Trends of Remote Sensing applications for Amazon monitoring

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Abstract

The Amazon is home to a vast biodiversity and plays a crucial role in the maintenance and conservation of the planet. The progress of anthropogenic activities in the region is one of the drivers of land cover change. Studying these changes through remote sensing enables the monitoring of degradation and deforestation in the Amazon rainforest. Using bibliometric tools this study analyses the different remote sensing approaches for land use and land cover monitoring in the Amazon. The methodology includes 1) data search and collection, 2) tool selection and data processing, and 3) data and trend analysis. The results indicate that studies on forest loss and biodiversity are trending in the field. Emerging topics focus on new tools for environmental impact assessment and evaluating new computational technologies for satellite data management.

1. Introduction

The largest proportion (45%) of forest area in the world is found in the tropical zone (FAO, 2020). The Amazon is the world's largest tropical rainforest, covering approximately 6.9×10^6 km^2 (Borma et al., 2022). It is one of the most biodiverse ecosystems, with great importance in local, regional hydrology, and continental climate, making it vital to generate strategies against climate change (Marengo et al., 2018). However, the Amazon faces numerous threats, including land-use changes and forest fires, which lead to deforestation and degradation.

Despite its extensive natural wealth, constant changes in land use and land cover (LULC) can negatively impact this territory. Part of the Amazon rainforest has been lost due to deforestation, agricultural expansion, logging, land occupation, and infrastructure projects, causing significant changes in the Amazon ecosystem (Roberts et al., 2021). The LULC transition can have a high impact, such as the complete loss of the above-ground carbon stock and alteration of biodiversity (Nunes et al., 2022).

The research of LULC dynamics is a crucial tool for environmental planning and territorial management (Armenteras et al., 2019). Through remote sensing, it is possible to map land cover, land use, ecological disturbance, and vegetation phenology, as well as estimate their changes over time (Sánchez-Díaz, 2018). Several studies have utilized remote sensing to examine the Amazon. These studies include mapping and monitoring land degradation (Lu et al., 2007), identifying African palm plantations and previous land uses before cultivation (Furumo and Aide, 2017), and determining areas most vulnerable to human activities (Fiedler et al., 2023).

Few studies show the development of this research area through bibliometric analysis. Among these studies is the analysis of wetland remote sensing in South America (Kandus et al., 2018). The objective of this study is to identify which remote sensing approaches are used to study land use and cover change in the Amazon region. Bibliometric analysis techniques and tools effectively describe the state of knowledge, characteristics, and trends in this discipline and can be useful to generate insights that could help the integral development of the research area (Velastegui-Montoya et al., 2022).

2. Materials and Methods

The methodology of the study (Figure 1) consisted of three phases: a) search and data collection through keyword selection and application of the search strategy; b) tool selection and data processing, which included final data filtering and processing in the software; and c) data and trend interpretation through performance and intellectual structure analysis.

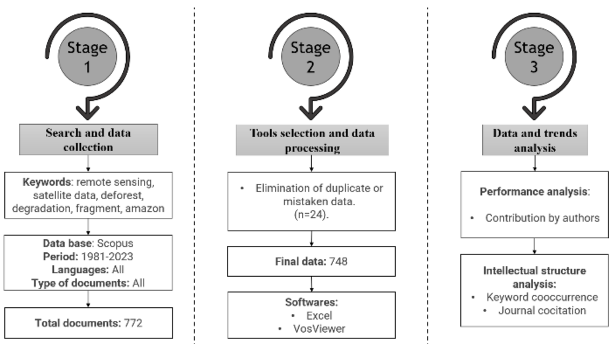

Figure 1. Methodological approach.

2.1 Search and data collection

Data collection was carried out exclusively using the Scopus database, with a defined period from 1981 to 2023. The sample of articles was selected, focusing on studies that use satellite data to analyse deforestation, degradation, and fragmentation of the Amazon rainforest. The detailed search string used was: TITLE-ABS-KEY ("remote sensing*") OR ("satellite data*") AND TITLE-ABS-KEY ("deforest*") OR ("degradation") OR ("fragment*") AND TITLE-ABS-KEY ("amazon*").

In addition, the year 2024 was excluded as it is the current year, and all types of documents (articles, book chapters, conference papers, reviews, etc.) and publications in all languages were included.

2.2 Tools selection and data processing

The bibliographic information was exported from Scopus as a comma-separated values (CSV) file. The downloaded database includes information on authors, institutions, journals, language, keywords, abstracts, and references for each document. This bibliometric study used two software packages.

Microsoft Excel (Version 2404) was used for pre-processing, which involved organizing and reviewing the information, and eliminating duplicates and incomplete data (Velastegui-Montoya et al., 2023a). It also analysed the dataset and created tables to estimate the performance of the scientific output.

VOSviewer (version 1.6.19) enabled the visualization of two-dimensional bibliographic networks, known as bibliometric maps (van Eck and Waltman, 2017). It visually displayed statistical results related to the distribution of keywords and journals.

2.3 Data and trends analysis

This study employed two approaches in its analysis: (1) performance analysis and (2) science mapping (Donthu et al., 2021). The first approach involves evaluating scientific output using bibliometric indicators, emphasizing the contributions of authors and affiliations (Lam et al., 2022). The second approach focuses on creating bibliometric maps to visualize relationships between variables such as co-occurrence of author keywords and citations from sources (Liu and Li, 2021).

3. Results and Discussion

The total number of documents downloaded from the database was 772. After the data cleaning and cleaning process, the resulting final database was 748 documents. The publications are mostly distributed in journal articles (76%) and conference papers (18%).

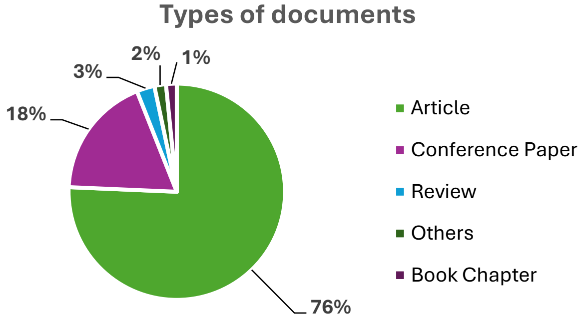

Figure 2. Distribution of the total publications.

3.1 Performance analysis

3.1.1. Top 5 Leading Authors: Author analysis reveals the most productive researchers and facilitates research collaboration for other academics (Donthu et al., 2020). Table 1 lists the authors according to their number of publications and total citations. The three main authors, based on the number of publications, are Yosio Shimabukuro, Luiz Aragao, and Marcos Adami. All three authors are from Brazil and are affiliated with the National Institute for Space Research (INPE, acronym in Portuguese). The fourth position is shared by Gregory Asner and Dar Roberts, both from US affiliations. Asner is from Arizona State University (ASU) and Roberts is from the University of California (UC). The last author, Liana Anderson, is affiliated with the National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN, acronym in Portuguese) in Brazil.

R	Authors	Affiliation	ND	HI	TC
1	Shimabukuro Y.	INPE	46	46	2123
2	Aragão L.E.		29	69	1107
3	Adami M.		17	27	802
4	Asner G.P.	ASU	16	123	2458
	Roberts D.A.	UC		76	1223
5	Anderson L.O.	CEMADEN	15	38	781

Table 1. Top 5 leading authors. R = Ranking; ND = number of documents; HI = H-index; TC = total number of citations.

Yosio Shimabukuro leads the ranking with 46 publications, and shares some studies with Luiz Aragão, Marcos Adami and Liana Anderson. The work of these authors comprises different approaches such as estimating carbon losses due to edge effect and deforestation, through forest mapping and carbon stock mapping using LiDAR data (Silva Junior et al., 2020). Other work focuses on understanding forest dynamics associated with the occurrence of forest fires. These studies use MODIS-derived data to conclude that the landscape is most susceptible at the onset of deforestation (Silva Junior et al., 2018) and that fires have effects after up to three years on energy, water and carbon fluxes in forests (de Oliveira et al., 2021).

Furthermore, assessments of carbon stock potential and quantification in secondary forests have been conducted using tools such as the MapBiomas collection (Heinrich et al., 2021) and spatial and temporal patterns of degraded growth and secondary forests obtained from Landsat data (Heinrich et al., 2023). Other approaches have analysed deforestation pressures on Brazilian indigenous communities using remotely sensed datasets (PRODES and DETER) (Silva-Junior et al., 2023).

Gregory Asner and Dar Roberts have not collaborated with each other or with the other authors in the ranking. However, Asner is the most cited author (2458 citations) in the study area, and his most influential work was a large-scale, high-resolution analysis of selective logging in the Brazilian Amazon (Asner et al., 2005). In addition, he has employed remote sensing to investigate the impacts of gold mining in the Peruvian Amazon. For instance, he assessed the annual changes in the extent of mining in protected forests using time-series Landsat satellite data (Asner and Tupayachi, 2016). Furthermore, another study estimated carbon stocks and emissions from mining using Planet Dove imagery, Sentinel-1, topography and LiDAR measurements (Csillik and Asner, 2020).

Roberts, D. has conducted studies to map changes and damage to the Amazon forest canopy caused by selective logging and forest fires, using Landsat ETM+ imagery (Souza et al., 2005) and

LiDAR data from the GEDI system (East et al., 2023). It also used Landsat TM data to determine the potential of remote sensing for the quantification of biophysical properties of grasslands or the analysis of grazing impacts (Numata et al., 2007). The multiple contributions of the authors have led to a better understanding of the dynamics of the Amazon due to anthropogenic pressures and have driven the constant monitoring of the region and the creation of strategies for the sustainable management of the Amazon forest.

3.2 Intellectual structure analysis

3.2.1. Author Keywords Co-Occurrence Network: This analysis allows us to detect central research topics and their trends. Figure 2 shows the co-occurrence network of author keywords, finding 62 nodes (relevant topics) and 6 clusters. The minimum number of co-occurrences was five.

The clusters overlap, demonstrating their complementarity among the various themes (keywords). The themes with the highest occurrence and closely related to the other themes are Amazon (total link strength 615), deforestation (total link strength 521), remote sensing (total link strength 482), land use and land cover (total link strength 370), forest degradation (total link strength 155) and Landsat (total link strength 154).

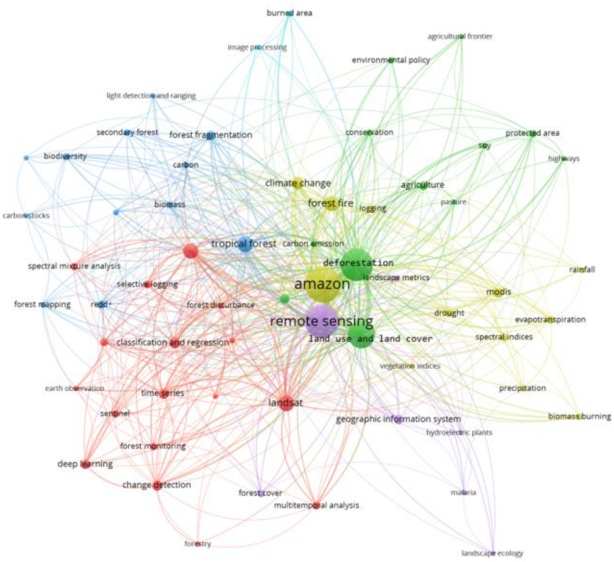

Figure 2. Keywords co-occurrence map

Cluster 1 (red) was the most significant with 17 elements and 279 occurrences. The topics grouped in cluster 1 connect the term “*forest degradation*” with current methods such as machine learning and deep learning recently used for Amazon monitoring. Different machine learning methods have been used and compared to detect and characterise forest disturbances (Reygadas et al., 2021). In addition, the detection of deforestation changes has been explored using Landsat data and convolutional neural networks (de Bem et al., 2020). Other topics include monitoring forest degradation resulting from selective logging and tracking subsequent forest restoration (Wu et al., 2020). Time series analysis of Landsat data has also been used to map degradation and natural disturbances (Bullock et al., 2020).

Cluster 2 (green) correlated 12 nodes and 450 occurrences. The central term of this cluster is “*deforestation*”, which is one of the main activities causing changes in LULC. Research themes include the analysis of inter-annual and intra-annual patterns of evapotranspiration and precipitation in pasture and cropland areas (de Oliveira et al., 2020). The mapping of road expansion is highlighted to understand its spatial-temporal dynamics and its impact on forest cover (Nascimento et al., 2021). Likewise, LULC mapping and identification of undue occupation in preservation areas were carried out (Gurgel et al., 2017). This group included topics related to environmental policies, for example, one study proposes an environmental analysis of policy implementation that encompasses monitoring using Sentinel imagery of mining activity (Dethier et al., 2023).

In cluster 3 (blue) there are 12 elements and 147 occurrences. The three main themes are “*tropical forest”, “forest fragmentation”, “redd+”.* This cluster includes the analysis of secondary forests. Different satellite data are used to assess the patterns and dynamics of carbon storage in secondary forests (Yang et al., 2020). Also, LiDAR technology is used to assess vegetation structure in secondary forests and correlate it with biodiversity (Coddington et al., 2023). Biomass research topics are also grouped in this cluster, with one study highlighting the importance of up-to-date LULC information to improve estimates of emissions from biomass burning (Mataveli et al., 2023). Finally, it is mentioned that satellite assessment and mapping of changes in tropical forests can be useful for REDD+ applications (Potapov et al., 2014).

Cluster 4 (yellow) contains 12 themes and 421 occurrences. The most relevant and strongly linked to the central theme of the study (*amazon*) are “*forest fire*” and “*climate change*”. Within these themes, different studies are carried out that include assessing the vulnerability of the Amazon forest to post-fire grass invasion under present and future climate scenarios (De Faria et al., 2021). The evaluation of recovery times for Amazonian forests following droughts and fires, as well as their implications, was also explored (De Faria et al., 2020). Within this group it is combined the application of multi-temporal remote sensing, spectral indices and unsupervised learning models to simultaneously map and measure fire risk in forest areas (Luz et al., 2022). Additionally, it investigates how deforestation and degradation impact local climate by assessing differences in precipitation, evapotranspiration, and potential evapotranspiration between forested and deforested areas (de Oliveira et al., 2018).

Clusters 5 (purple) and 6 (light blue) encompass 9 themes with 277 occurrences. The central term of this group is “*remote sensing”*, so there is a strong relationship with the other clusters. One of the themes of this cluster is the use of remote sensing technology integrated in geographic information systems. This is aimed at predicting risks such as the occurrence of malaria associated with deforestation (Ilacqua et al., 2018) and the land cover mapping as a tool for land-use planning (Iliquín Trigoso et al., 2020). The application of remote sensing to assess burned area patterns in new deforestation frontiers (Dutra et al., 2022) and to analyse LULC changes around hydropower infrastructures are also highlighted (Chen et al., 2015).

Emerging research trends suggest a focus on cloud-based platforms like Google Earth Engine, which are increasingly adopted for effectively managing large volumes of satellite data (Velastegui-Montoya et al., 2023b). For example, it has been employed to analyse forest degradation from fires in the Brazilian Amazon (Arai et al., 2019). Another potential thematic area is the use of artificial intelligence technologies such as deep learning for image processing and data analysis (Safonova et al., 2023). Research has explored its application in mapping forest degradation, providing insights into the causes of degradation (Dalagnol et al., 2023).

3.2.2. Journal’s Co-Citation Network (JCA): This analysis determines the research accumulated over time in this field of study from various disciplines reflected in the journals found in the references. Figure 3 shows the co-citation network of journals, composed of 115 nodes (journals) with at least 30 citations, distributed in 4 clusters.

Cluster 1 (red), "Multidisciplinary and Environmental Sciences", represents 45 nodes totalling 6371 citations. In this cluster, the main journals are Science (The United States, 1301 citations), Proceedings of the National Academy of Sciences of the United States of America (The United States, 674 citations), Environmental Research Letters (The United Kingdom, 430 citations), Conservation Biology (The United Kingdom, 356 citations) and PLoS ONE (The United States, 244 citations). The journals in this group have a broadly multidisciplinary focus, covering various disciplines such as agriculture, geography, conservation, economics and environmental sustainability.

Cluster 2 (green), "Geophysical and Atmosphere" includes 29 journals with a total of 3312 citations. This cluster mainly studies different areas such as geophysics, water sciences, atmospheric sciences including implications for climate change. The leading journals are: Geophysical Research Letters (The United States, 367 citations), Journal of Climate (The United States, 261 citations), Atmospheric Chemistry and Physics (Germany, 248 citations), Nature Climate Change (The United Kingdom, 198 citations) and Journal of Geophysical Research: Atmospheres (The United States, 186 citations).

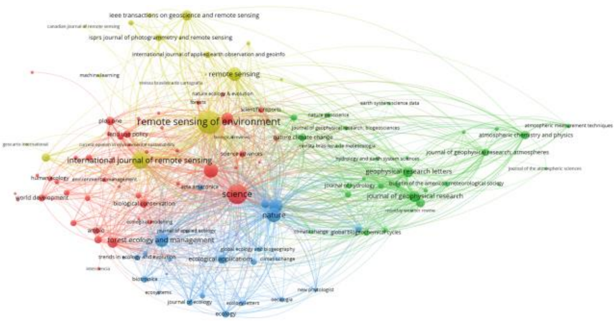

Figure 3. Journal co-citation network.

Cluster 3 (blue), "Biology", groups 25 journals with a total of 4076 citations. The journals in this cluster cover different branches of biological sciences, covering ecology, biogeography and evolution. The cluster primarily consists of: Nature (The United Kingdom, 667 citations), Forest Ecology and Management (The Netherlands, 610 citations), Global Change Biology (The United Kingdom, 573 citations), Ecological Applications (The United States, 269 citations) and Philosophical Transactions of the Royal Society B: Biological Sciences (The United Kingdom, 225 citations).

Cluster 4 (yellow), "Geoinformation and Remote Sensing" contains 16 nodes totalling 4751 citations. In this cluster, the main journals are: Remote Sensing of Environment (The United States, 3554 citations), International Journal of Remote Sensing (The United Kingdom, 994 citations), Remote Sensing (Switzerland, 632 citations), IEEE Transactions on Geoscience and Remote Sensing (The United States, 345 citations) and Photogrammetric Engineering and Remote Sensing (The United States, 227 citations). This group covers disciplines related to science and engineering applied to earth sensing such as photogrammetry and remote sensing.

According to the analysis of the co-citation network, the red cluster comprises the largest number of nodes and citations due to its multidisciplinary. The yellow cluster contains fewer journals but includes two of the journals with the highest number of publications in Remote sensing (40 publications) and Remote Sensing of Environment (38 publications). The remote sensing applications covered by the journals in the network are varied. The journals publish research about changes in climate and environment due to pressures caused by LULC changes. Also, explore the potential of remote sensing in studying ecology and nature conservation, while addressing new computational applications for mapping dynamics in the Amazon region.

4. Conclusions

This study provides a bibliometric analysis of remote sensing applications in monitoring Amazon deforestation and degradation. It is an expanding area of research involving global institutions. Various approaches associated with land use and land cover changes tend to focus on analysing multiple anthropogenic activities causing forest degradation and changes in ecological dynamics. Remote sensing application has continuously evolved with the emergence of different sensors and satellite missions, providing broader data coverage and expanding research opportunities. It has integrated new technologies or conceptual frameworks allowing for better assessment of the Amazon rainforest. The study reveals that approaches to monitoring land use and land cover significantly contribute to understanding environmental and social issues, providing essential information for decision-makers regarding global changes and regional development.

The main limitation of the study is the exclusive use of Scopus data, potentially excluding other significant contributions. Future research could include or combine other databases and academic search engines to ensure a comprehensive analysis of the study area's evolution. The use of remote sensing tools to study tropical rainforests has generated new insights and research themes, evolving alongside new technologies. Therefore, it is essential to consider underexplored topics such as studies focused on the Amazonian coast and the Andean-Amazonian region. Lastly, some countries like Bolivia, Suriname, and Venezuela have limited representation in scientific productivity, presenting an opportunity to understand Amazonian dynamics in these areas and support conservation efforts.

References

Arai, E., Shimabukuro, Y.E., Dutra, A.C., Duarte, V., 2019. Detection and Analysis of Forest Degradation by Fire Using Landsat/Oli Images in Google Earth Engine, in: IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium. IEEE, Yokohama, pp. 1649–1652. https://doi.org/10.1109/IGARSS.2019.8899250

Armenteras, D., Murcia, U., González, T.M., Barón, O.J., Arias, J.E., 2019. Scenarios of land use and land cover change for NW Amazonia: Impact on forest intactness. *Glob. Ecol. Conserv*. 17. https://doi.org/10.1016/j.gecco.2019.e00567

Asner, G.P., Knapp, D.E., Broadbent, E.N., Oliveira, P.J.C., Keller, M., Silva, J.N., 2005. Selective Logging in the Brazilian Amazon. *Science* 310, (480–482). https://doi.org/10.1126/science.1118051

Asner, G.P., Tupayachi, R., 2016. Accelerated losses of protected forests from gold mining in the Peruvian Amazon. *Environ. Res. Lett*. 12, (094004). https://doi.org/10.1088/1748-9326/aa7dab

Borma, L.S., Costa, M.H., da Rocha, H.R., Arieira, J., Nascimento, N.C.C., Jaramillo-Giraldo, C., Ambrosio, G., Carneiro, R.G., Venzon, M., Neto, A.F., van der Hoff, R., Oliveira, B.F.A., Rajão, R., Nobre, C.A., 2022. Beyond Carbon: The Contributions of South American Tropical Humid and Subhumid Forests to Ecosystem Services. *Rev. Geophys*. 60, (1–60). https://doi.org/10.1029/2021RG000766

Bullock, E.L., Woodcock, C.E., Souza, C., Olofsson, P., 2020. Satellite-based estimates reveal widespread forest degradation in the Amazon. *Glob. Chang. Biol.* 26, (2956–2969). https://doi.org/10.1111/gcb.15029

Chen, G., Powers, R.P., de Carvalho, L.M.T., Mora, B., 2015. Spatiotemporal patterns of tropical deforestation and forest degradation in response to the operation of the Tucuruí hydroelectric dam in the Amazon basin. *Appl. Geogr*. 63, (1–8). https://doi.org/10.1016/j.apgeog.2015.06.001

Coddington, C.P.J., Cooper, W.J., Mokross, K., Luther, D.A., 2023. Forest structure predicts species richness and functional diversity in Amazonian mixed-species bird flocks. *Biotropica* 55, (467–479). https://doi.org/10.1111/btp.13201

Csillik, O., Asner, G.P., 2020. Aboveground carbon emissions from gold mining in the Peruvian Amazon. *Environ. Res. Lett.* 15, (014006). https://doi.org/10.1088/1748-9326/ab639c

Dalagnol, R., Wagner, F.H., Galvão, L.S., Braga, D., Osborn, F., Sagang, L.B., da Conceição Bispo, P., Payne, M., Silva Junior, C., Favrichon, S., Silgueiro, V., Anderson, L.O., Aragão, L.E.O. e C. de, Fensholt, R., Brandt, M., Ciais, P., Saatchi, S., 2023. Mapping tropical forest degradation with deep learning and Planet NICFI data. *Remote Sens. Environ.* 298, (113798). https://doi.org/10.1016/j.rse.2023.113798

de Bem, P., de Carvalho Junior, O., Fontes Guimarães, R., Trancoso Gomes, R., 2020. Change Detection of Deforestation in the Brazilian Amazon Using Landsat Data and Convolutional Neural Networks. *Remote Sens.* 12, (901). https://doi.org/10.3390/rs12060901

De Faria, B.L., Marano, G., Piponiot, C., Silva, C.A., Dantas, V. de L., Rattis, L., Rech, A.R., Collalti, A., 2020. Model-Based Estimation of Amazonian Forests Recovery Time after Drought and Fire Events. *Forests* 12, (8). https://doi.org/10.3390/f12010008

De Faria, B.L., Staal, A., Silva, C.A., Martin, P.A., Panday, P.K., Dantas, V.L., 2021. Climate change and deforestation increase the vulnerability of Amazonian forests to post-fire grass invasion. *Glob. Ecol. Biogeogr.* 30, (2368–2381). https://doi.org/10.1111/geb.13388

de Oliveira, G., Brunsell, N.A., Chen, J.M., Shimabukuro, Y.E., Mataveli, G.A. V., dos Santos, C.A.C., Stark, S.C., de Lima, A., Aragao, L.E.O.C., 2021. Legacy Effects Following Fire on Surface Energy, Water and Carbon Fluxes in Mature Amazonian Forests. *J. Geophys. Res. Biogeosciences* 126. https://doi.org/10.1029/2020JG005833

de Oliveira, G., Chen, J.M., Mataveli, G.A. V., Chaves, M.E.D., Rao, J., Sternberg, M., dos Santos, T. V., dos Santos, C.A.C., 2020. Evapotranspiration and Precipitation over Pasture and Soybean Areas in the Xingu River Basin, an Expanding Amazonian Agricultural Frontier. *Agronomy* 10, (1112). https://doi.org/10.3390/agronomy10081112

de Oliveira, J.V., Ferreira, D.B. da S., Sahoo, P.K., Sodré, G.R.C., de Souza, E.B., Queiroz, J.C.B., 2018. Differences in precipitation and evapotranspiration between forested and deforested areas in the Amazon rainforest using remote sensing data. *Environ. Earth Sci.* 77, (239). https://doi.org/10.1007/s12665-018-7411-9

Dethier, E.N., Silman, M.R., Fernandez, L.E., Espejo, J.C., Alqahtani, S., Pauca, P., Lutz, D.A., 2023. Operation mercury: Impacts of national-level armed forces intervention and anticorruption strategy on artisanal gold mining and water quality in the Peruvian Amazon. *Conserv. Lett.* 16. https://doi.org/10.1111/conl.12978

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., Lim, W.M., 2021. How to conduct a bibliometric analysis: An overview and guidelines. *J. Bus. Res.* 133, (285–296). https://doi.org/10.1016/j.jbusres.2021.04.070

Donthu, N., Kumar, S., Pattnaik, D., 2020. Forty-five years of Journal of Business Research: A bibliometric analysis. *J. Bus. Res.* 109, (1–14). https://doi.org/10.1016/j.jbusres.2019.10.039

Dutra, D.J., Anderson, L.O., Fearnside, P.M., Graça, P.M.L. de A., Yanai, A.M., Dalagnol, R., Burton, C., Jones, C., Betts, R., Aragão, L.E.O. e C. de, 2022. Fire Dynamics in an Emerging Deforestation Frontier in Southwestern Amazonia, Brazil. *Fire* 6, (2). https://doi.org/10.3390/fire6010002

East, A., Hansen, A., Armenteras, D., Jantz, P., Roberts, D.W., 2023. Measuring Understory Fire Effects from Space: Canopy Change in Response to Tropical Understory Fire and What This Means for Applications of GEDI to Tropical Forest Fire. *Remote Sens.* 15, (696). https://doi.org/10.3390/rs15030696

FAO, 2020. Global Forest Resources Assessment 2020. FAO, Rome. https://doi.org/10.4060/ca9825en

Fiedler, N.C., De Jesus, R.M.M., Moreira, F.Z., Ramalho, A.H.C., Dos Santos, A.R., Souza, K.B., 2023. Environmental vulnerability evolution in the Brazilian Amazon. *An. Acad. Bras. Cienc.* 95. https://doi.org/10.1590/0001-3765202320210333

Furumo, P.R., Aide, T.M., 2017. Characterizing commercial oil palm expansion in Latin America: Land use change and trade. Environ. *Res. Lett.* 12. https://doi.org/10.1088/1748-9326/aa5892

Gurgel, R.S., Farias, P.R.S., Oliveira, S.N. de, 2017. Land use and land cover mapping and identification of misuse in the permanent preservation areas in the Tailândia Municipality - PA. *Semin. Ciências Agrárias* 38, (1145). https://doi.org/10.5433/1679-0359.2017v38n3p1145

Heinrich, V.H.A., Dalagnol, R., Cassol, H.L.G., Rosan, T.M., de Almeida, C.T., Silva Junior, C.H.L., Campanharo, W.A., House, J.I., Sitch, S., Hales, T.C., Adami, M., Anderson, L.O., Aragão, L.E.O.C., 2021. Large carbon sink potential of secondary forests in the Brazilian Amazon to mitigate climate change. *Nat. Commun.* 12, (1785). https://doi.org/10.1038/s41467-021-22050-1

Heinrich, V.H.A., Vancutsem, C., Dalagnol, R., Rosan, T.M., Fawcett, D., Silva-Junior, C.H.L., Cassol, H.L.G., Achard, F., Jucker, T., Silva, C.A., House, J., Sitch, S., Hales, T.C., Aragão, L.E.O.C., 2023. The carbon sink of secondary and degraded humid tropical forests. *Nature* 615, (436–442). https://doi.org/10.1038/s41586-022-05679-w

Ilacqua, R.C., Chaves, L.S.M., Bergo, E.S., Conn, J.E., Sallum, M.A.M., Laporta, G.Z., 2018. A method for estimating the deforestation timeline in rural settlements in a scenario of malaria transmission in frontier expansion in the Amazon Region. *Mem. Inst. Oswaldo Cruz* 113. https://doi.org/10.1590/0074-02760170522

Iliquín Trigoso, D., Salas López, R., Rojas Briceño, N.B., Silva López, J.O., Gómez Fernández, D., Oliva, M., Quiñones Huatangari, L., Terrones Murga, R.E., Barboza Castillo, E., Barrena Gurbillón, M.Á., 2020. Land Suitability Analysis for Potato Crop in the Jucusbamba and Tincas Microwatersheds (Amazonas, NW Peru): AHP and RS–GIS *Approach. Agronomy* 10, (1898). https://doi.org/10.3390/agronomy10121898

Kandus, P., Minotti, P.G., Morandeira, N.S., Grimson, R., González Trilla, G., González, E.B., San Martín, L., Gayol, M.P., 2018. Remote sensing of wetlands in South America: status and challenges. *Int. J. Remote Sens.* 39, (993–1016). https://doi.org/10.1080/01431161.2017.1395971

Lam, W.S., Lee, P.F., Lam, W.H., 2022. Cellulose nanofiber for sustainable production: A bibliometric analysis. *Mater. Today Proc.* 62, (6460–6467). https://doi.org/10.1016/j.matpr.2022.04.198

Liu, C., Li, K., 2021. Mapping the field: a bibliometric analysis of land use and carbon emissions (LUCE) research from 1987 to 2018. *Libr. Hi Tech* 39, (396–411). https://doi.org/10.1108/LHT-12-2019-0252

Lu, D., Batistella, M., Mausel, P., Moran, E., 2007. Mapping and monitoring land degradation risks in the Western Brazilian Amazon using multitemporal Landsat TM/ETM+ images. *L. Degrad. Dev.* 18, (41–54). https://doi.org/10.1002/ldr.762

Luz, A.E.O., Negri, R.G., Massi, K.G., Colnago, M., Silva, E.A., Casaca, W., 2022. Mapping Fire Susceptibility in the Brazilian Amazon Forests Using Multitemporal Remote Sensing and Time-Varying Unsupervised Anomaly Detection. *Remote Sens.* 14, (2429). https://doi.org/10.3390/rs14102429

Marengo, J.A., Souza, C.M., Thonicke, K., Burton, C., Halladay, K., Betts, R.A., Alves, L.M., Soares, W.R., 2018. Changes in Climate and Land Use Over the Amazon Region: Current and Future Variability and Trends. *Front. Earth Sci.* 6. https://doi.org/10.3389/feart.2018.00228

Mataveli, G., Pereira, G., Sanchez, A., de Oliveira, G., Jones, M.W., Freitas, S.R., Aragão, L.E.O.C., 2023. Updated Land Use and Land Cover Information Improves Biomass Burning Emission Estimates. *Fire* 6, (426). https://doi.org/10.3390/fire6110426

Nascimento, E. de S., Silva, S.S. da, Bordignon, L., Melo, A.W.F. de, Brandão, A., Souza, C.M., Silva Junior, C.H.L., 2021. Roads in the Southwestern Amazon, State of Acre, between 2007 and 2019. *Land* 10, (106). https://doi.org/10.3390/land10020106

Numata, I., Roberts, D.A., Chadwick, O.A., Schimel, J., Sampaio, F.R., Leonidas, F.C., Soares, J. V., 2007. Characterization of pasture biophysical properties and the impact of grazing intensity using remotely sensed data. *Remote Sens. Environ.* 109, (314–327). https://doi.org/10.1016/j.rse.2007.01.013

Nunes, C.A., Berenguer, E., França, F., Ferreira, J., Lees, A.C., Louzada, J., Sayer, E.J., Solar, R., Smith, C.C., Aragão, L.E.O.C., de Lima Braga, D., de Camargo, P.B., Cerri, C.E.P., de Oliveira, R.C., Durigan, M., Moura, N., Oliveira, V.H.F., Ribas, C., Vaz-De-Mello, F., Vieira, I., Zanetti, R., Barlow, J., 2022. Linking land-use and land-cover transitions to their ecological impact in the Amazon. *Proc. Natl. Acad. Sci. U. S. A.* 119, (1–9). https://doi.org/10.1073/pnas.2202310119

Potapov, P. V, Dempewolf, J., Talero, Y., Hansen, M.C., Stehman, S. V, Vargas, C., Rojas, E.J., Castillo, D., Mendoza, E., Calderón, A., Giudice, R., Malaga, N., Zutta, B.R., 2014. National satellite-based humid tropical forest change assessment in Peru in support of REDD+ implementation. *Environ. Res. Lett.* 9, (124012). https://doi.org/10.1088/1748-9326/9/12/124012

Reygadas, Y., Spera, S., Galati, V., Salisbury, D.S., Silva, S., Novoa, S., 2021. Mapping forest disturbances across the Southwestern Amazon: tradeoffs between open-source, Landsat-based algorithms. *Environ. Res. Commun.* 3, (091001). https://doi.org/10.1088/2515-7620/ac2210

Roberts, P., Hamilton, R., Piperno, D.R., 2021. Tropical forests as key sites of the "Anthropocene": Past and present perspectives. *Proc. Natl. Acad. Sci.* 118, (1–7). https://doi.org/10.1073/pnas.2109243118

Safonova, A., Ghazaryan, G., Stiller, S., Main-Knorn, M., Nendel, C., Ryo, M., 2023. Ten deep learning techniques to address small data problems with remote sensing. *Int. J. Appl. Earth Obs. Geoinf.* 125, (103569). https://doi.org/10.1016/j.jag.2023.103569

Sánchez-Díaz, B., 2018. La teledetección en investigaciones ecológicas como apoyo a la conservación de la biodiversidad: una revisión. *Rev. científica* 3, (243–253). https://doi.org/10.14483/23448350.13370

Silva-Junior, C.H.L., Silva, F.B., Arisi, B.M., Mataveli, G., Pessôa, A.C.M., Carvalho, N.S., Reis, J.B.C., Silva Júnior, A.R., Motta, N.A.C.S., e Silva, P.V.M., Ribeiro, F.D., Siqueira-Gay, J., Alencar, A., Saatchi, S., Aragão, L.E.O.C., Anderson, L.O., Melo, M., 2023. Brazilian Amazon indigenous territories under deforestation pressure. *Sci. Rep.* 13, (5851). https://doi.org/10.1038/s41598-023-32746-7

Silva Junior, C., Aragão, L., Fonseca, M., Almeida, C., Vedovato, L., Anderson, L., 2018. Deforestation-Induced Fragmentation Increases Forest Fire Occurrence in Central Brazilian Amazonia. *Forests* 9, (305). https://doi.org/10.3390/f9060305

Silva Junior, C.H.L., Aragão, L.E.O.C., Anderson, L.O., Fonseca, M.G., Shimabukuro, Y.E., Vancutsem, C., Achard, F., Beuchle, R., Numata, I., Silva, C.A., Maeda, E.E., Longo, M., Saatchi, S.S., 2020. Persistent collapse of biomass in Amazonian forest edges following deforestation leads to unaccounted carbon losses. *Sci. Adv.* 6. https://doi.org/10.1126/sciadv.aaz8360

Souza, C.M., Roberts, D.A., Cochrane, M.A., 2005. Combining spectral and spatial information to map canopy damage from selective logging and forest fires. *Remote Sens.* Environ. 98, (329–343). https://doi.org/10.1016/j.rse.2005.07.013

van Eck, N.J., Waltman, L., 2017. Citation-based clustering of publications using CitNetExplorer and VOSviewer. *Scientometrics* 111, (1053–1070). https://doi.org/10.1007/s11192-017-2300-7

Velastegui-Montoya, A., Escandón-Panchana, P., Peña-Villacreses, G., Herrera-Franco, G., 2023a. Land use/land cover of petroleum activities in the framework of sustainable development. *Clean. Eng. Technol.* 15, (100659). https://doi.org/10.1016/j.clet.2023.100659

Velastegui-Montoya, A., Montalván-Burbano, N., Carrión-Mero, P., Rivera-Torres, H., Sadeck, L., Adami, M., 2023b. Google Earth Engine: A Global Analysis and Future Trends. *Remote Sens.* 15, (3675). https://doi.org/10.3390/rs15143675

Velastegui-Montoya, A., Montalván-Burbano, N., Peña-Villacreses, G., de Lima, A., Herrera-Franco, G., 2022. Land Use and Land Cover in Tropical Forest: Global Research. *Forests* 13, (1709). https://doi.org/10.3390/f13101709

Wu, J., Chen, B., Reynolds, G., Xie, J., Liang, S., O'Brien, M.J., Hector, A., 2020. Monitoring tropical forest degradation and restoration with satellite remote sensing: A test using Sabah Biodiversity Experiment. pp. 117–146. https://doi.org/10.1016/bs.aecr.2020.01.005

Yang, Y., Saatchi, S., Xu, L., Keller, M., Corsini, C.R., Aragão, L.E.O.C., Aguiar, A.P., Knyazikhin, Y., Myneni, R.B., 2020. Interannual Variability of Carbon Uptake of Secondary Forests in the Brazilian Amazon (2004-2014). *Global Biogeochem. Cycles* 34. https://doi.org/10.1029/2019GB006396