Biospectrum Horizons:
A Journal of Life Science Research (JASLSRI)
(An international peer-reviewed journal)
Email: editorinchief@jaslsri.org
Website: www.jaslsri.org
ISSN Online: 3139-1524

Critical Slowing Down and Regime Shifts: Assessing Early-Warning Indicators of Climate-Driven Transitions

Nisha Verma[1], Rajeev Kumar Yadav[2*]

[1]*Department of Botany, V.R.A.L. Rajkiya Mahila Mahavidyalaya, Bareilly, Uttar Pradesh, India*
[2]*Department of Botany, Bareilly College, Bareilly, Uttar Pradesh, India*
(Affiliated to MJP Rohilkhand University, Bareilly)
**Corresponding author email: rajeevbotany@rediffmail.com*

Received: 19 February 2026, Revised: 08 April 2026, Accepted: 01 May 2026, Available Online: 30 June, 2026

https://doi.org/10.5281/zenodo.21095363

Abstract

As climate changes, ecological and socio-economic systems will become increasingly vulnerable, and the likelihood of experiencing abrupt and irreversible changes (known as tipping points) will increase. Tipping points are the points of no return in terms of switching between different regimes. For example, if there are small ecological changes in an ecosystem (e.g., loss of biodiversity), they can lead to a disproportionately large response from the ecosystem (e.g., shifting from one ecosystem form to another). One of the most important aspects of climate adaptation science is understanding how these transitions occur; how to identify early-warning signals to detect them; and how to improve the resilience of socio-environmental systems to these transitions. The current study investigates several of the dynamics and factors that are involved in climate-induced tipping points, including: feedback loops; biodiversity loss; and biogeochemical stressors, as well as early-warning indicators, such as: critical slowing down; increased variance; spatial correlation; and flickering. Improved long-term monitoring and increased opportunities for continued modelling of these early-warning signals may improve our ability to anticipate climate-related tipping points. The discussion also encompasses socio-environmental resilience, noting anticipatory, autonomous, and transformative adaptations and governance models which would support society to cope with uncertainty. We must incorporate tipping-point science into policies to address ecological collapse and reduce cascading social risks. Resilience in integrated human nature systems is to be developed through coordinated governance, community involvement, ecological restoration and flexible adaptation strategies and especially as climate pressures intensify and the risk of crossing irreversible thresholds increases, the paper concludes.

Keywords

Climate change; tipping points; regime shifts; socio-environmental resilience; early-warning signals; ecological thresholds; adaptive governance; climate adaptation; critical slowing down; ecosystem stability.

1. Introduction

Among the many environmental problems facing mankind in this century, climate change is one of the largest and most important. It is affecting every type of system (ecosystem, hydrosystem, atmosphere and social and economic systems) on a worldwide basis. Environmental degradation caused by climate change is occurring at an accelerating rate due to global warming, changes in precipitation patterns, increasing numbers of extreme weather events, ocean warming, and increasing concentrations of CO2 in the atmosphere. The potential for future environmental degradation caused by climate change is very significant. The Intergovernmental Panel on Climate Change (IPCC) has predicted that further emissions of greenhouse gases will greatly increase the likelihood of severe and/or irreversible impacts on ecosystems and human societies in the upcoming decades [1, 2].

A key concern of climate scientists is the existence of ecosystem tipping points (adefined as critical environmental thresholds above which small incremental environmental changes can set into motion rapid, non-linear, and often irreversible transitions in the structure and function of ecosystems). Unlike gentle or gradual responses of ecosystems to gradual environmental changes, tipping points can cause rapid deviations in the dynamics, diversity, and services of ecosystems. Once the critical threshold of an ecosystem has been passed, the ecosystem may not return to its preperturbed state, even if the original environmental conditions that caused the perturbation are restored. Therefore, prevention of going past the tipping point is significantly preferred over any restoration efforts made after the tipping point [3, 4].

Numerous worldwide significant ecosystems are nearing or have already suffered from the effects of tipping point behaviour. The Arctic Sea ice ecosystem, for example, has seen a rapid decline because of the ice-albedo feedback, which is the process by which melting ice reveals dark ocean surfaces beneath it which can then absorb more solar energy, thus making both the ongoing ice loss and subsequent warming worse [5]. Similarly, the Amazon rainforest, which is one of the largest terrestrial carbon storage systems on Earth, is also at ever-increasing risk of changing to a savanna-like ecosystem as a result of continued tree-cutting and recurrent drought conditions and higher temperatures, most likely resulting in massive releases of carbon that has been stored. Coral reef ecosystems are also at risk from increased sea temperatures and ocean acidification, both of which contribute to significant coral bleaching events and coral loss, loss of biodiversity, and long-term damage to marine habitats. All of these examples show how climate change-induced tipping points can have cascading effects on the ecological health of ecosystems both regionally and globally [6]. The processes driving ecological tipping points are driven by complex interactions among climate forcing, biodiversity loss, biogeochemical processes, and non-linear feedback loops. Positive feedback processes amplify environmental disturbances and hasten the degradation of ecosystems, reducing their ability to withstand these disturbances [7, 8, 9].

Diminishing the variety of life in Earth's ecosystems causes declining biodiversity to contribute to the reduction of ecological stability, such as by minimizing the ability of species groups to have multiple species within that group that have the same function and are able to adapt - ultimately leading to more vulnerable ecosystems in the presence of outside disturbances [10]; and through intensification of multiple anthropogenic (man-made), landscape disturbance factors including but not limited to land-use change, pollution, fragmentation of habitat, and over-exploitation of natural resources, each of which will contribute to increasing the rate of the likelihood of irreversible ecosystem non-recoverable transitions [11].

Ecological collapse typically occurs over very short amounts of time; therefore, an abundance of research has concentrated on how to find early warning signs indicating declining ecosystem resilience prior to critical thresholds being crossed within a given ecosystem. Of the many potential early warning signs, the most widely recognized early warning sign is referred to as ‘critical slowing down’ - in which the amount of time required for an ecosystem to recover from a given disturbance continues to increase as resilience decreases [12]. Other early warning signs include, but are not limited to, increases in temporal variance, increases in autocorrelation, changes in spatial patterns, increases in spatial correlation, flickering, in which the ecosystem alternately transitions back and forth between two or more different stable states prior to some permanent regime shift occurring [13,14].

Recent technological advances, including but not limited to satellite remote sensing, ecological monitoring, use of machine learning algorithms, and application of mathematical models have improved the ability to use an array of potential detection tools for the identification of these early warning signals to monitor terrestrial, freshwater, and marine ecosystems [15].

Climate-induced tipping points can have consequences that go far beyond simply degrading ecosystems; they also have a major impact on socioeconomic systems, too. Worldwide, abrupt ecosystem transitions affect food security, freshwater availability, agricultural productivity, fisheries, public health, and energy systems, while at the same time increasing the risk of disasters and the cost of those disasters [16]. There are many communities that directly depend on climate-sensitive natural resources for their livelihoods, which leave them vulnerable to changes in the environment. As a result, a primary focus of the climate adaptation research community has been on strengthening communities' socio-environmental resilience. Resilience is defined as the ability of combined human-environment systems to absorb disturbances, reorganize and learn, and adapt without losing either ecological function or social well-being [17].

Broadly speaking there are three types of strategies available for adapting to climate change: anticipatory, autonomous and transformative. Anticipatory adaptation focuses mainly on preventing or minimising the impacts of climate change prior to irreversible changes occurring by means of proactive planning through ecosystem restoration, climate-resilient infrastructure, sustainable land management and disaster preparedness [18]. Autonomous adaptation consists of individual and community-level responses to climate stresses that occur spontaneously, whereas transformative adaptation focuses on creating or implementing significant systemic institutional, technological and policy changes to produce a socially and ecologically sustainable development path [19]. Adaptive governance frameworks designed to be flexible, participatory, polycentric and that foster continuous learning are effective means for managing the uncertainties inherent in complex social-ecological systems [20]. Diminishing the variety of life in Earth's ecosystems causes declining biodiversity to contribute to the reduction of ecological stability, such as by minimizing the ability of species groups to have multiple species within that group that have the same function and are able to adapt - ultimately leading to more vulnerable ecosystems in the presence of outside disturbances; and through intensification of multiple anthropogenic (man-made), landscape disturbance factors including but not limited to land-use change, pollution, fragmentation of habitat, and over-exploitation of natural resources, each of which will contribute to increasing the rate of the likelihood of irreversible ecosystem non-recoverable transitions.

Ecological collapse typically occurs over very short amounts of time; therefore, an abundance of research has concentrated on how to find early warning signs indicating declining ecosystem resilience prior to critical thresholds being crossed within a given ecosystem. Of the many potential early warning signs, the most widely recognized early warning sign is referred to as ‘critical slowing down’ - in which the amount of time required for an ecosystem to recover from a given disturbance continues to increase as resilience decreases. Other early warning signs include, but are not limited to, increases in temporal variance, increases in autocorrelation, changes in spatial patterns, increases in spatial correlation, flickering, in which the ecosystem alternately transitions back and forth between two or more different stable states prior to some permanent regime shift occurring. Recent technological advances, including but not limited to satellite remote sensing, ecological monitoring, use of machine learning algorithms, and application of mathematical models have improved the ability to use an array of potential detection tools for the identification of these early warning signals to monitor terrestrial, freshwater, and marine ecosystems.

2. Climate-Induced Ecological Tipping Points

Climate-induced ecological tipping points are critical thresholds that are surpassed causing ecosystems to change abruptly, nonlinearly, yet often irreversibly as a result of a relatively small change in the environment. Depending upon whether the response of the system is gradual, tipping points will correspond to a rapid change in state (between two different stable states) subsequent to the gradual loss of resilience in the system due to the cumulative effects of long-term climatic or anthropogenic stresses [21, 22]. After the tipping point has been crossed, if the environment subsequently improves, many ecosystems may continue to lack the capacity to recover to their original state. These ongoing difficulties with restoring ecosystems make the process of restoration economically prohibitive.

The frequency and intensity of climate-induced disturbances is accelerating the time at which ecosystems around the world will approach ecological tipping points. There are multiple global drivers which impact physical characteristics of ecosystems such as increasing global temperatures, extended periods of drought, altered precipitation patterns, increases in sea levels, increases in ocean acidification, and increases in atmospheric concentrations of greenhouse gases [23], all of which adversely affect many ecosystem processes simultaneously. These global drivers interact with a variety of local stressors on ecosystems, including habitat fragmentation, pollution, the introduction of invasive species, as well as unsustainable land-use practices, thereby contributing to the loss of resilience of the ecosystem and increasing the possibility of an abrupt ecological transformation occurring [24]. There are several large ecosystems that are identified as possible climate tipping points because they are ecologically critical to the world and are vulnerable to climate change. One such example is that of the Arctic Sea Ice System, which is one of the best-documented examples of these tipping elements. As the temperature increases, the positive feedback loop of ice-albedo will cause ice to melt more rapidly than normal. The black ocean (which absorbs more solar energy) will take the place of the white reflective ice, thus causing more warming and more ice loss through this positive feedback loop [25, 26].

Like the Arctic Sea Ice, both the Greenland and West Antarctic ice sheets, if melted irreversibly, will be significant contributors to global sea level rise and will also produce alterations in global ocean circulation. Similarly, the loss of the Amazon rainforest, due to increased deforestation, repeated droughts, and increased temperatures, is rendering large sections of the rainforest to be below the threshold necessary to produce regional rainfall through evapotranspiration. This tipping point will dramatically change large areas of the Amazon rainforest to savanna-type ecosystems and result in dramatic reductions in biodiversity as well as the release of vast amounts of carbon that have been stored in the biomass of the ecosystem into the atmosphere, thus accelerating global climate change. Coral reefs are clearly at significant risk of catastrophic losses due to marine heat waves and acidification of the ocean [27, 28]. These impacts lead to recurrent episodes of coral bleaching, decreased rates of calcification, decreased biodiversity, and an eventual transformation to an algae-dominated community that has minimal ecological functionality. There is evidence that freshwater ecosystems, peatland ecosystems, mangrove forests and areas of permafrost can show tipping-point behaviour, but these two are not the only types of ecosystems exhibiting behaviours associated with 'tipping points'; permafrost thawing releases large amounts of methane and carbon dioxide, which contributes to greenhouse gas feedbacks, thus contributing further to the overall warming of the earth [29] - similarly, peatland degradation has caused these ecosystems to lose capacity as long-term carbon stores while increasing their vulnerability to wildfire and increasing their greenhouse gas emissions [30]. The interconnection of the above mentioned tipping elements points out that ecological transitions do not happen in isolation, and will usually have cascading effects throughout regional and/or global-wide environmental systems. The identification of ecological tipping points have changed how climate adaptation research is undertaken by moving from a focus of studying gradual change in the environment towards researching the possibility of abrupt scenario changes as a result environmental shocks. The understanding of critical threshold margin of ecosystems in relation to tipping points, the nearness of ecosystems to tipping point and what types of management intervention may delay or stop regime shifts are among some of the most significant questions facing contemporary environmental science. [31].

3. Mechanisms Driving Regime Shifts

The emergence of ecological regime shifts caused by the complex interactions of climatic forcing, ecological processes and human activities, leading to a gradual decrease in ecosystem resilience until they exceed a critical threshold are often multi-causal. The cumulative impacts of multiple stressors, acting across a wide variety of temporal and spatial scales, are predominantly responsible for many ecological regime shifts [32]. Climate change has exacerbated these interactions through changes in temperature, precipitation patterns, hydrological cycles, nutrient availability and species distributions increasing the instability of ecosystems. A significant number of the mechanisms contributing to regime shifts operate through positive feedback loops, amplifying (rather than dampening) the impacts of environmental disturbances once they have been initiated, establishing a cycle of ecosystem degradation and driving the beginning of a shift towards an alternative stable state. A classic example of this phenomenon is the Arctic ice-albedo feedback in which the melting of sea ice exposes darker, more highly absorptive oceanic surfaces to solar radiation, which results in additional warming and further melting of sea ice [33]. There are parallels to this process occurring in tropical forests, whereby the loss of vegetation cover results in reduced amounts of evapotranspiration, reduced amounts of regional precipitation, increased frequency of wildfires and further degradation of the tropical rainforest [34]. Biodiversity loss is one of the main causes of tipping points in ecology. Biodiversity adds to the resilience of ecosystems by allowing them to have functional redundancy, ecological interactions, and the ability to adapt to stress from the environment. As biodiversity decreases, ecosystems are more sensitive to disturbances because the ecological functions that different species provided have now been shifted to fewer species, which creates a greater risk of large responses from disturbances in drought, disease outbreaks, invasive species, and extreme weather. Reducing biodiversity also diminishes the ecosystem services performed by ecosystems (such as pollination, nutrient cycling, soil formation, water purification, and carbon storage), thereby reducing the integrity of ecosystems and humans' quality of life. Changes in biogeochemical cycles and processes also cause shifting regimes by disrupting the natural cycling of carbon, nitrogen, phosphorus, and water. Changes in atmospheric carbon dioxide concentrations, excess nitrogen loading, soil erosion, ocean acidification, and hydrological cycle changes are making ecosystems less productive, changing the composition of species, increasing vulnerability to stress from the environment, and ultimately making ecosystems less stable. In aquatic ecosystems, communities that receive excess nitrogen often undergo eutrophication, develop algal blooms, have reduced oxygen levels, and eventually lose their biodiversity. In terrestrial ecosystems, nutrients affect the structure of vegetation, reduce microbial activity, and decrease carbohydrate stores, which affect the long-term stability of the ecosystem**.** These ecological mechanisms are often impacted by human pressures in ways that will quicken the dynamics of tipping points. Urbanisation, agricultural expansion, deforestation, mining, over-grazing, pollution and excessive resource extraction all cause fragmentation of habitats causing a reduction in ecological connectivity and limiting the ability of species to migrate or adapt as climate changes [35]. These anthropogenic disturbances have a synergistic effect when combined with climate change having cumulative effects that exceed what ecosystems can recover from. The combination of factors like positive feedback cycles, losses of biodiversity, disrupted biogeochemical cycles, and ongoing anthropogenic pressures continue to erode ecological resilience. The reduction in resilience causes ecosystems to be more vulnerable to abrupt and irreversible transitions that can fundamentally change their structure, functioning and ability to provide vital ecosystem services. Understanding these factors is essential to being able to identify vulnerable ecosystems, do predictive modelling with improved accuracy, and develop effective management plans that can help prevent catastrophic ecological collapse.

4. Early-Warning Signals of Ecological Collapse

Often, ecosystems will show measurable behavioural changes as they enter a critical threshold, prior to experiencing a sudden transition in their operating regime. These behavioural changes, commonly known as "early-warning signals," are important indicators of potential ecological collapse and can inform timely management decisions to prevent or limit such collapses. Although some ecosystems exhibit instantaneous (in a defined and rapid way) changes, many ecosystems will exhibit ongoing and typical declines in resilience, where changes will be evidenced by changes in the dynamics of the ecosystem itself. Enhancements in methods for ecological monitoring, remote sensing technologies, artificial intelligence, and mathematical models have increased the ability to identify (determine) these early-warning signals for ecosystems across land, freshwater and oceans. An example of an early-warning indicator which is commonly accepted is "critical slowing down." As ecosystem resilience decreases, the time that the ecosystem takes to recover from disturbances increases. Therefore, the duration of environmental variability increases because the ecosystem can no longer recover quickly enough to establish equilibrium. The slow recovery from disturbance demonstrates that the ecosystem's internal regulatory systems are becoming weaker and that the ecosystem is nearing a tipping point. Critical slowing down has been observed in many types of ecological systems, including forests, lakes, coral reefs and polar regions. Increased variability in ecological variables is another key indicator. As resilience declines, there will be an increase in variability within ecosystems due to increased sensitivity to environmental disturbances. Therefore, vegetation cover, species abundance, nutrient concentration, water levels, or climatic variables will display significantly larger variations than previously observed. The amount of temporal variability will serve as an indicator that a system is becoming unstable and less capable of achieving equilibrium as environmental conditions change. Thus, long-term fluctuations in variance are a good indication that an ecosystem is approaching its critical threshold.

Spatial correlations among different ecosystems can also provide valuable information about system resiliency. Generally, healthy ecosystems maintain heterogeneous landscapes that arise from the complexities of ecological interactions and habitat diversity. However, as environmental stress is experienced, spatial patterning among neighbouring areas tends to become more homogeneous, as ecological disturbances travel through the landscape in a more uniform manner. As a result, increased spatial correlations, vegetation homogenization or fragmentation generally will indicate decreased resilience and diminished ecological complexity. The advancement in satellite imagery and high-resolution spatial datasets will provide researchers with an invaluable tool to track changes to these patterns over large geographical areas. Another major indicator of changed ecological status is flickering (i.e., temporary alternation between two or more alternative stable states) before permanently transitioning to one alternative stable state. During flickering, ecosystems will tend to switch between opposing ecological conditions multiple times in response to small disturbances. Intermittent changes in a system show that the system is at its critical point and that even small changes to that system could create a situation where the system would no longer be operable. In order to determine when a system has undergone a major change, it is important to use multiple early warning signals together with other types of early warning signals (i.e., sensors) so that a reliable prediction can be made. Using a combination of long-term ecological data, satellite remote sensing, machine learning algorithms, Earth system models, and continuous monitoring of environmental conditions can provide information about vulnerable ecosystems and provide evidence-based recommendations for climate adaptation strategies.

5. Socio-Environmental Resilience and Climate Adaptation

Increased socio-environmental resilience has become an important focus of sustainable development as climate change accelerates. Socio-environmental resilience refers to the ability of human and natural systems to remain functional, reorganize after disturbances, and provide ecological and social benefits in a world that is increasingly unstable. Unlike the prevailing view that attempts to keep environmental change from happening, resilience emphasizes an emphasis on adapting, learning, and transforming in response to growing uncertainty. One key component of resilience is anticipatory adaptation, which refers to proactive adaptation efforts that are undertaken before ecological thresholds are crossed. Examples of anticipatory adaptation measures include ecosystem restoration, climate-resilient infrastructure, sustainable management of water resources, conservation of biodiversity, disaster preparedness, and land-use planning that considers climate impacts. By reducing vulnerability prior to natural disturbances, anticipatory adaptation achieves reduced long-term ecological and economic impacts, thereby promoting increased capacity to adapt. Autonomous adaptations are those that arise spontaneously in response to changing environmental conditions from individuals, households, communities, and local institutions without the use of centralised planning. Farmers can change their crops to adapt to climate variability; pastoralists can change their grazing methods; coastal communities can do things differently for their livelihoods; and households can implement water conservation practices in response to changes in climate patterns. Autonomous adaptation typically occurs quickly and uses local knowledge, but there are constraints to how successfully it can be implemented, such as limited financial resources, technological capacity, and institutional support. Continuing increases in climate risk may means that only incremental adaptations may not be enough and that transformative adaptations may become more essential. Transformative adaptations require fundamental changes to social systems, economic systems, technological systems, and institutional systems, so that long term vulnerability can be decreased. Transformative adaptation includes examples, such as using renewable sources of energy, designing urban infrastructure to be resilient to climate change, utilizing regenerative agricultural methods, restoring degraded ecosystems, managed retreat from highly vulnerable coastal regions, and changing development pathways to achieve sustainability. These transformational actions show that continuing to use the systems as we currently do, will no longer be possible as climate change continues to accelerate.

Adaptation requires not only technological innovation but also a strong institutional framework to support adaptive governance. Adaptive governance involves flexible decision-making, participation of stakeholders, collaboration across disciplines, decentralized institutions, continuous learning, and iterative policy development. Adaptive governance has the ability to provide an effective, flexible way for societies to react to new and unexpected changes in their environment while involving expanded uses of scientific evidence to improve the quality of decision-making processes. By fostering partnerships among governments, research institutions, local communities, Indigenous peoples, and businesses, there is increased capacity to manage uncertainty and build long-term ecosystem resilience in complex socio-ecological systems.

Policy Implications and Future Directions

Due to the high likelihood of climate change-related ecological tipping points occurring in the future, it is crucial to reform existing environmental policies from a reactive crisis management approach to a proactive risk prevention approach. Current environmental policies have relied and continue to rely upon the assumption that ecosystems will respond in a gradual manner; however, since tipping point science has clearly demonstrated that ecosystems can undergo sudden and permanent transformation as a result of the crossing of critical thresholds, climate adaptation policy integration must recognize and incorporate threshold dynamics, resilience assessment methods and early warning monitoring methods into long-term frameworks for planning and policy development. Countries should develop comprehensive national climate strategies that include integration of ecosystem resilience with biodiversity conservation, sustainable land management, disaster risk reduction and climate change mitigation. Nature-based approaches such as large scale reforestation, wetland restoration, peatland conservation, mangrove restoration, and sustainable watershed management represent multiple opportunities for reducing greenhouse gases, increasing biodiversity and enhancing the resilience of ecosystems at relatively low cost. The protection of wildlife corridors and the rehabilitation of degraded landscapes is equally critical to maintaining ecosystem functions during times of climate change. Climate governance in the future will require an interdisciplinary approach to include ecologists and climate scientists as well as economists, engineers, and policy-makers with the involvement of the social sciences and local communities. There is potential to increase the integration of Earth observation technology, artificial intelligence technologies, environmental modelling, and real-time techniques for ecological monitoring into national and international systems for supporting environmental decisions. The expansion of long-term ecological monitoring networks will help in better assessing the vulnerability of ecosystems and provide a basis for better adaptive management strategies. Community involvement must continue to be a fundamental aspect of climate change adaptability, as local knowledge and traditional ecological management practices create better results with community involvement. Increasing regulatory capacity, improving climate education, increasing investment into ecosystem restoration, and encouraging collaboration in scientific research will help build resilience against climate-related events. More research needs to focus on supporting enhanced prediction of tipping points for ecosystems, understanding the interactions of multiple climate-related stressors, quantifying risk cascades across complex systems of interacting ecosystems, and creating accurate, multi-indicator early warning systems. In particular, improvements in ecological theory and earth system science, remote sensing, and artificial intelligence technologies as well as linking socio-economic data with science will greatly improve the ability to predict sudden changes in ecosystems and assist in evidence-based decision-making.

7. Conclusion

Climate-driven tipping points of this nature will be among the most difficult 21st-century scientific and policy issues because Climate-induced ecological tipping points signify irreversible changes that can fundamentally alter the structure, function, and delivery of essential services provided by ecosystems. Climate events such as extreme weather events; the decline of biodiversity; the degradation of habitats; and anthropogenic (human-caused) pressures on ecosystems are reducing their ability to withstand disturbances, and as a result, many of the Earth's most important tipping elements are nearing irreversible thresholds. When thresholds are crossed, the likelihood of recovery becomes uncertain, and the potentially lasting environmental, economic, and social impacts may take centuries to resolve. The present paper reviews what we currently know about ecological regime shifts (i.e., regime changes) that are brought about through the combination of positive feedback loops, loss of biodiversity, and changes to large-scale biogeochemical cycles. In addition to this, it is equally important to recognise that ecosystems often have measurable early-warning signals prior to any abrupt shift occurs (i.e., critical slowing down; increased variances; spatial patterns; flickering). The advancement of Earth observation technology, ecological monitoring programmes, artificial intelligence, and mathematical modelling methods has created exceptional potential for detecting early-to-moderate warning signals of tipping points in ecosystems, thereby enhancing the predictability of ecosystem failures before irreversible damage has occurred. Climate-driven tipping points of this nature will be among the most difficult 21st-century scientific and policy issues because Climate-induced ecological tipping points signify irreversible changes that can fundamentally alter the structure, function, and delivery of essential services provided by ecosystems. Climate events such as extreme weather events; the decline of biodiversity; the degradation of habitats; and anthropogenic (human-caused) pressures on ecosystems are reducing their ability to withstand disturbances, and as a result, many of the Earth's most important tipping elements are nearing irreversible thresholds. When thresholds are crossed, the likelihood of recovery becomes uncertain, and the potentially lasting environmental, economic, and social impacts may take centuries to resolve. The present paper reviews what we currently know about ecological regime shifts (i.e., regime changes) that are brought about through the combination of positive feedback loops, loss of biodiversity, and changes to large-scale biogeochemical cycles. In addition to this, it is equally important to recognise that ecosystems often have measurable early-warning signals prior to any abrupt shift occurs (i.e.,

critical slowing down; increased variances; spatial patterns; flickering). The advancement of Earth observation technology, ecological monitoring programmes, artificial intelligence, and mathematical modelling methods has created exceptional potential for detecting early-to-moderate warning signals of tipping points in ecosystems, thereby enhancing the predictability of ecosystem failures before irreversible damage has occurred.

References

[1] IPCC, *Climate Change 2023: Synthesis Report*. Geneva, Switzerland: Intergovernmental Panel on Climate Change, 2023.

[2] IPCC, *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Cambridge, UK: Cambridge University Press, 2022.

[3] T. M. Lenton, H. Held, E. Kriegler, et al., "Tipping elements in the Earth's climate system," *Proceedings of the National Academy of Sciences*, vol. 105, no. 6, pp. 1786–1793, 2008.

[4] M. Scheffer, S. Carpenter, J. A. Foley, et al., "Catastrophic shifts in ecosystems," *Nature*, vol. 413, pp. 591–596, 2001.

[5] M. Scheffer, *Critical Transitions in Nature and Society*. Princeton, NJ: Princeton University Press, 2009.

[6] J. E. Overland and M. Wang, "When will the summer Arctic be nearly sea ice free?" *Geophysical Research Letters*, vol. 40, pp. 2097–2101, 2013.

[7] C. A. Nobre and T. Lovejoy, "Amazon tipping point: Last chance for action," *Science Advances*, vol. 4, no. 2, eaat2340, 2018.

[8] T. P. Hughes, J. T. Kerry, M. Álvarez-Noriega, et al., "Global warming and recurrent mass bleaching of corals," *Nature*, vol. 543, pp. 373–377, 2017.

[9] J. Rockström, W. Steffen, K. Noone, et al., "A safe operating space for humanity," *Nature*, vol. 461, pp. 472–475, 2009.

[10] B. Cardinale, J. E. Duffy, A. Gonzalez, et al., "Biodiversity loss and its impact on humanity," *Nature*, vol. 486, pp. 59–67, 2012.

[11] IPBES, *Global Assessment Report on Biodiversity and Ecosystem Services*. Bonn, Germany, 2019.

[12] M. Dakos, E. H. van Nes, P. D'Odorico, and M. Scheffer, "Slowing down as an early warning signal for abrupt climate change," *Proceedings of the National Academy of Sciences*, vol. 105, pp. 14308–14312, 2008.

[13] M. Scheffer, J. Bascompte, W. A. Brock, et al., "Early-warning signals for critical transitions," *Nature*, vol. 461, pp. 53–59, 2009.

[14] V. Dakos, S. Carpenter, E. van Nes, and M. Scheffer, "Resilience indicators: Prospects and limitations," *Nature Climate Change*, vol. 5, pp. 289–296, 2015.

[15] D. G. Goodenough, S. Franklin, and M. Wulder, "Remote sensing for ecosystem monitoring," *Remote Sensing of Environment*, vol. 231, 2019.

[16] N. Stern, *The Economics of Climate Change: The Stern Review*. Cambridge University Press, 2007.

[17] C. S. Holling, "Resilience and stability of ecological systems," *Annual Review of Ecology and Systematics*, vol. 4, pp. 1–23, 1973.

[18] B. Smit and J. Wandel, "Adaptation, adaptive capacity and vulnerability," *Global Environmental Change*, vol. 16, pp. 282–292, 2006.

[19] K. O'Brien, "Global environmental change II: From adaptation to deliberate transformation," *Progress in Human Geography*, vol. 36, no. 5, pp. 667–676, 2012.

[20] C. Folke, T. Hahn, P. Olsson, and J. Norberg, "Adaptive governance of social-ecological systems," *Annual Review of Environment and Resources*, vol. 30, pp. 441–473, 2005.

[21] S. Carpenter, B. Walker, J. M. Anderies, and N. Abel, "From metaphor to measurement: Resilience of what to what?" *Ecosystems*, vol. 4, pp. 765–781, 2001.

[22] B. Walker and D. Salt, *Resilience Thinking*. Washington, DC: Island Press, 2006.

[23] W. Steffen, K. Richardson, J. Rockström, et al., "Planetary boundaries," *Science*, vol. 347, 2015.

[24] F. Berkes, J. Colding, and C. Folke, *Navigating Social-Ecological Systems*. Cambridge University Press, 2003.

[25] T. M. Lenton, "Climate tipping points," *Annual Review of Environment and Resources*, vol. 38, pp. 1–29, 2013.

[26] J. Hansen, M. Sato, P. Hearty, et al., "Ice melt, sea level rise and superstorms," *Atmospheric Chemistry and Physics*, vol. 16, pp. 3761–3812, 2016.

[27] T. Lovejoy and C. A. Nobre, "Amazon tipping point," *Science Advances*, vol. 5, eaaw2079, 2019.

[28] O. Hoegh-Guldberg, "Climate change and coral reefs," *Marine and Freshwater Research*, vol. 50, pp. 839–866, 1999.

[29] E. A. G. Schuur, A. D. McGuire, C. Schädel, et al., "Climate change and the permafrost carbon feedback," *Nature*, vol. 520, pp. 171–179, 2015.

[30] H. Joosten and D. Clarke, *Wise Use of Mires and Peatlands*. International Mire Conservation Group, 2002.

[31] Stockholm Resilience Centre, *Planetary Boundaries Framework*, Stockholm University, 2023.

[32] M. Scheffer and S. Carpenter, "Anticipating critical transitions," *Science*, vol. 338, pp. 344–348, 2012.

[33] J. Stroeve and D. Notz, "Changing state of Arctic sea ice," *Annual Review of Marine Science*, vol. 10, pp. 541–570, 2018.

[34] D. C. Zemp, C. F. Schleussner, H. M. J. Barbosa, et al., "Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks," *Nature Communications*, vol. 8, 2017.

[35] D. Tilman, F. Isbell, and J. M. Cowles, "Biodiversity and ecosystem functioning," *Annual Review of Ecology, Evolution, and Systematics*, vol. 45, pp. 471–493, 2014.