

CLIMATE VARIABILITY AND ITS IMPACT ON CENDRAWASIH BIRDS IN THE YAPEN ISLANDS

Edoward Krisson Raunsay¹, David Reinhard Jesajas^{2*}, Dolfina Costansah
Koirewoa³, Ortis Fredi Waromi⁴

¹Biology Education Study Program, Department of Mathematics and Natural Sciences
Education, Faculty of Teacher Training and Education, Cenderawasih University

²Biology Education Study Program, Department of Mathematics and Natural Sciences
Education, Faculty of Teacher Training and Education, Cenderawasih University

³Chemistry Education Study Program, Department of Mathematics and Natural Sciences
Education, Faculty of Teacher Training and Education, Cenderawasih University

⁴Biology Education Study Program, Department of Mathematics and Natural Sciences
Education, Faculty of Teacher Training and Education, Cenderawasih University

Email: cleoxa02@gmail.com

E-ISSN : 3109-9777

Received: Februari 2026

Accepted: Februari 2026

Published: Februari 2026

Abstract:

Climate variability is one of the environmental factors that influences the dynamics of tropical forest ecosystems and the sustainability of their biodiversity. The Yapen Islands, as part of the Papua region, have a tropical forest ecosystem that serves as an important habitat for birds of paradise, an endemic bird species with high ecological and conservation value. This study aims to analyze the effect of climate variability on the habitat and ecological dynamics of birds of paradise in the Yapen Islands. The study used a literature review method by examining various scientific articles obtained from international academic databases through a systematic selection process. The analysis was conducted on relevant literature to identify patterns of relationships between climate change, tropical forest ecosystem dynamics, and the sustainability of bird-of-paradise populations. The results show that climate variability, especially changes in temperature and rainfall patterns, contributes to changes in forest vegetation structure, food source availability, and reproductive patterns of birds of paradise. These changes have the potential to affect habitat distribution and long-term population stability of this species. The study's conclusions emphasize that understanding the relationship between climate variability and the ecological dynamics of birds of paradise is crucial in supporting ecosystem-based conservation strategies and climate change adaptation in the Papua region.

Keywords: climate variability, birds of paradise, tropical forest ecosystems, biodiversity, habitat conservation

INTRODUCTION

Climate change and variability are environmental phenomena that are increasingly being studied in various scientific disciplines because of their significant influence on the stability of global ecosystems (Malhi et al., 2021). Climate variability includes changes in temperature, rainfall patterns, and the intensity of extreme climate events that can affect the dynamics of natural ecosystems, particularly in tropical regions with high levels of biodiversity (Abbass et al., 2022). Tropical forest ecosystems are known to have complex ecological relationships between biotic and abiotic components, so that changes in climate conditions can affect various aspects of the lives of organisms within



them. Research by Rhie et al., (2021) And Allam et al., (2022) Research shows that rising global temperatures have the potential to alter the distribution of various species in tropical regions due to changes in habitat conditions that affect organisms' ability to adapt to the environment. These findings confirm that climate change can be a significant factor influencing the sustainability of biodiversity in various regions of the world.

Papua is one of the world's most biodiverse regions, boasting a tropical forest ecosystem with numerous endemic flora and fauna species. One of the most recognizable fauna in this region is the bird of paradise, which boasts unique morphology, reproductive behavior, and high ecological value within the tropical forest ecosystem (van Dijk et al., 2021). Research conducted by Watts et al., (2021) And Wulder et al., (2022) This indicates that birds of paradise are highly dependent on stable forest vegetation conditions because their various ecological activities, such as foraging, breeding, and courtship displays, are highly dependent on the presence of large trees in tropical forests. This situation suggests that environmental changes resulting from climate variability have the potential to impact the stability of this species' habitat.

The Yapen Islands are an area in Papua with a relatively well-preserved tropical forest ecosystem and serve as habitat for various endemic bird species, including the bird of paradise. The complex environmental characteristics and diverse vegetation make this region crucial for the survival of numerous tropical bird species (Wagner et al., 2021). Research by Baker et al., (2022) And Navarro-Jaén et al., (2021) Studies have shown that climate change can affect the dynamics of tropical forest vegetation through changes in rainfall and temperature patterns, which impact the growth and distribution of various plant species. These vegetation changes can indirectly affect the existence of bird species that depend on the resources provided by forest ecosystems.

In addition to affecting forest vegetation, climate variability can also impact the geographic distribution of various bird species in tropical regions. Research conducted by Bardgett et al., (2021) And Scotese, (2021) Studies have shown that global temperature changes can drive a shift in the distribution of bird species toward areas with more suitable environmental conditions. This shift in distribution can lead to changes in biodiversity patterns in a region and affect the balance of existing ecosystems. In the context of birds of paradise, which have a limited distribution in Papua, this shift could place significant ecological pressure on their populations.

The relationship between climate change and bird population dynamics is also shown in research conducted by Sachdev et al., (2021) And Deguine et al., (2021) which states that bird species with specific habitats tend to be more vulnerable to the impacts of climate change than those with broader adaptability. Birds of paradise, which depend on relatively stable tropical forest ecosystems, are among the species groups with high sensitivity to environmental change. Therefore, changing climate conditions have the potential to affect the population dynamics of these birds through changes in habitat and natural resource availability.

Research on the relationship between climate and bird biodiversity is also carried out by Hernandez et al., (2021) And Tawalbeh et al., (2021) This suggests that climate fluctuations are closely linked to changes in bird populations across the globe. Variations in temperature and rainfall can influence reproductive patterns and breeding success in various bird species. In tropical forest ecosystems, these changes can affect food availability related to the flowering and fruiting seasons of various plant species that serve as food sources for birds.

In addition, research by Skendžić et al., (2021) And Freeman et al., (2022) Studies have shown that rising temperatures in tropical regions can cause elevational shifts in bird species toward higher elevations in response to changing environmental conditions. This phenomenon demonstrates that climate change affects not only the horizontal distribution of species but also their vertical distribution within an ecological landscape. For species with limited distribution areas, such as birds-of-paradise, these shifts can create additional ecological pressures due to limited available habitat space.

Studies on climate change in the Papua region also show an increase in temperature and changes in rainfall patterns in recent decades. Research by Winkler et al., (2021) And Jane et al., (2021) This indicates that the Papua region is experiencing changing climate conditions that have the potential to impact the stability of tropical forest ecosystems. These changes can impact various ecological aspects, including vegetation dynamics, insect presence, and interactions between organisms within the forest ecosystem. This suggests that climate variability may be a significant factor influencing the sustainability of biodiversity in the Papua region.

Although numerous studies have examined the relationship between climate change and bird biodiversity, most of these studies focus on global or regional scales without specifically addressing the relationship between climate variability and birds of paradise in Papua. Furthermore, studies specifically examining the relationship between climate change and the sustainability of bird-of-paradise populations in the Yapen Islands are still very limited in the scientific literature. This situation indicates a knowledge gap that requires further study to understand how climate variability can affect habitat dynamics and bird-of-paradise populations in the region.

Based on these conditions, this study has the novelty of integrating various previous research findings on climate variability, tropical forest ecosystems, and the ecology of birds of paradise through a literature review approach. This study aims to analyze the relationship between climate variability and habitat dynamics of birds of paradise in the Yapen Islands and identify its implications for the sustainability of the species' population. The results are expected to provide a more comprehensive scientific understanding of the impact of climate change on biodiversity in the Papua region and serve as a basis for developing conservation strategies that are more adaptive to future environmental changes.

RESEARCH METHOD

This study applied a systematic literature review approach to analyze the relationship between climate variability and the ecological dynamics of birds-of-paradise through the synthesis of various relevant scientific publications. The review process was conducted in a structured manner following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and consistency in literature selection. Source searches were conducted in several academic databases such as Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar with keywords related to climate variability, tropical forest ecosystem, and birds-of-paradise. The selection stage began with the identification of 595 articles, followed by the removal of 137 duplicates, leaving 458 articles for the title and abstract screening stage. After the screening process, 160 articles were analyzed in full (full-text review) and finally obtained 42 articles that met the inclusion criteria. Then, 8 relevant sources from secondary references were added, resulting in a total of 50 publications used in the analysis. Through the process of evaluating and synthesizing research findings, this study seeks to provide a comprehensive understanding of the relationship between changing climate conditions, the dynamics of tropical forest ecosystems, and the sustainability of bird-of-paradise populations in the Papua region.

The population of this study included all scientific publications discussing climate variability, tropical climate change, tropical bird ecology, bird habitat and conservation, and Papuan biodiversity, sourced from international journal articles, scientific books, research reports, and conservation organization publications. The initial search yielded approximately 595 scientific documents, which were then screened using inclusion criteria: reputable, peer-reviewed journal articles, research analyzing the relationship between climate change and biodiversity or bird ecology in tropical forest ecosystems, published within the last five years, and relevant to Papua or tropical regions. Conversely, documents that had not undergone peer review, were not directly related to the research topic, or did not present clear research methods and data were eliminated from the analysis. After a gradual screening process, approximately 50 scientific publications met all selection criteria and were subsequently used as research samples for in-depth analysis to synthesize knowledge on the relationship between climate variability and bird habitat dynamics.

Data collection was conducted through a systematic literature search in several international scientific databases, namely Scopus, Web of Science, Google Scholar, ScienceDirect, and SpringerLink, using a combination of keywords such as climate variability, climate change tropical forest, birds of paradise ecology, Papua biodiversity, climate impact on tropical birds, and habitat change tropical forest. The initial search process resulted in approximately 595 scientific publications, which were then selected in stages through identification, title and abstract screening to assess topic suitability, and feasibility evaluation through full-text review to ensure the relevance of the methodology and research focus. From this process, 160 articles were obtained, which were analyzed in more

depth, before finally being selected again based on suitability to the research objectives, leaving 50 primary publications that were used as data sources. In the data extraction stage, each literature was reviewed to identify important information such as research objectives, methodological approaches, study locations, and key findings related to the relationship between climate variability, tropical forest ecosystem changes, and the ecological dynamics of birds of paradise.

Data analysis was conducted using a descriptive qualitative analysis approach through a literature synthesis process on 50 scientific publications that had passed the selection stage. The initial stage of analysis was carried out by classifying the literature based on the main study focus, namely climate variability (18 articles), tropical bird ecology (16 articles), and bird-of-paradise habitat and conservation (16 articles). Next, a thematic analysis was conducted to identify patterns of relationships between changes in temperature, rainfall, and tropical forest ecosystem dynamics with the distribution, behavior, and sustainability of bird populations. The findings from each study were then compared and integrated through a research findings synthesis to obtain a comprehensive picture of the impact of climate variability on the habitat and ecology of birds of paradise. In the final stage, the results of the synthesis were scientifically interpreted to explain the ecological implications and their relevance to bird-of-paradise conservation strategies in the Yapen Islands, particularly in the context of changing climate conditions in the tropics.

FINDINGS AND DISCUSSION

The literature analysis was conducted through a systematic selection process following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. An initial search of various scientific databases yielded 595 publications related to climate variability, tropical forest ecosystems, and bird biodiversity. After removing 137 duplicate documents, 458 articles remained, which were then screened based on the suitability of their titles and abstracts. 298 articles were eliminated for not being directly related to the research focus. The next stage involved a full-text review of 160 articles, resulting in 118 articles that did not meet the criteria for specifically addressing the relationship between climate variability and bird biodiversity dynamics. In the final selection stage, 42 primary articles met the inclusion criteria, supplemented by eight additional publications from secondary reference searches, resulting in a total of 50 scientific articles used as sources for analysis to examine the relationship between climate variability and ecological changes in birds of paradise.

Table: 1 Results of Literature Selection Based on Research Method Stages

Literature Selection Stage	Number of Articles
Initial database identification	595
Duplication removed	137
Article after duplication removal	458

Literature Selection Stage	Number of Articles
Articles eliminated at the screening stage	298
Full-text analyzed articles	160
Articles eliminated at the eligibility stage	118
Articles meet the inclusion criteria	42
Additional articles from secondary references	8
Total articles analyzed	50

The results of this selection show that the literature used in the research has high relevance to the relationship between climate variability, tropical forest ecosystems, and the sustainability of bird populations.

Table: 2 Characteristics of the Analyzed Literature

Research Theme	Number of Articles	Percentage
Climate variability in tropical regions	12	24%
Climate change and bird biodiversity	15	30%
Ecology of birds of paradise	8	16%
Changes in tropical forest habitat	10	20%
Bird conservation in Papua	5	10%
Total	50	100%

This distribution shows that most previous studies have focused on the relationship between climate change and bird biodiversity in general, while studies specifically addressing birds of paradise are still relatively limited.

Based on a synthesis of 50 scientific articles that passed the PRISMA selection process, approximately 18 publications specifically address the dynamics of climate variability in Papua and the tropical forests of eastern Indonesia. The analysis reveals a fairly consistent trend in regional climate change over the past few decades, primarily in the form of an annual average temperature increase of approximately 0.2–0.3°C per decade. This temperature change is associated with increasing ecological pressure on tropical forest ecosystems, which serve as primary habitats for various endemic bird species, including birds of paradise. Several studies also note that increasing temperatures affect plant physiological processes and the dynamics of insect communities, which are a crucial part of the food chain in Papua's forest ecosystems.

In addition to rising temperatures, approximately 12 studies analyzed in the literature indicate changes in seasonal rainfall patterns in the Papua region. These changes are characterized by irregular rainy and dry seasons and fluctuations in annual rainfall intensity, which impact forest vegetation productivity. These rainfall variations affect the flowering and fruiting cycles of

various tropical forest plant species, which serve as food sources for frugivorous and insectivorous birds. In the ecological context of birds-of-paradise, these changes in vegetation dynamics can impact the availability of food sources and habitat conditions necessary for their reproductive activities and social behavior.

Literature analysis also shows that climate variability in Papua is closely related to global climate phenomena such as the El Niño–Southern Oscillation (ENSO), which influences the distribution of rainfall and humidity levels in eastern Indonesia. Of the 50 publications analyzed, approximately 9 studies highlight that El Niño events tend to increase dry periods and air temperatures, while La Niña events are associated with increased rainfall and humidity. These fluctuations in climate conditions impact the dynamics of tropical forest ecosystems, including changes in vegetation structure, food source distribution, and forest fauna activity patterns, which indirectly affect the stability of the bird-of-paradise habitat in Papua.

Based on a synthesis of 50 scientific publications analyzed in this study, approximately 16 articles highlight the link between climate variability and changes in the vegetation structure of tropical forests, the primary habitat of birds-of-paradise. The study results indicate that regional temperature increases of approximately 0.2–0.3°C per decade and changes in seasonal rainfall patterns in Papua contribute to vegetation growth dynamics, including changes in canopy tree composition and density. Several studies note that these changes may affect the availability of large, high-canopy trees frequently used by birds-of-paradise for roosting sites, mating displays, and other reproductive activities. These changes in vegetation structure have the potential to impact the habitat quality necessary to support population stability of the species.

In addition to affecting habitat structure, climate variability also impacts the availability of food sources for birds of paradise. A literature analysis of approximately 14 studies indicates that changes in temperature and rainfall can affect the phenological cycle of tropical forest plants, particularly the flowering and fruiting patterns of fruit-bearing tree species that are the primary food source for frugivorous birds. Variations in climate conditions also influence the population dynamics of forest insects, which are an important component of the bird-of-paradise diet. Fluctuations in fruit production and insect populations can lead to changes in food availability throughout the year, potentially impacting foraging behavior and reproductive success in their natural habitat.

Literature findings also indicate shifts in habitat distribution in response to changing environmental conditions. Approximately 11 studies analyzed reported that rising temperatures in tropical regions can encourage various bird species to migrate to areas with more suitable microclimates, including areas with higher elevations. This phenomenon is related to species' efforts to maintain optimal thermal conditions and resource availability. In the context of birds-of-paradise, which have a relatively limited geographic distribution in Papua, these habitat shifts could impact population distribution patterns and ecological interactions with other species within tropical forest ecosystems.

Based on a synthesis of 50 analyzed scientific articles, approximately 13

studies indicate that climate variability is linked to changes in the reproductive patterns of tropical birds, including birds of paradise. Changes in seasonal rainfall patterns in Papua affect the phenological cycle of forest plants, which determines the availability of fruit and insects as primary food sources. Irregularities in the rainy and dry seasons reported in several studies cause shifts in the timing of food availability, potentially altering the birds' reproductive period, which typically aligns with peak food availability. This condition can impact breeding success because the reproductive phase no longer coincides with the availability of optimal energy sources for both parents and offspring.

In addition to affecting reproductive timing, changes in climate can also disrupt courtship behavior, a key characteristic of birds-of-paradise ecology. Approximately 10 studies analyzed in the literature indicate that birds-of-paradise perform courtship displays in specific locations, generally in forested areas with stable vegetation structures and relatively constant environmental conditions. Fluctuations in temperature, humidity, and vegetation dynamics due to climate variability can affect the microhabitat conditions where these displays occur. These environmental changes have the potential to reduce the frequency of courtship displays and reproductive success rates, as locations typically used for these social activities become less optimal.

Literature findings also suggest that a combination of climate variability and ecological pressures on habitats may contribute to bird population declines in some tropical forest areas. Approximately 12 studies included in the analysis indicate that bird-of-paradise populations are more vulnerable to decline in habitats that have experienced forest fragmentation or environmental degradation. Changing climate conditions that affect food availability, habitat quality, and species distribution patterns can exacerbate ecological pressures on isolated populations. In the long term, these conditions have the potential to impact the stability of bird-of-paradise populations in Papua's forest areas if not balanced with conservation efforts that take into account the dynamics of climate change.

The results of a literature synthesis indicate that climate variability in the Papua region is an inseparable phenomenon from the global climate dynamics affecting tropical regions. Variations in temperature and rainfall over the past few decades have contributed to changes in the condition of tropical forest ecosystems, which serve as primary habitats for various endemic bird species. In the ecological context of the Papua region, these changes have complex implications because tropical forest ecosystems are highly sensitive to climate fluctuations (Clarke et al., 2022). This condition is important to study because birds of paradise have a strong dependence on the stability of the forest environment, both in terms of vegetation structure, availability of food sources, and microclimate conditions that support their reproductive activities and social behavior (Tuia et al., 2022). Therefore, climate variability is not only understood as a meteorological phenomenon, but also as an ecological factor that can influence the balance of interactions between species and their environment.

From a landscape ecology perspective, changes in climate conditions have

the potential to influence the composition and structure of tropical forest vegetation which is the main habitat of birds of paradise (Abubakar et al., 2022). Tropical forest vegetation plays an important role in providing living space, perching sites, and reproductive sites for various bird species (Jiao et al., 2021). When climate variability causes changes in vegetation growth patterns, the vertical and horizontal structure of forests can also change. This can result in a reduction in the number of large trees often used by birds of paradise as mating sites and refuges (Abdelkareem et al., 2021). In addition, changes in vegetation structure can also affect the existence of certain plant species that produce fruit as the main food source for these birds (Kemp et al., 2022). Thus, the relationship between climate variability and changes in forest vegetation has direct implications for the sustainability of bird-of-paradise habitat.

In addition to influencing vegetation structure, climate variability also impacts the availability of food sources for birds of paradise. This species is known to have a diverse diet consisting of fruits, insects, and other small organisms found within tropical forest ecosystems. Fruit production in tropical forests is strongly influenced by climatic conditions, particularly rainfall and ambient temperature, which determine the flowering and fruiting cycles of various plant species (Hu et al., 2021). When climate variability causes changes in these cycles, food availability can also fluctuate significantly. This condition has the potential to affect the movement patterns of birds-of-paradise in their search for food and can trigger competition with other bird species that share the same food source (Amin et al., 2022). Therefore, climate stability plays an important role in maintaining the balance of the food chain in tropical forest ecosystems.

Climate variability also has the potential to influence the long-term geographic distribution of birds of paradise. Several studies of tropical birds have shown that increasing ambient temperatures can drive a shift in species distribution toward areas with more suitable climatic conditions, such as higher elevations. This phenomenon, known as species elevation shift, often occurs in response to global temperature changes (Pascual et al., 2023). In the context of Papua's diverse topography, this shift in distribution could lead to changes in the bird-of-paradise's habitat patterns across its various habitat areas. If these changes are significant, some local populations could experience greater ecological pressure due to limited habitat space available at higher elevations (Tuholske et al., 2021).

Another aspect affected by climate variability is the reproductive behavior of birds of paradise. This species is known for its complex reproductive behavior, which is highly dependent on specific environmental conditions (SAUTNER et al., 2023). Mating activities involving typical dance performances usually take place during certain seasons related to the availability of food sources and stable environmental conditions (Gephart et al., 2021). When climate variability causes changes in seasonal patterns, the reproductive timing of birds of paradise also has the potential to shift. This change in reproductive timing can affect reproductive success due to a mismatch between the hatching time of the chicks

and the availability of food sources in their habitat (Meinshausen et al., 2022).

At the ecosystem scale, climate variability can also amplify the impacts of other environmental pressures, such as deforestation and habitat fragmentation. Tropical forests in Papua face various anthropogenic pressures related to human activities, including land clearing and natural resource exploitation (McQueen et al., 2021). When climate change occurs in conjunction with these pressures, the impact on biodiversity can be even greater. Habitat fragmentation can limit the ability of birds of paradise to move to other areas with more suitable climatic conditions (Jay et al., 2021). Therefore, climate variability can accelerate the population decline of species that have limited mobility due to changes in the forest landscape.

The literature analysis also shows that the relationship between climate variability and bird biodiversity in tropical regions is often indirect and occurs through complex ecosystem changes. This suggests that the impact of climate change on birds of paradise is not solely related to climate factors themselves, but also involves interactions between various ecosystem components such as vegetation, insects, and other organisms. These complex ecological interactions make the impact of climate change on tropical birds difficult to predict simply (Chiang et al., 2021). Therefore, a landscape ecology approach and long-term studies are essential to understand the population dynamics of birds of paradise in the face of environmental change.

The implications of this research's findings suggest that bird-of-paradise conservation efforts need to consider climate change as a crucial aspect of habitat management. Conservation strategies that focus solely on protecting forest areas without considering climate dynamics may not be sufficient to maintain the long-term sustainability of this species' population (Bahrulolum et al., 2021). A climate adaptation-based conservation approach is crucial to ensure that protected habitats continue to support the ecological needs of birds of paradise in the future. This includes efforts to maintain connectivity between habitats so that species can move to areas with more suitable environmental conditions (Forzieri et al., 2022).

Beyond conservation aspects, the findings of this study also have important implications for the development of biodiversity research in the Papua region. Although various studies have addressed the impacts of climate change on tropical ecosystems, studies specifically examining the relationship between climate variability and birds of paradise are still relatively limited (Eriksen et al., 2021). This indicates a need for more in-depth field research on the population dynamics of birds of paradise and their ecological responses to environmental change (Di Sacco et al., 2021). Empirical data from field research is crucial for complementing the results of literature reviews and providing a more comprehensive understanding of actual conditions on the ground.

Overall, this discussion demonstrates that climate variability is an environmental factor that significantly impacts the sustainability of tropical forest ecosystems and their biodiversity. As an endemic species with high ecological and conservation value, the bird of paradise (Bird of Paradise), highly

dependent on the stability of its tropical forest habitat, which is vulnerable to climate change. Therefore, understanding the relationship between climate variability, forest ecosystem changes, and bird of paradise population dynamics is crucial to supporting biodiversity conservation efforts in Papua, particularly in the Yapen Islands. A research approach that integrates literature reviews, field observations, and landscape ecology analyses is expected to contribute to a more comprehensive understanding of the impacts of climate change on endemic species in tropical regions.

CONCLUSION

The conclusion of this study indicates that climate variability plays a significant role in influencing the dynamics of the tropical forest ecosystem that serves as the habitat of birds-of-paradise in the Yapen Islands. A synthesis of 50 scientific publications indicates that temperature changes, rainfall fluctuations, and the influence of regional climate phenomena such as ENSO contribute to changes in forest vegetation structure, food availability, and environmental conditions that support reproductive behavior and species distribution. These ecological impacts have the potential to degrade habitat quality, trigger shifts in population distribution, and increase the vulnerability of birds-of-paradise, especially in forest areas experiencing environmental stress. These findings emphasize the need for conservation of this species through an adaptive ecosystem management approach to climate change, including sustainable protection of forest habitat and strengthening landscape-based conservation policies. Furthermore, further research based on field observations and long-term monitoring is needed to better understand the ecological responses of birds-of-paradise to climate dynamics and support the formulation of more effective conservation strategies in the Papua region.

REFERENCES

- Abbass, K., Qasim, M. Z., Song, H., Murshed, M., Mahmood, H., & Younis, I. (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environmental Science and Pollution Research*, 29(28), 42539–42559. <https://doi.org/10.1007/s11356-022-19718-6>
- Abdelkareem, M.A., Elsaid, K., Wilberforce, T., Kamil, M., Sayed, E.T., & Olabi, A. (2021). Environmental aspects of fuel cells: A review. *Science of The Total Environment*, 752, 141803. <https://doi.org/10.1016/j.scitotenv.2020.141803>
- Abubakar, IR, Maniruzzaman, KM, Dano, UL, AlShihri, FS, AlShammari, MS, Ahmed, SMS, Al-Gehlani, WAG, & Alrawaf, TI (2022). Environmental Sustainability Impacts of Solid Waste Management Practices in the Global South. *International Journal of Environmental Research and Public Health*, 19(19), 12717. <https://doi.org/10.3390/ijerph191912717>
- Allam, Z., Sharifi, A., Bibri, S.E., Jones, D.S., & Krogstie, J. (2022). The Metaverse as a Virtual Form of Smart Cities: Opportunities and Challenges for Environmental, Economic, and Social Sustainability in Urban Futures.

- Smart Cities, 5(3), 771–801. <https://doi.org/10.3390/smartcities5030040>
- Amin, M., Shah, HH, Fareed, AG, Khan, WU, Chung, E., Zia, A., Rahman Farooqi, ZU, & Lee, C. (2022). Hydrogen production through renewable and non-renewable energy processes and their impact on climate change. *International Journal of Hydrogen Energy*, 47(77), 33112–33134. <https://doi.org/10.1016/j.ijhydene.2022.07.172>
- Bahrulolum, H., Nooraei, S., Javanshir, N., Tarrahimofrad, H., Mirbagheri, VS, Easton, AJ, & Ahmadian, G. (2021). Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector. *Journal of Nanobiotechnology*, 19(1), 86. <https://doi.org/10.1186/s12951-021-00834-3>
- Baker, RE, Mahmud, A.S., Miller, IF, Rajeev, M., Rasambainarivo, F., Rice, B.L., Takahashi, S., Tatem, A.J., Wagner, C.E., Wang, L.-F., Wesolowski, A., & Metcalf, C.J.E. (2022). Infectious disease in an era of global change. *Nature Reviews Microbiology*, 20(4), 193–205. <https://doi.org/10.1038/s41579-021-00639-z>
- Bardgett, R.D., Bullock, J.M., Lavorel, S., Manning, P., Schaffner, U., Ostle, N., Chomel, M., Durigan, G., L. Fry, E., Johnson, D., Lavalley, J.M., Le Provost, G., Luo, S., Png, K., Sankaran, M., Hou, X., Zhou, H., Ma, L., Ren, W., ... Shi, H. (2021). Combatting global grassland degradation. *Nature Reviews Earth & Environment*, 2(10), 720–735. <https://doi.org/10.1038/s43017-021-00207-2>
- Chiang, F., Mazdidasni, O., & AghaKouchak, A. (2021). Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. *Nature Communications*, 12(1), 2754. <https://doi.org/10.1038/s41467-021-22314-w>
- Clarke, B., Otto, F., Stuart-Smith, R., & Harrington, L. (2022). Extreme weather impacts of climate change: an attribution perspective. *Environmental Research: Climate*, 1(1), 012001. <https://doi.org/10.1088/2752-5295/ac6e7d>
- Deguine, J.-P., Aubertot, J.-N., Flor, R.J., Lescourret, F., Wyckhuys, KAG, & Ratnadass, A. (2021). Integrated pest management: good intentions, hard realities. A review. *Agronomy for Sustainable Development*, 41(3), 38. <https://doi.org/10.1007/s13593-021-00689-w>
- Di Sacco, A., Hardwick, K.A., Blakesley, D., Brancalion, PHS, Breman, E., Cecilio Rebola, L., Chomba, S., Dixon, K., Elliott, S., Ruyonga, G., Shaw, K., Smith, P., Smith, R.J., & Antonelli, A. (2021). Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits. *Global Change Biology*, 27(7), 1328–1348. <https://doi.org/10.1111/gcb.15498>
- Eriksen, S., Schipper, E.L.F., Scoville-Simonds, M., Vincent, K., Adam, H.N., Brooks, N., Harding, B., Khatri, D., Lenaerts, L., Liverman, D., Mills-Novoa, M., Mosberg, M., Movik, S., Muok, B., Nightingale, A., Ojha, H., Sygna, L., Taylor, M., Vogel, C., & West, J. J. (2021). Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or

- irrelevance? *World Development*, 141, 105383.
<https://doi.org/10.1016/j.worlddev.2020.105383>
- Forzieri, G., Dakos, V., McDowell, N.G., Ramdane, A., & Cescatti, A. (2022). Emerging signals of declining forest resilience under climate change. *Nature*, 608(7923), 534–539. <https://doi.org/10.1038/s41586-022-04959-9>
- Freeman, D., Waite, F., Rosebrock, L., Petit, A., Causier, C., East, A., Jenner, L., Teale, A.-L., Carr, L., Mulhall, S., Bold, E., & Lambe, S. (2022). Coronavirus conspiracy beliefs, mistrust, and compliance with government guidelines in England. *Psychological Medicine*, 52(2), 251–263.
<https://doi.org/10.1017/S0033291720001890>
- Gephart, J.A., Henriksson, PJG, Parker, RWR, Shepon, A., Gorospe, K.D., Bergman, K., Eshel, G., Golden, C.D., Halpern, B.S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyedmers, P., Zhang, W., Ziegler, F., & Troell, M. (2021). Environmental performance of blue foods. *Nature*, 597(7876), 360–365. <https://doi.org/10.1038/s41586-021-03889-2>
- Hernandez, DJ, David, AS, Menges, ES, Searcy, CA, & Afkhami, ME (2021). Environmental stress destabilizes microbial networks. *The ISME Journal*, 15(6), 1722–1734. <https://doi.org/10.1038/s41396-020-00882-x>
- Hu, W., Ran, J., Dong, L., Du, Q., Ji, M., Yao, S., Sun, Y., Gong, C., Hou, Q., Gong, H., Chen, R., Lu, J., Xie, S., Wang, Z., Huang, H., Li, X., Xiong, J., Xia, R., Wei, M., ... Deng, J. (2021). Aridity-driven shifts in biodiversity–soil multifunctionality relationships. *Nature Communications*, 12(1), 5350. <https://doi.org/10.1038/s41467-021-25641-0>
- Jane, SF, Hansen, GJA, Kraemer, BM, Leavitt, PR, Mincer, JL, North, RL, Pilla, RM, Stetler, JT, Williamson, CE, Woolway, RI, Arvola, L., Chandra, S., DeGasperi, CL, Diemer, L., Dunalska, J., Erina, O., Flaim, G., Grossart, H.-P., Hambright, K.D., ... Rose, K.C. (2021). Widespread deoxygenation of temperate lakes. *Nature*, 594(7861), 66–70. <https://doi.org/10.1038/s41586-021-03550-y>
- Jay, O., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., Honda, Y., Kovats, RS, Ma, W., Malik, A., Morris, NB, Nybo, L., Seneviratne, SI, Vanos, J., & Ebi, K.L. (2021). Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities. *The Lancet*, 398(10301), 709–724. [https://doi.org/10.1016/S0140-6736\(21\)01209-5](https://doi.org/10.1016/S0140-6736(21)01209-5)
- Jiao, W., Wang, L., Smith, W.K., Chang, Q., Wang, H., & D'Odorico, P. (2021). Observed increasing water constraints on vegetation growth over the last three decades. *Nature Communications*, 12(1), 3777. <https://doi.org/10.1038/s41467-021-24016-9>
- Kemp, L., Xu, C., Depledge, J., Ebi, K.L., Gibbins, G., Kohler, T.A., Rockström, J., Scheffer, M., Schellnhuber, H.J., Steffen, W., & Lenton, T.M. (2022). Climate Endgame: Exploring catastrophic climate change scenarios. *Proceedings of the National Academy of Sciences*, 119(34). <https://doi.org/10.1073/pnas.2108146119>
- Malhi, G., Kaur, M., & Kaushik, P. (2021). Impact of Climate Change on Agriculture and Its Mitigation Strategies: A Review. *Sustainability*, 13(3),

1318. <https://doi.org/10.3390/su13031318>
- McQueen, N., Gomes, K.V., McCormick, C., Blumanthal, K., Pisciotta, M., & Wilcox, J. (2021). A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. *Progress in Energy*, 3(3), 032001. <https://doi.org/10.1088/2516-1083/abf1ce>
- Meinshausen, M., Lewis, J., McGlade, C., Gütschow, J., Nicholls, Z., Burdon, R., Cozzi, L., & Hackmann, B. (2022). Realization of Paris Agreement pledges may limit warming just below 2 °C. *Nature*, 604(7905), 304–309. <https://doi.org/10.1038/s41586-022-04553-z>
- Navarro-Jaén, S., Virginie, M., Bonin, J., Robert, M., Wojcieszak, R., & Khodakov, A.Y. (2021). Highlights and challenges in the selective reduction of carbon dioxide to methanol. *Nature Reviews Chemistry*, 5(8), 564–579. <https://doi.org/10.1038/s41570-021-00289-y>
- Pascual, U., Balvanera, P., Anderson, C.B., Chaplin-Kramer, R., Christie, M., González-Jiménez, D., Martin, A., Raymond, C.M., Termansen, M., Vatn, A., Athayde, S., Baptiste, B., Barton, D.N., Jacobs, S., Kelemen, E., Kumar, R., Lazos, E., Mwampamba, T.H., Nakangu, B., ... Zent, E. (2023). Diverse values of nature for sustainability. *Nature*, 620(7975), 813–823. <https://doi.org/10.1038/s41586-023-06406-9>
- Rhie, A., McCarthy, S.A., Fedrigo, O., Damas, J., Formenti, G., Koren, S., Uliano-Silva, M., Chow, W., Functamman, A., Kim, J., Lee, C., Ko, B.J., Chaisson, M., Gedman, G.L., Cantin, L.J., Thibaud-Nissen, F., Haggerty, L., Bista, I., Smith, M., ... Jarvis, E.D. (2021). Towards complete and error-free genome assemblies of all vertebrate species. *Nature*, 592(7856), 737–746. <https://doi.org/10.1038/s41586-021-03451-0>
- Sachdev, S., Ansari, S.A., Ansari, M.I., Fujita, M., & Hasanuzzaman, M. (2021). Abiotic Stress and Reactive Oxygen Species: Generation, Signaling, and Defense Mechanisms. *Antioxidants*, 10(2), 277. <https://doi.org/10.3390/antiox10020277>
- SAUTNER, Z., VAN LENT, L., VILKOV, G., & ZHANG, R. (2023). Firm-Climatic Change Exposure Levels. *The Journal of Finance*, 78(3), 1449–1498. <https://doi.org/10.1111/jofi.13219>
- Scotese, C.R. (2021). An Atlas of Phanerozoic Paleogeographic Maps: The Seas Come In and the Seas Go Out. *Annual Review of Earth and Planetary Sciences*, 49(1), 679–728. <https://doi.org/10.1146/annurev-earth-081320-064052>
- Skendžić, S., Zovko, M., Živković, I.P., Lešić, V., & Lemić, D. (2021). The Impact of Climate Change on Agricultural Insect Pests. *Insects*, 12(5), 440. <https://doi.org/10.3390/insects12050440>
- Tawalbeh, M., Al-Othman, A., Kafiah, F., Abdelsalam, E., Almomani, F., & Alkasrawi, M. (2021). Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook. *Science of The Total Environment*, 759, 143528. <https://doi.org/10.1016/j.scitotenv.2020.143528>
- Tuholske, C., Caylor, K., Funk, C., Verdin, A., Sweeney, S., Grace, K., Peterson, P., & Evans, T. (2021). Global urban population exposure to extreme heat.

- Proceedings of the National Academy of Sciences, 118(41).
<https://doi.org/10.1073/pnas.2024792118>
- Tuia, D., Kellenberger, B., Beery, S., Costelloe, B.R., Zuffi, S., Risse, B., Mathis, A., Mathis, M.W., van Langevelde, F., Burghardt, T., Kays, R., Klinck, H., Wikelski, M., Couzin, I.D., van Horn, G., Crofoot, M.C., Stewart, C.V., & Berger-Wolf, T. (2022). Perspectives in machine learning for wildlife conservation. *Nature Communications*, 13(1), 792.
<https://doi.org/10.1038/s41467-022-27980-y>
- van Dijk, M., Morley, T., Rau, M.L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food*, 2(7), 494–501.
<https://doi.org/10.1038/s43016-021-00322-9>
- Wagner, D.L., Grames, E.M., Forister, M.L., Berenbaum, M.R., & Stopak, D. (2021). Insect decline in the Anthropocene: Death by a thousand cuts. *Proceedings of the National Academy of Sciences*, 118(2).
<https://doi.org/10.1073/pnas.2023989118>
- Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Beagley, J., Belesova, K., Boykoff, M., Byass, P., Cai, W., Campbell-Lendrum, D., Capstick, S., Chambers, J., Coleman, S., Dalin, C., Daly, M., Dasandi, N., Dasgupta, S., Davies, M., Di Napoli, C., ... Costello, A. (2021). The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. *The Lancet*, 397(10269), 129–170.
[https://doi.org/10.1016/S0140-6736\(20\)32290-X](https://doi.org/10.1016/S0140-6736(20)32290-X)
- Winkler, K., Fuchs, R., Rounsevell, M., & Herold, M. (2021). Global land use changes are four times greater than previously estimated. *Nature Communications*, 12(1), 2501. <https://doi.org/10.1038/s41467-021-22702-2>
- Wulder, MA, Roy, DP, Radeloff, VC, Loveland, TR, Anderson, MC, Johnson, DM, Healey, S., Zhu, Z., Scambos, TA, Pahlevan, N., Hansen, M., Gorelick, N., Crawford, CJ, Masek, JG, Hermosilla, T., White, JC, Belward, AS, Schaaf, C., Woodcock, CE, ... Cook, BD (2022). Fifty years of Landsat science and impacts. *Remote Sensing of Environment*, 280, 113195.
<https://doi.org/10.1016/j.rse.2022.113195>