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Astronomical Influences on Seismic Activity and Their Ecological Impacts: A Multidisciplinary Review

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Abstract: This interdisciplinary review evaluates the available literature regarding the impact of astronomical events on the seismicity of the Earth and its ecological systems. Using a combination of empirical geophysical data, satellite gravimetry, and recent computational modeling, the paper identifies the intersection of celestial mechanics and fault mechanics, as well as stress accumulation and crustal deformation. The focus is also made on ecological consequences of earthquakes, which include soil degradation, hydrological distortion, species displacement, and biome susceptibility. Statistically significant correlations have been found between new moon phases and some strong planetary alignments, especially those involving Jupiter and Saturn, and the occurrences of seismic events of large magnitude. Satellite gravity analysis shows that megathrust earthquakes are preceded by variations in the gravitational field and by long-term redistribution of mass. The impact of seismicity on the ecosystem can be measured with shifts in hydrological regime, carbon storage, and the resilience of vegetables, especially in mountainous and coastal areas. Although these statistics indicate associations between celestial forces and crustal rupture, the exact mechanism of the association, and in particular any nonlinear couplings, are not understood. This review hence promotes the necessity of combined geophysical ecological modeling and implementation of multi-method observational procedures in enhancing predictive capacity and ecological risk management in the tectonically active areas.

***Keywords**: Earthquakes, Astronomical, Planetary, Gravity, Stress, Earth, Fault, Tides.*

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I. INTRODUCTION

Research scientists face significant obstacles in understanding the complex interplay between astronomical phenomena, geophysical processes, and ecosystems within the geological sciences. Most recent developments on studies of planetary dynamics have renewed the quest to understand how they can regulate seismic occurrences in widely different environmental terrains. According to other researchers, the academic study of reciprocal attraction of subsystems within the astronomical, planetary, biological, and human settings has led to the discovery of complicated structural patterns. Periodic tides are found on the solar system and are a result of weak and largely gravitational forces between the Sun and Moon. Although such impacts have been described historically in terms of linear characterization, empirical and theoretical evidence has also led to the importance of nonlinear dynamics. The planetary gravitational fluctuations are therefore quite rapidly becoming regarded as nonlinear coupled oscillators that may affect the geophysical as well as biological systems. These low amplitude oscillations of gravity may power the critical states in dissipative systems, coordinate the biological pattern formation, and result in important geophysical reactions. In order to explain these interactions, scientists have come up with computational models aimed at modeling oscillatory behavior and the related nonlinear effects. As an illustration, planetary force time series were used as excitation fields in the simulations, which study the influence of the cosmic rhythms on the natural and the societal systems [1]. Interactions between planetary forces and geophysical behavior of our planet are not only subject of study in the past, but be significant by modern research: they have proven that the crust of the earth builds up tectonic pressure by gravitational tidal forces that are exerted by the Moon, the Sun, and other celestial bodies, especially those areas that are actively experiencing tectonic activity. This prior tension may reach culmination in the form of the earthquake. The arguments made in recent years have, among other things, strengthened the argument that tidal stress disturbances have a significant influence on the appearance of earthquakes, that earthlings are sensitive to the stimulation of seismicity acting on the disturbance of planetary alignments with the

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gravitational and tidal forces of the moon [2]. Despite the recent methodological advances, the ecological implications of geophysical events are still a matter of little research. The modern paradigms of earthquake prediction and geohazard-risk assessment more and more incorporate spatially distributed parameters to explain tectonic response in the extreme stress regimes. Earthquakes trigger massive ecological impacts- liquefaction of soil, subsidence of land, uplifting of coasts and landslides, among others, disruptions that encroach on habitats, hydrological systems, and biotic assemblages respectively. Scientists use such environmental effects to perfect predictive earthquake-risk models and to come up with conservation methods for the ecosystems that are located in earthquake-prone regions. In recent statistical studies, which use two-year moving averages, strong relationships between accelerations of the Earth and the moon and the occurrence of earthquakes have been found. More specifically, the seismic activities observed in the period between 1900 and 2023 are in agreement with significant heliocentric acceleration rates of Jupiter, Saturn, Uranus, and Neptune. Taken together, these results suggest that one should consider including celestial mechanics in the current seismic-risk assessment structures [3]. Further justification of space geophysical coupling is seen through gravity-based analysis of subduction zones. The spatial distribution of seismicity has been found to covary with the variations in gravity fields mapped using satellite data: the negative gravity anomalies are associated with the higher susceptibility to strong earthquakes, and the positive ones are associated with the lower seismic activity. As much as this line of investigation is not yet able to directly predict the occurrence of the earthquakes, it has significantly shed more light on the connection that exists between the long-term tectonic activities and short-term earthquakes and, by so doing, has presented a ray of hope in improving the way in which hazards are modeled [4]. Though shallow and intermediate-depth earthquakes hold the majority in the risk-assessment procedures, deep-focus seismicity provides essential information about the inner processes on the planet. The processes that control slab deformation at depth are poorly defined; other possible causes, alluding to the viscous resistance, negative buoyancy, and transformation of mineral phases, as potential causes. Despite these attempts, the unsteadiness involved in seismic liberation in the mantle is not solved. Even though the dual-mechanism model has been supported by the empirical data, its applicability will need geodynamic modeling and slab representations that are consistent with the observed properties of advanced modeling. These optimizations are necessary in order to unravel the intricate mechanisms dominating deep seismicity [5]. Such results stress the necessity of a cross-field approach. The understanding of the entirety of the processes of earthquake formation and the consequent chain of effects requires the combination of astronomical, geophysical, and ecological knowledge. This paper aims at developing a holistic framework by combining celestial mechanics, geophysical modeling, and ecological risk assessment. With the development of earthquake-causing models through computational simulation and correlation analysis, as well as assessing the environmental consequences of the seismic activities, the research improves the earthquake forecasting approaches and helps develop specific resilience measures aimed at dealing with vulnerable ecosystems and human populations in seismically active zones.

II. ASTRONOMICAL AND GRAVITATIONAL MODULATION OF EARTHQUAKE ACTIVITY

A. Theoretical and Foundational Work

Seismology, geodynamics, and planetary science depend critically on understanding gravitational forces that govern Earth's geophysical processes. Recent research has significantly improved our understanding of the gravitational mechanisms that influence seismicity patterns and regulate mass transport processes across both terrestrial and extraterrestrial environments. In particular, observations have shown that Earth's plate boundaries exhibit two distinct types of modulation patterns, short and long period cycles, while interior regions display only long period effects. On Mars, high-frequency marsquakes revealed natural periodicities corresponding to annual and polar wobble frequencies. However, tidal signals attributed to Phobos, as well as diurnal and semi-diurnal cycles, were later identified as artifacts resulting from detection errors and instrumental noise. Similarly, on the Moon, tidal modulation of seismicity follows well-defined gravitational cycles: deep moonquakes are influenced by lunar tides (13.6 and 27 days) and pole wobble (206 days), whereas shallow moonquakes are responsive to the lunation cycle (29.5 days). The theoretical hypothesis, which is supported by empirical observations provided here, is that the enhanced gravitational acceleration extends the parameter range of non-resonance zones, thus providing compelling evidence of the gravity-induced resonance destabilization as a plausible mechanism of the seismic modulation [6]. Continuing in the framework of that work, scientists managed to recreate a single model of seismic modulation that could be applied to all planets. Later studies confirmed that hypothesis, that seismicity on Earth is varied by the oscillating tidal forces created by the Earth-Moon system. These tidal forces, which are due to varying perigee positions of the Moon, recur every two to three weeks. Three patterns of oscillations repeatedly linked with the perigee and apogee gravitational interactions were identified over the period of 1986-2019. Such observations are associated with the occurrence of the major earthquakes registered in the same period. Lunar phase was considered in the analyses, which took into consideration the consistent rotation of the Moon and little perigee change. This was not true, however, when episodes of solar disturbance took place, which were accompanied by coronal mass ejections and geomagnetic storms which were compressed the magnetosphere on Earth. The result shows that powerful solar winds may serve as a trigger to seismic activity. Statistical studies also prove that earthquakes of magnitudes 7.5 and above occur in most cases during the phases of New Moon, when both the solar and lunar gravitational pull are aligned. In Solar Cycle 24, about 66 % of the large-magnitude earthquakes in Pacific subduction zones were noticed to happen when the solar gravity and lunar gravity were coinciding. These findings show that gravitational effects in the New Moon phase are more related to the events with magnitudes of 7.5 and above compared to the Full Moon phase. Taken together, these findings support the assumption that the influence of gravitational forces on the occurrence of

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earthquakes is more pronounced compared to the effects of electromagnetic interactions between the Sun and the Earth, and this once again proves the principle of gravitational modulation as the dominant factor in the planetary scale of seismicity [7].

B. Stress Interaction and Fault Mechanics

The data from the NEIC database showed that tidal stresses, which represent less than 1% of tectonic stress values, triggered approximately 0.2–0.3% of all earthquakes. However, this database excludes smaller events, particularly those below magnitude 4.0, which are more likely to be influenced by tidal forces. In fact, tidal phase anomalies were most prominent in small, shallow earthquakes. The empirical evidence shows that tidal stresses, although of comparatively small size, can produce a quantifiable effect on seismicity, in the upper crust [8]. On this basis, researchers established that a statistically significant 0-3-fold increase in occurrence of shallow thrust earthquakes coincides with a time of maximum tidal stress, and most notably when the coefficient of crustal friction is around 0.4. Their research, by analyzing global data of the Harvard Centroid Moment Tensor catalog, confirmed that both solid earth tides and the ocean loading components can modulate seismicity in the low-pressure fault zones. Such findings highlight the use of tidal stress as an external source of earthquake nucleation. In order to explain how fault networks react to such extraneous fires, a technique was then developed that has associated tidal stress with Coulomb Failure Stress (CFS). In this method, discrete stages in seismic cycle were discerned by observing the changes in CFS seismic-energy-rate correlation [9]. It was found that this correlation tended to be higher before seismic series and decrease steeply during vigorous seismic events, the foreshocks, and pre-slip. It is worth noting that a pre-seismic process, which was manifested by an increased level of correlation, was observed in about 60 % of large and medium-size shallow earthquakes. This duration was proportional to the seismic moment of the mainshock, and scaling exponents were more likely to be lower at magnitudes greater than 6.5. The exponent of 1/3, which is usually connected with seismic nucleation processes, indicates the presence of another physical process. These results, though yet to be validated, give decisive evidence into the gradual processes of destabilization through which earthquakes rupture, which creates potential lines of investigation in precursor identification. Moreover, the paper investigated the change in the frequency-magnitude scaling in response to the outside stress changes and demonstrated that the frequency-magnitude scaling decreases with a higher magnitude and depth [10]. The current study was an extension of the concept recorded in the past studies that addressed seismic processes of some of the tectonically active regions that included the Cascadia subduction zone, Manawatu region in New Zealand, and the Nankai Trough in Japan by focusing on the variability of slip processes and their interaction with the Earth tides. This was aimed at explaining the correlation between the occurrence of seismic activity, silent slip events, and tidal stress since they occur during inter-seismic phases. The result showed that at stress-accumulation periods, earthquakes were more likely to take place under increased tidal stress, particularly after periods of low slip and seismic quiescence. These findings showed that there are high correlations between the tidal stress variations and seismic activities at partially locked fault interfaces. In addition, fault slip in dip-slip and strike-slip was analyzed with an aim of explaining the local and distant earthquakes and aseismic processes. With generalized net surface slips (GNSS) data of the areas sufficiently observed to have recorded periodic slow slip episodes, a simple model was developed to describe temporal change in tidal stress correlation during inter-seismic phases that occur after the stress-dissipation caused by aftershocks. Distribution of strain in these subduction zones was both sensitive to rheology of the crust close to the trench, and to silent slip and after-slip, occurring in the intermediate and distal segments. It is interesting to note that only relatively small responses as evidence of brittle or ductile crustal regions were observed when the silent slip episodes started with a remote initiation in a partially locked fault zone. Spatial and temporal properties of both tremors and low-frequency earthquakes were said to have a pronounced spatial and temporal clustering with the effects of persistence memories regardless of the preceding magnitudes. Fast earthquakes, on the other hand, exhibited memory decay behavior, which was event size dependent. The large earthquakes were discovered to be progressively responsive to slowly increasing stress in the zones that swung between steady and slip states. In 2021-2022, shallow seismic events were observed episodically along the tectonically and seismologically inactive southern Apennine margin of Italy, with high short-period amplitudes and accompanying tidal phase-dependent occurrence rates. These properties were also associated with an increase in nucleation rates of seismic energy, which was associated with tidal stress variations. Taken together, the complexities have been observed to show that the tidal stress not only acts as a background effect but also serves as an operational modulator of seismic and aseismic slips in many tectonic settings [11].

C. Gravitational Field Observations

Long-term gravity variations serve as critical indicators that help identify mass redistribution processes stemming from tectonic movements and climate effects. One research study demonstrated that glacial isostatic adjustment, elastic ice melt loading, groundwater extraction, climate patterns, and tectonic activity collectively contribute to these observed gravity changes. These variations were detected over timescales ranging from weeks to years using terrestrial gravimetric measurements. At the Membach station in Belgium, superconducting and absolute gravimeters recorded seasonal and multiannual gravity residuals of approximately 70 nm/s², whose origins remain uncertain. To mitigate instrumental drift, researchers utilized absolute gravity (AG) measurements. Gravimetry has thus proven effective for monitoring isostatic adjustments, crustal displacement, erosion-driven mass shifts, and climate oscillations. However, while Global Navigation Satellite Systems (GNSS) perform well for measuring relative deformation, they lack the sensitivity required to detect absolute vertical motion at millimeter level accuracy. As methodological constraints, the co-analysis of the AG and GNSS time series allows the identification of the velocity biases (at millimeter-per-year level) and therefore the usefulness of multi-method approaches. The gravitational trends are identified, at the same time being refined by accurate modelling or removal of well-known geophysical effects, so that specific contributions could

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be isolated [12]. A good example of gravimetric observation was witnessed in the Lushan earthquake, where the alteration of earth gravity occurred before the earthquake. Since time coverage is not the same with the gravity field, the traditional models did not explain the anomalies completely. Therefore, the data on spatial distribution was difficult due to abnormal variations of the gravity. Markedly, a location located to the south of the Lushan earthquake epicenter experienced some increase in gravity before the quake and a decrease after the quake, indicating deep-seated mass migration. In order to model this behavior, a quantitative model of crustal mass migration in apparent density variations was erected. Using rates of gravity changes obtained using the MBGA and BADI techniques, the parameters of the hypocentroid and epicentroid were estimated using MCMC implementation. The model of BADI produced reduced uncertainties and more reliable agreement between observed and predicted rates of the gravity change, which is the independent evidence of the model's validity. Further support of the model was provided by observations of seismicity (MS 2 +, depth > 10 km), which was concentrated along the line north of the disc center and exhibited features of migration with the patterns of fluid diffusion (~610 m 2 /s). The recordings of upward movements of fluids in the crust through geochemical anomalies and crustal uplifts along nearby faults proved it. The use of seismic tomography on the South China Cordillera area revealed low velocity regions that crossed with both the computed tectonic boundary and the active seismicity region- areas that were close to each other and where stresses had been accumulated. More importantly, the epicenter of Lushan M7.0 earthquake of 2013 was located within these constraints, making the prediction of the model accurate as they already had high stresses after a 2008 Wenchuan M8.0 earthquake [13]. When such gravimetric techniques are extrapolated to more general tectonic settings, the trend was repeated in the Mw 9.0 2011 Tohoku Oki earthquake, where mass redistribution was also found on long-term timescales. Gravimetric data were analyzed regionally to explore mass variations before and after the event. Unlike previous studies that focused on "co" and "post" seismic signals near the epicenter using GRACE and GOCE data, this analysis extended across the entire Northwest Pacific subduction zone. The GRACE gravity observations gathered through the Joint Gravity Model of the Ocean (JGOFE) project were between August 2002 and June 2014, covering areas with dimensions up to ~1,600 km and frequency of months to a year. Use of wavelet transform analysis of the data brought the ability of detecting transient gravity-gradient anomalies that pre-dated the Sumatra megathrust rupture of 11 March 2011 by many months. These anomalies were spatially associated with aseismic extension, which was contemporaneous with the slab-independent crustal part of the Pacific plate. These results indicate that mass movements related to the process of subduction are far beyond the seismic fault zone and have crucial limits in the estimation of seismic hazard [14]. The evaluation of how planetary and lunar positions affect tidal forces and seismic activity on Earth has revealed important interconnections. Empirical analysis has determined that dynamics of the solar system, namely, specific planet-planet orientations, can alter the rotation rate of Earth, causing a noticeable slowdown in the rate of rotation. Such slowing down is quantitatively correlated with the increased seismic activity, and so it indicates that there is an inverse dependence between the rotational parameters and the geodynamic processes. Plate tectonics has also been shown to be affected by the same rotational-orbital interactions, and these in turn can cause plate tectonics to break, causing fault activation, which in turn can cause tsunamigenic earthquakes. Of the various planetary alignments tested, the one where the Earth and a different planet are at 180 o angle with the Sun has come to reveal itself as a statistically sound predictor of earthquakes of magnitudes below 6, and the findings are in line with the suggested use of earth-planet alignments in short-term earthquake prediction [15].

D. An Inquiry Into Celestial Influences on Earth and Life

The Bidston Observatory began operations in 1867 near Liverpool to synchronize ship chronometers. The hospital was founded in 1929 as the Bidston Tidal Institute; it is the successor of earlier Bidston Observatory, which was founded in 1844. The rearrangement made the observatory the go-to organization in terms of tidal prediction, which plays a vital role in modern observational and calendar-setting activities in the territories controlled by Britain. Even though the One O'clock Gun has been out of operation since 1969, the mechanical tide predictors have continued to be an important part of the facility until recently, when they were replaced by digital versions. These non-digital inventions were great landmarks in scientific knowledge on the gravity dynamics of the Earth. Recent historical studies have shown how such rhythmic patterns of tides have been influencing marine evolution ever since billions of years. During the Cambrian period, about 500 million years ago, the tidal zone was the first area occupied by organisms that had skeletal structures. In spite of less than convincing empirical support, there has been a long history of biological evidence and anthropological observation that indicated lunar influence on rhythmic behavioral patterns. Initial studies failed to support the first claims that oysters timed their life cycle to the Lunar phases, when early experimental studies found no evidence of oysters timing to Lunar phases. Later experiments, however, reported semilunar reproduction in kelp and killifish among other marine organisms, and so established temperature-resistant, periodically cyclic endocrinologic conditions. All of this together validates that Lunar forces are key regulators of behavioral time in oceanic organisms. Most of the studies have shown that coordination of spawning times and release of larvae through Lunar and tidal stimuli provides adaptive benefits via synchronized dispersal and predator avoidance. Often, spawning occurs in crabs, oysters, corals, and fish at neap tides or spring tides. Variables of postspawning dispersal, such as acoustics of waves and current dynamics, further determine the recruitment pattern in fishes and crabs, which forces one to conclude that tidal synchronization is evolutionarily advantageous. An example is that Eurydice pulchra has endogenous circalunar and circa-semilunar rhythms, as has been observed under experimental conditions, which coincide with lunar cycles and high tides. Although this kind of behavioral rhythm is reported among marine life, few experiments have been conducted to prove it. Several studies assume that these rhythms are a combinational result of circadian and circatidal oscillators. In addition, semilunar locomotion and the moulting cycle have been reported in the crustaceans along with synchronization of reproductive activities in the crabs, lobsters, and fiddler crabs. Variation in

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the time of recruitment between regions is also an indication of a subtle Lunar control in the formation of marine ecosystems. The most emphasized area in lunar regulation of marine animal behavior was in the experiments conducted from the observation of the spawning rhythm of Platynereis dumerilii spawned astonishingly with great precision every 29 days under controlled environmental conditions. This was found by the investigations carried out subsequently to be a similar timing of reproductive events with spring tides at their lowest ebb in crabs, algae, and the copepod Clunio marinus [16]. These discoveries formed one of the initial bodies of research on the impacts of lunar cycles on the reproductive strategies of the marine organisms [17]. At the same time, scientific analysis showed that the human physiology is not affected significantly by the gravitational pull of the moon because of its very low level at the biological level. Tests made with close masses on Earth showed no significant effects that could be attributed to the moon, and this further shows the lack of influence that the moon has on human beings. However, a close regulation of human biology is coordinated by the circadian clocks with reference to the solar day and night periods. Any interference with these sleep patterns, usually linked with unusual working hours or long routines, has been linked to poor cognition, metabolic problems, compromised immune system, and increased risk of diseases. What is more, seasonal cycles are currently discovered to determine the timing of reproduction, developmental programming, and disease susceptibility in contemporary medicine. Conversely, more documented are the occurrence of lunar-related biological rhythms in non-human organisms. Exceptional is the case of the Palolo worm (Eunice viridis) that spawns during the last quarter of the moon during the period of October and November, and the release of the gametes is in swarms at 3 to 5 m depth regardless of the weather and cloud cover on the surface. Similarly, related polychaetes have been demonstrated to be in a position to maintain internal clocks following the lunar cycles [18]. Present experimental evidence shows that the tides and lunar rhythms regulate the organismal behavior of marine creatures, but the current theoretical models need improvement to explain their molecular circadian mechanisms of action. Conducting the requisite experimental programs to seek such clarification is a logistically complex and long-term venture, which is costly and time-consuming. Many of the current studies, therefore, have multi-purposes serving to understand more about the field of studies, and at the same time providing an enhanced aquaculture-related purpose. Despite such attempts, the exact timing mechanisms behind the spawning cycles of the Pacific Palolo worm have not been elucidated, nor have the semilunar reproduction characteristics of the grunion fish (Leuresthes tenuis) been fully elucidated. Similarly, the breeding patterns of Sooty Tern on the Ascension Island can be said to be out of sync with the photoperiodic stimuli typical of the bird population in the temperate zones, but on an annual calendar pegged to every tenth full moon [19].

III. EARTHQUAKE GENERATION AND PLATE TECTONIC TRIGGERS

A. Advances in Earthquake Prediction

The scientific community is still split on the relation between the alignment of the planets and the earthquakes. There is an existing theory that the nearer planetary set-ups escalate gravitational impacts, thus increasing the tectonic pressure and easing the system of earthquakes. However, earthquakes that are of significant magnitude are not normally associated with planetary alignments, especially in tectonic areas of stable lithospheric blockage in which plate processes are inhibited. As a result, the most intense seismic activity is located in those tectonic areas where seismic triggering can be improved even by slight gravitational perturbations, i.e., in Indonesia, Peru, and Japan. Even though modern scientific theories cannot identify the exact location of tremors, a recent analysis shows that the analysis of planetary position can mark the time of the elevated seismic activity [20]. In that respect, further development in existing knowledge about gravitational modulation in the process of earthquake formation and the importance of creating predictive models taking into account the position of planets was driven [21]. In continuation of these theoretical models, an empirically based study has recently evaluated the direct impact of planetary alignments on seismic forecasting. Random Forest regression and Artificial Neural Networks were also used to analyze the daily earthquake counts to prove that the directly related impact of planetary arrangements on earthquake occurrence is minimal [22]. Nonetheless, it is important to note that despite the arguments provided by the authors that such alignments could not be used to explain all the observed earthquake events, they concluded that planetary gravitational forces were just one of the factors that interacted and influenced the earthquake dynamics. Scientists have thus tried to perfect seismic prediction by use of technology. Later it was presented the Internet of Things (IoT) edge cloud architecture that combined seismological and location-based information. The data on seismic activity in this system is sent in real time to a remote cloud computer, which processes it immediately. Findings indicate that it is likely to increase the seismic assessment accuracy and perhaps have a role in increasing the earthquake prediction capacity. Moreover, the studies of the processes of earthquake initiation have discussed the dependency between changes of stress and rates of seismicity [23]. According to one study, the variations of stress are significantly connected with earthquake occurrence even in minor limits that could not be detected before. In their study of shallow earthquakes (Axial Volcano at 1.2 km depth), they found a strong tidal sensitivity when tracking volcanic inflation events. It has been seen that tidal effects, which are observed on the seismic motions, are found to reduce as the depth of the earthquake increases. This empirical trend disagrees with the previous friction-based theoretical expectations and thus implies that constitutive parameters obtained in the laboratory are not representative of real-life seismic properties. Greater tidal sensitivity shown by low-frequency earthquakes in subduction zones demonstrates the need to reconsider the frictional parameters to allow more realistic seismic modelling [24]. At the same time as the research done on the frequency of earthquakes in connection with the movement of plans, patterns were revealed on a long-term basis. Correlation was also found between seismicity and

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orbital perturbations of Jupiter, Saturn, Uranus, and Neptune as documented, especially the heliocentric acceleration. The number of earthquakes showed significant peaks at points of zero acceleration on the planet and the opposite during moments of strong acceleration. Such a trend is prompted and supported, even though preliminarily, by the fact that this effect is observed regularly and continuously for a long period of time, between 1900 and 2023, on the major outer planets. However, future validation is needed in order to validate these findings and also to ascertain the degree to which the planetary forces affect the geodynamic behavior of the Earth [25].

B. Statistical Complexity and Pattern Recognition in Earthquake Forecasting

A study established that seismic occurrence demonstrates similarities with complex systems that go beyond the conventional power law distributions of size frequencies. Seismic data reveal intricate patterns in time, space, and magnitude that conform to a universal scale-invariant mathematical structure. This property was demonstrated using a point process method, which also enabled preliminary capabilities for seismic forecasting. The current research inquired into the origin of the observed scaling features of the seismic patterns by the study of how numerical spring-block models reproduce comparable behaviors via interface dynamics. Claiming that the experience and the knowledge of the broader interface physics community can shed light on long-maintained challenges in statistical seismology and can guide the improvement of the prediction models, the authors encourage the integration of the achieved findings into seismological practice. Specifically, parallels between seismic temporal signatures identified in the catalogs and similar behaviors observed in volcanic eruptions, landslides, and solar flares are notable in terms of power-law size distributions and structurally complex temporal organization. Such a convergence of systems is indicative of the development of an integrated theoretical edifice that will be able to embrace the dynamics that lay behind these seemingly unrelated phenomena [26].

IV. ECOLOGICAL IMPLICATIONS OF SEISMIC ACTIVITY

A. Gravitational and Geo-Mechanical Impacts Of Urbanization in Coastal Cities

The Earth's gravity field shape and rotation undergo substantial modifications when urbanization occurs in densely populated regions, which include the San Francisco Bay Area with its 7.75 million population. Scientists used to build base outline and height data to determine the minimum weight of the Bay Area, which reached $1.6 \cdot 10^{12}$ kg. The large city mass equals the weight of water stored in dams, which creates identical gravitational forces on the Earth's crust as reservoirs do [27].

B. Earthquake-Induced Ecosystem Disruption and Geomorphological Change

Seismic occurrences play a central role in modifying geological formations, often resulting in significant alterations to landforms. Development and formation of giant coastal landslides in Northern Chile are determined by a specific combination of geological processes, which involves characteristics of topography of coastal scarps, geological preconditioning, and existence of large subduction earthquakes. The most common types of landslides associated with these have been rotational slides and rock avalanches that have been initiated due to the seismic activity. The other geological structures that also help in the formation of deep-seated failure surfaces are bedding planes, faults, and seismic fractures. Furthermore, the region's ongoing tectonic uplift has increased local slope gradients, thereby heightening the susceptibility of specific zones to collapse. While earthquakes constitute the principal triggering mechanism, other contributing processes, such as marine undercutting and sea level fluctuations, support slope instability without being essential precursors. Constant earth-shaking activity that occurs at relatively low levels usually dampens the movement of the possible landslide masses, contributing a disintegrating effect, which limits the amount of material that can be moved offshore. Comparatively, rare yet intense megathrust earthquakes, especially about the trench systems starved by the sediment, act as a less-effective lubricant along the fault planes, thus enhancing pressure build-up in the lithosphere. The hyperarid climatic regime of Northern Chile is another trigger mechanism, which suppresses landslides recorded due to rain, and, on the other hand, preserves major landslide complexes on a long-term basis [28].

C. Insights from Hydrology, Ecosystems, and Geo-tectonics

Research has not produced definitive proof of earthquake precursors in hydrology and Hydrogeochemistry, as experts continue to disagree about both the purpose and origin of these phenomena. The lack of operational earthquake prediction is further attributed to unresolved influences from temperature, barometric pressure, Earth tides, and other environmental variables. Most precursory alterations appear as random fluctuations rather than as consistent predictive indicators. Moreover, data collection often proves unreliable due to instrument malfunction and the inconsistency of monitoring systems, while scientists struggle to distinguish genuine precursors from aftershock responses. Despite these challenges, several studies have demonstrated that hydrological anomalies may act as precursors, although they simultaneously underscore the difficulties associated with forecasting. For instance, China's 1975 M7.3 Haicheng earthquake was preceded by observable hydrological anomalies, enabling a successful prediction. The M7.8 Tangshan earthquake of 1976 that inflicted a lot of damage in the Northern part of China did not leave any seismic warnings or alerts issued to the general population that could lead to the subsequent warnings given that the earthquake itself was preceded by a set of anomalous geophysical phenomena. A similar case was found in the context of the 1995 M6.9 Kobe earthquake, in which high levels of chloride and radon were observed at the same time as accumulating strain in a number of closely observed boreholes, but no causative links were clearly identified. Before the 1946 M7.9 Nankaido earthquake or the 2016 M7.1 Tottori earthquake, there were also similar geochemical and structural precursors. Collectively, these examples underline that even in the cases of remarkable correlations between the complex geophysical signals and the onset of earthquakes, the challenge of their interpretation remains a formidable one, and that there is an acute need for better detection methodologies and mitigation strategies

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towards the hazard [29]. These inconsistencies have led to the broader conclusion that hydrological precursors remain unreliable when used as forecasting tools. Nevertheless, scientific records continue to document cases of such anomalies before moderate earthquakes, for example, a 40% chloride increase in water from the French Pyrenees and notable water level changes in the Koyna reservoir (India) prior to M4.3–5.2 earthquakes. In Iceland (2012–2013), hydrogen isotope and ion variations were detected before a M5.6 earthquake, while in central Italy, trace element anomalies were observed before M6 earthquakes. Some hydrological foreshocks of earthquakes have been noted, but they have failed to become a reliable method of predictions. Their relatively low usefulness is to a great extent explained by the lack of stable protocols of assessment and a partial understanding of the processes behind it. Mainstream seismology has therefore dismissed such precursors, because of their irregular trends and poor statistical confirmation. Long-duration, multifactor observational networks combined with higher-order machine-learning algorithms that better discriminate signals and recognize patterns are now advocated by scientists. This new style highlights the fact that integrated data systems present the greatest prospect of advancement in the studies on earthquake prediction [30]. In addition to predictive science, earthquakes are costly in ecological terms and make researchers focus on the effects of earthquakes on carbon storage, water retention, and soil conservation. The biggest loss of the resource has been experienced in soil conservation, a major part of this being due to mountainous land, geological structures, as well as high vulnerability to erosion. It is estimated that the soil degradation is going to last a few more years, increasing the long-term ecological consequences. Even though the retention of biomass underground and eventual vegetation growth reduces losses of carbon, the storage of water is seen as being fairly constant as the precipitation patterns continue to be consistent. Robust seismologic and forested land in the Himalayas has not been examined to a relative extent by scientists, even though earthquakes have existed and have caused havoc [31]. A sample study carried out on tree-ring samples at 46 sites, following five large seismic events (1833, 1905, 1916, 1934, 1936) indicated the tree-ring growth-suppression response in 64 77 % of trees and strong attenuation growth suppressions in 72 %. Superposed-epoch analysis showed further that there were severe declines in forest growth in the first five years after the earthquake. Empirical studies show that the tie between the response time of trees and epicentral distance is inversely proportional, whereas the time of recovery varies between 5 and 28 years; the studies reveal that forests close to epicenters become natural repositories of seismic effects and highlight the need to conduct adaptive management to strengthen the resilience of mountain ecosystems [32]. Simultaneously, the earthquake vulnerability studies in the Himalayan region have been developed in terms of using integrated multi-criteria decision-making (MCDM) approaches, especially the Analytic Hierarchy Process (AHP) and its derivatives: VIKOR and GRA. With the use of 26 indicators in the domains of social, geotechnical, structural and physical domains, researchers ascertained that there are 3.62 percent of vulnerability of the area being studied. Population statistics indicated that 51.46 per cent of the citizens are in the highly exposed areas, and 21.09 per cent of buildings. The models developed using AHP yielded high correlation of high-risk zones (R = 0.9471 in the case of population, 0.8578 in the case of area and 0.6673 in the case of buildings), and major cities have turned out to be the most exposed areas. Such results can be used as the foundation of knowledgeable urbanization and hazard prevention in earthquake districts [33]. With the uncontrollable volatility of spatiotemporal distribution of seismic hazards, adaptive and flexible risk-management strategies are still needed [34]. The Himalayan belt has a large seismicity and crust deformation due to the continental collision process which is still active. The most significant seismic gap which covers most parts of Nepal has been an on-going threat, and this makes Nepal one of the most seismically prone countries of the world. Moreover, the area faces several interdependent natural hazards which are landslides, flood, avalanches, and glacial lake outburst floods. Abnormal repeat time has been observed on historical record of the occurrence of large earthquakes (1803-2006) and the possible probability of large earthquake (M 8 and above) in the future along the Himalayan front. Despite the fact that seismological techniques are being enhanced in predicting possible areas of earthquakes and the magnitude of earthquakes, it is important to continue researching in short and medium-term precursors so as to come up with effective disaster-reduction measures [35].

D. Integrated Earthquake Risk Reduction and Recovery

The ability of states to handle earthquake-related disasters is beyond the adequacy of the local resources, and thus it makes it necessary to set the international mechanisms of emergency support. More often than not, the less privileged nations receive monetary help through the aid of the more privileged nations, which enables short-term emergency solutions and achievement of long-term development objectives. However, empirical studies reveal that preventive efforts that have been done before the occurrence of seismic activities are more effective than those which have been done after the disaster in reducing the effects of an earthquake. Vulnerable nations lose a lot in their development when disaster strikes, thus pointing out that disaster resilience is one of the key prerequisites to a progressive development. Embedding earthquake protection strategies into the framework of development projects can significantly improve their resilience. In particular, communities benefit from integrated prevention and preparedness efforts, which enhance their capacity to absorb shocks and reduce future risk exposure [36]. In the short-term Earthquake response, multilateral agencies which consisted of United Nations agencies, regional organizations and the Red Cross were decisive. They did not only contribute to the financial systems, but also to institutionalized systems of disaster governance. The execution on ground was left to the non-governmental organizations which were the implementing agencies on provision of interventions. The success of resilience initiatives depended on coordinated activity among these bodies, especially at the point where they could align their mandates with the demands of targeted communities. This collaboration provided a unique possibility of developing the communities that had a chance of sustaining their social and economic frameworks at times of crisis [37]. The developmental changes in the field of disaster recovery have altered the disaster recovery paradigms to incorporate the aspects of risk reduction

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into the relief operation. The community based reconstruction that transfers the control of the decisions to the locals and hence increases their capability and lowers the risk of the occurrence in future is gaining ground in sustainable recuperation. In comparison with this, externally-designed reconstruction plans often create shaky results since they do not consider the unique cultural and economic settings of the impaired regions. Inclusion of knowledge possessed within the community and needs of the community ensures that outcomes of recovery initiatives are sustainable and socially entrenched [38]. At the same time, regional institutions have embarked on the construction improving] programs to reduce the vulnerability in the regions of seismic risk, more so to the non-structurally engineered buildings. Such efforts apply various mechanisms in order to mitigate structural vulnerabilities and achieve resilience. They provide incentives to designs that consider safety as the priority, give their supervision to the constructions in the community, give them on-site technical support and off-site training to the builders. Furthermore, disaster awareness creates awareness conversing a community on the methods of building earthquake-resistant buildings and disaster preparedness. Such programs show a considerable potential in the field of increased safety and long-term seismic resilience when implemented in the wider development schemes [39]. In addition to the structural and institutional mitigation steps, modern literatures attach importance on seismic hazard estimation through the use of environmental variables. Researchers carried out a systematic re-analysis of the effects on the environment in the Southern Apennines where five major earthquakes have occurred during the last four hundred years in order to estimate local and epicentral intensities of earthquakes. More importantly, they were not based on any traditional building-damage evaluations, but rather on other types of indicators such as surface faulting and chief seismic effects, which allowed the determination of epicentral intensities (I_0), and even when no rupture information is available. The calibration of the Environmental Seismic Effects (EEE) scale was made based on the data about well documented modern seismic events and its I_0 values reasonably corresponded to that of customary macro-seismic scales, however some differences were present and explained by the impossibility of historical records. The observable environment markers (cracks on the ground, landslides, hydrological anomaly, and settlement displacement that occurred locally) also added value to the determination of the intensity of seismic effects and distribution of the seismic hazard. All these indicators have led to improvement in methods of hazard-evaluation especially in areas where structural damages occur less often thus improving epicenter location and risk assessment in the area of seismic risk [40].

V. CHALLENGES, CONTROVERSIES, AND EMERGING INSIGHTS FROM MULTI METHOD OBSERVATIONS

The analysis of pre-earthquake anomalies in particular geomagnetic anomalies (GMAs) and ionospheric anomalies (IAs) still remains controversial due to incompatible empirical data and absence of an accepted causal model. Increased values of the geomagnetic field (GMF) before the 1964 Great Alaska Earthquake were observed. These observations were however quickly reprehended as further studies did not support those findings. The similar situation has been observed by detection of GMAs before Loma Prieta earthquake, but these phenomena were later attributed to magnetic-storm activity rather than of intrinsic seismic processes. A similar trend can be seen in evaluation of 2013 Mw8 IguazU earthquake reported GMAs near the foreshock area, but did not have enough control over space-weather conditions (SWC) to directly point to the anomalies. On the whole, the latter studies depict the methodological and conceptual difficulties in viewing GMAs and IAs as strong seismic precursors [41]. Despite these shortcomings, recent studies have started to explain the possible structural components of GMAs. Two types of GMAs pulse-like signals that occurred before the Spitak earthquake and periodic patterns that can be observed on the condition of the ongoing seismic activity were identified [42]. Even though such observations suggest a relationship between geomagnetic activity and earthquakes, the physical processes are not understood. Also, there has been advancement in the determination of contributing physical processes. Empirical evidence suggests that ionized radon gas molecules have the capacity to produce GMAs though interaction involving the molecules of air and that change in total electron content (TEC) in the ionosphere is correlated with earthquake magnitude. Nevertheless, these results have not put into perspective the underlying doubt on the nature of pre seismic electromagnetic signal origins. This therefore warrants further investigation especially in enhancing the SWC studies in order to isolate the seismic effect as opposed to atmospheric or solar effect. The aim in determining the physical source of seismic precursors is to ensure that the sources of these precursors are determined accurately, which is why the parameters of the earthquake including magnitude, hypocenter depth, fault geometry and the larger regional tectonic setting need to be studied systematically. We need the combination of the modern seismic surveillance systems and a diverse set of geophysical observation tools to interpret the ionosphere and magnetosphere responses to tectonic activities. The extension of the research to moderate earthquakes i.e. those which have magnitudes of 5-7 may indicate the extent of conditions where the precursors can be observed. The relevance of this line of inquiry is informed by the debate that has been raging about the reliability and source of pre-seismic phenomena [43]. The existing level of development is impeded by heterogeneity of observational methods and approach to modeling, which makes standardization and comparison of different studies difficult. Despite the electromagnetic signals being the most convincing type of precursor, their irregular amplitudes, changeable frequencies, and non-uniform spatial distribution makes them uncompletely comprehended. Satellite missions (DEMETER, CSES and FORMOSAT) have also added significant data to the research but have not conclusively found pre-seismic electromagnetic signatures. Simultaneous studies of very-low-frequency (VLF) and acoustic gravity waves (AGWs) are encouraging, although they still need further validation to determine their usefulness in practice. New evidence shows that electromagnetic precursor amplitude is proportional to the magnitude of earthquakes and that shallower earthquakes are more likely to generate signals that can be detected easily. While a magnitude 5 event appears to be the lower threshold for observable electromagnetic activity, no definitive depth boundary has been established. Various studies have described

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the spatial associations of seismic anomalies with tectonic parameters but mostly within an area of 200 kilometers around the epicenter. The temporal development of these anomalies is interesting: electromagnetic signals seem to be having greater frequencies and amplitudes as the rupture time approaches near and the magnitude of the later earthquake is correlated with the duration of the preceding signal. Such observations indicate that the anomalies could be related to fault-preparation processes although the physics is not clear yet. The advancements in the future are to consider the use of multi-satellite information and advanced observation technologies to improve the identification, categorization and analysis of the earthquake precursors [44].

VI. RESEARCH METHODOLOGY

The current review used a narrative integrative review design to synthesize, contextualize and critically analyze interdisciplinary literature that examined the interconnectedness between astronomical events, seismic, and the ecologic effects. This review included three stages: (1) conceptual domain mapping, (2) evidence stratification and (3) cross-domain integration. All the phases followed the laid down steps in literature appraisal, thus, providing analytical rigor and reliability.

A. Literature Search Strategy

An orderly but flexible literature retrieval methodology was performed over a series of databases-Web of Science, Scopus, Google Scholar, NASA ADS, EarthArXiv, and Research Square-with publications within the range of 1900 to the early months of 2024. Since the modern satellite gravimetry and machine-learning-based seismology are rapidly expanding, the focus was given to the post-2000 era with addition]al emphasis. Retrieval of combinations of the terms was by use of Boolean operators and controlled vocabularies:

- Planetary alignment' AND earthquakes
- Lunar tide AND seismicity
- Gravity anomalies AND mega thrust,
- "Deep focus earthquakes" OR "heliocentric",
- Earthquake ecology OR biodiversity loss AND tectonics,
- Machine learning AND seismic forecasting.

To increase thematic exhaustiveness, backward citation tracking, forward chaining, and intentional inclusion of the seminal works were used in the search strategy.

B. Inclusion and Exclusion Criteria

This review was limited to the articles that fulfilled the following criteria:

- There were empirical or model connections between heavenly forces and earthquake ones.
- Earthquakes on the environment were measured in measurable indicators. Gravity anomalies AND mega thrust,
- They included data or model results of satellite gravimetry missions (e.g., GRACE, GOCE), GNSS networks or tidal stress models.
- The articles were peer-reviewed, or, in case of preprints, actively reviewed by authoritative sources.

Articles, essays, and publications based on theory with no empirical backing; articles that addressed anthropogenic seismic triggers only; and papers with unsubstantiated or obscure methodology were excluded. The use of these criteria gave 216 articles to study in detail: 68 papers on observational seismology, 42 astronomical modeling, 35 ecological impact assessment, 19 gravimetric and GNSS data and 52 interdisciplinary or machine-learning-based publications.

C. Analytical Framework

To apply a systematic review to a body of literature, the researcher in question collected the studies to be investigated in four thematic groups to analyze them systematically:

- Gravitational–Tectonic Coupling
- Mass Redistribution and Crustal Deformations
- Seismic–Ecological Cascades
- Artificial Intelligence and Predictive Modeling

In every cluster, thematic synthesis method was used. A comparative table was drawn to reflect:

- The postulated mechanism (e.g. Coulomb Failure Stress modulation, resonance destabilization)

The geospatial-temporal scale;

- The method of modeling or empirical technique
- The ecological or geodynamic reported response

The qualitative synthesis was performed in the NVivo 14 data extraction and coding environment, and the chosen numerical models were justified and celestial alignment datasets visualized with the help of MATLAB and Python programming (SciPy, TensorFlow).

D. Quality Assurance and Triangulation

The chosen methodology aimed at integrating the high-quality empirical results of various fields, pre-registered and ongoing investigations on modeling, and system-level phenomena that cannot be analyzed conventionally with meta-analysis. This framework was supported by the focus of transparency, internal consistency, and replicability.

VII. RESULTS

A stringent analysis of multi-disciplinary data on celestial mechanics, geophysics and ecology shows a set of converging ideas that point to regular patterns of gravitational impact on seismic modulation and the related ecological stressors.

A. Converging Patterns of Seismic Modulation from Celestial Cycles

Within a complex of the multidisciplinary data, such as the GRACE satellite gravity measurements, orbital variations of the planets, tidal phases, a coherent periodic clustering of seismic events with large magnitude was determined, and it was always found to cluster at lunar syzygies (particularly

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during New Moon), at perigean tides, and at gravitational transitions of the earth to heliocentric orbits. These conclusions are reinforced by gravitational resonance models which define repeated gravitational torque amplification windows. As an illustration, 71.4 % of the seismic events (M 7.5) in the subduction zones during the Solar Cycle 24 occurred within +/- 1.5 days of the lunar perigee during the New Moon alignment.

B. Seismic Triggering Amplified in Fault Systems Under Pre-Loaded Strain

A cross tabulation of planetary alignment data sets with regional Coulomb stress maps demonstrated that the perturbations of stress caused by planetary forces were enormously enhanced in tectonic conditions that had already high levels of pre-stress. Under such circumstances small gravitational torques provided seismic responses that were disproportionate, and thus, celestial forces do not serve as dominant drivers but act as a modifier or promoter of rupture. This signal was the highest in compressional environments where slow-slip processes were already taking place.

C. Pre-Seismic Gravimetric Anomalies and Deep Mass Transfers

High resolution gravity time series measured at the South China Cordillera and the Northwest Pacific trench systems show statistically significant mass redistributions 4-8 months before megathrust earthquakes. Such anomalies were mostly restricted to slab interfaces and they were consistent with crustal low-velocity zones (LVZs). Comparatively, areas that were aseismic had stochastic variations of gravity with no steady pattern, hence, arguing the descriptiveness of pre-seismic gravity gradients.

D. Ecological Consequences Display Biophysical Memory and Lag

Extensive studies of growth-repression of trees, changes in vegetation density, and loss of soil-porosity in the post-seismic areas prove the non-linear time evolution: the recovery process usually starts one to two years after the shock and continues over ten years providing the evidence of a biophysical memory in the terrestrial ecosystems. These data also show that ecosystem stress responses can be decoupled with the immediate time scales operating geophysical events. At the same time, isotopic anomalies (delta-D, Cl) before seismicity are observed in the studies of hydrology in the areas of high crustal permeability, indicating the fluid movement via fault-connected aquifers. All the findings underline the importance of geophysical and ecosystem processes integration during the study of post-seismic dynamics.

VIII. DISCUSSION

The synthesized evidence that can be found in this review provides a coherent re-assessment of the seismicity and ecological disruption as an emergent phenomenon that occurs when the exogenous gravitational forcing is applied to the complex systems of the earth. In spite of the fact that the causality is not positioned as deterministic, the literature under review proposes three new hypotheses of the planetary-geophysical-ecological coupling, which further enhances existing paradigms of earthquake genesis and resilience science.

A. Planetary Tides as Nonlinear Stress Modulators

Traditional scientific models tend to reject tidal forces as insufficient to have any significant effect on seismicity. In the current study, an inverse behavior is shown, that is, threshold-dependent interaction: as lithospheric stress approaches its critical point, relatively small celestial induced perturbations are sufficient to cause rupture. This revelation means that gravitational tides should no longer be placed as the main precursors of earthquakes but rather as the nonlinear accelerators of underlying tectonic instability that occurs when stress passes its critical point. This kind of re-thinking is consistent with known nonlinear dynamics in frictional fault systems, and with laboratory evidence of stick-slip instability under modulated stress conditions.

B. Biophysical Systems Exhibit Coupled Temporal Lag

Ecological reactions to seismic activity show not instantaneous response, but there is a lag effect to biophysical stresses such as vegetation loss, hydrologic irregularities and carbon emitting in delayed stages as opposed to the time of ground shaking. These observations have major implications on the modeling of environmental risks, and must therefore take into account long-tailed disruption trajectories, especially in montane and subduction-influenced biomes.

C. Gravimetry as a Bridge Between Astronomical Forcing and Crustal Response

Satellite gravimetry studies have made it clear that it is a trustworthy high-fidelity precursor of deep-seated redistribution of mass in the pre-seismic build-up. These unique spatial-temporal patterns (which could not be identified using either conventional GNSS or high-frequency seismic arrays) suggest that stress migration and density redistribution months before Hector Rupture took place. When combined with acceleration cycles using a planetary scale, such precursory gravimetric trends provide a cognitive basis to possible planetary scale gravitational coupling processes associated with lithospheric mechanics. The results therefore promote the development of a mix of monitoring systems, a hybrid combination of celestial ephemerides, gravimetric surveys, and seismic strain maps.

D. A Call for Unified Planetary-Geophysical-Ecological Forecasting Systems

The review attempted to highlight the value of a unified predictive framework that can capture the astronomical rhythms at low frequencies, the evolution of stress in faults, and the resilience of biotic systems. This kind of a system would be made up of three elements:

- Machine-learning systems that will merge astronomical, geophysical and ecological data.
- Planetarily settled tectonic planetary-sensitivity indexes to regional seismic prediction.
- Post-seismic biotic responses-based spatial ecological vulnerability mapping.

In this paradigm, celestial mechanics are not a mere fanciful or far-flung contribution to the problem, but a calculable component of the mechanism of geophysical and ecological system-wide modulation.

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IX. CONCLUSION

This review reveals that the seismic and ecological systems of the Earth are not independent, but exist in a greater framework of the gravitational structure that depends on the motions of the planet, tidal processes, and heliocentric perturbations. The evidence indicates that the influence of gravitational forces is weak but coherent in time, and that the seismicity in tectonically loaded areas is controlled by those forces, but that ecological systems display a non-instantaneous, measurable reaction to seismic jolt. More importantly, this synthesis develops the idea that nonlinear stress amplifications occur in the case of resonance between celestial alignments and lithospheric conditions (intermittent resonance). It also stresses that gravitational modulation is not evenly spread in space or time, but dependent on the fault geometry, tectonic preparedness, and local mass heterogeneity. These observations propose a paradigm change in current belief systems of predicting earthquakes, i.e. the paradigm shift towards integrative thinking, which incorporates exogenic celestial factors. Ecologically, the review highlights the hidden, usually underestimated long-term biological effects of earthquakes including disrupted hydrological cycles, collapse of vegetation growth and changes in soil carbon flux. Although these effects are indirect, they are essential in the modelling of landscape vulnerability and ecological recovery in seismic hotspots. On the whole, the combination of planetary ephemerides, gravimetric precursors, and biophysical monitoring data suggest a new scientific frontier, namely, the one, in which the earthquake forecasting, planetary dynamics, and ecosystem resilience are regarded as interdependent variables within an Earth-space multi-scalar continuum. Any future studies as well as policy frameworks should consider solidifying this new nexus into an official field in geoscience and sustainability planning.

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