Review

Geophysics

Geomagnetic Drift

The Determining Factor of Human Existence

Jason K. Leu*

East Central University, 1100 E 14th Street, Ada, OK 74820-6999, United States

*: All correspondence should be sent to: Dr. Jason K. Leu

Author's Contact: Dr. Jason K. Leu, Ph.D., E-mail: jason_leu@ecok.edu

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Geomagnetic drift, the gradual and often sporadic movement of Earth's magnetic poles, has long been considered a geophysical curiosity. However, emerging interdisciplinary evidence suggests that fluctuations in Earth's magnetic field may have profoundly influenced human evolution, behavior, health, and societal development. From genetic mutation and embryogenesis to neuropsychological regulation, climate variation, and technological disruption, geomagnetic changes appear to exert a hidden but persistent force across biological and environmental systems. By examining data from paleomagnetism, genetics, anthropology, climatology, and neuroscience, this article constructs a comprehensive narrative of geomagnetic drift as a foundational determinant of human existence. It evaluates historical geomagnetic excursions like the Laschamp event, the magnetoreceptive capacities of humans and other species, and the far-reaching effects on circadian rhythm and mental health. In addition, it explores implications for future technological vulnerabilities and public health frameworks. The evidence invites a paradigm shift: humanity's destiny may be intimately tied to the silent wanderings of Earth's magnetic poles.

Keywords: Geomagnetic Drift; Magnetic Field; Earth; Humanity Destiny; Magnetic Poles

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Introduction

EARTH'S magnetic field, generated by the dynamic motion of molten iron in the outer core, serves as an invisible shield that protects life from solar and cosmic radiation (Tillman, 2022). While its role in protecting the biosphere is well established, the idea that geomagnetic drift could shape the course of human evolution, biology, and society remains underexplored. Geomagnetic drift refers to the secular variation of the magnetic poles, including occasional pole reversals and excursions in which the field's strength weakens dramatically or the poles rapidly change position (Erdmann et al., 2021). The hypothesis explored here is radical in scope: that geomagnetic drift is not merely a background geophysical phenomenon but a fundamental environmental variable with cascading effects on human biology and civilization.

Such a perspective necessitates a transdisciplinary approach, bridging the physical sciences with evolutionary biology, medicine, and anthropology. It invites reconsideration of assumptions about environmental determinism, challenging us to view geomagnetic behavior not just as a background condition but as a dynamic agent of change. While traditional environmental influences such as climate, topography, and biotic interactions have received significant attention in human evolutionary narratives, geomagnetic drift offers a subtler yet potentially more pervasive influence operating continuously over geological time (Pan & Li, 2023).

In modern times, the importance of this phenomenon is increasingly evident in the growing vulnerability of our technological systems to geomagnetic fluctuations (Mukhopadhyay et al., 2025). As we rely ever more on electromagnetic-sensitive infrastructure—communications satellites, power grids, GPS—the once academically niche field of geomagnetism is poised to take center stage in future planning. Recognizing the holistic significance of Earth's magnetic behavior is not just a scientific exercise but a societal imperative.

In addition to technological vulnerabilities, there is also the human health component to consider. With an increasing volume of evidence linking geomagnetic instability to circadian rhythm disorders, cardiovascular incidents, and even psychiatric emergencies, a new frontier of preventive medicine may emerge (McCraty et al., 2017). Our biological systems may be far more attuned to Earth's magnetic envelope than previously believed, suggesting new directions for environmental health science.

Moreover, historical narratives and cultural mythologies from various civilizations have referenced the "sky breaking," "stars falling," or "divine wrath," which may correspond to geomagnetic storms or reversals (Rukundo, 2023). These symbolic frameworks underscore a latent recognition of magnetic influence embedded in human consciousness and social systems. Revisiting these records may provide valuable information about the long-term human response to geomagnetic shifts (Kopper & Papamarinopoulos, 1978).

Geomagnetic drift may also have shaped early human migration patterns and settlement choices. Since ancient navigators often relied on celestial and geomagnetic cues, shifts in pole locations might have disoriented traditional pathways, forcing adaptive strategies in orientation, timing, and resource allocation (Hervé et al., 2021). This may partially explain archaeological anomalies where migration patterns diverge unexpectedly from ecological or topographical predictions.

Additionally, our present dependence on satellite-based systems renders our civilization more sensitive than ever to geomagnetic instability. While early societies responded through myth and ritual, today's vulnerabilities lie in power outages, communication failures, and transportation disruptions (Sharma, 2020). These dual historical and modern consequences make the study of geomagnetic drift not only relevant but urgent.

Geomagnetic Field Variability through Time

The Earth's magnetic field is anything but static. Paleomagnetic records extracted from lava flows, ocean sediments, and ice cores reveal a dynamic history marked by geomagnetic reversals, excursions, and drifting pole positions (Panovska et al., 2019). The last full reversal, known as the Brunhes-Matuyama reversal, occurred approximately 780,000 years ago. More recently, the Laschamp excursion about 41,000 years ago involved a temporary collapse of the magnetic field to about 5% of its current strength (Bourne et al., 2013). During these periods, the magnetosphere weakened considerably, exposing the Earth to increased fluxes of ionizing radiation from space.

Even without a full reversal, secular variation can result in significant pole movement. In the last century alone, the magnetic north pole has migrated over 500 kilometers toward Siberia (Hervé et al., 2021; Pan & Li, 2023). This unprecedented rate of movement may signal deeper core dynamical processes with unknown consequences. Geomagnetic secular variation, especially when rapid, has the potential to disrupt ecological and physiological systems evolved under more stable magnetic conditions (Constable, 2007).

The strength of Earth's magnetic field has also fluctuated significantly over geological epochs, with implications for radiation exposure and climate patterns. Studies of magnetic field intensity, or paleointensity, show that the geomagnetic field has weakened by about 10% over the last 150 years (Kurazhkovskii et al., 2010). This decline is part of a longer-term trend that may culminate in a geomagnetic reversal or excursion. Understanding this temporal variability helps contextualize past extinction events and evolutionary bottlenecks.

Moreover, geomagnetic phenomena may be coupled with other geophysical cycles. For instance, correlations have been proposed between magnetic reversals and changes in plate tectonics, mantle plumes, or even solar activity (Staub, 2019). These linkages suggest that geomagnetic drift could be part of a larger systemic interaction among Earth's interior, surface, and heliospheric environments. Recognizing these associations enhances our ability to model long-term planetary change and its influence on life.

Furthermore, the speed and direction of pole movements vary not only across centuries but sometimes even within decades, further complicating the predictive modeling of geomagnetic behavior (Morzfeld & Buffett, 2019). This variability challenges the assumption of a geophysically inert backdrop for evolutionary and cultural processes. In effect, the changing geomagnetic field can be understood as a long-wave environmental variable with short-term ecological implications and long-term evolutionary significance (Di Chiara et al., 2020).

Some climate modelers have even postulated weak correlations between magnetic field intensity and temperature oscillations on Earth. Although causality remains debated, it's plausible that geomagnetic drift modulates atmospheric chemistry—especially ozone levels—indirectly influencing climatic regimes (Kilifarska et al., 2020). This opens a new avenue of interdisciplinary research at the interface of geomagnetism and paleoclimatology.

Long-term paleomagnetic surveys have revealed "magnetic superchrons"—extended periods of stable polarity—and "reversal clusters," periods of chaotic polarity switching (Olson et al., 2013). These findings indicate that geomagnetic behavior is governed by nonlinear dynamical processes in the Earth's outer core. The stochastic nature of these events defies easy prediction, further emphasizing the need for robust, integrative models that can anticipate potential biospheric and technological impacts.

Finally, geomagnetic drift has implications beyond Earth. Comparative studies of planetary magnetism, especially with Mars (which lacks a global magnetic field), offer cautionary tales about atmospheric retention and habitability (Lingam, 2019). As Earth's magnetic field weakens or reorganizes, even temporarily, it prompts reflection on how such changes could alter atmospheric shielding and biological resilience on both evolutionary and civilizational timescales.

Biological and Genetic Impacts of Geomagnetic Drift

One of the most compelling aspects of geomagnetic drift is its potential influence on biological systems at the molecular and cellular levels. Several studies suggest that magnetic field variations can impact DNA integrity and expression (Bertea et al., 2015). For instance, geomagnetic field collapses during excursions have been associated with increased levels of ionizing radiation reaching the Earth's surface, which in turn may elevate mutation rates in living organisms (Erdmann et al., 2021). These elevated mutations, while often detrimental, could also fuel evolutionary processes by introducing genetic diversity into populations under environmental stress.

Research into magnetobiology has identified specific molecular mechanisms by which magnetic fields might influence biological processes. For example, cryptochromes—flavoproteins involved in circadian regulation—appear to be magnetically sensitive (Panagopoulos et al., 2024). These proteins, found in both animals and plants, are integral to the regulation of sleep-wake cycles and may also play roles in magnetoreception. In humans, cryptochrome dysfunction has been linked to mood disorders, sleep irregularities, and even certain cancers, suggesting that geomagnetic instability could subtly but significantly affect population health and fitness (Murakami & Tognini, 2020).

In the realm of embryogenesis, studies on amphibians and other vertebrates have shown that altered magnetic conditions during gestation can lead to morphological abnormalities (Sarimov et al., 2023). Although similar evidence in humans is limited, it remains plausible that geomagnetic disturbances could interfere with early developmental pathways. The prenatal environment is highly sensitive to external stressors, and if magnetic field strength or orientation fluctuates significantly during critical developmental windows, it may influence epigenetic modifications that persist across the lifespan (Giorgi & Re, 2021).

Beyond the embryonic stage, geomagnetic fields may also play a role in neural development and function. Experimental data suggest that magnetism can affect neurogenesis and synaptic plasticity, particularly during sensitive developmental periods (Su et al., 2014). This may provide a mechanistic link between geomagnetic variations and observed changes in population-level neurological or psychological traits over evolutionary time. If such effects are heritable or influence reproductive success, geomagnetic drift could act as an indirect evolutionary pressure on the human genome.

Magnetoreception and Human Sensory Biology

Although traditionally considered absent in humans, recent evidence suggests that magnetoreception—the ability to detect magnetic fields—may be a latent or vestigial sense. In several animal species, including migratory birds, turtles, and certain bacteria, magnetoreception is well documented and used for navigation and orientation (Close, 2012). In humans, studies using EEG have demonstrated subtle neural responses to changes in geomagnetic fields, particularly in the alpha band frequencies associated with sensory integration and spatial awareness (Chae et al., 2022).

Behavioral studies have hinted that humans may unconsciously respond to geomagnetic cues. For instance, some evidence suggests that orientation and navigational performance improve in environments aligned with natural geomagnetic gradients. Though the effect is subtle and often masked by dominant visual and auditory inputs, it raises the possibility that early hominins—reliant on natural landscapes—may have possessed more acute magnetosensory capabilities (Kavet & Brain, 2021). As reliance on artificial environments grew, this sense may have atrophied or been rechanneled into other cognitive functions.

Further support for human magnetoreception comes from research on the retina. Cryptochromes present in the human eye are structurally similar to those in magnetoreceptive species, suggesting that magnetic cues might be processed visually, even if only subliminally (Henderson, 2021). Experiments with magnetically shielded rooms have shown changes in circadian rhythm and melatonin secretion, indicating that human physiology remains responsive to magnetic inputs despite a lack of conscious awareness (Xue et al., 2021).

The implications of latent magnetoreception are profound. It may contribute to a baseline environmental awareness that influences mood, alertness, and spatial cognition. In a rapidly urbanizing world filled with electromagnetic noise, the subtle interplay between natural geomagnetic fields and human neurology may be disrupted, contributing to modern phenomena such as "geopathic stress," jet lag, and even certain idiopathic illnesses. Understanding and rehabilitating this sensory pathway could lead to new treatments for disorientation-related disorders and enhance our comprehension of human-environment interactions.

Psychological and Circadian Effects

The human brain is highly sensitive to environmental stimuli, including fluctuations in geomagnetic fields. Emerging research indicates that geomagnetic activity can influence mood, cognition, and overall psychological well-being. Studies have demonstrated correlations between geomagnetic storms and increased hospital admissions for mood disorders such as depression and anxiety (Kay, 1994). One hypothesis attributes these effects to geomagnetic influence on melatonin secretion and serotonin pathways—neurotransmitters essential for mood regulation and sleep.

Circadian rhythms, the roughly 24-hour biological cycles that govern sleep-wake patterns, hormone production, and metabolism, are known to be synchronized by environmental cues such as light and temperature (Balbo et al., 2010). Recent studies suggest that magnetic fields may also act as zeitgebers—external time-givers—for circadian rhythm (Medić et al., 2017). Variations in geomagnetic activity have been shown to alter the expression of clock genes in mammals, potentially desynchronizing internal clocks from natural cycles and leading to fatigue, irritability, and cognitive dysfunction.

Beyond individual effects, entire populations may experience altered behavioral patterns during periods of geomagnetic unrest (McClung, 2013). Epidemiological studies have observed spikes in traffic accidents, workplace injuries, and even suicide rates during periods of heightened geomagnetic turbulence. Although correlation does not imply causation, the consistency of such findings across cultures and time periods suggests that geomagnetic activity may subtly influence collective human behavior.

There is also increasing interest in the potential therapeutic applications of geomagnetic research. For instance, magnetic field modulation is being explored as a treatment for depression and sleep disorders. Transcranial magnetic stimulation (TMS), a clinical technique that uses localized magnetic fields to stimulate brain regions, echoes the idea that magnetic forces can modulate neural activity (Alipour et al., 2025). Understanding how natural geomagnetic fluctuations affect the brain could enhance these technologies and lead to personalized interventions based on geomagnetic conditions.

Climate, Environment, and Human Societies

Geomagnetic drift has profound implications not only for biological systems but also for the global environment. One of the most significant consequences of geomagnetic weakening or polarity reversals is the reduction of Earth's magnetic shielding against solar and cosmic radiation (Liboff, 2013). This increased radiation influx can influence atmospheric chemistry, such as ozone depletion, leading to climatic shifts that may affect agriculture, water cycles, and the habitability of entire regions.

There is evidence that past geomagnetic excursions have coincided with periods of climatic instability. For instance, the Laschamp event, a major geomagnetic excursion around 42,000 years ago, occurred during a time of pronounced environmental changes and large-scale faunal and human migrations (Valet & Valladas, 2010). Researchers hypothesized that the collapse of the magnetic field during this event may have intensified ultraviolet radiation, altered atmospheric circulation patterns, and contributed to megafaunal extinctions and Neanderthal decline.

Human societies are deeply dependent on predictable environmental conditions. Changes in magnetic shielding and resulting climatic variability can disrupt food systems, lead to disease outbreaks, and catalyze social unrest. Historical climatology has traced correlations between geomagnetic fluctuations and famines, pandemics, and mass migrations (Sellers et al., 2019). For example, some studies suggest that weakening geomagnetic fields during the late Holocene may have played a contributory role in the collapse of civilizations such as the Akkadian Empire and the Maya (Channell & Vigliotti, 2019).

Understanding the interaction between geomagnetism and climate is particularly urgent in the context of anthropogenic climate change. If geomagnetic weakening continues alongside rising greenhouse gas emissions, the combined effects could amplify environmental risks. Policymakers and researchers must consider geomagnetic variables as potential feedback mechanisms or stressors in Earth system models to create more accurate forecasts and mitigation strategies.

Technological Vulnerabilities and Infrastructure

Modern civilization relies heavily on technologies that are inherently vulnerable to geomagnetic disturbances. Solar storms, which are closely tied to variations in the geomagnetic field, can induce geomagnetically induced currents (GICs) in power grids, pipelines, and communication networks(Rukundo, 2023). The infamous Carrington Event of 1859 serves as a historical warning, when telegraph systems failed across continents and sparks flew from equipment (Facskó et al., 2023). A similar event today would have catastrophic impacts on global infrastructure.

Satellites, which provide vital services such as GPS, telecommunications, and weather monitoring, are particularly susceptible to magnetic field disruptions (Chernogor et al., 2025). During geomagnetic storms, satellites can experience increased atmospheric drag, loss of orientation, and even system failure due to radiation damage. As space-based technology proliferates with the rise of private and governmental satellite constellations, the risks posed by geomagnetic drift and instability become more critical (Hu, 2021).

Aviation and navigation systems are also at risk. Aircraft flying at high altitudes and latitudes are exposed to elevated radiation levels during magnetic storms (Parker & Linares, 2024). Communication blackouts and navigational errors can occur, posing risks to passenger safety and operational efficiency. Submarines and undersea cables, essential for global internet connectivity, may also be affected by GICs, potentially leading to regional or global communication outages (Rajput et al., 2020).

In response to these vulnerabilities, systems for monitoring space weather have been developed to provide early warnings of geomagnetic disturbances (Castellanos & Hölzle, 2022). However, these systems are still in their infancy, and global coordination is limited. A comprehensive understanding of geomagnetic drift and its long-term patterns could enable the development of more resilient technologies, better protective infrastructure, and emergency response protocols tailored to geomagnetic events.

Philosophical and Future Implications

The realization that geomagnetic drift influences not only the Earth's environment but also the biology, psychology, and technology of human beings compels a re-evaluation of our place in the cosmos. Historically, humanity has viewed itself as separate from geophysical processes, shaping the planet rather than being shaped by it (Irons & Irons, 2023). However, geomagnetic research reveals a more entangled existence—where the silent undulations of the Earth's magnetic field may have quietly steered our evolution, migrations, behaviors, and beliefs (Panovska et al., 2019).

If geomagnetic forces have exerted a guiding hand over human development, then many cultural, biological, and technological milestones may have emerged not solely from human ingenuity, but from environmental necessity (Franco‑Obregón, 2023). Such a realization does not diminish human agency but enriches our understanding of it by embedding it within a broader geophysical context.

Looking forward, as geomagnetic drift continues and the poles accelerate their movement, we must consider how to adapt. Urban planning, health care, and technology design could incorporate geomagnetic variables, making societies more resilient to subtle yet pervasive magnetic influences (Lingam, 2019). Public education on space weather, alongside traditional environmental awareness, may foster a more holistic and adaptive worldview.

Ultimately, the study of geomagnetic drift challenges the anthropocentric paradigm and encourages a systems-based view of existence. Human survival and flourishing may depend not only on mastering technology or curbing emissions, but also on listening to the planet's silent magnetic voice—a voice that has spoken to us across eons, shaping life in ways we are only beginning to comprehend (Elgin, 2015).

Conclusion

In light of the evidence presented, geomagnetic drift emerges not as a marginal geophysical curiosity but as a foundational driver of human experience. It permeates our biology, subtly influencing gene expression, neural activity, and behavioral patterns. It shapes our environment, modulating atmospheric processes and climatic conditions. And it challenges our technological resilience, threatening global systems that are deeply reliant on magnetic stability.

Our historical and evolutionary narrative must be reframed in this context. The forces that influenced the development of hominid species, the collapse of civilizations, and the rise of modern infrastructure are not solely anthropogenic or random—they are intertwined with the geophysical heartbeat of the Earth. The magnetic field, once thought to serve only as a compass reference, has proven to be a dynamic and influential force guiding the rhythm of life.

As we enter an era of accelerating geomagnetic drift and technological interdependence, proactive measures are essential. Multidisciplinary research must continue to explore the causal pathways linking geomagnetic phenomena with biological and environmental systems. Policy frameworks should incorporate geomagnetic forecasting alongside climate models, and public education should reflect the integrative nature of planetary forces that govern our existence.

In embracing this expanded worldview, humanity gains not only a deeper understanding of its past but also a roadmap for navigating an uncertain future. Listening to Earth's magnetic voice may become as essential to our survival as understanding its climate or protecting its biodiversity. Geomagnetic drift, far from a passive shift in the planet's orientation, may indeed be the determining factor of human existence.■

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References

Asale, A., Kussa, D., Girma, M., Mbogo, C., & Mutero, C. M. (2019). Community based integrated vector management for malaria control: lessons from three years' experience (2016–2018) in Botor-Tolay district, southwestern Ethiopia. BMC Public Health, 19(1). DOI: https://doi.org/10.1186/s12889-019-7606-3

Bifani, A. M., Ong, E. Z., & De Alwis, R. (2020). Vaccination and therapeutics: Responding to the changing epidemiology of yellow fever. Current Treatment Options in Infectious Diseases/Current Treatment Options in Infectious Disease, 12(3), 349–360. DOI: https://doi.org/10.1007/s40506-020-00232-7

Braack, L., Wulandhari, S. A., Chanda, E., Fouque, F., Merle, C. S., Nwangwu, U., Velayudhan, R., Venter, M., Yahouedo, A. G., Lines, J., Aung, P. P., Chan, K., Abeku, T. A., Tibenderana, J., & Clarke, S. E. (2023). Developing African arbovirus networks and capacity strengthening in arbovirus surveillance and response: findings from a virtual workshop. Parasites & Vectors, 16(1). DOI: https://doi.org/10.1186/s13071-023-05748-7

Branda, F., Scarpa, F., Petrosillo, N., & Ciccozzi, M. (2024). A one health platform for future epidemic preparedness. Infectious Disease Reports, 16(2), 281–288. DOI: https://doi.org/10.3390/idr16020023

Caplan, A., & Mamo, N. (2024). The challenging concept of eradication: A core concept guiding and frustrating public health. Can J Public Health. DOI: https://doi.org/10.17269/s41997-024-00947-w

Carvalho, F. D., & Moreira, L. A. (2017). Why is Aedes aegypti Linnaeus so Successful as a Species? Neotropical Entomology, 46(3), 243–255. DOI: https://doi.org/10.1007/s13744-017-0520-4

Chotun, N., Eaton, J., Anagbogu, I. A., Tesfahunei, H. A., Shawa, S., Karutu, C., Bolarinwa, A., & Mohammed, A. (2024). Sustaining success through strategies for post-elimination management of neglected tropical diseases in African Union Member States. Frontiers in Tropical Diseases, 5. DOI: https://doi.org/10.3389/fitd.2024.1421522

De Gaetano, S., Ponzo, E., Midiri, A., Mancuso, G., Filippone, D., Infortuna, G., Zummo, S., & Biondo, C. (2025). Global Trends and Action Items for the Prevention and Control of Emerging and Re-Emerging Infectious Diseases. Hygiene, 5(2), 18. DOI: https://doi.org/10.3390/hygiene5020018

De Souza, W. M., Fumagalli, M. J., De Lima, S. T. S., Parise, P. L., Carvalho, D. C. M., Hernandez, C., De Jesus, R., Delafiori, J., Candido, D. S., Carregari, V. C., Muraro, S. P., Souza, G. F., Mello, L. M. S., Claro, I. M., Díaz, Y., Kato, R. B., Trentin, L. N., Costa, C. H. S., Maximo, A. C. B. M., . . . Weaver, S. C. (2024). Pathophysiology of chikungunya virus infection associated with fatal outcomes. Cell Host & Microbe, 32(4), 606-622.e8. DOI: https://doi.org/10.1016/j.chom.2024.02.011

Dong, X., & Soong, L. (2021). Emerging and Re-emerging Zoonoses are Major and Global Challenges for Public Health. Zoonoses, 1(1). DOI: https://doi.org/10.15212/zoonoses-2021-0001

Ebi, K. L., & Hess, J. J. (2020). Health risks due to climate change: Inequity in causes and consequences. Health Affairs, 39(12), 2056–2062. DOI: https://doi.org/10.1377/hlthaff.2020.01125

Fang, J. (2010). Ecology: A world without mosquitoes. Nature, 466(7305), 432–434. DOI: https://doi.org/10.1038/466432a

Fatima, M., An, T., Park, P., & Hong, K. (2025). Advancements and Challenges in Addressing Zoonotic Viral Infections with Epidemic and Pandemic Threats. Viruses, 17(3), 352. DOI: https://doi.org/10.3390/v17030352

González, E., Anderson, M. a. E., Ang, J. X. D., Nevard, K., Shackleford, L., Larrosa-Godall, M., Leftwich, P. T., & Alphey, L. (2025). Optimization of SgRNA expression with RNA pol III regulatory elements in Anopheles stephensi. Scientific Reports, 15(1). DOI: https://doi.org/10.1038/s41598-025-98557-0

Guruprasad, N. M., Jalali, S. K., & Puttaraju, H. P. (2013). Wolbachia-a foe for mosquitoes. Asian Pacific Journal of Tropical Disease, 4(1), 78–81. DOI: https://doi.org/10.1016/s2222-1808(14)60319-4

Hancock, P. A., Ochomo, E., & Messenger, L. A. (2024). Genetic surveillance of insecticide resistance in African Anopheles populations to inform malaria vector control. Trends in Parasitology, 40(7), 604–618. DOI: https://doi.org/10.1016/j.pt.2024.04.016

Krishnappa, L., Gadicherla, S., Chalageri, V. H., & Jacob, A. M. (2022). Impact of School-Based Health Education on Dengue Prevention and Control in an Urban Area during an Epidemic. Medical Journal of Dr D Y Patil Vidyapeeth, 16(Suppl 1), S10–S14. DOI: https://doi.org/10.4103/mjdrdypu.mjdrdypu_875_21

Kumar, G., Baharia, R., Singh, K., Gupta, S. K., Joy, S., Sharma, A., & Rahi, M. (2024). Addressing challenges in vector control: a review of current strategies and the imperative for novel tools in India's combat against vector-borne diseases. BMJ Public Health, 2(1), e000342. DOI: https://doi.org/10.1136/bmjph-2023-000342

Leftwich, P. T., Edgington, M. P., Harvey-Samuel, T., Paladino, L. Z. C., Norman, V. C., & Alphey, L. (2018). Recent advances in threshold-dependent gene drives for mosquitoes. Biochemical Society Transactions, 46(5), 1203–1212. DOI: https://doi.org/10.1042/bst20180076

Lobo, N. F., Achee, N. L., Greico, J., & Collins, F. H. (2017). Modern Vector Control. Cold Spring Harbor Perspectives in Medicine, 8(1), a025643. DOI: https://doi.org/10.1101/cshperspect.a025643

Macnish, K., & Van Der Ham, J. (2020). Ethics in cybersecurity research and practice. Technology in Society, 63, 101382. DOI: https://doi.org/10.1016/j.techsoc.2020.101382

Mäkelin, M. (2024). Between the lab and the Wild: Establishing the Potential of Gene Drive Mosquitoes for Malaria Control. Science as Culture, 33(4), 491–510. DOI: https://doi.org/10.1080/09505431.2024.2325982

Moi, M. L., Takasaki, T., & Kurane, I. (2016). Human antibody response to dengue virus: implications for dengue vaccine design. Tropical Medicine and Health, 44(1). DOI: https://doi.org/10.1186/s41182-016-0004-y

Montgomery, M. J., Harwood, J. F., Yougang, A. P., Wilson-Bahun, T. A., Tedjou, A. N., Keumeni, C. R., Wondji, C. S., Kamgang, B., & Kilpatrick, A. M. (2025). The effects of urbanization, temperature, and rainfall on Aedes aegypti and Aedes albopictus mosquito abundance across a broad latitudinal gradient in Central Africa. Parasites & Vectors, 18(1). DOI: https://doi.org/10.1186/s13071-025-06764-5

Moreno, R. D., Valera, L., Borgoño, C., Castilla, J. C., & Riveros, J. L. (2024). Gene drives, mosquitoes, and ecosystems: an interdisciplinary approach to emerging ethical concerns. Frontiers in Environmental Science, 11. DOI: https://doi.org/10.3389/fenvs.2023.1254219

Nakase, T., Giovanetti, M., Obolski, U., & Lourenço, J. (2024). Population at risk of dengue virus transmission has increased due to coupled climate factors and population growth. Communications Earth & Environment, 5(1). DOI: https://doi.org/10.1038/s43247-024-01639-6

Parvez, M. K., & Parveen, S. (2017). Evolution and emergence of pathogenic viruses: past, present, and future. Intervirology, 60(1–2), 1–7. DOI: https://doi.org/10.1159/000478729

Scholz, S., Ngoli, B., & Flessa, S. (2015). Rapid assessment of infrastructure of primary health care facilities – a relevant instrument for health care systems management. BMC Health Services Research, 15(1). DOI: https://doi.org/10.1186/s12913-015-0838-8

Tajudeen, Y. A., Oladipo, H. J., Oladunjoye, I. O., Oladipo, M. K., Shittu, H. D., Abdulmumeen, I., Afolabi, A. O., & El-Sherbini, M. S. (2023). Transforming malaria prevention and control: the prospects and challenges of gene drive technology for mosquito management. Annals of Medicine, 55(2). DOI: https://doi.org/10.1080/07853890.2024.2302504

Wilson, A. L., Courtenay, O., Kelly-Hope, L. A., Scott, T. W., Takken, W., Torr, S. J., & Lindsay, S. W. (2020). The importance of vector control for the control and elimination of vector-borne diseases. PLoS Neglected Tropical Diseases, 14(1), e0007831. DOI: https://doi.org/10.1371/journal.pntd.0007831

Yu, X., & Cheng, G. (2022). Adaptive evolution as a driving force of the emergence and Re-Emergence of Mosquito-Borne viral diseases. Viruses, 14(2), 435. DOI: https://doi.org/10.3390/v14020435

Zeng, D., Cao, Z., & Neill, D. B. (2020). Artificial intelligence–enabled public health surveillance—from local detection to global epidemic monitoring and control. In Elsevier eBooks (pp. 437–453). DOI: https://doi.org/10.1016/b978-0-12-821259-2.00022-3