JEE ISSN: 2288-1220
https://doi.org/10.5141/jee.24.037
Journal of Ecology and Environment (2024) 48:27

RESEARCH

# Peatland restoration research: a global overview with insights from Indonesia

Kushartati Budiningsih[1]*, Prakoso Bhairawa Putera[2]*, Ari Nurlia[3], Nur Arifatul Ulya[1], Fitri Nurfatriani[4], Mimi Salminah[4], Dhany Yuniati[1] and Asmanah Widarti[3]

[1]Research Center for Behavioral and Circular Economics, National Research and Innovation Agency (BRIN), Jakarta 12710, Indonesia
[2]Research Center for Public Policy, National Research and Innovation Agency (BRIN), Jakarta Selatan 12710, Indonesia
[3]Research Center for Society and Culture, National Research and Innovation Agency (BRIN), Jakarta Selatan 12710, Indonesia
[4]Directorate of Environment, Maritime - Natural Resources and Nuclear Policy, National Research and Innovation Agency (BRIN), Jakarta Pusat 10340, Indonesia

**ARTICLE INFO**
**Received** March 25, 2024
**Revised** June 28, 2024
**Accepted** July 1, 2024
**Published on** August 5, 2024

***Corresponding authors**
Kushartati Budiningsih
**E-mail** ra.kushartati.budiningsih@brin.go.id
Prakoso Bhairawa Putera
**E-mail** prak002@brin.go.id

**Background:** Repeated and severe fires have led to a large investment in research directed towards recapturing the natural values of Indonesia's peatland forest resources. The aim of this study was to identify the patterns and trends in research on peatland restoration-related literature available on the Scopus database. Methods in this paper a bibliometric methodology, the Scopus database and VOSviewer were used explore the trends in the published peatland restoration literature in the period 1994–2021; the leading journals and most influential authors, affiliations, countries, documents and research themes were identified.
**Results:** Three hundred and seventeen documents including 266 journal articles were identified. The leading journals based on numbers of articles published and citations were *Restoration Ecology* and *Ecological Engineering*. Authors affiliated to institutions in Canada and the United Kingdom were the most influential. Indonesia was the third most influential based on numbers of documents. The most influential article was "The underappreciated potential of peatlands in global climate change mitigation strategies" by Liefield J in *Nature Communications* with an annual average citation rate of 66/year. A keyword co-occurrence network identified nine main themes in peat restoration research.
**Conclusions:** The findings of the study are used to outline the types of research in peat restoration now required to meet the outstanding and unmet challenges confronted in Indonesia. Three significant challenges have been identified: (1) anthropogenic, those that encompass issues related to community acceptance and participation in peatland restoration, (2) ecological, those associated with severely degraded peatlands, and (3) economic, the absence of secure funding to cover substantial costs.

**Keywords:** bibliometric, degraded peatland, global overview, Indonesia, peatland restoration, VOSviewer

## Introduction

Peatlands or mires are wetland ecosystems, with or without vegetation, resulting from the accumulation of organic matter that is produced and stored at a rate greater than that of its decomposition (Paavilainen and Päivänen 1995); at the surface there is at least 30% by dry mass of dead organic material (Joosten and Clarke 2002). Peatlands are a significant carbon pool (Dohong et al. 2018), and play an important role in regulating the carbon cycle and supporting a variety of ecosystem services: climate regulation, water storage and purification, conservation of biodiversity (Andersen et al. 2016). They also provide livelihoods for local communities (Syahza et al. 2020). Peatlands are spread over all continents, and have varied structures and functions that are influenced by geomorphology, hydrology, local climate, and vegetation (Tan et al. 2021). However, their functions can be compromised by disturbances to the hydrology and surface vegetation (Joosten and Clarke 2002).

The global peatland area is estimated as 4.23 M km$^2$, or approximately 2.84% of the global land area (Xu et al. 2018). Asia accounts for 38.4% of the coverage, North America 36.1% (mostly Canada and Alaska), and Europe, South America, Africa, Australasia and Oceania for 31.6%,

12.5%, 11.5%, 4.4%, and 1.6%, respectively (Xu et al. 2018). There are three types of peatlands, boreal, temperate and tropical that have distinct topographical features, dominant vegetation types, climate, and biodiversity (Tan et al. 2021).

Peat ecosystems have physical, chemical and biological characteristics that make them fragile and prone to degradation (Noor et al. 2016). Between 1850 and 2015 in temperate and boreal climates, the area subjected to peatland degradation was 26.7 Mha, and in tropical climates was 24.7 Mha (Leifeld et al. 2019). In tropical South-East Asia, logging, conversion to industrial plantations, drainage, and repeated fires are the main direct drivers of peatland degradation, and this is exacerbated by the direct and indirect effects of socioeconomic policy and climate change (Dohong 2017; Yuwati et al. 2021). In North America that combines temperate and boreal climates, centuries of degradation can be attributed to hunting, grazing, charcoal production, the gathering of small berries and more recently, peat mining for horticulture (Chimner et al. 2017). In Western Europe, unprotected peatlands are still being extracted, drained for agriculture and forestry, or abandoned (Andersen et al. 2016).

The high cost of degraded peatlands being unable to provide ecosystem services has led to an increased awareness of the importance of peatland restoration (Andersen et al. 2016). Restoration attempts to return a disturbed ecosystem to its original function (Baur 2014), and is the main preventative action against fire, subsidence, and hydrological disturbance caused by the construction of drainage canals (Terzano et al. 2022). Peatland restoration has attracted substantial attention from various actors in Western Europe (Andersen et al. 2016) and North America (Chimner et al. 2017). In Indonesia, it was first initiated by non-governmental organizations, and conservation and research organizations in the early 2000s in response to the alarming rate of peatland degradation and its related impacts (Dohong et al. 2018).

The hydrological techniques required for restoration have been shown to differ with peatland type and these have been adopted to deal with all types of disturbance on peatland: roads: agriculture, grazing, erosion, forestry, and industrial infrastructure (Chimner et al. 2017). However, restoration activities must be based on the likelihood of their success vs. their cost (Andersen et al. 2016). For tropical peatlands, nature-based restoration of degraded peatland ecosystems that employs the features and processes of a sustainable and natural growth cycle, is considered the most cost-effective intervention for conserving biodiversity and carbon stocks, and climate-change mitigation (Puspitaloka et al. 2021), while at the same time accounting for the welfare and livelihoods of local communities and building their resilience to changing climates (Terzano et al. 2022). The United Nations has declared a Decade on Ecosystem Restoration 2021–2030 as a measure to mitigate climate change. Its aim is to arrest ecosystem damage; peatland restoration is a central target in the declaration. To support its implementation, it is crucial to map historical and current peatland restoration-related research and identify the outstanding challenges.

To meet this requirement, we undertook a bibliometric review on global peatland restoration. Such a review is a statistical technique to quantitatively analyze academic literature on a selected topic (Zhong et al. 2016). The aim of this study was to identify the patterns and trends in research on peatland restoration-related literature available on the Scopus database. Four main questions were asked: how are articles on peatland restoration classified?; what are the current trends in peatland restoration-related research?; what topics have been well-researched?; and what topics are recommended for further investigation? The lessons learnt are taken forward into an Indonesian and global context. Indonesia is rich in peatlands and has an opportunity to become a role model for peatland restoration measures, particularly in the tropics.

## Materials and Methods

The Scopus platform provides data regarding publication year, source of publication, authorship and various other attributes. The retrieval process uses several parameters, a semi-systematic technique and a broad scope of questions to examine the research area, track its development over time, and identify themes in the literature (Fig. 1) (Snyder 2019).

The article retrieval process was conducted in March 2022 and used the Boolean search operator as follows: (TITLE-ABS KEY("peatland restoration") AND PUBYEAR < 2022 AND ( LIMIT-TO ( DOCTYPE,"ar" ) OR LIMIT-TO ( DOCTYPE,"cp" ) OR LIMIT-TO ( DOCTYPE,"re" ) OR LIMIT-TO ( DOCTYPE,"ch" ) OR LIMIT-TO ( DOCTYPE,"bk" ) ) AND ( LIMIT-TO ( SUBJAREA,"ENVI" ) OR LIMIT-TO ( SUBJAREA,"AGRI" ) OR LIMIT-TO ( SUBJAREA,"EART" ) OR LIMIT-TO ( SUBJAREA,"SOCI" ) OR LIMIT-TO ( SUBJAREA,"ECON" ) OR LIMIT-TO ( SUBJAREA,"ENER" ) OR LIMIT-TO ( SUBJAREA,"ENGI" ) OR LIMIT-TO ( SUBJAREA,"DECI" ) OR LIMIT-TO ( SUBJAREA,"ARTS" ) OR LIMIT-TO ( SUBJAREA,"MULT" ) OR LIMIT-TO ( SUBJAREA,"BUSI" ) OR LIMIT-TO ( SUBJAREA,"CHEM" ) OR LIMIT-TO ( SUBJAREA,"MATE" ) ) AND ( LIMIT-TO ( LANGUAGE,"English" ) ) ).

Three hundred and seventeen documents were retrieved consisting of 266 journal articles, 25 conference papers, 14 reviews, 10 book chapters, and 2 books. The 317 documents were associated with 7,070 citations. VOSviewer software was then used to visualize the results (van Eck and Waltman 2014), the general trend of publications and

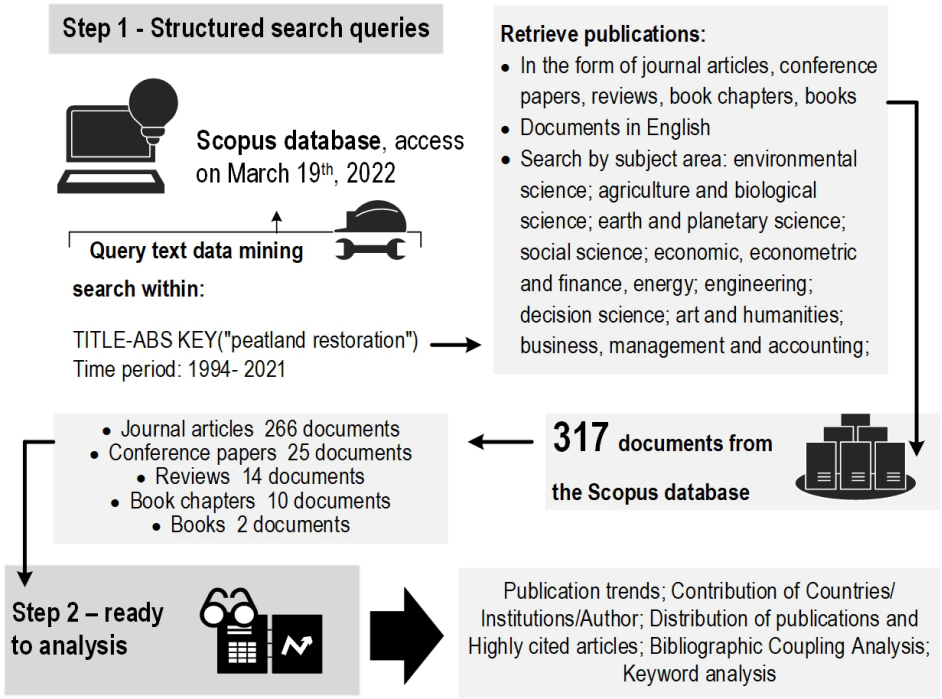


**Fig. 1** Retrieval process of relevant publication data.

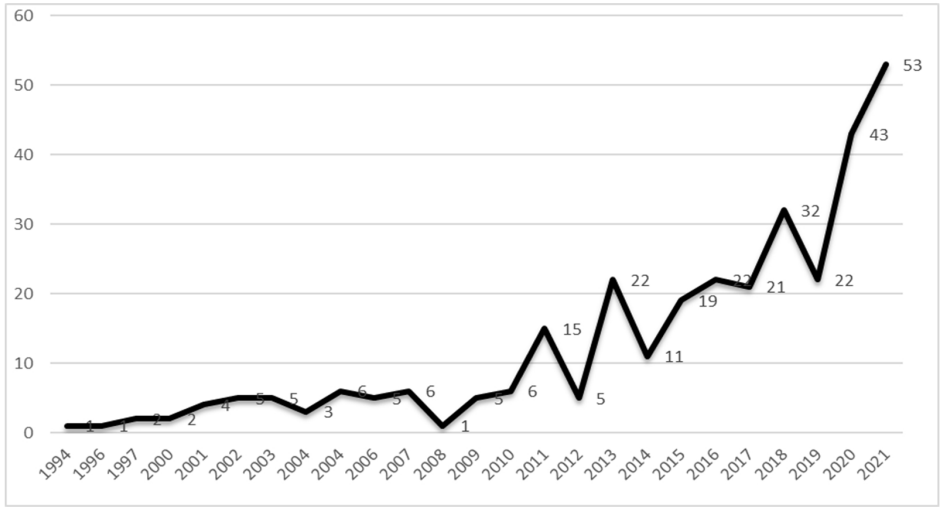


**Fig. 2** Publication trend of the 317 documents on peatland restoration.

the main indicators, such as distribution and influence of journals, influential authors and countries of publications, highly cited articles, and keywords analysis.

# Results

## Publication trends

The first document, a journal article, published in 1994, was entitled "The future of research in Canadian peatlands: A brief survey with particular reference to global change". It was written by Eville Gorham in the journal Wetlands volume 14 issue 3, and affiliated to the Department of Ecology, Evolution, and Behavior, University of Minnesota, United States. This article described the various fields of research in peatland ecology and biogeochemistry; Gorham cited his own journal article "The Development of Peatlands" published in the *Quarterly Review of Biology* in 1957. In 1995, no publications relating to peatland restoration were recorded by Scopus. From 1997 there was a gradual increase that accelerated after 2010 (Fig. 2).

## Leading journals

For the period 1994 to 2021 inclusive, the leading journals and their total citations were classified by applying the bibliographic coupling algorithm. The threshold criteria were at least five articles per journal and a minimum of 10 citations per article. Fourteen journals met these criteria out of the 111 journals examined (Table 1).

*Restoration Ecology*, *Ecological Engineering*, *Science of*

**Table 1** The leading journals with the highest number of citations

| Rank | Name of journal | Number of articles (A) | Number of citations (C) | Impact factor in 2020[a] | h-index[b] |
|---|---|---|---|---|---|
| 1 | *Restoration Ecology* | 20 | 571 | 1.21 | 100 |
| 2 | *Ecological Engineering* | 20 | 564 | 1.10 | 128 |
| 3 | *Science of the Total Environment* | 14 | 311 | 1.80 | 244 |
| 4 | *Wetlands Ecology and Management* | 12 | 591 | 0.49 | 62 |
| 5 | *Wetlands* | 11 | 287 | 0.70 | 87 |
| 6 | *Mires and Peat* | 11 | 76 | 0.57 | 13 |
| 7 | *Journal of Hydrology* | 10 | 359 | 1.68 | 226 |
| 8 | *Peatland Restoration and Ecosystem Services Science Policy and Practice* | 9 | 141 | Book published by Cambridge University Press | Book published by Cambridge University Press |
| 9 | *Hydrological Processes* | 9 | 114 | 1.22 | 161 |
| 10 | *Ecohydrology* | 8 | 105 | 0.98 | 54 |
| 11 | *Biogeosciences* | 8 | 314 | 1.74 | 127 |
| 12 | *Journal of Applied Ecology* | 7 | 192 | 2.50 | 181 |
| 13 | *Ecological Indicators* | 5 | 64 | 1.32 | 127 |
| 14 | *Journal of Environmental Management* | 5 | 57 | 1.44 | 179 |

[a]Impact factor is defined as the number of citations a journal receives in a given year (here 2020), divided by the total number of citable articles published in the journal in the previous two years. [b]The Hirsch or h-index is defined as the number of publications with a citation number greater than or equal to H.

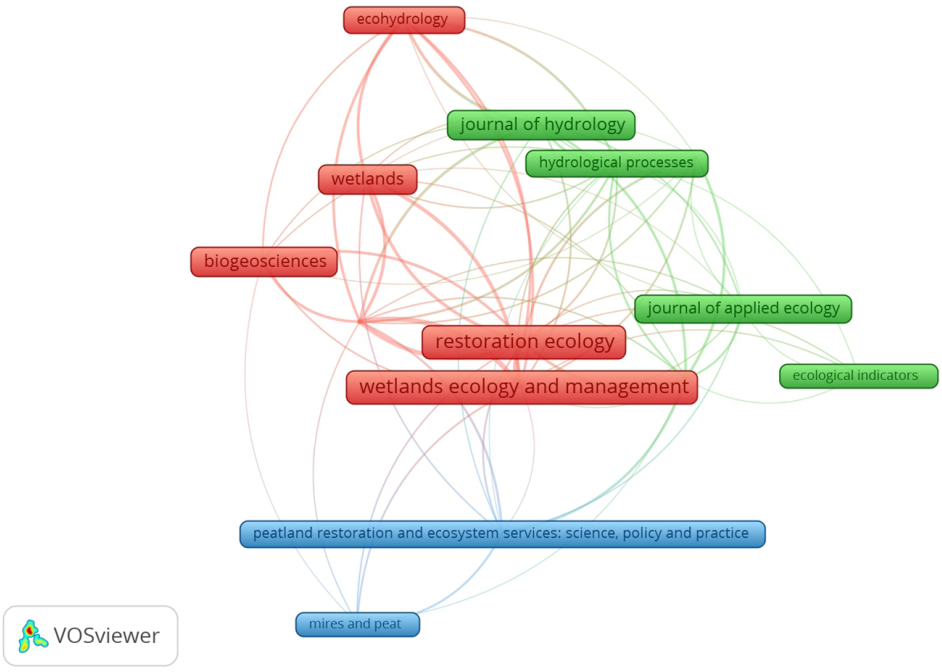


**Fig. 3** Citation network among the leading journals.

*the Total Environment*, and *Wetlands Ecology and Management* emerged as the four journals providing the highest number of journal articles, A (≥ 12) and citations, C (≥ 311) (Table 1). The *Journal of Hydrology* and *Biogeosciences* published fewer (A ≤ 10), but also highly cited (C ≥ 314) articles.

The impact factors (IFs), IF ranged from 0.57 (mires and peat) to 2.50 (*Journal of Applied Ecology*) (Table 1). Of the 14 journals that met the threshold criteria, nine had IF > 1.0; *Wetlands Ecology and Management* that had the highest citations per article (C/A = 49.3) had the lowest IF, 0.49. The h-indexes ranged from 13 (mires and peat) to 244 (*Science of the Total Environment*).

The size of the dot combines the number of relevant articles (A) and their citations (C) in all types of publication listed by Scopus (Rakhel and Putera 2021); the color of the clusters refers to publications related to each other based on citation patterns, and the links represent the citation relationship between individual publications (van Eck and Waltman 2022). The results were similar using VOSviewer. *Restoration Ecology* and *Ecological Engineering* were considered the leading journals (Fig. 3). There are three citation network clusters among prominent journals: *Biogeosciences*, *Ecohydrology*, *Ecological Engineering*, *Restoration*

*Ecology*, *Wetlands*, and *Wetlands Ecology and Management* (red cluster); *Ecological Indicators*, *Hydrological Processes*, *Journal of Applied Ecology*, *Journal of Environmental Management*, *Journal of Hydrology*, and *Science of the Total Environment* (green cluster); and *Mires and Peat*, and *Peatland Restoration and Ecosystem Services: Science, Policy and Practice* (blue cluster).

## Influential author

The 317 documents written on the theme of peatland restoration were associated with 983 authors (Table 2). Of the 15 most influential authors, based on their number of journal documents (D) and number of citations, Rochefort L was ranked top (35 and 1,110) followed by Holden J (19 and 723) (Table 2). Waddington JM was ranked 10th but had the highest citations per document C/D (45.7). The first relevant article by Rochefort L was published in *Ecological Engineering* volume 7 issue 3 in 1996. It was "Water and peat chemistry comparisons of natural and post-harvested peatlands across Canada and their relevance to peatland restoration" by Wind-Mulder et al. (1996).

## Influential author affiliation

One hundred and sixty institutions were affiliated with the 983 authors who contributed to the 317 documents. The top 15 were universities and other types of research organizations (Table 3). These institutions undertook all or at least part of their research in the fields of natural resources, environment, forestry, sustainable development and conservation. They were located in Canada, Europe (United Kingdom, Finland, and Germany), and Asia (Indonesia); all countries that have peatlands. Most (6) were in the United Kingdom. However, the top institution, Université Laval and three of the four top-ranked institutions for author affiliation were in Canada; IPB University in Indonesia was ranked 10th.

**Table 2** Influential authors

| Rank | Author | Number of documents (D) | Number of citations (C) | C/D |
|---|---|---|---|---|
| 1 | Rochefort L | 35 | 1,110 | 31.7 |
| 2 | Holden J | 19 | 723 | 38.1 |
| 3 | Strack M | 15 | 304 | 20.3 |
| 4 | Andersen R | 14 | 256 | 18.3 |
| 5 | Price JS | 13 | 488 | 37.5 |
| 6 | Joosten H | 8 | 179 | 22.4 |
| 7 | Evans M | 8 | 168 | 21.0 |
| 8 | Evans MG | 8 | 123 | 15.4 |
| 9 | Hugron S | 8 | 88 | 11.0 |
| 10 | Waddington JM | 7 | 320 | 45.7 |
| 11 | Bonn A | 7 | 246 | 35.1 |
| 12 | Price J | 7 | 98 | 14.0 |
| 13 | Chapman PJ | 7 | 33 | 4.7 |
| 14 | Pouliot R | 6 | 180 | 30.0 |
| 15 | Evans CD | 6 | 132 | 22.0 |

## Influential countries of publication

Of the 17 most influential countries of publication, the first was the United Kingdom which produced 97 documents that received 2,213 citations followed by Canada and Indonesia. Canada's documents received the most citations, 2,308 (Table 4). Although fewer documents were published, the most cited were from Switzerland (69.9) and Sweden (45.9).

In Canada, the peak time period of publication was 2014, in the United Kingdom around 2016, and in Indonesia around 2018 (Fig. 4).

## Influential article

The 10 most cited documents were all journal articles. At

**Table 3** The most influential affliations

| Rank | Affiliation | Country |
|---|---|---|
| 1 | Université Laval | Canada |
| 2 | University of Leeds | United Kingdom |
| 3 | University of Waterloo | Canada |
| 4 | Centre D'Etudes Nordiques, Rimouski | Canada |
| 5 | The University of Manchester | United Kingdom |
| 6 | The James Hutton Institute | United Kingdom |
| 7 | IPB University | Indonesia |
| 8 | Helsingin Yliopisto | Finland |
| 9 | Universität Greifswald | Germany |
| 10 | Center for International Forestry Research, West Java | Indonesia |
| 11 | University of the Highlands and Islands | United Kingdom |
| 12 | Natural Resources Institute Finland Luke | Finland |
| 13 | Royal Society for the Protection of Birds | United Kingdom |
| 14 | UK Centre for Ecology and Hydrology | United Kingdom |
| 15 | University of Oulu | Finland |

**Table 4** The most influential countries of publication based on number of documents

| Rank | Countries | Number of documents (D) | Number of citations (C) | C/D |
|---|---|---|---|---|
| 1 | United Kingdom | 97 | 2,213 | 22.8 |
| 2 | Canada | 78 | 2,308 | 29.6 |
| 3 | Indonesia | 55 | 554 | 10.1 |
| 4 | Germany | 46 | 997 | 21.7 |
| 5 | United States | 28 | 928 | 33.1 |
| 6 | Finland | 26 | 763 | 29.3 |
| 7 | Netherlands | 14 | 437 | 31.2 |
| 8 | Australia | 13 | 274 | 21.1 |
| 9 | Sweden | 12 | 551 | 45.9 |
| 10 | Ireland | 11 | 222 | 20.2 |
| 11 | Estonia | 9 | 296 | 32.9 |
| 12 | France | 8 | 240 | 30.0 |
| 13 | China | 8 | 97 | 12.1 |
| 14 | Switzerland | 7 | 489 | 69.9 |
| 15 | Poland | 7 | 79 | 11.3 |
| 16 | Denmark | 6 | 69 | 11.5 |
| 17 | Norway | 5 | 68 | 13.6 |

The number of documents exceeds 317 because many are affiliated to more than one country.

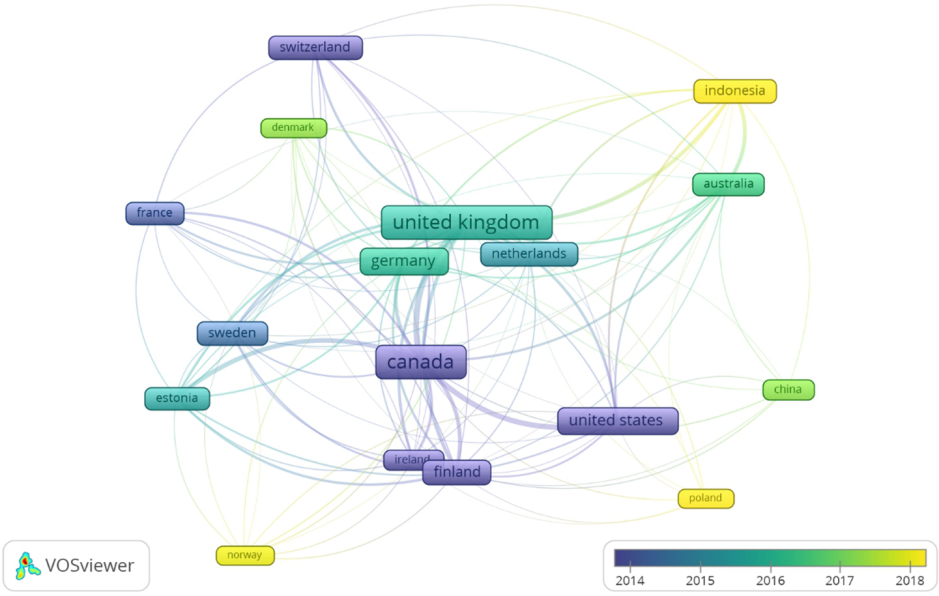


Fig. 4 Influential countries of publication based on a number of documents The colors denote the peak time period of publication.

the top was "Peatland hydrology and carbon release: Why small-scale process matters" published by *Philosophical Transactions of the Royal Society A*: Mathematical, Physical and Engineering Sciences with 274 citations and an average annual citation rate of 17. However, the first ranking for average annual citation rate was "The underappreciated potential of peatlands in global climate change mitigation strategies" published in *Nature Communications* with an average annual citation rate of 66/year. This article assesses the current and future greenhouse gas (GHG) emissions from degraded peatlands and estimates the potential GHG sequestration that could be achieved through restoration (Table 5).

## Keyword co-occurrence analysis and thematic cluster analysis

The 317 documents used 899 keywords. Using a threshold of three keywords, 85 met this criterion. Peatland restoration, peatland and restoration were the top keywords (Fig. 5). Peatland restoration was linked 60 times to other keywords (light blue nodes), peatland 47 links (purple nodes), and restoration 41 links (blue nodes).

The keywords co-occurrence network visualization of the 317 documents published on peatland restoration. The 77 dots met the three-word combination threshold. The colors represent different clusters (see Table 6). Based on keyword co-occurrence analysis, nine literature clusters can be identified (Table 6 referenced to colors in Fig. 5) that indicate the large volume of research on peatland restoration. The eight main themes are: peatland ecosystem restoration for climate change mitigation and water quality improvement, ecological restoration of peatlands to address global change, sustainable management of tropical peatlands in indonesia, climate change mitigation through peatland restoration and greenhouse gas management, biogeochemistry and ecohydrology in peatland restoration, peatland restoration through water chemistry and microbial activity management, microtopography and biodiversity in wetland restoration in scotland, and water retention management in wetland ecosystems.

The three keyword threshold identified no keywords that relate to social, economic, and policy themes. However, using one-word co-occurrence, several of the 317 documents exhibited keywords pertaining to social (village fund, social capital, and resilience), economic (economic incentive) and policy (policy formulation) areas.

## Types of publication

The types of publication between 2010–2020 differed with time (Fig. 6). In the early part of this period, publications on regeneration, water management, and plant reintroduction were dominant (blue); in the middle period publications on fire, peatland, rewetting and carbon sequestration (green), and latterly publications on tropical peatland, cutover peatland, climate-change mitigation, and agroforestry (yellow).

The keywords peatland restoration, *Sphagnum*, peatland, water quality, and drainage were the most frequently used in peatland restoration publications (Fig. 7). This analysis also confirms the lack of frequency of keywords relating to social, economic and policy themes.

# Discussion

## Publication rate, authorship, and affiliation

This Scopus analysis has shown that after a long period of very few publications on peatland restoration 1994–2009, the numbers accelerated. This acceleration can be attributed to a growing awareness of the significance of peat-

**Table 5** The 10 most highly cited documents on peatland restoration

| Documents | Authors | Source | Year published | Volume/ pages | Number of citations | Average annual citation rate (/y) |
|---|---|---|---|---|---|---|
| Peatland hydrology and carbon release: Why small-scale process matters | Holden J | *Philosophical Transactions of the Royal Society A* | 2005 | 363/ 2891–2913 | 274 | 17 |
| North American approach to the restoration of *Sphagnum* dominated peatlands | Rochefort L | *Wetlands Ecology and Management* | 2003 | 11/ 3–20 | 197 | 11 |
| The underappreciated potential of peatlands in global climate change mitigation strategies | Leifeld J | *Nature Communications* | 2018 | 9/ 1–7 | 197 | 66 |
| Agricultural peatland restoration: Effects of land-use change on greenhouse gas ($CO_2$ and $CH_4$) fluxes in the Sacramento-San Joaquin Delta | Knox SH | *Global Change Biology* | 2015 | 21/ 750–765 | 185 | 31 |
| Peat-water interrelationships in a tropical peatland ecosystem in Southeast Asia | Wosten JHM | *Catena* | 2008 | 73/ 212–224 | 171 | 13 |
| Status and restoration of peatlands in northern Europe | Vasander | *Wetlands Ecology and Management* | 2003 | 11/ 51–63 | 143 | 8 |
| Developing hydrologic thresholds for *Sphagnum* recolonization on an abandoned cutover bog | Price JS | *Wetlands* | 2001 | 21/ 32–40 | 108 | 5 |
| Water table dynamics in undisturbed, drained and restored blanket peat | Holden J | *Journal of Hydrology* | 2011 | 402/ 103–114 | 108 | 11 |
| Sensitivity of C sequestration in reintroduced *Sphagnum* to water-level variation in a cutaway peatland | Tuttila ES | *Restoration Ecology* | 2004 | 12/ 483–493 | 106 | 6 |
| Peatland restoration: A brief assessment with special reference to *Sphagnum* bogs | Gorham E | *Wetlands Ecology and Management* | 2003 | 11/ 109–119 | 94 | 5 |


**Fig. 5** Network visualization of keywords co-occurrence.

**Table 6** Thematic clusters of various keywords in the peatland restoration field

| Cluster (color) | Nodes | Keywords (no. in bracket) | Main theme | Cluster (color) | Nodes | Keywords (no. in bracket) | Main theme |
|---|---|---|---|---|---|---|---|
| 1 (red) | 19 Nodes | Biodiversity; blanket bog; carbon; climate change; co 2; dissolved organic carbon; doc; drainage; ecosystem services; forestry; mires; monitoring; nutrients; poc; raised bog; restoration ecology; runoff; water color; water quality | Peatland ecosystem restoration for climate change mitigation and water quality improvement | 5 (purple) | 11 Nodes | Biogeochemistry; ecohydrology; organic matter; peatland; peatland hydrology; remote sensing; *Sphagnum* moss; water table; water management; wetland; wetland restoration | Biogeochemistry and ecohydrology in peatland restoration |
| 2 (green) | 13 Nodes | Bog; cutover peatlands; ecological restoration; eriophorum vaginatum; fen; global change; mire; plant reintroduction; regeneration; rehabilitation; revegetation; *Sphagnum*; spontaneous revegetation | Ecological restoration of peatlands to address global change | 6 (light blue) | 10 Nodes | Carbon sequestration; cutover bog; decomposition; ditch blocking; felling; microbial activity; peatland restoration; photosynthesis; respiration; water chemistry | Peatland restoration through water chemistry and microbial activity management |
| 3 (blue) | 12 Nodes | Agroforestry; deforestation; fire; hydrology; Indonesia; Kalimantan; paludiculture; peatland rewetting; reclamation; restoration; tropical peatland; water level | Sustainable management of tropical peatlands in Indonesia | 7 (orange) | 8 Nodes | Microtopography; peat; rewetting; Scotland; species richness; vascular plants; vegetation; wetlands | Microtopography and biodiversity in wetland restoration in Scotland |
| 4 (yellow) | 11 Nodes | Carbon dioxide; choice experiment; climate change mitigation; cutover peatland; ecosystem restoration; eddy covariance; greenhouse gas emissions; methane; peat extraction; peatland degradation; peatlands | Climate change mitigation through peatland restoration and greenhouse gas management | 8 (brown) | 1 Nodes | Water retention | Water retention management in wetland ecosystems |

The color of each cluster is shown in Figure 5.

lands as crucial ecosystems and for carbon storage (Harenda et al. 2018). Consequently, the restoration of peatlands emerged as a pivotal research topic, as degraded peatlands release substantial quantities of greenhouse gases which contribute to global warming. It also coincided with the emergence of new journals, for example *Sustainability* in 2009, *Forests* in 2010, the *Journal of Environmental Economics and Policy*, *Ecosystem Services, and Land* in 2012, and *Forest and Society* in 2017 that attracted publications on this topic, and after 2015, because new countries were undertaking research on peatland restoration. One of these countries was Indonesia which from 2017, contributed to the publication rate on this topic. This increase was related to its experience of the extensive forest and peatland fires that produced haze which impacted other countries and first became an international issue in 2015 and which triggered a focus on peatland restoration as a scientific and social issue (Hansson and Dargusch 2018; Sumarga 2017). The article by Sumarga (2017) that considered spatial indicators for human activities as factors explaining the 2015 fire hotspot distribution in Central Kalimantan, Indonesia, was the first published in this area by an Indonesian author.

The themes of these publications from Indonesia have been primarily focused on the responses to peatland damage and degradation by fire, the success or otherwise of rehabilitation initiatives through agroforestry, paludiculture and rewetting (Budiman et al. 2020; Gunawan 2018; Tata


**Fig. 6** Keyword overlay visualization in which the different colors classify the peak time periods of different types of publication.

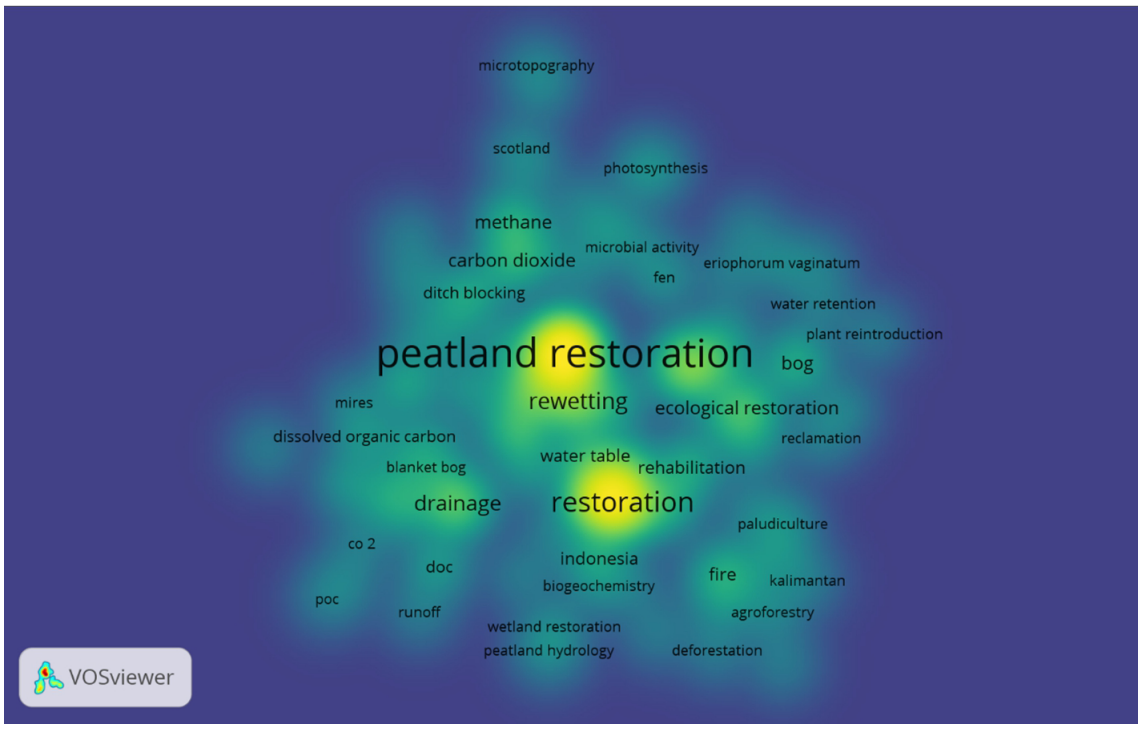


**Fig. 7** Keyword density visualization. Different colors classify density of the co-occurrence, the yellower the stronger the density.

2019a), and the consequences for communities that are reliant on peatland (Gunawan 2018) In this way these publications currently form the largest body of work undertaken on peatland that has been compromised by fire. Although this work has been undertaken in tropical peatland, it has added to that undertaken on boreal and temperate peatlands where the focus has been primarily on their ecology (Bugnon et al. 1997; Tuittila et al. 2000; Waddington and Price 2000), physical and chemical characteristics (Wind-Mulder et al. 1996), vegetation (Famous and Taylor 2005; Robroek et al. 2009), as well as restoration (Howie et al. 2009; Lavoie et al. 2001). It is also contributing to an understanding of the potential consequences of climate change on the world's peatlands.

Two authors based at Canadian institutions, Rochefort L who is affiliated to the Peatland Ecology Research Group, Université Laval and Waddington JM who is affiliated to the Canada Research Group in Ecohydrology, McMaster University were respectively the most influential for numbers of documents published (D = 35) and citations (C = 1,110), and citations per document (45.7). Rochefort's main contribution to knowledge creation in peatland restoration has been in the fields of peatland vegetation (Rochefort et al. 2002) and ecological function (Sottocornola et al. 2007),

while that of Waddington has been in hydrology (Waddington et al. 2011) and carbon cycling (Waddington and Day 2007; Waddington and Warner 2001). In Indonesia, the most influential author to date has been Tata in the field of peatland ecology and paludiculture (Tata et al. 2018; Tata 2019a, b).

## Peatland restoration: Indonesia and global context

In 2021, the final year of this study, over one-third (19) of the 57 documents on peatland restoration retrieved from the Scopus database originated from Indonesia. While Sumarga (2017) was the first Indonesian publication about peatland restoration after the 2015 fire, there were earlier papers by Wösten et al. (2006) on modelling tropical peatland water management in Jambi Province, Sumatra, and by (Medrilzam et al. 2014) on the socio-ecological factors influencing changes in land cover in peatlands in Central Kalimantan, Borneo.

Between 2017–2021 when Indonesian publications were at their peak, there were discernible changes and increasing complexity in their thematic content. The focus of earlier papers was the potential costs of peatland restoration (Hansson and Dargusch 2018) and creating an understanding of the characteristics of peatland vegetation (Indriani et al. 2019). From 2019, papers on paludiculture which investigated the potential benefits of agroforestry for local communities (Budiman et al. 2020; Tata 2019b), strategies for revegetating degraded peatlands (Jaya et al. 2021; Wulandari et al. 2021), the impact of drainage on peatlands (Lu et al. 2021), assessing the condition of peatland soil (Astiani et al. 2020), effective strategies for peatland restoration (Rotinsulu et al. 2022) and emissions from peatland forests (Deshmukh et al. 2021) were published. This later period also saw the emergence of the first published papers on social, economic and political aspects of peatland restoration: stakeholder perceptions regarding the importance of peatland restoration (Ward et al. 2020, 2021), community responses to peatland restoration programs (Laia et al. 2021), financing peatland restoration (Sari et al. 2021), the politics surrounding peatland governance (Astuti 2020; Januar et al. 2021), and obstacles and hurdles to peatland restoration (Lestari et al. 2021; Puspitaloka et al. 2021).

This publication record confirms that Indonesia's research community has responded quickly to address the consequences of the catastrophic fires in 2015. However, it remains important to identify the outstanding and as yet unmet challenges that can be addressed by new research initiatives. Three significant challenges have been identified by Puspitaloka et al. (2021): anthropogenic, those that encompass issues related to community acceptance and participation in peatland restoration and conflicts arising from human activities which directly compete with restoration efforts, a significant area being the expansion of oil palm plantations through peatland clearance, and the community's perception that their lives would improve by cultivating peatland for high-yielding crops (Lestari et al. 2021); ecological, those associated with severely degraded peatlands which resist rewetting and remain highly prone to fire and/or have limited access for restoration; and economic, the absence of secure funding to cover substantial costs; Indonesia has a target to restore up to 2 Mha costing USD 2B which far exceeds the available restoration budget (Sari et al. 2021), and the complexity associated with governance.

Peatlands, which cover around 3% of the land area, are unique habitats characterized by high sensitivity to climate; these complex ecosystems impact both the water and carbon cycles on local and global scales, and they are valuable for their ability to mitigate floods and soil erosion, as well as store and filter water in the landscape (Harenda et al. 2018). Tropical peatlands have an important role related to climate change, because its store more than 20% of the carbon stock of global peatlands, even though they only cover 12% of the global peatland area (381 Mha) (Joosten 2010). Indonesia's tropical peatlands play an important role because 87% of tropical peatlands are located in Indonesia (Page et al. 2011) and a major carbon store, with an estimated storage of more than 55 gigatons of the nearly 70 gigatons of carbon stored in Southeast Asia's peat soils (Elz et al. 2015). It also plays a crucial role in cycling and storing substantial amounts of carbon on a global scale (Harrison et al. 2020; Hergoualc'h et al. 2018; Tan et al. 2021; Ward et al. 2020). Additionally, it plays a critical role in managing water supply, food production, water resource regulation, flood and fire prevention, riverbank stabilization, carbon sequestration and storage, prevention of saline intrusion in coastal areas, and the provision of timber and non-timber forest products (Terzano et al. 2022). It also supporting local communities, promoting ecotourism, and serving as locations for education and research (Syahza et al. 2020), and serves as a crucial habitat for endangered species like orangutans and plays a vital role in providing homes for migratory birds (Hergoualc'h et al. 2018; Posa et al. 2011).

Even though peatlands have an important role, tropical peatlands which naturally covered by forests (Dohong et al. 2017; Rydin and Jeglum 2013) are in a degraded condition (Dohong et al. 2017; Miettinen et al. 2012b; Murdiyarso et al. 2019). Peat decomposition can contribute 58% of global emissions (Ramdani and Hino 2013) so that role can change from carbon storage to carbon emitter (Miettinen et al. 2017; Sari et al. 2021). Considering that the carbon stores of tropical peatlands are very large, peatland restoration in Indonesia is important to prevent worsening global climate conditions (Dohong et al. 2017, 2018; Murdiyarso et al. 2019). When compared with the 2015 fires, it is estimated that after peat restoration is completed, the burned area will be reduced by 6%, reducing $CO_2$ emissions by

18% (Kiely et al. 2021).

Peatland restoration initiatives have been undertaken in various regions, in Southeast Asia, countries such as Indonesia, Malaysia, Brunei Darussalam, Laos, Vietnam, Myanmar, and Thailand have implemented restoration efforts (Terzano et al. 2022). Northern Europe, including Estonia, Sweden, and Finland, has also been active in these efforts (Vasander et al. 2003), alongside regions in North America (Chimner et al. 2017) and Western Europe, notably the UK and Germany (Andersen et al. 2016).

Indonesia employs the 3Rs approach on peatland restoration including rewetting drained peatlands, revegetating fragmented peatlands, and revitalizing local livelihoods (Dohong 2017, 2018). Recognizing fire as a major degradation driver, Harrison et al. (2020) expanded this to the 4Rs by adding fire reduction. Community-led interventions under this framework have proven effective (Terzano et al. 2022), with socio-economic factors being crucial for success (Puspitaloka et al. 2021; Yuwati et al. 2021). European and American restoration focuses on climate change mitigation and biodiversity conservation (Grundling and Grobler 2005; Grundling and Grootjans 2018; Grundling et al. 2021; León Valdebenito et al. 2021). Given the complexity of peatland restoration system, effective efforts require multi-stakeholder collaboration, engaging governments, NGOs, local communities, and the private sector that is supported by robust regulatory frameworks. These challenges are significant not only in developing countries but also in peatland-rich developed nations such as the UK (Reed et al. 2010), Ireland (Flood et al. 2022; O'Riordan et al. 2019), and Russia (Sirin et al. 2021), which face difficulties in developing sustainable restoration framework.

Global interest in Indonesian peatland restoration is evidenced by substantial funding allocated for research and various restoration activities spanning from national initiatives to site-specific projects. Table 6 show that the second most prominent research cluster focuses on "peatland restoration," with frequently associated keywords including restoration, Indonesia, fire, tropical peatland, paludiculture, reclamation, agroforestry, peatland rewetting, Kalimantan, and deforestation. This body of research comprises contributions not only from Indonesian scientists but also from international researchers such as Fleming et al. (2021), Kiely et al. (2021), Merten et al. (2021), Miettinen et al. (2012a, b), Page et al. (2011), and Xu et al. (2018). These efforts are supported by prominent international research institutions, including ACIAR, CSIRO, ICRAF, the World Resources Institute, Wetlands International, and the CARBOPEAT Project. Peatland restoration activities across various regions of Indonesia benefit from international support through projects funded by organizations such as German Agency for International Cooperation, the Korea Indonesia Forest Center, the Japan International Cooperation Agency, the Government of Norway, the United Kingdom, and Australia. Additionally, international companies have shown interest in peatland restoration by obtaining ecological restoration permits from the Indonesian government.

## Conclusions

Articles on peatland restoration are classified based on publication trends, influential journals, authors, affiliations, and countries, with key journals like *Restoration Ecology* and *Ecological Engineering* leading in terms of publication volume and citations. Influential authors are predominantly from Canada and the United Kingdom, with Indonesia emerging as a significant contributor. Current research trends show a growing focus on the ecological, hydrological, and socio-economic aspects of peatland restoration, especially post-2010, with increased interest in restoration techniques, climate change mitigation, and community engagement. Well-researched topics include restoration techniques, carbon sequestration, greenhouse gas emissions, and the ecological impacts of peatland degradation and restoration, with significant contributions from studies in Southeast Asia's tropical peatlands. Future research should address socio-economic challenges, long-term ecological outcomes of restoration projects, cost-effective restoration strategies, and the integration of traditional knowledge with scientific methods. These lessons provide a framework for effective peatland restoration, balancing ecological sustainability, economic viability, and community resilience in both Indonesian and global contexts.

### Abbreviations

IF: Impact factor

### Acknowledgements

We would like to thank Dr Chris Beadle, CSIRO Australia for his comments and advice on an earlier version of this manuscript.

### Authors' contributions

KB initiated the study and conceptualization; analysis data and interpretation; writing the first manuscript and revising the final manuscript. PBP contributed in conceptualization, data collection and revising the final manuscript. AN, NAU FN, MS, DY, and AW contributed writing the first manuscript and revising the final manuscript.

### Funding

Not applicable.

### Availability of data and materials

Not applicable.

### Ethics approval and consent to participate
Not applicable.

### Consent for publication
Not applicable.

### Competing interests
The authors declare that they have no competing interests.

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