33	0.47	0.35	0.36	0.02	0.05	0.07	0.02	0.37	**0.85**
5	Bare ground	2.24	1.53	0.68	0.35	0.02	0.06	0.11	0.07	0.66	**0.91**

Table 2. Statistical comparison of key parameters in Taiwan and the two selected catchments.

4. Conclusions

This study provides an integrated approach to assess dew condensation potential across diverse land use types in Taiwan by combining the Nocturnal Condensation Potential Index (NCPI) with satellite-derived data on Leaf Area Index (LAI) and Land Use/Land Cover (LULC). Our research highlights the critical role of seasonal climatic variations and land use in shaping dew formation patterns, offering insights into dew condensation dynamics and their implications for hydrology and resource management. Key findings include:

(1) NCPI demonstrated a significant negative correlation with daily dew yield, providing a reliable indicator of condensation potential. Higher NCPI values were observed during the cold season, while warm seasons exhibited greater variability, as reflected by higher Cv values.

(2) By integrating LAI and NCPI, the LCP effectively captured spatial and seasonal variations in dew condensation potential. The highest LCP values were associated with dense vegetation in forested areas, while urban and riverine environments exhibited high variability.

(3) Among LULC classes, trees consistently exhibited the highest mean LAI values and the lowest Cv, indicating stable and dense vegetation coverage. Urban and riverine areas demonstrated higher variability in LAI and LCP, potentially influenced by microclimatic and hydrological factors.

(4) Seasonal differences revealed higher dew condensation potential in the cold season, while warm seasons were marked by greater variability in vegetation indices.

This study underscores the importance of considering seasonal and spatial variability when evaluating dew condensation potential, particularly in regions with diverse topography and land use. By highlighting the interplay between NCPI, LAI, and LULC, the findings contribute to a better understanding of dew’s role in hydrology and its implications for agricultural and forestry practices, urban planning, and resource management. These insights are particularly valuable for optimizing water resource utilization and supporting sustainability efforts in regions like Taiwan and beyond.

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