Cumulative geomagnetic disturbances modulate global photosystem stoichiometry through temperature-dependent gating

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1. Abstract

Space weather exerts profound effects on Earth's technological systems, yet its influence on the terrestrial biosphere remains largely unexplored at the global scale. While local experiments suggest magnetic sensitivity in plants (Galland and Pazur 2005; Belyavskaya 2004), observational evidence for a planetary-scale vegetative response to geomagnetic disturbances is lacking. Here, we analyze a decade of satellite-derived solar-induced chlorophyll fluorescence (SIF) data alongside geomagnetic indices to isolate non-seasonal physiological anomalies. Using temperature-stratified cumulative correlation analysis and multivariate models controlling for radiative and hydrological drivers, we identify a robust, cumulative, and thermally gated association between geomagnetic activity and vegetation fluorescence.

We report a global synchronization of photosystem stoichiometry, inferred from the SIF_{757}/SIF_{771} ratio, with recurrent geomagnetic disturbances, exhibiting maximal coherence under cold and moderate thermal conditions and weakening under optimal and heat-stress regimes. This response intensifies with increasing integration window length, indicating progressive physiological integration of repeated perturbations. Comparative analyses demonstrate that geomagnetic forcing systematically outperforms major climatic drivers in explaining fluorescence variability within biologically active regimes.

We propose a mechanism consistent with magnetic modulation of radical pair spin dynamics in iron–sulfur clusters and cryptochromes, potentially influencing reactive oxygen species generation and redox-regulatory adaptation. Our findings suggest that plants have evolutionarily co-opted geomagnetic variability as an informational signal, integrating it into existing redox-regulatory networks. Rather than a passive mechanical perturbation, the observed response reflects an evolved sensitivity that operates near physiological criticality—a hypothesis that opens new frontiers in understanding magnetosphere–biosphere coupling.

Keywords: geomagnetic activity, solar-induced chlorophyll fluorescence (SIF), plant stress physiology, temperature-dependent regulation, cumulative environmental forcing, photosynthetic redox balance, magnetosphere–biosphere coupling, space weather impacts, evolutionary co-option, biological information processing

2. Introduction

Understanding how geomagnetic activity influences terrestrial biospheric processes remains an open question at the intersection of space physics and biogeosciences. While magnetic fields are known to influence navigation in birds *via* cryptochromes (Wiltschko and Wiltschko 2019; Xu et al. 2021), plants remain largely considered "blind" to geomagnetic fields in the context of gross primary production. However, recent evidence suggests that cryptochromes in plants may have retained or co-opted similar magnetosensitivity mechanisms (Mattei and Hore 2014; Galland and Pazur 2005; Nordmann, Hochstoeger, and Keays 2022). Recent experimental studies have documented magnetic field effects on plant growth, gene expression, and stress responses (Belyavskaya 2004; Parmagnani and Maffei 2022). We therefore hypothesize that weak geomagnetic disturbances can exert detectable cumulative effects on photosynthetic regulation under specific physiological conditions, particularly under cold-induced sink limitation and associated redox imbalance.

The physical basis for such sensitivity likely involves the radical pair mechanism, where weak magnetic fields modulate the spin dynamics of short-lived radical pairs (Hore and Mouritsen 2016). In photosynthetic organisms, potential targets include not only cryptochromes but also iron–sulfur (Fe–S) clusters within the electron transport chain (Parmagnani and Maffei 2022). From an evolutionary perspective, the ubiquity of magnetosensitive elements in core metabolic machinery—Fe–S clusters, radical-pair intermediates, and cryptochromes—raises the possibility that sensitivity to geomagnetic variability is not an accident but an ancient and conserved feature of biological systems. Plants may have

evolved to perceive geomagnetic fluctuations not as noise, but as an informational layer of their environment, integrating it into existing redox-regulatory networks that govern stress responses and acclimation (Johnsen and Lohmann 2005; Meert et al. 2016).

The main methodological challenge lies in the temporal scale disparity between instantaneous magnetic events and physiological responses, which are expected to integrate repeated weak perturbations over days to weeks through regulatory and buffering processes. Magnetic disturbances occur on timescales ranging from minutes to days, whereas photosynthetic acclimation and stress responses operate through hierarchical regulatory networks spanning hours to weeks. Resolving such multi-scale interactions requires analytical approaches capable of detecting cumulative and condition-dependent effects rather than isolated transient responses.

To bridge this gap, we utilize satellite SIF data, which has established itself as a robust proxy for gross primary production and photosynthetic regulation (Guanter et al. 2014; Frankenberg et al. 2011). Remote sensing of solar-induced chlorophyll fluorescence has been comprehensively reviewed, including retrieval approaches, limitations, and physiological interpretation across spatial and temporal scales (Meroni et al. 2009; Mohammed et al. 2019). Because SIF responds sensitively to changes in the redox state and energy dissipation pathways of the photosynthetic apparatus (Samuilov et al. 1998), it provides a unique window into physiological perturbations that may not be captured by conventional vegetation indices.

Here we combine temperature-stratified cumulative correlation analysis with multivariate controls for radiative and hydrological drivers to identify distinct global patterns of SIF modulation by geomagnetic disturbances. Long-term satellite SIF products provide consistent global constraints on photosynthetic variability and have been benchmarked against ecosystem carbon exchange across diverse biomes (Mohammed et al. 2019). By applying harmonic regression, temperature stratification, and multivariate screening to a decade-long dataset, we distinguish genuine physical signals from spurious correlations driven by seasonality and environmental confounding. This framework enables a systematic assessment of whether weak geomagnetic variability can be integrated into photosynthetic regulation at ecosystem scale under specific physiological constraints.

To our knowledge, this represents the first global-scale, physiologically stratified assessment of cumulative geomagnetic effects on terrestrial photosynthesis.

3. Results

Signal Robustness and Spatiotemporal Structure

To distinguish potential biophysical coupling from instrumental noise and environmental confounding, we examined the multi-scale association between SIF anomalies and geomagnetic forcing across four geographic scenarios (Supplementary Table S1, Fig. 1).

The abiotic control (`Sahara`, Fig. 1D) and the high-radiation anomaly South Atlantic Anomaly (`SAA`, Fig. 1C) are dominated by stochastic variability, characterized by wide confidence intervals and intermittent statistical significance. The absence of a coherent window-dependent structure in these controls provides no evidence for systematic retrieval artifacts associated with energetic particle precipitation.

To assess potential solar and radiative confounding, we overlaid correlations with solar radio flux (F10.7) in the global analysis (Fig. 1A). Across integration windows, F10.7 exhibits a weaker response and most importantly lacks the cumulative structure observed for geomagnetic forcing, indicating that the detected signal is not explained by concurrent solar variability alone.

In contrast, biologically active ecosystems (`Global High-LAI` and `Control North`) exhibit narrow confidence intervals and consistently high statistical significance. The Northern Hemisphere `Control North` analysis (Fig. 1B) reveals a pronounced temperature-dependent morphology: a cumulative negative association confined to cold thermal regimes (<12 °C), peaking at integration windows of approximately 20–30 days. This structure is partially smoothed in the global aggregate, consistent with spatial averaging across heterogeneous climatic regimes.

The biophysical origin of the signal is supported by the robust cumulative response observed in the `Global High-LAI` and `Control North` regions (Fig. 1A,B), which contrasts sharply with the absence of such patterns in the radiation-intense `SAA` and the barren `Sahara` (Fig. 1C,D). Crucially, if the observed anomalies were driven by particle-induced sensor noise, the correlation would be most pronounced within the `SAA` due to the significantly higher particle flux

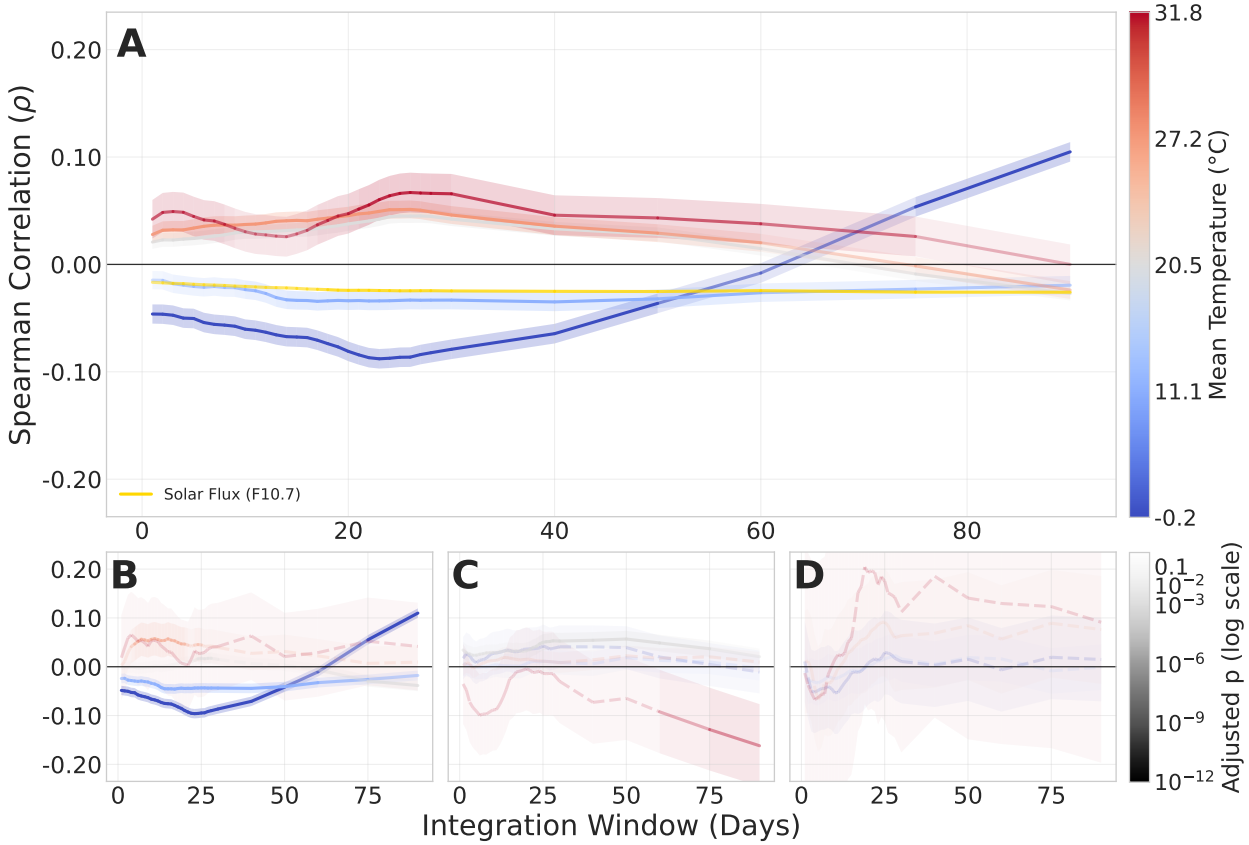

Figure 1: **Temperature-dependent cumulative response of vegetation fluorescence to geomagnetic activity.** Spearman's rank correlation coefficients (ρ) between detrended SIF at 771 nm and the cumulative Storm Intensity Index (SII) are shown across integration windows up to 90 days (evaluated on a predefined sparse grid: 1–28 daily, plus 30, 40, 50, 60, 75, and 90 days). Panels compare biologically active ecosystems: (A) `Global High-LAI`, (B) `Control North`, with instrumental and abiotic controls: (C) `SAA`, (D) `Sahara`. Curves are stratified by ambient temperature; shaded regions indicate 95% confidence intervals, and line style and opacity encode statistical significance (p-values adjusted for false discovery rate, FDR). The gold curve in (A) shows the correlation with solar radio flux (F10.7) for a representative thermal bin; F10.7 correlations are nearly identical across temperature bins (Supplementary Fig. S1). Qualitatively comparable but weaker patterns are observed for SIF wavelengths 740 and 757, and SIF_{757}/SIF_{771} stress indicator (Supplementary Figs. S3–S5).

(Schaefer et al. 2016; Crisp et al. 2017). The lack of such amplification in the SAA, combined with the strong signal in radiation-stable vegetated regions, rules out instrumental artifacts as the driver of the observed phenomenon.

Analogous analyses of individual SIF wavelengths (740, 757 nm) and the stress-sensitive spectral index (SIF_{757}/SIF_{771}) reveal qualitatively similar but systematically weaker cumulative patterns (Supplementary Figs. S3–S5). By contrast, the far-red 771 nm channel, located at the long-wavelength tail of the fluorescence emission spectrum and preferentially associated with Photosystem I, exhibits enhanced sensitivity to redox imbalance and acceptor-side limitation (Porcar-Castell et al. 2014; Cendrero-Mateo et al. 2015), consistent with its stronger and more coherent cumulative response (Fig. 1).

To evaluate whether these cumulative patterns could be explained by conventional climatic variability, we next quantified the relative contribution of geomagnetic and environmental drivers across temperature regimes (Fig. 2).

Comparative statistical screening further supports this interpretation by revealing a strong thermal modulation of signal efficacy. In the `Optimum` thermal regime, geomagnetic forcing (geomagnetic Storm Intensity Index, SII) systematically outperforms solar irradiance (F10.7), exhibiting superior explanatory power. The cumulative signal strength in the `Optimum` regime, quantified by the area under the correlation spectrum (AUC), is approximately 19-fold higher for SII relative to F10.7 (AUCratio ≈ 19.3).

Under `Extreme Heat` conditions, this contrast sharply declines (AUCratio ≈ 0.9) and becomes indistinguishable from stochastic variability, consistent with thermal modulation of the underlying coupling mechanism.

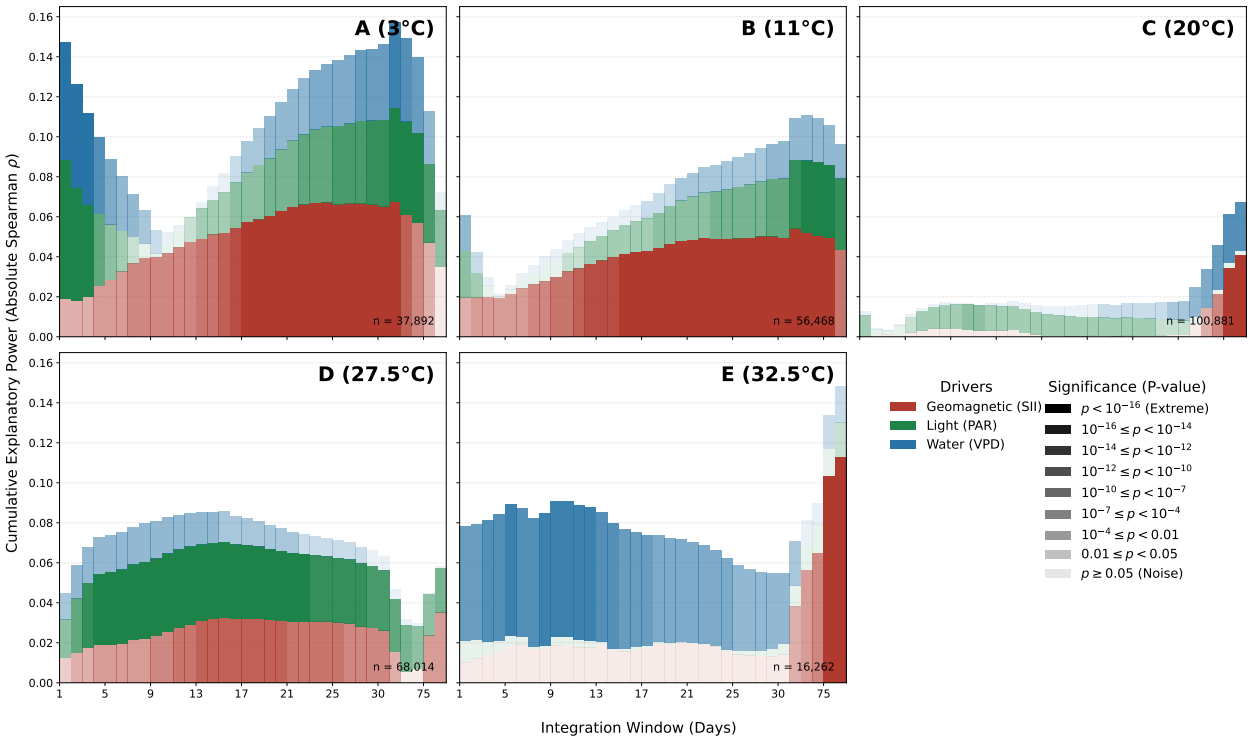

Figure 2: **Relative dominance of geomagnetic versus climatic drivers across timescales and temperature regimes.** Stacked spectra summarize the magnitude of associations between detrended fluorescence stress anomalies (SIF_{757}/SIF_{771}) and three cumulative drivers—geomagnetic forcing (SII), radiative forcing (Photosynthetically Active Radiation, PAR), and atmospheric dryness (Vapor Pressure Deficit, VPD)—across integration windows (as in Fig. 1) for the `Global High-LAI` scenario. For each temperature regime (A–E; `Cold` to `Extreme Heat`), bars show the cumulative sum of absolute Spearman correlations (|ρ|) at each window, stacked by driver (SII in red, PAR in green, VPD in blue). Bar opacity encodes statistical significance (p-values adjusted for false discovery rate, FDR; legend in panel F).

Driver dominance across temperature regimes

This pattern is further illustrated in Fig. 2, which summarizes the relative magnitude of associations between SIF stress anomalies and cumulative SII, PAR, and VPD across temperature regimes. Across most analyzed SIF spectral channels, geomagnetic forcing exhibited detectable associations with vegetation fluorescence that were comparable in magnitude to those of major climatic drivers, including PAR and VPD. This pattern was consistently observed across multiple geographic scenarios and temporal integration windows, as confirmed by representative supplementary analyses.

However, the strength, coherence, and thermal specificity of the cumulative response were markedly enhanced for the stress-sensitive spectral index (SIF_{757}/SIF_{771}). This metric exhibited superior signal-to-noise ratio, reduced sensitivity to radiative variability, and more stable window-dependent structure, thereby enabling a more direct physiological interpretation of the observed associations and motivating its central role in subsequent dominance and robustness analyses (Figs. 2–3).

The preferential amplification of geomagnetic associations in the stress index, which reflects photochemical regulation and non-photochemical quenching, is consistent with a physiological modulation of photosynthetic efficiency under geomagnetic disturbance. Although the underlying mechanisms remain uncertain, this pattern suggests an interaction between geomagnetic activity and plant stress-response pathways.

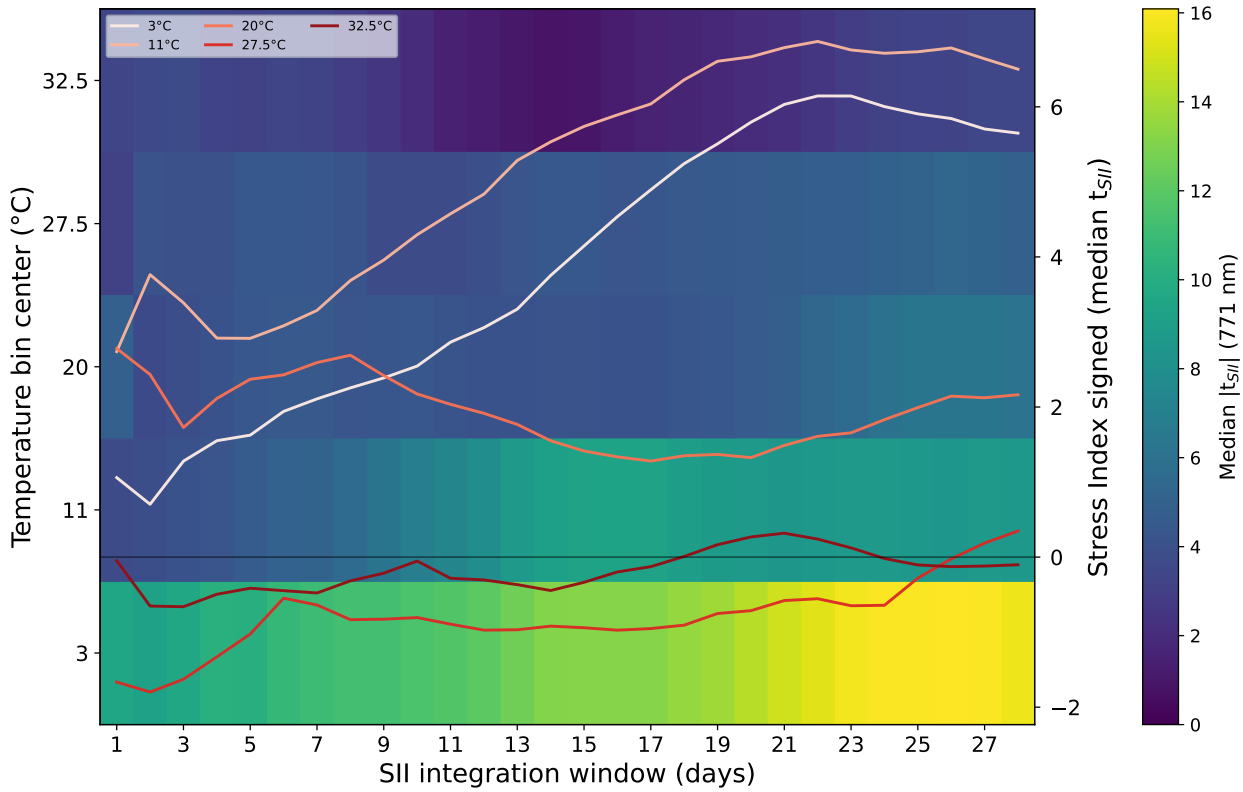

Figure 3: **Robustness and directionality of geomagnetic effects revealed by multivariate matrix search.** The heatmap shows the median absolute t-statistic of the partial SII regression coefficient (median $|t_{SII}|$) for detrended SIF at 771 nm across SII integration windows (1–28 days; x-axis) and physiological temperature-bin centers (white to red indicating `Cold` to `Extreme Heat` regimes: °C; y-axis), aggregated as the median across all tested combinations of PAR and VPD integration windows for the `Global High-LAI` scenario. The 771 nm channel is shown as a heatmap because it provides the most stable estimate of effect magnitude. Overlaid lines (right y-axis) show the signed median t-statistic (median t_{SII}) for the SIF_{757}/SIF_{771} stress index across the same windows, highlighting strong positive responses in the `Cool` and `Cold` regimes and increased sign variability under warm conditions. Results for the `Control North` scenario are qualitatively similar and are therefore not shown.

High $|t_{SII}|$ values in `Cold` and `Cool` regimes and their systematic amplification with increasing integration window indicate a robust cumulative geomagnetic signal that persists after controlling for radiative and hydrological drivers.

Figure 3 provides an independent robustness assessment of the geomagnetic signal using the exhaustive multivariate matrix search. Across all spectral channels and both biological scenarios, the strongest and most coherent SII effects are concentrated in the `Cold` and `Cool` temperature regimes, where median $|t_{SII}|$ values exceed 6 and increase monotonically with integration window length. This pattern indicates a cumulative, rather than impulsive, response to geomagnetic forcing.

In contrast, SII effects weaken substantially under `Optimal` and `Warm` conditions and approach background variability under `Extreme Heat` stress, despite explicit control for PAR and VPD. The spatial structure of Fig. 3 closely mirrors the temperature-dependent correlation patterns observed in Fig. 1 and the dominance spectra shown in Fig. 2, providing convergent evidence for a thermally modulated geomagnetic influence on vegetation fluorescence.

Notably, the stress index exhibits its strongest positive response in the `Cool` regime (bin center ≈11 °C), with a secondary maximum in the `Cold` regime (≈3 °C), both peaking at SII integration windows of ~22 days. In contrast, the warm regimes show markedly reduced amplitudes and increased sign variability (including weak sign changes with window length), consistent with the signal approaching background variability under thermal stress. This spectral divergence suggests that extreme cold primarily constrains canopy-level fluorescence emission, while moderate cool conditions preserve sufficient physiological activity for stress-regulatory processes to dominate the spectral response.

Together, these results confirm that geomagnetic forcing exerts a statistically robust, cumulative, and physiologically structured influence on vegetation fluorescence that cannot be explained by concurrent radiative or hydrological variability alone.

4. Discussion

Summary of main findings

Our analyses based on cumulative correlations (Fig. 1), driver dominance spectra (Fig. 2), and multivariate matrix search (Fig. 3) consistently demonstrate a temperature-dependent and cumulative association between geomagnetic activity (SII) and global vegetation fluorescence. The effect is strongest under `Cold` and `Cool` regimes, peaks at integration windows of approximately 20–30 days, and weakens under `Optimal` and `Heat-Stress` conditions, with maximal coherence and dominance observed in the stress-sensitive $\mathrm{SIF}_{757}/\mathrm{SIF}_{771}$ index. Instrumental and abiotic controls show no comparable structure (Fig. 1C,D). While solar forcing (F10.7) showed no effect (Fig. 1A), a comparison with key climatic drivers—PAR and VPD—reveals that geomagnetic forcing dominates the association spectrum specifically under cool conditions (Fig. 2B–C). Direct solar forcing (F10.7) exhibits weak and incoherent associations, and its correlations are nearly identical across temperature bins (Supplementary Fig. S1).

These convergent lines of evidence indicate that the observed signal reflects a biologically mediated response rather than radiative, climatic, or instrumental artifacts. Importantly, the cumulative structure of the signal suggests that the underlying mechanism is not impulsive. Instead, it operates through integration across repeated perturbations. This pattern implies the involvement of regulatory and redox-buffering pathways rather than direct photophysical disruption alone.

Thermal modulation and sink limitation

Photosynthetic performance is strongly constrained by the kinetic mismatch between temperature-insensitive photochemical reactions and temperature-dependent biochemical carbon fixation. Notably, the strongest geomagnetic associations consistently emerge at integration windows of approximately 20–30 days (Fig. 1), indicating that the underlying mechanism operates through physiological buffering and cumulative redox imbalance rather than through instantaneous perturbations. Primary charge separation and electron transport exhibit low thermal sensitivity ($Q_{10} \approx 1.0$) (Ensminger, Busch, and Huner 2006), whereas Rubisco carboxylation and Calvin–Benson cycle turnover display much higher temperature dependence ($Q_{10} \approx 2$–3) (Sage and Kubien 2007; Yamori, Hikosaka, and Way 2014).

Under low-temperature conditions, this mismatch leads to sink limitation, accumulation of reducing equivalents, and over-reduction of the photosynthetic electron transport chain (Huner, Öquist, and Sarhan 1998; Tikkanen and Aro 2014). Although plants have evolved multiple protective and compensatory mechanisms operating across different temporal scales—including rapid non-photochemical quenching and xanthophyll cycling (Demmig-Adams and Adams 1996; Müller, Li, and Niyogi 2001), intermediate regulation *via* cyclic electron flow and alternative sinks (Munekage et al.

2004; Shikanai 2014), and longer-term adjustments in photosystem stoichiometry and antenna organization (Anderson, Chow, and Park 1995; Walters 2005)—these responses cannot fully eliminate transient excitation pressure under persistent cold stress.

Our temperature stratification is based on daily and multi-day mean values, which integrate pronounced diurnal variability. In the `Cool` regime in particular, plants are frequently exposed to nocturnal or early-morning temperatures approaching or falling below freezing, followed by near-optimal daytime conditions. Such rapid thermal oscillations preclude full physiological and epigenetic acclimation (Way and Yamori 2014; Atkin and Tjoelker 2003). As a result, photosynthetic machinery remains in a quasi-transitional state characterized by recurrent redox imbalance.

This recurrent redox tension defines a physiological window of sensitivity in which long-lived reduced intermediates accumulate and reaction kinetics slow. Under these conditions, weak external perturbations can exert a measurable influence. Cold-induced sink limitation therefore enhances excitation pressure at photosystem I and prolongs the lifetime of reduced acceptor-side components, increasing the susceptibility of the system to subtle magnetic modulation.

As temperature approaches the physiological optimum for C3 photosynthesis (approximately 25 °C), enzymatic turnover accelerates and redox balance is restored (Kumarathunge et al. 2019). Under these conditions, excitation pressure decreases and the geomagnetic signal progressively dissipates into background physiological variability. It becomes effectively masked by dominant metabolic fluxes.

By contrast, high-temperature stress primarily affects photosynthesis through enzyme destabilization, membrane perturbation, and large-scale metabolic and whole-plant physiological reprogramming (Sharkey 2005; Yamori, Hikosaka, and Way 2014). These processes operate at higher levels of systemic organization and are dominated by strong thermal and oxidative constraints. As a consequence, the relative contribution of weak magnetic effects is reduced. Although heat represents a severe stress condition, it fails to sustain the specific redox and kinetic environment required for magnetic sensitivity. In this sense, cold stress exposes a redox-controlled biophysical regime, whereas heat stress primarily reorganizes whole-plant physiology at scales where spin-dependent perturbations are comparatively negligible.

Sensitivity of PSI acceptor-side processes

Photosystem I is particularly vulnerable to acceptor-side limitation and photoinhibition under conditions of redox imbalance (Sonoike 2011; Tiwari et al. 2016). Over-reduction of Fe–S clusters (F_X, F_A, F_B) and impaired electron export increase susceptibility to oxidative damage and modify electron-transfer kinetics (Tikkanen and Aro 2014).

Iron–sulfur clusters are central components of many biological electron-transfer systems in which spin-dependent radical-pair intermediates have been implicated in magnetic-field sensitivity. Experimental and theoretical studies in non-photosynthetic systems have demonstrated that Fe–S–associated redox reactions can participate in magnetically modulated radical-pair dynamics (Rodgers and Hore 2009; Hore 2016; Evans and Hore 2013). Although direct evidence for such effects in photosystem I is currently lacking, the presence of long-lived reduced intermediates under stress conditions suggests a physically plausible interface for weak magnetic perturbations.

Numerous studies demonstrate that PSI redox regulation plays a central role in coordinating photoprotection and metabolic demand (Pfannschmidt et al. 2009; Tikkanen and Aro 2014). The preferential sensitivity of the 771 nm fluorescence channel in our data is consistent with perturbations localized to PSI and far-red emission.

The enhanced coherence and dominance of the $\mathrm{SIF}_{757}/\mathrm{SIF}_{771}$ stress index further indicate a redistribution of excitation energy between the two photosystems and a coordinated adjustment of light-harvesting and energy-dissipation pathways. Such spectral rebalancing is consistent with physiological analyses linking far-red fluorescence ratios to dynamic redistribution of excitation energy and regulation of photosystem stoichiometry (Porcar-Castell et al. 2014; Cendrero-Mateo et al. 2015).

Radical-pair dynamics and magnetic compatibility

Charge separation and recombination in photosynthetic reaction centers generate short-lived radical pairs whose spin dynamics can be influenced by weak magnetic fields (Rodgers and Hore 2009; Hore 2016). Experimental and theoretical studies have established the physical plausibility of magnetic modulation of singlet–triplet interconversion in biological systems, including photosynthetic complexes (Ritz, Adem, and Schulten 2000; Evans and Hore 2013).

Although direct measurements of geomagnetic sensitivity in PSI are scarce, the presence of long-lived radical intermediates under acceptor-side limitation suggests compatibility with radical-pair mechanisms. Our results are therefore consistent with, though not direct evidence for, magnetic modulation of reaction-center dynamics.

Iron–sulfur centers are also present in the cytochrome b6f complex, where the Rieske protein plays a pivotal regulatory role in controlling electron flux and excitation balance between the two photosystems (Kurisu et al. 2003; Stroebel et al. 2003). Because b6f represents a major kinetic bottleneck within the photosynthetic electron transport chain, perturbations at this level may propagate system-wide effects on energy distribution and redox signaling.

Rieske-type Fe–S proteins belong to a widespread family of redox-active cofactors involved in central metabolic intersections across prokaryotes and eukaryotes (Imlay 2006). Their recurrent involvement in spin-dependent redox reactions supports the plausibility of radical-pair–mediated magnetic sensitivity as a general physical interface between weak magnetic fields and metabolism.

Within this framework, the radical-pair mechanism represents one of the most extensively developed candidates for biological magnetoreception (Hore 2016; Ritz, Adem, and Schulten 2000). Although originally formulated in the context of animal navigation, its underlying principles are directly applicable to photosynthetic and redox-active protein complexes. Our observations are therefore compatible with a scenario in which geomagnetic perturbations subtly modulate radical-pair dynamics within PSI and b6f-associated pathways, thereby influencing downstream regulatory processes.

ROS-mediated amplification and photoprotective signaling

Perturbations of PSI electron transport enhance electron leakage to molecular oxygen, generating superoxide ($O_2^{\bullet -}$) and hydrogen peroxide (H_2O_2) (C. H. Foyer and Noctor 2005; Apel and Hirt 2004). The progressive strengthening of geomagnetic effects with increasing integration window length (Figs. 1 and 3) suggests that such redox perturbations are repeatedly accumulated and integrated within cellular regulatory networks. Photosystem II also represents a major source of singlet oxygen (^1O_2), particularly under conditions of excitation imbalance and impaired electron flow at the QB site (Krieger-Liszkay 2005; Pospíšil 2016). Additional redox-active components in the chloroplast stroma and thylakoid membrane further contribute to ROS production.

The observed suppression of SIF under geomagnetic disturbances likely reflects a rapid systemic adjustment to oxidative stress. Elevated levels of reactive oxygen species (ROS), particularly hydrogen peroxide, are known to act as potent inhibitors of the photosynthetic machinery. Experimental evidence indicates that H_2O_2 accumulation directly suppresses photosynthetic electron transport in the Hill reaction and inhibits the activity of both Photosystem II and Photosystem I (Samuilov et al. 2001). Such direct biochemical inhibition, coupled with the magnetic modulation of radical pair dynamics, suggests that the geomagnetic signal in SIF represents a real-time proxy for the redox state of the photosynthetic apparatus rather than a simple phenological shift.

Beyond the chloroplast, the mitochondrial electron transport chain constitutes another major and dynamically regulated source of superoxide (Rhoads and Subbaiah 2006; Møller, Jensen, and Hansson 2007). Crosstalk between chloroplast and mitochondrial redox states coordinates cellular energy balance and stress signaling.

These multiple ROS sources are closely coupled to primary charge-separation and recombination reactions involving radical-pair intermediates. Perturbations of spin-dependent reaction pathways may therefore influence both electron-transfer kinetics and the probability of ROS formation at multiple redox-sensitive sites.

ROS occupy a dual functional role in plant physiology. At high concentrations, they cause oxidative damage to proteins, lipids, and nucleic acids. At controlled levels, they act as central signaling molecules regulating acclimation, gene expression, and metabolic reconfiguration (C. H. Foyer and Noctor 2005; Suzuki et al. 2006; Mittler et al. 2011).

This duality is widely discussed as reflecting an evolutionary shift in which reactive by-products of aerobic metabolism, initially dominated by damaging effects, were progressively incorporated into regulated signaling circuits (C. Foyer and Noctor 2009; Noctor, Reichheld, and Foyer 2018). In this view, oxidative stress responses gradually developed into information-processing modules capable of integrating environmental variability.

Redox perturbations originating in PSI, PSII, or mitochondria can therefore be transduced into coordinated regulatory responses through interconnected signaling networks (Rhoads and Subbaiah 2006; Møller, Jensen, and Hansson 2007; Noctor, Reichheld, and Foyer 2018). Subtle shifts in electron-transfer probabilities, including those potentially influ-

enced by magnetic-field–dependent radical-pair modulation, may alter ROS formation rates across multiple sites (Hore 2016; Evans and Hore 2013).

From this perspective, ROS signaling provides a plausible channel of magnetic sensitivity within redox-regulatory networks that operates in parallel with Fe–S–associated mechanisms. Weak magnetic perturbations may bias existing redox-sensitive pathways that have been optimized to detect small deviations from homeostasis (Mittler et al. 2011; C. Foyer and Noctor 2009). Magnetically induced redox fluctuations may therefore be interpreted as inputs into pre-existing regulatory architectures governing stress perception and acclimation (Noctor, Reichheld, and Foyer 2018; Suzuki et al. 2006).

Cryptochromes as integrative regulatory nodes

Cryptochromes are flavoproteins that have undergone evolutionary specialization for light-dependent redox cycling involving radical intermediates and exhibit magnetic sensitivity *in vitro* and *in vivo* (Ritz et al. 2004; Ahmad et al. 2016). The first systematic evidence for plant magnetoreception came from studies showing magnetic field effects on germination and early seedling development (Galland and Pazur 2005). Subsequent ultrastructural analyses revealed that magnetic fields can alter calcium homeostasis and cellular organization in root meristems (Belyavskaya 2004).

In plants, cryptochromes have so far been shown to regulate antioxidant capacity, stomatal conductance, circadian rhythms, and stress-responsive gene expression. These functions suggest a primary role in coordinating cellular redox state with environmental light cues (Chaves et al. 2011; Cosentino et al. 2019). A recent comprehensive review synthesizes the current understanding of plant magnetoreception, emphasizing the central role of cryptochromes and radical-pair chemistry (Nordmann, Hochstoeger, and Keays 2022).

Magnetic modulation of cryptochrome signaling influences physiological and behavioral responses in several organisms (Gegear et al. 2010; Hore 2016). In plants, such modulation is increasingly interpreted within a broader framework of environmental signal integration, linking light perception, redox dynamics, hormonal signaling, and transcriptional regulation (Ahmad et al. 2016; Chaves et al. 2011).

Recent reviews emphasize growing consensus regarding the involvement of cryptochromes and radical-pair chemistry in plant magnetoreception (Thoradit et al. 2023; Nordmann, Hochstoeger, and Keays 2022). Within this framework, cryptochromes may function as integrative nodes that accumulate repeated redox perturbations and translate them into longer-term regulatory states.

Integrated transduction framework

Taken together, our results from cumulative correlations (Fig. 1), driver dominance spectra (Fig. 2), and multivariate robustness analyses (Fig. 3) support a hierarchical transduction pathway linking solar forcing to photosynthetic regulation. Solar variability modulates radiative and particle fluxes, which are transformed by the magnetosphere into geomagnetic disturbances. These disturbances interact with redox-active cofactors and radical-pair systems within chloroplasts, subtly perturbing PSI and b6f electron-transfer dynamics. The sensitivity of plants to such weak magnetic perturbations is supported by a substantial body of experimental evidence (Galland and Pazur 2005; Belyavskaya 2004; Parmagnani and Maffei 2022). The resulting redox imbalances promote ROS production and activate regulatory signaling pathways. Through cryptochrome-mediated and redox-sensitive networks, these signals are integrated over time and drive sustained adjustments in photosystem stoichiometry, energy dissipation, and carbon assimilation.

This framework reconciles short-term physical interactions with long-term ecosystem-scale responses and provides a mechanistic basis for the observed cumulative and temperature-dependent structure of the geomagnetic signal.

An evolutionary hypothesis: geomagnetic field as biological information

The pervasive presence of magnetosensitive elements—Fe–S clusters, radical-pair intermediates, and cryptochromes—across diverse taxa suggests that magnetic sensitivity may be an ancient and conserved feature of life (Imlay 2006; Rodgers and Hore 2009). Rather than evolving *de novo* in response to specific selective pressures, we propose that plants have co-opted pre-existing magnetosensitive components into regulatory networks that integrate multiple environmental signals.

This perspective shifts the interpretation of our observations: the cumulative, temperature-dependent response of SIF to geomagnetic disturbances reflects not a passive mechanical perturbation but an active biological perception. Plants appear to have evolved mechanisms to extract information from geomagnetic variability, much as they do from light, temperature, and water availability. The magnetosphere, in this view, functions as a dynamic mediator that transmits structured solar variability into the biosphere—a signal that plants have learned, over evolutionary time, to interpret.

Periods of geomagnetic instability, including polarity reversals and excursions, have been associated with major transitions in plant evolution and diversification (Meert et al. 2016; Glassmeier and Vogt 2009). While causal links remain speculative, such correlations are consistent with the hypothesis that magnetic variability has acted as a selective pressure, shaping the evolution of stress-response networks.

Within this framework, the observed suppression of SIF under geomagnetic disturbances represents not damage, but a regulated physiological adjustment—a recalibration of photosynthetic machinery in response to perceived environmental change. The cumulative nature of the response (Figs. 1, 3) suggests integration over time, a hallmark of biological information processing rather than simple physical insult.

This hypothesis generates testable predictions: (1) magnetically sensitive components should be embedded within broader stress-signaling networks; (2) the response should exhibit hallmarks of biological information processing, including adaptation, memory, and context-dependence; (3) organisms from lineages with different evolutionary histories should show different sensitivities, reflecting the selective pressures they have experienced.

Limitations and outlook

Our study is observational and cannot establish causality at the molecular level. Direct experimental tests using controlled magnetic-field manipulations and targeted measurements of PSI redox dynamics, ROS production, and cryptochrome signaling are required. Pioneering work on plant magnetoreception (Galland and Pazur 2005; Belyavskaya 2004) provides methodological frameworks for such experimental approaches. Improved mechanistic understanding will require coordinated laboratory, field, and satellite studies (Nordmann, Hochstoeger, and Keays 2022).

The molecular and biophysical foundations of magnetic-field effects in biological systems have been extensively discussed in recent reviews and theoretical analyses (Mattei and Hore 2014; Hore 2016; Thoradit et al. 2023). Integrating these advances with large-scale ecological observations represents a promising avenue for future research.

Conclusions

Vegetation fluorescence responds preferentially to magnetospherically mediated solar variability rather than direct irradiance. The response is cumulative, temperature-dependent, and physiologically structured—hallmarks of biological information processing rather than passive mechanical perturbation.

Geomagnetic variability participates in photosynthetic regulation across multiple organizational levels, from short-term redox dynamics to long-term physiological acclimation. We propose that plants have evolutionarily co-opted geomagnetic signals as an informational layer of their environment, integrating them into existing redox-regulatory networks that govern stress responses. In this sense, geomagnetic forcing functions not merely as a physical perturbation, but as an evolved sensory input to which terrestrial vegetation has become functionally attuned.

The observed response implies that the magnetosphere may function not only as a physical shield but also as a dynamic mediator transmitting structured solar variability into biological regulation. Weak geomagnetic fluctuations, though energetically negligible, may become biologically effective precisely because they are interpreted through evolved sensory mechanisms rather than acting as direct physical agents. This perspective opens new frontiers in understanding magnetosphere–biosphere coupling and suggests that the search for mechanisms should focus on regulatory networks, not merely on isolated physical effects.

5. Methods

Data Sources and Processing

Geomagnetic variability was characterized using the Disturbance Storm Time index (Dst) from the OMNI2 dataset (Papitashvili and King 2020); see also (King and Papitashvili 2005) for details on solar wind data. We defined the

Storm Intensity Index as $SII = -Dst$ to intuitively represent geomagnetic stress from a biological perspective. Solar activity was controlled using the F10.7 cm radio flux. Both indices were aggregated to daily means. To capture potential cumulative physiological effects alongside acute triggers, we computed both cumulative moving averages (1–90 days) and discrete time lags (1–90 days) for space weather indices.

Global SIF measurements were obtained from the OCO-2 Level 2 "Lite" datasets (V11r/V11.2r) (OCO-2 Science Team, Payne, and Chatterjee 2022). The OCO-2 instrument and its radiometric performance are described in detail by Crisp et al. (Crisp et al. 2017). We analyzed the 757/771 nm emission ratio (Stress Index) and individual emission lines aggregated to a daily $0.5^\circ \times 0.5^\circ$ grid. To minimize viewing geometry effects on SIF retrievals, we followed quality filtering recommendations (Sun et al. 2018) and applied strict thresholds for cloud and aerosol fractions. Strict quality filtering was applied based on MODIS (MCD12/MOD08) ancillary data (Myneni, Knyazikhin, and Park 2021): Cloud Fraction $< 60\%$, Aerosol Fraction $< 50\%$, and Leaf Area Index (LAI) ≥ 0.15. A 3×3 spatial dilation kernel was applied to the vegetation mask to minimize artifacts arising from grid mismatches between datasets.

To identify SIF anomalies, we fitted a seasonal trend model to each grid cell, accounting for linear trends and annual harmonic cycles. The resulting residuals were standardized using a Z-score transformation (SIF_{resid}) to ensure inter-variable comparability across different wavelengths and physiological indices.

Environmental controls (PAR, VPD, Temperature, Total Cloud Cover) were derived from ERA5 reanalysis (Hersbach et al. 2020, 2023) and resampled to the analysis grid. A critical distinction was made in the temporal processing of environmental variables: unlike geomagnetic indices, environmental variables were primarily used to define the instantaneous physiological context and to isolate the specific contribution of space weather forcing.

Multivariate Matrix Search

To isolate the unique influence of geomagnetic activity from concurrent meteorological drivers, we implemented an exhaustive multivariate search using an Ordinary Least Squares (OLS) framework. For every grid cell within a given scenario and temperature bin, we evaluated a comprehensive matrix of models where SIF_{resid} was regressed against combinations of SII, PAR, and VPD at varying integration windows (w):

$$SIF_{resid}(t) = \beta_0 + \beta_{SII} \cdot SII_{MA}(t, w_1) + \beta_{PAR} \cdot PAR_{MA}(t, w_2) + \beta_{VPD} \cdot VPD_{MA}(t, w_3) + \epsilon$$

This approach allowed us to calculate the partial regression coefficient (β_{SII}) and its associated t-statistic while rigorously controlling for light availability and vapor pressure deficit. The high-performance implementation enabled the processing of 10^9 model combinations, ensuring that the reported space-weather signals are not artifacts of environmental confounding.

While cumulative correlations were evaluated up to 90 days (on a sparse window grid), the multivariate matrix search was restricted to short windows (1–28 days; limited by collinearity and computational tractability). This range captures the dominant physiologically relevant response timescale identified in the correlation analysis, while avoiding severe collinearity and computational intractability inherent to higher-dimensional regression at longer integration scales.

Temperature Stratification

The dataset was stratified into five physiological temperature bins based on the 10-day moving average of ambient temperature (T_{MA}): `Cold` ($T_{MA} < 12^\circ$C), `Cool` ($12^\circ\text{C} \leq T_{MA} < 22^\circ$C), `Optimum` ($22^\circ\text{C} \leq T_{MA} < 28^\circ$C), `Warm Stress` ($28^\circ\text{C} \leq T_{MA} < 32^\circ$C), and `Extreme Heat` ($T_{MA} \geq 32^\circ$C).

This stratification reflects established plant physiological thresholds, ranging from cold-induced metabolic limitation and excitation pressure (Sage and Kubien 2007; Ensminger, Busch, and Huner 2006; Huner, Öquist, and Sarhan 1998; Tikkanen and Aro 2014), through the broad photosynthetic optimum for C_3 vegetation (Yamori, Hikosaka, and Way 2014; Kumarathunge et al. 2019; Slot and Winter 2017), to progressive heat-induced impairment of Rubisco activity and electron transport (Crafts-Brandner and Salvucci 2000; Sharkey 2005; Allakhverdiev et al. 2008; Wahid et al. 2007).

This framework ensured that geomagnetic signals were evaluated within relatively stable physiological regimes, minimizing confounding by thermal stress.

Statistical Correction (N_{eff})

To account for temporal autocorrelation inherent in geophysical time series, which inflates Type I error rates, we adjusted the effective degrees of freedom (N_{eff}) following the method of Chelton (Chelton 1983), as modified by Pyper and Peterman (Pyper and Peterman 1998). The effective sample size was estimated based on the lag-1 autocorrelation coefficients (r_1) of the predictor (X) and response (Y) series:

$$\frac{1}{N_{eff}} \approx \frac{1}{N} + \frac{2}{N}\frac{r_1(X)r_1(Y)}{1 - r_1(X)r_1(Y)}$$

This correction was applied to all significance tests and confidence interval calculations.

Spatial Meta-Analysis

Global results were synthesized using an Inverse-Variance Weighting scheme (Cochran 1954). Local correlation coefficients were aggregated into regional means weighted by their statistical precision, approximated by the effective sample size (N_{eff}), ensuring robust estimation in sparse-data regions. To validate biological causality, we contrasted the signal strength in biological masks (`Control North`, `Global High-LAI`) against a non-biological negative control located in the Sahara Desert (`Sahara`). To differentiate between genuine biophysical responses and potential instrumental artifacts, we defined a `South Atlantic Anomaly` (SAA) scenario. The SAA is a region where the Earth's inner Van Allen radiation belt reaches its lowest altitude, exposing satellite sensors to increased fluxes of ionizing radiation and high-energy protons (Heirtzler 2002; Schaefer et al. 2016). For sun-synchronous spectrometers like OCO-2, these particles can induce transient "spikes" or increased dark current noise in the detectors (Crisp et al. 2017). By comparing the SIF-geomagnetic coupling in the SAA against radiation-stable regions (`Control North`), we assessed whether the observed signals were biologically grounded or driven by sensor-particle interactions.

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