Forest Systems
31 (3), e021, 12 pages (2022)
eISSN: 2171-9845
https://doi.org/10.5424/fs/2022313-19539
INIA-CSIC

RESEARCH ARTICLE

OPEN ACCESS

Application of Land Surface temperature from Landsat series to monitor and analyze forest ecosystems: A bibliometric analysis

Marcela Rosas-Chavoya[1], Pablito M. López-Serrano[2], Daniel J. Vega-Nieva[3], Christian A. Wehenkel[2] and José C. Hernández-Díaz[2]

[1]Programa Institucional de Doctorado en Ciencias Agropecuarias y Forestales. Universidad Juárez del Estado de Durango, Durango 34239, Mexico. [2]Instituto de Silvicultura e Industria de la Madera. Universidad Juárez del Estado de Durango, Durango 34239, Mexico. [3]Facultad de Ciencias Forestales, Universidad Juárez del Estado de Durango, Durango, 34239, Mexico.

Abstract

Aim of study: Land surface temperature (LST) is an essential variable to monitor and characterize forest ecosystems. This variable has been consistently captured for almost four decades by the Landsat program. The current study aimed at identifying trends, knowledge gaps and opportunity areas in the use of Landsat derived LST for the monitoring and analysis of forest ecosystems.

Materials and methods: A bibliometric analysis of scientific articles indexed in Scopus in the period 1995-2020 was conducted.

Main results: Annual increase rate in the number of publications on the topic analyzed was 22.58%. The journal with more publications on the topic was Proceedings of SPIE, followed by Remote Sensing. The authors with the highest productivity on this topic were C. Quintano, I. Vorovencii, O. E. Yakubailik and M. A. Zoran. Regarding productivity by country, 38 countries with publications on this topic were identified, with the highest productivity located in China, USA and India. This group of countries also represented the most solid network of cooperation between countries. Forest ecosystems more frequently analyzed were temperate forests, followed by tropical forests. The analysis of keywords highlighted topics such as remote sensing, NDVI, MODIS and evapotranspiration. The analysis of thematic evolution indicated that areas of research and interpretation of LST data has evolved in parallel with remote sensing areas.

Research highlights: Landsat LST analysis is an evolving topic with potential to contribute to improve ecosystem knowledge and to support diverse challenges in forest resources decision-making.

Additional key words: Thematic Mapper; Enhanced Thematic Mapper; Thermal Infrared Sensor; Thermal infrared; LST.

Abbreviations used: ETM+ (enhanced thematic mapper plus); JCR (Journal Citation Report); LAI (leaf area index); LIDAR (light detection and ranging o laser imaging detection and ranging); LST (land surface temperature); MODIS (moderate resolution imaging spectroradiometer); NDVI (normalized difference vegetation index); TIRS (thermal infrared sensor); TM (thematic mapper).

Citation: Rosas-Chavoya, M; López-Serrano, PM; Vega-Nieva, DJ; Wehenkel CA; Hernández-Díaz, JC (2022). Application of Land Surface temperature from Landsat series to monitor and analyze forest ecosystems: A bibliometric analysis. Forest Systems, Volume 31, Issue 3, e021. https://doi.org/10.5424/fs/2022313-19539

Supplementary material (Tables S1-S5) accompanies the paper on Forest System´s website.

Received: 03 May 2022. **Accepted:** 04 Nov 2022.

Funding agencies/institutions: Mexican National Science and Technology Council (CONACYT).

Competing interests: The authors have declared that no competing interests exist.

Correspondence should be addressed to Pablito M. López-Serrano: pmslopez@gmail.com

Introduction

Land surface temperature (LST) is an important parameter to characterize the energy exchange between the land surface and the atmosphere (Amalyahya, 2015; Quispe-Reymundo & Révolo-Acevedo, 2020). It is considered an essential climate variable to analyze land surface processes by the Global Climate Observing System (GCOS, 2016). LST data allow analyzing evapotranspiration, climate change, hydrological cycles, fire monitoring, and other phenomena influencing the functioning of forest ecosystems (Li *et al*., 2013; Vlassova & Pérez-Cabello, 2016; Bendib *et al*., 2017). LST can be estimated from satellite information, allowing an opportunity to study the thermal dynamics in forest ecosystems at regional to global scales (Bendib *et al*., 2017).

The Landsat program has captured land surface information in the thermal infrared spectrum consistently for almost four decades (Table S1 [suppl]), since the launch of Landsat 4 TM (Thematic Mapper), followed by Landsat 5 TM, Landsat 7 ETM+ (enhanced thematic mapper plus) and Landsat 8 TIRS (Thermal Infrared Sensor), making possible LST estimation (Wang *et al.,* 2015). Thermal information from Landsat satellites has represented an opportunity for the analysis of various aspects of forests ecosystems (Banskota *et al*., 2014). For example, Landsat LST has been used to quantify the impact of climate change on forest ecosystems (Arekhi *et al*., 2018; Ghazaryan *et al*., 2018; Savastru *et al*., 2020), to analyze land use change in forest areas (Sabajo *et al*., 2017; Del Mundo & Tiburan Jr, 2019; Herrero *et al*., 2019), to evaluate forest evapotranspiration processes (Zhu *et al*., 2010; Yang *et al*., 2017) or to monitor urban forests (Huang *et al*., 2015; Jana *et al*., 2020).

While there are several studies that have used LST to monitor and analyze forest ecosystems, to our best knowledge, there is no previous study that has analyzed the scientific publications on this topic, which could allow identifying trends and areas of opportunity in the use of thermal information for the analysis of forest ecosystems. Bibliometric analyses are tools that allow to characterize publications with common topics, quantifying annual publication growth rate, analyzing citation, or identifying collaboration networks, among other bibliometric indicators. For example, Zhuang *et al*. (2013) conducted a bibliometric analysis on the trends in research using remote sensing in the 1991-2010 period. They concluded that topics more frequently analyzed were land use change, vegetation analysis and climate change and identified USA as the country with the highest scientific publication on this topic. Duan *et al*. (2020) analysed the use of remote sensing to monitor natural protected areas; they concluded that most utilized information was satellite data from Landsat and MODIS, together with LIDAR sensors and they identified international collaboration networks.

A bibliometric analysis on the scientific contributions utilizing Landsat LST to monitor and analyze forest ecosystems, could allow gaining a general perspective on the evolution of the main topics and applications of this research area. The current study aimed at identifying trends, challenges, and areas of opportunity in the use of Landsat LST on forest ecosystems, with the following goals: 1) to characterize scientific contributions on the topic; 2) to identify scientific networks between authors and countries in this research area; 3) to identify trends in research using LST to study forest ecosystems.

Material and methods

The scientific repository Scopus (https://www.scopus.com) was used for the literature search. Scopus is one of the most important scientific repositories, with more than 20,000 scientific journals registered, representing an adequate source to gather information for a bibliometric analysis (Joshi, 2017). Our search focused on words within the title, summary and keywords. One of the areas of knowledge more analyzed with LST is urban areas characterization (Rasul *et al*., 2017). The present study focused on investigations using LST to study forest ecosystems, therefore studies on urban climate and urban heat islands characterization were excluded from the analysis. The search period analyzed was from 1982, the year at which Landsat 4 TM was launched (Arvidson *et al*., 2013). The search equation used was: TITLE-ABS-KEY = ("land surface temperature" AND Landsat AND forests OR "forest ecosystem" OR forestry OR silviculture OR "natural forest" OR "forest plantations " AND NOT "urban heat island" AND NOT "urban heat") AND PUBYEAR > 1981 AND (EXCLUDE (PUBYEAR, 2021).

The search resulted in 195 initial registers. Some scientific documents such as reviews, notes, correction letters and editorial material were excluded, resulting in a total of 155 filtered documents. The database was downloaded in CSV format for analysis. The database was analyzed with the package Bibliometrix and the tool Biblioshiny (http://www.bibliometrix.org) that belong to RStudio (Aria & Cuccurullo, 2017; RStudio Team, 2020). Biblioshiny is a web interface that contains the central code of Bibliometrix. It allows for bibliometric analyses, including tools to visualize the annual scientific productivity rate, journals and authors with the highest number of publications on the topic, most utilized keywords analysis or thematic evolution and collaboration network analysis, among others (Xie *et al*., 2020a). In particular, the following analyses were performed:

—Wordtreemap: It identifies the frequency of keywords within the analyzed publications. The analysis consisted in identifying the 13 most frequent keywords in the articles from the database. The analysis of keywords frequency allows identifying the most studied topics in an area of research (Xie *et al*., 2020b).

—Multidimensional scaling analysis: It is a correspondence analysis that summarizes the main variables of the

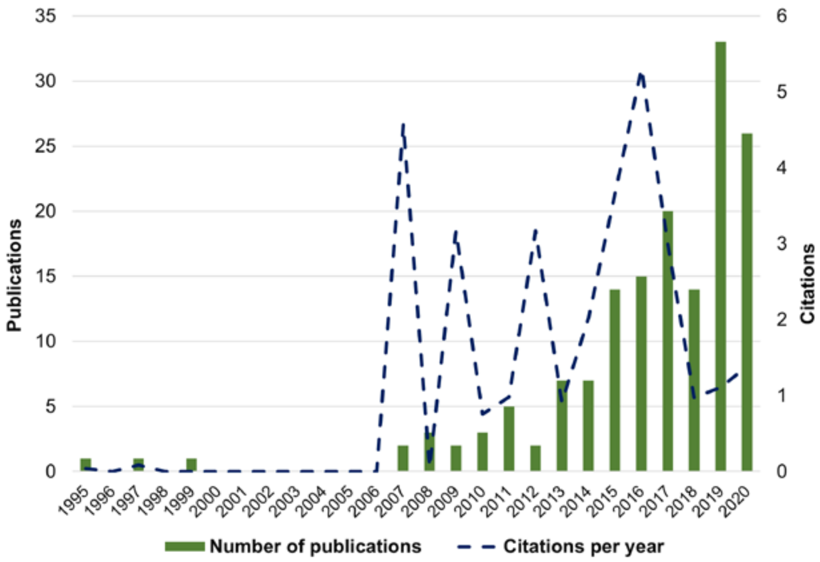

Figure 1. Number of publications and average citations.

articles analyzed and allows classifying the relationships between categorical variables (Ayele *et al*., 2014). This analysis considers the frequency of the keywords appearing together. Keywords are represented as dots and their position within the graph represent the coincidences between them. Groups are formed with keywords that appear together more frequently (Ayele *et al*., 2014; Aria & Cuccurullo, 2017).

—Thematic evolution analysis: This analysis allows visualizing the development and relative increase or decrease of some topics, identifying thematic evolution through time, represented by a Sankey diagram. Inside the Sankey diagram, each node represents one topic, the size of the node represents the number of keywords associated to that topic, the lines joining the nodes represent the direction of the topic evolution and the thickness of the line shows the strength of the relationships between topics (Xie *et al*., 2020b). Continuous lines between nodes of different years indicate that the topic has prevailed through time.

Finally, studies were classified by their main topic, out of 15 identified topics defined after careful review of all analyzed publications. Main topics were Classification land cover, Forest monitoring, Evapotranspiration/Dryness, Thermal analysis, Urban forests analysis, Wildfire, Deforestation, Vegetation indexes, Environmental quality analysis, Mountain ecology/Snow monitoring, Climatic change analysis, Phenological analysis, Desertification, Mining and Above-ground biomass estimation.

Results

General information

Search period started in 1982; nevertheless, the earliest identified publication was from 1995, resulting in a period of analysis from 1995 to 2020. The papers (155) about topic were written by 554 authors, with an average of 0.29 articles by author, with only four articles (3.1%) by one single author. The increase in the annual publication rate was 22.6% (Table S2 [suppl]). An increase in the number of publications can be observed after 2007. The year with the highest number of publications was 2019 with 33 articles, followed by 2020 with 26 articles.

Annual average citations (*i.e.* the average citations per article in each year), were almost null in the period 1995-2006; nevertheless, an increase was observed after the year 2007, fluctuating in the subsequent period (2007-2020), peaking with a maximum in 2016, and later diminishing (Fig. 1). A third (33.3%) of 2016 articles focused on LST dynamics related to vegetation and land use change, as well as on the characterization of LST between different vegetation types (Ara *et al*., 2016; Fu & Weng, 2016; Kayet *et al*., 2016; Sahana *et al*., 2016; Wang *et al*., 2016).

The scientific journals with the highest number of publications are shown in Table S3 ([suppl]). The journal with the highest number of publications in the topic is 'Proceedings of SPIE', which results from an annual congress specialized in spatial analysis. An example is the study by Ramdhani *et al*. (2019), who used Landsat 8 TIRS thermal images to evaluate post-mining forest remediation activities, comparing remediated areas with different forest species and years of plantation. Their results showed that all species used for forest remediation had a similar capacity to decrease LST; the reduction in LST was observed in a relatively short period of time.

The second journal with the highest number of articles in the topic was 'Remote Sensing'. This journal has a high impact factor (4.509, 2019), is listed in the first quartile of the Journal Citation Report (JCR) index, and has an annual rate of 1.5 articles published on LST since the start of the publication of the journal (Table S3 [suppl]). As an

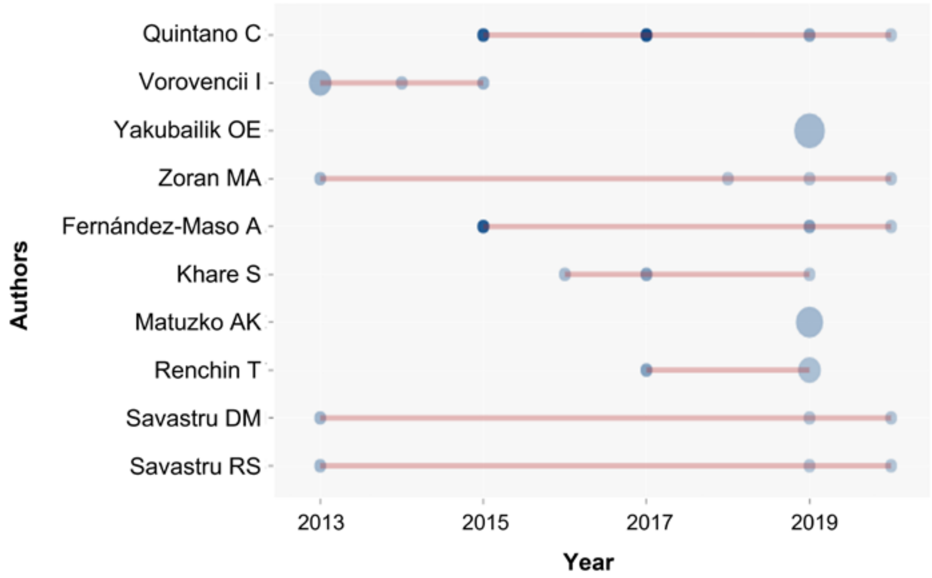

Figure 2. Authors' production over time in the field of land surface temperature derived from Landsat missions.

example of studies published in this journal, Sánchez *et al*. (2015) evaluated the energy balance in a forest area after a wildfire in a mediterranean forest in Almodóvar del Pinar, Spain. The authors used Landsat 5 TM and Landsat 7 ETM+ to estimate LST and the energy balance; their results showed the potential of LST to evaluate changes in thermal balances through time in areas with previous disturbances.

Table S4 [suppl] shows the most cited article on the topic. In the top is the study of Fu & Weng (2016), published in 'Remote Sensing of Environment'. It focuses on a multi-temporal analysis of LST increase with regards to the decrease in perennial forests and their substitution by urban areas. The second most cited study is the article of Xiao & Weng (2007), which evaluated land use change in a province at the Southeast of China; the study found that reforestation activities decreased LST in the region of study.

Main authors and collaborative networks

The productivity by author can be evaluated using Lotka´s law (Lotka, 1926). This criterion quantifies how often authors publish about a specific topic. Based on Lotka´s law, 86.7 % of authors who have published about LST have only published one article, while only one author has participated in 5 studies on the topic. Fig. 2 shows the authors with the highest scientific publication and the year of publication; the size of the circles represents the number of articles; the circle shading density represents the number of citations.

The four authors with the highest amount of publications on the topic in the last years are: Quintano C., Vorovencii I., Yakubailik O.E. and Zoran M.A., with four articles each. Quintano started publishing on the topic in 2015; this author works on topics related to the evaluation of forest fires from LST information. The most cited article from this author (57 citations, 2020) is a study published in International Journal of Applied Earth Observation and Geoinformation about fire severity evaluation from LST, estimated from Landsat 7 ETM+ images. A coefficient of determination > 0.85 was observed in this study between LST and a field fire severity index (composite burn index) (Quintano *et al*., 2015). In a later study, Quintano *et al.* (2017) combined MESMA fraction images with Landsat 7 ETM+ LST to analyze fire severity in a forest fire in Spain.

On the other hand, Vorovencii (2015) used thermal information from Landsat series to analyze land use change and desertification risk in Romania. This author evaluated and monitored desertification risk through vegetation indices and Landsat 5 TM LST data, observing that areas with extensive vegetation loss have higher LST and higher desertification risk.

The analysis of scientific productivity by country reveals that is a topic under development, since there are publications from 38 countries only, 7 from America, 10 from Europe, 5 from Africa, 15 from Asia and Australia (Fig. 3). The five countries with the highest scientific productivity are China, India, USA, Spain and Indonesia. The countries with the highest number of corresponding authors are China, India and Spain. In the case of China, 64% of the articles have conational authors and the rest of the articles (36%) were written with authors from other countries. In contrast, all the articles with corresponding authors from India were conducted by authors from the same country. Regarding type of ecosystems analyzed,

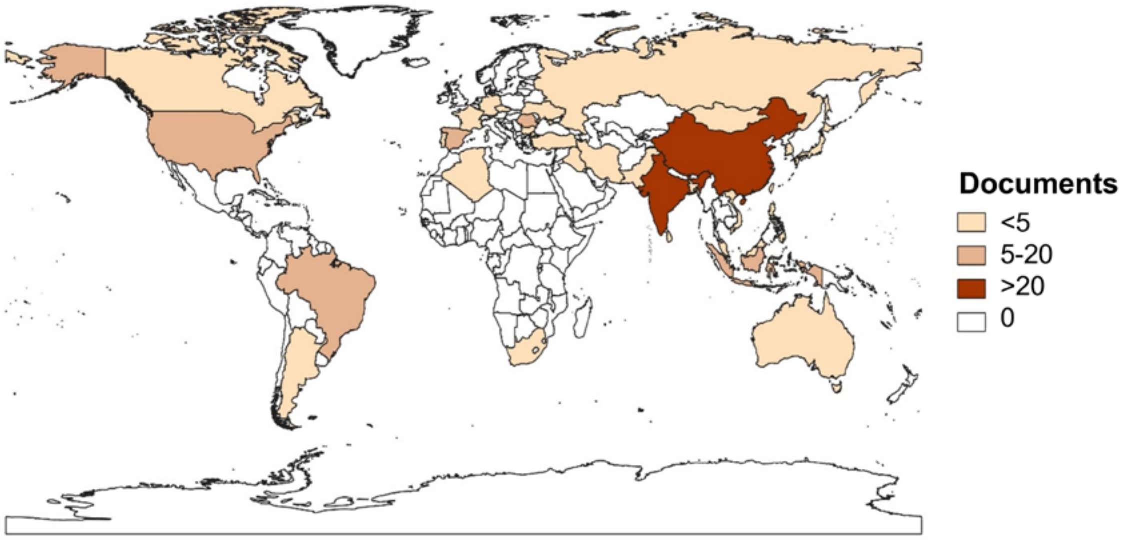

Figure 3. Country scientific production in the field of land surface temperature derived from Landsat missions.

temperate forests were the most analyzed ecosystems with Landsat LST, followed by tropical forests and urban forests (Fig. 4).

The collaboration network analysis is shown in Fig. 5. Nodes represent countries, lines show the collaboration between countries; the size of the nodes represent the relative amount of publications for each country. Four main groups of collaboration can be distinguished, the most notable collaboration network is integrated by China, USA and Spain; another network is integrated by Iran and Canada; a third one by Australia, China and Netherlands and another collaboration group can be distinguished between Germany and India. On the other hand, countries such as Brazil, Indonesia and Romania also have scientific production on LST but only with authors from the same country.

Keyword analysis and thematic evolution

Keyword analysis allowed for identifying the main topic of the articles in a systematic and intuitive manner. A WorldTreeMap was generated from the Biblioshyni interface to represent the most frequently used keywords (Fig. 6). Most used keywords (in addition to those used as criteria for the initial search *i.e.* "land surface temperature" and "Landsat") were: remote sensing (21%), NDVI (17%), MODIS (9%), Landsat 8 (8%), evapotranspiration (6%), land cover (6%), followed by burn severity, deforestation and soil moisture (each with 4%). Likewise, our analysis revealed that 40.4% of analyzed studies used Landsat 8 TIRS to estimate LST; 33.8% of studies used Landsat 4 and 5 TM; while Landsat 7 ETM+ was only used in 25.8% of studies.

Multidimensional analysis allows identifying main keywords and the frequency of the relationships between them. Three groups can be distinguished (Fig. 7): the first group includes topics related to characterization of terrestrial surface, including surface measurement, evapotranspiration, and regression analysis. A second group is integrated by the keywords land cover, deforestation and environmental monitoring in relation to urbanization. Finally, another group is formed only by three terms, artificial neural network, surface temperatures and climate change; this last group might represent an area of opportunity for the use of Landsat LST. One example is the study by Neinavaz *et al*. (2019), where Landsat 8 short wave infrared and thermal infrared data were analyzed with neuronal networks to improve Left Area Index (LAI) characterization in a forest ecosystem.

A gradual change was found in the topics of the analyzed articles using LST to characterize forest ecosystems (Fig. 8). In a first period (1995-2012), the most recurrent topics were: geology, vegetation, and evapotranspiration. Topics related to keywords landforms and meteorology

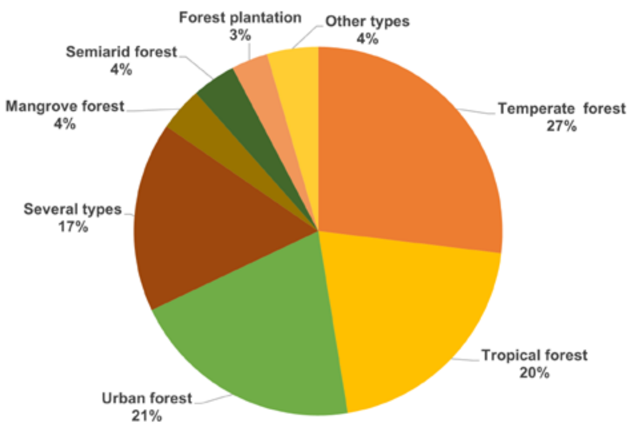

Figure 4. Forest types analyzed in the field of land surface temperature information from the Landsat missions.

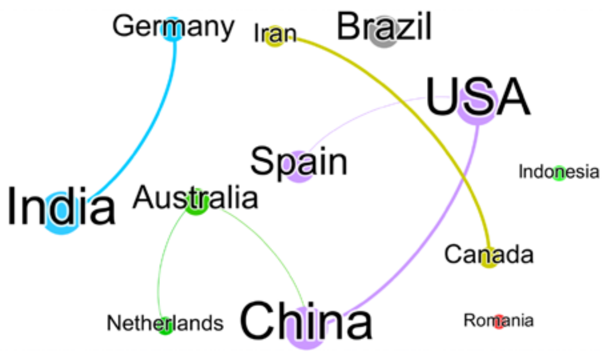

Figure 5. Country collaboration map of the 12 highest producing countries in the field of land surface temperature (1995-2020).

were frequent in years 2010 and 2012. Finally, in the most recent period keywords such as time series analysis and climate change were the most frequent.

Research topic analysis

The classification of the 155 analyzed studies by main research topic is shown in Table S5 [suppl]. The most frequent research topic (51 publications) was Classification of land cover. LST data can reflect changes in the temperature fluxes of land surfaces associated to land surface composition changes, which results in a widespread use to analyze land use and vegetation type changes (Tan *et al*., 2020). With regards to the documents centered on 'Forest monitoring', they focus on topics such as evaluating the dynamics of the cover and structure of forests (Siyal *et al*., 2017), monitoring natural protected areas (Gillespie *et al*., 2014), forest degradation analysis (Barros Santiago *et al*., 2019), forest cover change monitoring (van Leeuwen *et al*., 2011), and forest pests detection (Sprintsin *et al*., 2011).

Discussion

Bibliometric analyses have been widely used to understand and define the paths of scientific development in different areas of knowledge (Bonilla *et al*., 2015; Mora *et al*., 2017; Ahmad *et al*., 2020; Moral-Muñoz *et al*., 2020). This type of analysis helps to know the volume and characteristics of scientific research on a particular topic, as well as the topic evolution over time (Ramanan *et al*., 2020).

The results of this analysis showed that the use of thermal information from the Landsat time-series in forest ecosystems started to gain importance in 1995, even though the first Landsat satellite capable of capturing thermal infrared information was launched in 1985. This might be explained by a more extensive use of satellite platforms to analyze urban areas and agricultural lands, with a comparative delay in the thermal analysis of forest areas. The interest in thermal dynamics on the earth's surface became relevant after climate change was acknowledged as a global issue by the United Nations Framework Convention on Climate Change. There, 197 countries signed a treaty with 10 commitments to reduce human interference with the global climate system. Notable aspects of this agreement include the following: *Promote and cooperate in scientific, technological, technical, socio-economic and other research, systematic observation and development of data archives related to the climate system and intended to further the understanding and to reduce or eliminate*

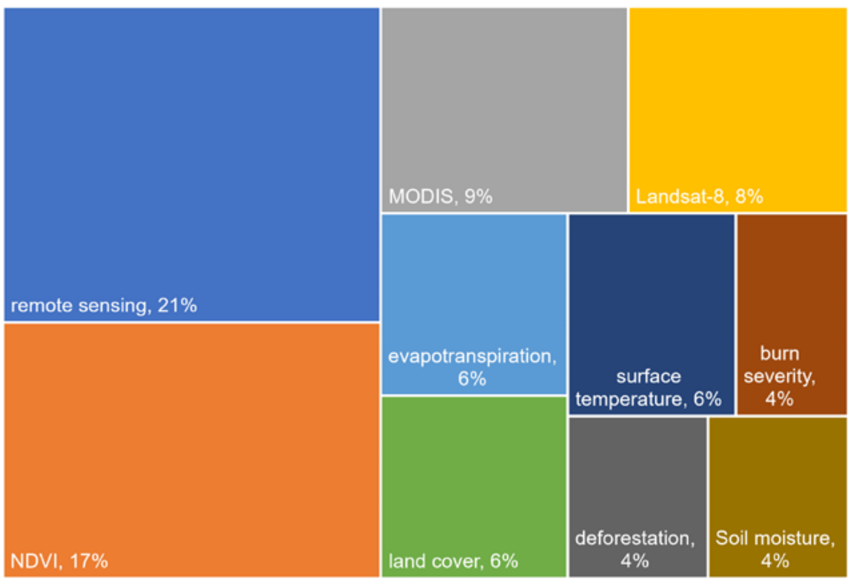

Figure 6. WordTreeMap of high-frequency keywords in the field of land surface temperature information from the Landsat missions (1995-2020).

Figure 7. Multidimensional scaling analysis of high-frequency keywords in the field of land surface temperature information from the Landsat missions (1995-2020).

the remaining uncertainties regarding the causes, effects, magnitude and timing of climate change (UN, 1992).

This shift in policy may have resulted in a growing interest among the scientific community in the use of thermal information to analyze the Earth's surface, at times with a multi-temporal approach (Boike *et al*., 2016; Kayet *et al*., 2016; Arif *et al*., 2019; Gosteva *et al*., 2019 a,b). For instance, Kayet *et al*. (2016) analyzed for three years (1994, 2004 and 2014) the LST for different land uses and vegetation in an African forest. They found that the rapid growth of the industrial zone and the loss of vegetation favor a significant increase in LST.

Some of the journals with the greatest number of articles published on the matter notably include Proceedings of SPIE and Remote Sensing. Both are journals with prestige and a high impact factor. Proceedings of SPIE is a pioneering journal in research on remote sensing, as it started publications in 1995, and publishes proceedings of 350 SPIE conferences. Some of these are focused on research in remote sensing. As such, it is a journal with high visibility among the scientific community. On the other hand, Remote Sensing is a specialized journal that publishes the most cutting-edge breakthroughs on remote sensing (Gallardo-Salazar *et al*., 2020). High visibility and impact are often characteristics of journals that matter most to members of the scientific community.

Regarding the type of ecosystems analyzed, temperate forests are the most analyzed ecosystems with Landsat LST, followed by tropical forests and urban forests. The FAO reports that the world's largest forests are tropical forests, followed by temperate and boreal forests (FAO, 2020). Therefore, the prevalence of these forests in studies related to surface temperature may be closely related to the surface they represent worldwide (Peters *et al*., 2013). In addition, countries with the highest production on the matter have temperate forests, which can be reflected in the type of vegetation studied under this approach.

China has the highest scientific production on the subject, which can be explained mainly by two conditions: (1) China is a developed country with an important investment in science and technology; in addition, the Chinese scientific community has expressed a commitment to obtain information to characterize and restore the environment (Xie *et al*., 2020a). (2) Since the previous decade, several Chinese researchers started to publish their contributions in English, which has strengthened collaboration networks between China and English-speaking countries such as the USA and Australia (Pan & Block, 2011; Ramanan *et al*., 2020). This is undoubtedly a positive dynamic for research on the matter, as the development of collaboration networks results in an increase in the quality of scientific contributions (Ramanan *et al*., 2020). Articles elaborated by Chinese institutions cover a variety of topics such as land use and vegetation type change detection (Tan *et al.,* 2020), impact of deforestation on LST (Shen *et al.,* 2020), relationships between environmental degradation and LST (Hou *et al.,* 2020), algorithms to identify snow (Wang *et*

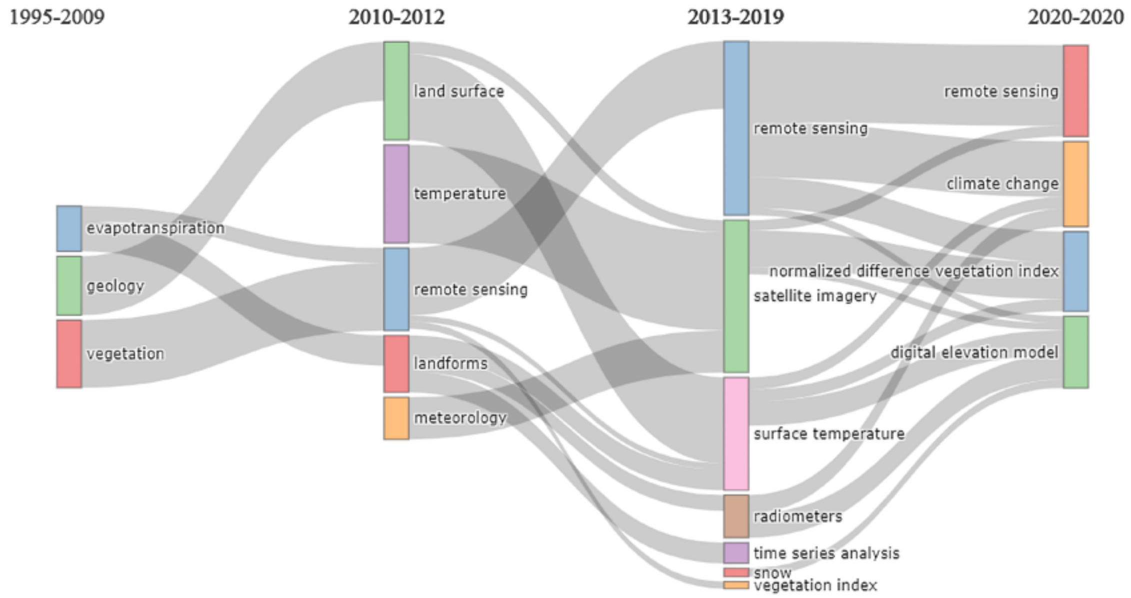

Figure 8. Thematic evolution of the field of land surface temperature information from the Landsat missions.

al., 2020), impact of green areas in decreasing LST (Yin *et al.,* 2019), evaluation of ecological indices and their relationship with LST (Zhu *et al.,* 2019), factors influencing forest canopy LST (Zuo *et al.,* 2018), multi-temporal evaluation of forest burned area (Wang *et al.,* 2017), among others.

Among articles analyzed, the most used sensors were TIRS (Landsat 8) and TM (Landsat 4 and 5). The latter might be related to the failure suffered in 2003 by the scanner line of the Landsat 7 ETM+ sensor, resulting in incomplete image capture that reduced its use in the scientific community (Yin *et al.,* 2017).

Similarly, widely used spectral indices such as NDVI have been analyzed jointly with LST data to understand physiological processes such as water stress and forest decline. NDVI is deemed as the most widely used spectral index, given its simplicity and dependence on spectral bands (NIR and red) that are easy to obtain (Huang *et al.,* 2021). The wide use of NDVI can be explained by the influence on thermal processes of the condition and amount of vegetation cover, which can be inferred from NDVI, a proxy of vegetation density and vegetative vigor. For example, Wan Mohd Jaafar *et al.* (2020) analyzed the influence of deforestation on LST, using NDVI to determine the conditions of the forest cover.

In addition to this, MODIS and Landsat products are often used jointly, which allows benefitting from Landsat's higher spatial resolution and from MODIS' temporal resolution (Guan *et al*., 2021). For example, in the study by Herrero *et al*. (2019), Landsat 8 LST was integrated with MODIS data to classify savanna forest types in Zambia. The authors concluded that using both data sources allowed to develop multi-temporal land use change analysis in African savannas.

Regarding the multidimensional scaling analysis, a link was observed between the terms evapotranspiration, vegetation index and vegetation. This finding can be related to the development of spectral indices, which use information from the thermal infrared band. For example: Temperature Dryness Vegetation Index (TDVI) and the Vegetation Temperature Condition Index (VTCI), which are based on the theoretical relationship between NDVI and LST, allowing to predict areas with greater potential evapotranspiration than humidity availability (Xu *et al.,* 2011).

Similarly, the topics urbanization, deforestation and land cover were grouped together, emphasizing the growing interest in understanding the processes of land use change and analysis of urban environments under a thermal approach (Wang & Zhang, 2015; Hua & Ping, 2018; Arif *et al*., 2019). For example, Jana *et al*. (2020) analyzed the impact of urban forests and green areas in the thermal dynamics of a city in Doon Valley, India, and concluded that the expansion of areas with urban land use in replacement of forests and green areas influenced an observed increase in LST of up to 8.6°C.

The thematic evolution plot indicates that the use of thermal information from the Landsat series in the analysis of forest ecosystems has been a matter that has changed over time. It was initially used for the analysis of processes, such as evapotranspiration in the vegetation cover. Subsequently, a trend was observed in the use of this information for climatic and meteorological analysis and the development of vegetation indices. In recent years, it has been used for the analysis of processes associated with climate change. This suggests that the topics of application and techniques of analysis have evolved in lockstep with remote sensing trends, also related to topics of global importance such as climate change. Other emerging topics such as phenomenological analysis, desertification, mining, or above-ground biomass estimation can represent areas of opportunity for the use of LST from Landsat series.

The paper herein has certain limitations, especially regarding the use of a single database (Scopus), which does not include all indexed journals and focuses on documentation only in English; therefore, this analysis could be excluding relevant documentation. In future studies, the search could be extended to other scientific databases such as Web of Science and Google Scholar. Lastly, it is worth noting the recently the Landsat 9 satellite was successfully launched. This satellite shares an orbit with Landsat 8, which increases the temporal resolution of images and reduces the risk of interrupted information (USGS, 2020). Without a doubt, Landsat 9 represents the commitment and interest in ensuring the continuity of the Landsat series' data collection.

Conclusions

The use of land surface temperature (LST) data from Landsat series to monitor and characterize forest ecosystems is a topic in evolution, with applications in vegetation cover classification, forest monitoring, and drought and evapotranspiration analysis, among others. There are several countries with scientific productivity on the topic, with other regions such as Africa or Central America (*e.g.* Mexico) showing potential for expanding its application. Thermal analysis of forest ecosystems has mainly focused on temperate forests, tropical forests, and urban forests. There is consequently an area of opportunity for the analysis of other types of vegetation with LST data. The analysis of collaboration between countries showed a limited cooperation between countries, centered on a relatively small amount of collaboration networks. Increasing the collaboration between countries in this topic will allow improving the knowledge of thermal dynamics of forest ecosystems and its application to improve forest decision making in diverse regions of the world. The use of Landsat LST in forest ecosystems has evolved in pair with the trends and methodologies of remote sensing, with some emerging topics such as climate change monitoring in the last years. The current bibliometric analysis allowed understanding the characteristics and evolution of this research topic. Future bibliometric research could focus on further comparing the thermal information from Landsat with those of other satellite platforms *i.e.* MODIS, Sentinel-3, NOAA-AVHRR, to obtain a multi-sensor perspective on the use of remote sensing for thermal characterization of forest ecosystems.

Authors' contributions

Conceptualization: M. Rosas-Chavoya, P.M. López-Serrano.
Data curation: M. Rosas-Chavoya.
Formal analysis: M. Rosas-Chavoya, P.M. López-Serrano.
Investigation: M. Rosas-Chavoya.
Methodology: P.M. López-Serrano.
Supervision: P.M. López-Serrano, D. Vega-Nieva, C.A. Wehenkel, J.C. Hernández-Díaz.
Writing – original draft: M. Rosas-Chavoya.
Writing – review & editing: P.M. López-Serrano, D. Vega-Nieva, C.A. Wehenkel, J.C. Hernández-Díaz.

References

Ahmad P, Asif JA, Alam MK, Slots J, 2020. A bibliometric analysis of Periodontology 2000. Periodontol 82: 286-297. https://doi.org/10.1111/prd.12328

Amalyahya A, 2015. Vegetation cover density and land surface temperature interrelationship using satellite data, case study of Wadi Bisha, South KSA. ARS 4: 248-262. https://doi.org/10.4236/ars.2015.43020

Ara S, Islam MA, Showkat S, 2016. Effect of land-use intensity on surface temperature: A study on Chittagong city corporation area. 5th Int Conf on Informatics, Electronics and Vision (ICIEV), pp: 72-77. https://doi.org/10.1109/ICIEV.2016.7759971

Arekhi M, Yesil A, Ozkan UY, Sanli FB, 2018. Detecting treeline dynamics in response to climate warming using forest stand maps and Landsat data in a temperate forest. For Ecosyst 5: 23. https://doi.org/10.1186/s40663-018-0141-3

Aria M, Cuccurullo C, 2017. Bibliometrix: An R-tool for comprehensive science mapping analysis. J Informetr 11: 959-975. https://doi.org/10.1016/j.joi.2017.08.007

Arif N, Khasanah AN, Jaya R, Gozan M, Hendrawan B, 2019. The effect of land surface temperature and land use on energy system development in Gorontalo City. J Phys Conf Ser 1179: 012103. https://doi.org/10.1088/1742-6596/1179/1/012103

Arvidson T, Barsi J, Jhabvala M, Reuter D, 2013. Landsat and thermal infrared imaging. In: Thermal infrared remote sensing: Sensors, methods, applications; Kuenzer C & Dech S (eds). Springer Netherlands, Dordrecht, pp: 177-196. https://doi.org/10.1007/978-94-007-6639-6_9

Ayele D, Zewotir T, Mwambi H, 2014. Multiple correspondence analysis as a tool for analysis of large health surveys in African settings. Afr Health Sci 14(4): 1036-1045. https://doi.org/10.4314/ahs.v14i4.35

Banskota A, Kayastha N, Falkowski MJ, Wulder MA, Froese RE, White JC, 2014. Forest monitoring using Landsat Time Series Data: A review. Can J Remote Sens 40: 362-384. https://doi.org/10.1080/07038992.2014.987376

Barros Santiago D, Correia Filho WLF, de Oliveira-Júnior JF, Silva-Junior CA, 2019. Mathematical modeling and use of orbital products in the environmental degradation of the Araripe Forest in the Brazilian Northeast. Model Earth Syst Environ 5: 1429-1441. https://doi.org/10.1007/s40808-019-00614-x

Bendib A, Dridi H, Kalla MI, 2017. Contribution of Landsat 8 data for the estimation of land surface temperature in Batna city, Eastern Algeria. Geocarto Int 32: 503-513. https://doi.org/10.1080/10106049.2016.1156167

Boike J, Grau T, Heim B, Günther F, Langer M, Muster S, *et al.,* 2016. Satellite-derived changes in the permafrost landscape of central Yakutia, 2000-2011: Wetting, drying, and fires. Glob Planet Change 139: 116-127. https://doi.org/10.1016/j.gloplacha.2016.01.001

Bonilla CA, Merigó JM, Torres-Abad C, 2015. Economics in Latin America: A bibliometric analysis. Scientometrics 105: 1239-1252. https://doi.org/10.1007/s11192-015-1747-7

Del Mundo VKM, Tiburan Jr CL, 2019. Analyzing the effects of land cover change on surface temperature in Mount Makiling Forest Reserve (MMFR) and its neighboring municipalities using Landsat data. ISPRS Archives XLII-4/W19: 165-172. https://doi.org/10.5194/isprs-archives-XLII-4-W19-165-2019

Duan P, Wang Y, Yin P, 2020. Remote sensing applications in monitoring of protected areas: A bibliometric analysis. Remote Sens 12(5): 772. https://doi.org/10.3390/rs12050772

FAO, 2020. Global forest resources assessment 2020: Main report. Rome. https://www.fao.org/documents/card/en/c/ca8753en/ [20 Sept 2021].

Fu P, Weng Q, 2016. A time series analysis of urbanization induced land use and land cover change and its impact on land surface temperature with Landsat imagery. Remote Sens Environ 175: 205-214. https://doi.org/10.1016/j.rse.2015.12.040

Gallardo-Salazar JL, Pompa-García M, Aguirre-Salado CA, López-Serrano PM, Meléndez-Soto A, 2020. Drones: Tecnología con futuro promisorio en la gestión forestal. Rev Mex Cienc Forest 11 (61). https://doi.org/10.29298/rmcf.v11i61.794

GCOS, 2016. Essential climate variables. Global Climate Observing System. https://gcos.wmo.int/en/essential-climate-variables [20 Sept 2021].

Ghazaryan G, Dubovyk O, Graw V, Schellberg J, 2018. Vegetation monitoring with satellite time series: An integrated approach for user-oriented knowledge extraction. Proc of SPIE 10783, Remote Sens Agr Ecosyst Hydrol XX, October 10. https://doi.org/10.1117/12.2325762

Gillespie TW, Willis KS, Ostermann-Kelm S, 2014. Spaceborne remote sensing of the world's protected areas. Prog Phys Geogr: Earth Environ 39: 388-404. https://doi.org/10.1177/0309133314561648

Gosteva A, Matuzko A, Yakubailik O, 2019a. Detection of changes in urban environment based on infrared satellite data. IOP Conf Ser: Mater Sci Eng 537: 062051. https://doi.org/10.1088/1757-899X/537/6/062051

Gosteva A, Matuzko A, Yakubailik O, 2019b. Identification of changes in urban environment on the basis of the satellite data of the infrared range (on the example of Krasnoyarsk). InterCarto InterGIS 25: 90-100. https://doi.org/10.35595/2414-9179-2019-2-25-90-100

Guan X, Shen H, Wang Y, Chu D, Li X, Yue L, *et al.,* 2021. Fusing MODIS and AVHRR products to generate a global 1-km continuous NDVI time series covering four decades. Earth Syst Sci Data. https://doi.org/10.5194/essd-2021-156

Herrero HV, Southworth J, Bunting E, Kohlhaas RR, Chil B, 2019. Integrating surface-based temperature and vegetation abundance estimates into land cover classifications for conservation efforts in savanna landscapes. Sensors 19(16): 3456. https://doi.org/10.3390/s19163456

Hou CH, Li FP, He BJ, Gu H, Song W, 2020. Study on surface thermal environment differentiation effect in mining intensive area through developing remote sensing assessment model. J Infrared Millim Terahertz Waves 39: 635-649.

Hua AK, Ping OW, 2018. The influence of land-use/land-cover changes on land surface temperature: A case study of Kuala Lumpur metropolitan city. Eur J Remote Sens 51: 1049-1069. https://doi.org/10.1080/22797254.2018.1542976

Huang H, Xie W, Sun H, 2015. Simulating 3D urban surface temperature distribution using ENVI-MET model: Case study on a forest park. Proc IEEE Int Geosci Remote Sens Symp (IGARSS). pp: 1642-1645. https://doi.org/10.1109/IGARSS.2015.7326100

Huang S, Tang L, Hupy JP, Wang Y, Shao G, 2021. A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. J For Res 32: 1-6. https://doi.org/10.1007/s11676-020-01155-1

Jana C, Mandal D, Shrimali SS, Alam NM, Kumar R, Sena DR, Kaushal R, 2020. Assessment of urban growth effects on green space and surface temperature in Doon Valley, Uttarakhand, India. Environ Monit Assess 192: 257. https://doi.org/10.1007/s10661-020-8184-7

Joshi A, 2017. Comparison between Scopus & ISI Web of science. J Glob Values 7: 2016.

Kayet N, Pathak K, Chakrabarty A, Sahoo S, 2016. Spatial impact of land use/land cover change on surface temperature distribution in Saranda Forest, Jharkhand. Model Earth Syst Environ 2: 127. https://doi.org/10.1007/s40808-016-0159-x

Li ZL, Tang BH, Wu H, Ren H, Yan G, Wan Z, *et al.,* 2013. Satellite-derived land surface temperature: Current status and perspectives. Remote Sens Environ 131: 14-37. https://doi.org/10.1016/j.rse.2012.12.008

Lotka AJ, 1926. The frequency distribution of scientific productivity. J Wash Acad Sci 16: 317-323

Mora L, Bolici R, Deakin M, 2017. The first two decades of smart-city research: A bibliometric analysis. J Urban Technol 24(1): 3-27. https://doi.org/10.1080/10630732.2017.1285123

Moral-Muñoz JA, Herrera-Viedma E, Santisteban-Espejo A, Cobo MJ, 2020. Software tools for conducting bibliometric analysis in science: An up-to-date review. Profesional de la Información 29(1). https://doi.org/10.3145/epi.2020.ene.03

Neinavaz E, Darvishzadeh R, Skidmore AK, Abdullah H, 2019. Integration of Landsat-8 thermal and visible-short wave infrared data for improving prediction accuracy of forest leaf area index. Remote Sens 11(4): 390. https://doi.org/10.3390/rs11040390

Pan L, Block, D, 2011. English as a "global language" in China: An investigation into learners' and teachers' language beliefs. System 39(3): 391-402. https://doi.org/10.1016/j.system.2011.07.011

Peters EB, Wythers KR, Zhang S, Bradford JB, Reich PB, 2013. Potential climate change impacts on temperate forest ecosystem processes. Can J For Res 43(10). https://doi.org/10.1139/cjfr-2013-0013

Quintano C, Fernández-Manso A, Calvo L, Marcos R, Valbuena L, 2015. Land surface temperature as potential indicator of burn severity in forest Mediterranean ecosystems. Int J Appl Earth Obs Geoinf 36: 1-12. https://doi.org/10.1016/j.jag.2014.10.015

Quintano C, Fernández-Manso A, Roberts DA, 2017. Burn severity mapping from Landsat MESMA fraction images and land surface temperature. Remote Sens Environ 190: 83-95. https://doi.org/10.1016/j.rse.2016.12.009

Quispe-Reymundo BJ, Révolo-Acevedo RH, 2020. Surface temperature and states of the vegetation of the forest of Polylepis spp, district of San Marcos de Rocchac, Huancavelica - Peru. Enfoque UTE 11: 69-86. https://doi.org/10.29019/enfoqueute.v11n3.592

Ramanan SS, George AK, Chavan SB, Kumar S, Jayasubha S, 2020. Progress and future research trends on Santalum album: A bibliometric and science mapping approach. Ind Crops Prod 58: 112972. https://doi.org/10.1016/j.indcrop.2020.112972

Ramdhani NF, Sulistyawati E, Sutrisno, 2019. Land surface temperature analysis of post-mining area using Landsat 8 imagery. Proc of SPIE 11372, 6th Int Symp on LAPAN-IPB Satellite 113720P, Dec 24. https://doi.org/10.1117/12.2541811

Rasul A, Balzter H, Smith C, Remedios J, Adam B, Sobrino JA, *et al.,* 2017. A review on remote sensing of urban heat and cool islands. Land 6(2): 38. https://doi.org/10.3390/land6020038

RStudio Team, 2020. RStudio: Integrated Development for R. RStudio, PBC, Boston, MA, USA. http://www.rstudio.com/ [20 Sept 2021].

Sabajo CR, le Maire G, June T, Meijide A, Roupsard O, Knohl A, 2017. Expansion of oil palm and other cash crops causes an increase of the land surface temperature in the Jambi province in Indonesia. Biogeosciences 14(20): 4619-4635. https://doi.org/10.5194/bg-14-4619-2017

Sahana M, Ahmed R, Sajjad H, 2016. Analyzing land surface temperature distribution in response to land use/land cover change using split window algorithm and spectral radiance model in Sundarban Biosphere Reserve, India. Model Earth Syst Environ 2: 81. https://doi.org/10.1007/s40808-016-0135-5

Sánchez JM, Bisquert M, Rubio E, Caselles V, 2015. Impact of land cover change induced by a fire event on the surface energy fluxes derived from remote sensing. Remote Sens 7(11): 14899-14915. https://doi.org/10.3390/rs71114899

Savastru DM, Zoran MA, Savastru RS, 2020. Assessing climate impacts on urban forest changes using time series satellite data. Proc SPIE, 8th Int Conf on Remote Sens Geoinform Environ (RSCy2020); 115241V. https://doi.org/10.1117/12.2570453

Shen W, He J, Huang C, Li M, 2020. Quantifying the actual impacts of forest cover change on surface temperature in Guangdong, China. Remote Sens 12(15): 2354. https://doi.org/10.3390/rs12152354

Siyal AA, Siyal AG, Mahar RB, 2017. Spatial and temporal dynamics of Pai forest vegetation in Pakistan assessed by RS and GIS. J For Res 28: 593-603. https://doi.org/10.1007/s11676-016-0327-x

Sprintsin M, Chen JM, Czurylowicz P, 2011. Combining land surface temperature and shortwave infrared reflectance for early detection of mountain pine beetle infestations in western Canada. J Appl Remote Sens 5: 1-14. https://doi.org/10.1117/1.3662866

Tan J, Yu D, Li Q, Tan X, Zhou W, 2020. Spatial relationship between land-use/land-cover change and land surface temperature in the Dongting Lake area, China. Sci Rep 10: 9245. https://doi.org/10.1038/s41598-020-66168-6

UN, 1992. United Nations framework convention on climate change. https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf [10 Nov 2021].

USGS, 2020. Landsat-Earth observation satellites. https://pubs.er.usgs.gov/publication/fs20153081 [15 Oct 2021].

van Leeuwen TT, Frank AJ, Jin Y, Smyth P, Goulden M, van der Werf GR, Randerson JT, 2011. Optimal use of land surface temperature data to detect changes in tropical forest cover. J Geophys Res Biogeosci 116. https://doi.org/10.1029/2010JG001488

Vlassova L, Pérez-Cabello F, 2016. Effects of post-fire wood management strategies on vegetation recovery and land surface temperature (LST) estimated from Landsat images. Int J Appl Earth Obs Geoinf 44: 171-183. https://doi.org/10.1016/j.jag.2015.08.011

Vorovencii I, 2015. Assessing and monitoring the risk of desertification in Dobrogea, Romania, using Landsat data and decision tree classifier. Environ Monit Assess 187: 204. https://doi.org/10.1007/s10661-015-4428-3

Wan Mohd Jaafar WS, Abdul Maulud KN, Muhmad Kamarulzaman AM, Raihan A, Md Sah S, Ahmad A, *et al.,* 2020. The influence of deforestation on land surface temperature- A case study of Perak and Kedah, Malaysia. Forests 11(6): 670. https://doi.org/10.3390/f11060670

Wang L, Zhang S, 2015. Analysis on the relationship between the pattern of green spaces and land surface temperature based on normalized difference vegetation index: A case study in Changchun city, China. Fresenius Environ Bull 24: 2444-2451.

Wang F, Qin Z, Song C, Tu L, Karnieli A, Zhao S, 2015. An improved mono-window algorithm for land surface temperature retrieval from Landsat 8 thermal infrared sensor data. Remote Sens 7(4): 4268-4289. https://doi.org/10.3390/rs70404268

Wang J, Qian YG, Han LJ, Zhou WQ, 2016. Relationship between land surface temperature and land cover types based on GWR model: A case of Beijing-Tianjin-Tangshan urban agglomeration, China. Chin J Appl Ecol 27: 2128-2136.

Wang Q, Yu X, Shu Q, 2017. Forest burned scars area extraction using time series remote sensing data. J Nat Disaster Sci 26: 1-10.

Wang X, Chen S, Wang J, 2020. An adaptive snow identification algorithm in the forests of Northeast China. IEEE J Sel Top Appl Earth Obs Remote Sens 13: 5211-5222. https://doi.org/10.1109/JSTARS.2020.3020168

Xiao H, Weng Q, 2007. The impact of land use and land cover changes on land surface temperature in a karst area of China. J Environ Manage 85: 245-257. https://doi.org/10.1016/j.jenvman.2006.07.016

Xie H, Zhang Y, Wu Z, Lv T, 2020a. A bibliometric analysis on land degradation: Current status, development, and future directions. Land 9(1): 28. https://doi.org/10.3390/land9010028

Xie H, Zhang Y, Zeng X, He Y, 2020b. Sustainable land use and management research: A scientometric review. Landsc Ecol 35: 2381-2411. https://doi.org/10.1007/s10980-020-01002-y

Xu L, Niu R, Li J, Dong Y, 2011. Soil moisture status estimation over Three Gorges area with Landsat TM data based on temperature vegetation dryness index. Proc SPIE 8006, MIPPR 2011: Remote Sensing Image Processing, GIS and Other Applications, 80061F, Nov 23. https://doi.org/10.1117/12.902433

Yang Y, Anderson MC, Gao F, Hain CR, Semmens KA, Kustas WP, *et al.,* 2017. Daily Landsat-scale evapotranspiration estimation over a forested landscape in North Carolina, USA, using multi-satellite data fusion. Hydrol Earth Syst Sci Discuss 21: 1017-1037. https://doi.org/10.5194/hess-21-1017-2017

Yin G, Mariethoz G, McCabe MF, 2017. Gap-filling of Landsat 7 imagery using the direct sampling method. Remote Sens 9(1): 12. https://doi.org/10.3390/rs9010012

Yin J, Wu X-x, Shen M, Zhang X, Zhu C, Xiang H, *et al.,* 2019. Impact of urban greenspace spatial pattern on land surface temperature: A case study in Beijing metropolitan area, China. Landsc Ecol 34: 2949-2961. https://doi.org/10.1007/s10980-019-00932-6

Zhu J, Ju W, Ren Y, 2010. Effects of land cover types and forest age on evapotranspiration detected by remote sensing in Xiamen City, China. Proc 18th Int Conf on Geoinformatics, June 18-20. pp: 1-5. https://doi.org/10.1109/GEOINFORMATICS.2010.5567518

Zhu X, Wang X, Yan D, Liu Z, Zhou Y, 2019. Analysis of remotely-sensed ecological indexes' influence on urban thermal environment dynamic using an integrated ecological index: a case study of Xi'an, China. Int J Remote Sens 40: 3421-3447. https://doi.org/10.1080/01431161.2018.1547448

Zhuang Y, Liu X, Nguyen T, He Q, Hong S, 2013. Global remote sensing research trends during 1991-2010: A bibliometric analysis. Scientometrics 96: 203-219. https://doi.org/10.1007/s11192-012-0918-z

Zuo S, Dai S, Song X, Xu C, Liao Y, Chang W, *et al.,* 2018. Determining the mechanisms that influence the surface temperature of urban forest canopies by combining remote sensing methods, ground observations, and spatial statistical models. Remote Sens 10(11): 1814. https://doi.org/10.3390/rs10111814