Spectral signatures of vegetation and their relevance for remote biosignature detection

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Abstract. The vegetation red edge (VRE) - a sharp increase in reflectance between approximately 700 and 750 nm arising from chlorophyll absorption of visible light and strong near-infrared scattering within leaf tissues - represents the most extensively studied surface biosignature for remote detection of photosynthetic life. This mini-review synthesizes current knowledge of terrestrial vegetation spectral signatures and their relevance to exoplanet biosignature searches. Earthshine and spacecraft observations have quantified the disk-integrated VRE as a few-percent feature whose strength varies with phase angle, cloud cover, and vegetated land fraction, requiring photometric accuracy of ~1% or better for reliable detection. Temporal variability linked to seasonal growth and senescence provides a critical discriminant against abiotic mineral edges. Complementary biosignatures, including circular spectropolarimetry rooted in molecular homochirality and photosynthetic fluorescence, offer independent confirmation pathways that reduce false-positive risk. Detectability on exoplanets depends on host-star spectral energy distribution, cloud fraction, surface coverage, and evolutionary stage of any biosphere; models indicate that VRE-like features could be recoverable on nearby rocky worlds with exposure times of tens to hundreds of hours under favorable conditions. Extrapolation to extraterrestrial environments is further informed by aquatic floating vegetation, extreme-environment analogues, and considerations of prebiotic chemistry. Collectively, these findings underscore that robust life detection will require multi-wavelength, time-resolved, and multi-technique observations rather than reliance on any single spectral feature.
Keywords: astrobiology, biosignatures, circular polarization, Earthshine, exoplanets, photosynthetic fluorescence, remote sensing, vegetation red edge.

Introduction. The search for life on exoplanets draws on Earth's biosphere as a primary analogue, where photosynthetic organisms have imprinted distinctive spectral features on the planet's reflected-light spectrum that are detectable from space (Schwieterman et al., 2018; O'Malley-James & Kaltenegger, 2019). Among these features, the vegetation red edge (VRE), a sharp rise in leaf reflectance near 700 nm, constitutes the most extensively studied surface biosignature for remote life detection (Schwieterman, 2018; O'Malley-James & Kaltenegger, 2019).

This review synthesizes current understanding of vegetation spectral signatures, their detectability from disk-integrated observations, complementary polarimetric and fluorescence biosignatures, and the extrapolation of terrestrial ecosystem analogues to potential extraterrestrial environments.

The Vegetation Red Edge as a Surface Biosignature. Terrestrial plant leaves absorb visible light through photosynthetic pigments, primarily chlorophyll, and strongly reflect near-infrared radiation (NIR) via internal leaf scattering, producing a steep reflectance increase between 700 and 750 nm (Seager et al., 2005; O'Malley-James & Kaltenegger, 2019; Murakami et al., 2025). This reflectance discontinuity, termed the vegetation red edge, is detectable in observations of Earth from the Galileo spacecraft and in the Earthshine spectrum—sunlight reflected from the lunar surface that serves as a proxy for observing Earth as an unresolved point (Seager et al., 2005; Arnold, 2007; Schwieterman et al., 2018; O'Malley-James & Kaltenegger, 2019). The VRE represents a more fundamental biosignature than any single biogenic gas because it is a general consequence of photosynthetic activity, independent of the specific biochemical pathways involved (Arnold et al., 2002).

Earthshine observations since 2001 have quantified the VRE as a small positive shift of a few percent above the continuum at 700 nm in the disk-integrated Earth spectrum (Arnold et al., 2002; Arnold, 2007). Arnold et al. (2002) measured a variable signal of 4 to 10±3% around 700 nm in Earth's albedo, consistent with model predictions of 2 to 10% depending on cloud cover and viewing geometry. The signal strength correlates with Earth's phase angle, which determines whether sunlit vegetated continents or ocean-dominated hemispheres face the observer (Arnold, 2007). Montañés-Rodríguez et al. (2006) found a strong correlation between the spectral intensity of the red edge and the cloud-free vegetated area, with an apparent reflectance change of approximately 0.005±0.0005 relative to a mean albedo of 0.25 at 680 nm. Detecting the VRE on Earth requires a photometric relative accuracy of 1% or better, a demanding threshold that underscores the challenge of identifying equivalent features on distant exoplanets (Arnold, 2007) (Table 1).

Table 1

Comparison of vegetation red edge signal strengths measured via different Earth observation methods

Observation method	*VRE signal strength*	*Key finding*	*References*
Earthshine	4-10±3% at 700 nm	Seasonal variation linked to visible land area	Arnold et al., 2002
Earthshine	~2.0±0.2% above mean albedo	Correlated with cloud-free vegetated area	Montañés-Rodríguez et al., 2006
Galileo flyby	Widely distributed surface pigment	Sharp reflection edge unexplained by geology	O'Malley-James & Kaltenegger, 2019
Earthshine	Few percent above continuum	Requires ≥ 1% photometric accuracy	Arnold, 2007.

Temporal Variability and Evolutionary History of the VRE. Temporal modulation of the VRE provides a critical discriminant against false positives, as seasonal changes in vegetation coverage produce predictable spectral variations that abiotic mineral edges cannot replicate (Seager et al., 2005; Schwieterman, 2018). Seager et al. (2005) emphasized that time variability is key to detecting weak surface biosignatures, presenting Earthshine observations from Apache Point Observatory that demonstrate seasonal shifts consistent with vegetation growth and senescence. Murakami et al. (2025) extended this concept to floating aquatic vegetation, showing that seasonal proliferation and decline of floating plants produce significant lake reflectance variations detectable over five-year satellite monitoring periods, with the seasonal signal proving robust to cloud interference.

The strength of Earth's VRE has not been constant through geological time. O'Malley-James and Kaltenegger demonstrated that the VRE has increased over approximately 500 million years of land plant evolution, with early plants such as mosses and liverworts that dominated 500-400 million years ago producing a red edge roughly half as strong as that of modern vegetation (O'Malley-James & Kaltenegger, 2018). In a complementary study, the same authors showed that lichens could extend the presence of a red edge surface biosignature to 1.2 billion years ago, while ocean surface algae and cyanobacteria could extend it to over 2 billion years ago, because chlorophyll is present in these organisms and produces a detectable spectral edge long before land vegetation became widespread. Earth's surface vegetation has provided a biosignature for only approximately one-ninth of the planet's lifetime, meaning that the VRE's utility as a universal biosignature depends on the evolutionary stage of the target planet's biosphere (O'Malley-James & Kaltenegger, 2019).

Complementary Biosignatures: Polarimetry and Fluorescence. The VRE alone is vulnerable to false positives from mineral reflectance edges that can mimic its slope and strength, albeit at different wavelengths (Seager et al., 2005; Schwieterman, 2018). Borges et al. (2024) confirmed that iron oxide slopes can produce false positive signals that complicate red edge interpretation, making the detection of multiple complementary biosignatures essential for robust life detection.

Circular spectropolarimetry offers a fundamentally different biosignature rooted in the homochirality of biological molecules, a property considered universal and agnostic because all biochemical life exhibits it (Patty et al., 2019; Patty et al., 2021; Patty et al., 2022). When unpolarized light scatters from photosynthetic organisms, the homochiral molecular assemblies induce fractional circular polarization that can be sensed remotely, producing a signal with a spectral shape tied to vegetation physiology that abiotic surfaces cannot replicate (Patty et al., 2021; Patty et al., 2022). Patty et al. (2021) demonstrated that circular spectropolarimetric measurements from a fast-moving helicopter could differentiate grass fields, forests, and abiotic urban areas within seconds at signal-to-noise ratios exceeding 5, and could even detect photosynthetic organisms in lakes using only nonzero circular polarization as a discriminant (Patty et al., 2021). The circular polarization-phase angle dependency of vegetation induces relatively small changes in spectral shape and primarily affects signal magnitude, making the technique robust across viewing geometries (Patty et al., 2022). Field measurements using the dedicated TreePol spectropolarimeter at distances up to several kilometers confirmed that photosynthetic life can be readily distinguished from abiotic matter under realistic remote sensing conditions (Patty et al., 2019).

Photosynthetic fluorescence provides a third complementary biosignature. Komatsu et al. (2023) examined the detectability of biological fluorescence from chlorophylls and bacteriochlorophylls on Earthlike planets around the Sun and M dwarfs, finding that atmospheric absorbers, including water vapor, methane, oxygen, and ozone, as well as the VRE itself, obscure chlorophyll fluorescence emissions. Bacteriochlorophyll-based fluorescence at 1000-1100 nm could serve as a suitable biosignature, but only in the absence of water cloud coverage or other strong absorbers near 1000 nm. Around ultracool red dwarfs such as TRAPPIST-1, the apparent reflectance excess from fluorescence is greatly enhanced due to the interplay between fluorescence and stellar absorption lines, potentially enabling detection with ground-based high-resolution follow-up observations. The simultaneous detection of fluorescence and the VRE is key to identifying photosynthesis, because absorption, reflectance, and fluorescence are physically connected processes (Komatsu et al., 2023) (Table 2).

Table 2
Comparison of four vegetation-related biosignature types by physical origin, advantages, and limitations

Biosignature type	*Physical origin*	*Key advantage*	*Key limitation*	*References*
Vegetation red edge	Chlorophyll absorption + NIR leaf scattering	Strong, well-characterized signal	Mineral false positives; requires ≥ 1% accuracy	Schwieterman, 2018; Arnold, 2007
Circular polarization	Homochirality of photosynthetic macromolecules	Agnostic; abiotic signals are spectrally flat	Low signal magnitude; instrumentation complex	Patty et al., 2022
Photosynthetic fluorescence	Chlorophyll/bacteriochlorophyll re-emission	Physically linked to VRE; species-specific	Obscured by atmospheric absorbers and clouds	Komatsu et al., 2023
Temporal variability	Seasonal vegetation growth/senescence cycles	Discriminates biotic from abiotic edges	Requires repeated observations over time	Seager et al., 2005; Schwieterman, 2018.

Exoplanet Detection Scenarios and Ecosystem Comparisons. The detectability of vegetation biosignatures on exoplanets depends on stellar host type, planetary climate, cloud coverage, and the evolutionary state of any surface biosphere. O'Malley-James and Kaltenegger proposed that older and hotter Earth-like planets are favorable targets for VRE detection, because hotter climate conditions can encourage vegetation spread, and dry exoplanets with some water may present lower cloud fractions and reduced atmospheric water vapor that facilitate surface feature detection (O'Malley-James & Kaltenegger, 2018). Cui et al. (2017) modeled land plant distribution on tidally locked planets around M dwarfs using general circulation models, finding that observation times on the order of days using a 25 m² telescope would suffice for VRE detection on nearby Earth-mass planets if a large continent faces the observer, and that hypothetical exovegetation VRE features are easier to detect than Earth's own vegetation signal even under cloudy conditions.

Borges et al. (2024) paired a Habitable Worlds Observatory instrument noise model with radiative transfer simulations to estimate exposure times for detecting surface biosignatures on rocky exoplanets, determining that pigments and the red edge could be detected within 1000 hours at distances within 15 parsecs for planets with 0-50% cloud coverage, and within 100 hours at distances within 11 parsecs. Their results also indicate that anoxygenic photosynthetic biosignatures could be more easily detectable than nonphotosynthetic pigments and the photosynthetic red edge when compared against false positive iron oxide slopes, and that detecting multiple biosignature types—carotenoids, phycobilins, chlorophylls, and in some cases a red edge—would strengthen the robustness of any positive life detection (Borges et al., 2024).

The question of whether extraterrestrial photosynthetic organisms would produce a red edge at the same wavelength as terrestrial vegetation remains open. Seager et al. (2005) speculated that while extraterrestrial light-harvesting organisms have no compelling reason to display the same red edge feature as terrestrial vegetation, they might exhibit similar sharp spectroscopic features at different wavelengths determined by the spectral energy distribution of their host star. This implies that future terrestrial-planet-characterizing missions should obtain data that allow time-varying sharp spectral features at unknown wavelengths to be identified, rather than searching only at 700 nm. Schwieterman et al. (2018) framed this as a series of open questions: whether a red edge from vegetation or cyanobacteria can be expected on another planet, at what wavelengths it might appear, and how environmental factors such as atmospheric opacity and surface mineralogy limit detectability.

Table 3

VRE detectability across different planetary target types and observation scenarios

Target type	*VRE detectability*	*Favorable conditions*	*References*
Present-day Earth (disk-integrated)	Few percent above continuum	Land-facing hemisphere, low clouds	O'Malley-James & Kaltenegger, 2018; Arnold, 2007
M dwarf tidally locked planets	Days of observation (25 m² telescope)	Large continent facing observer	Cui et al., 2017
Hot/dry Earth-like exoplanets	Enhanced relative to present Earth	Low cloud fraction, low water vapor	O'Malley-James & Kaltenegger, 2018
Rocky exoplanets within 15 pc	≤1000 hr exposure (HWO model)	0-50% cloud coverage	Borges et al., 2024
Early Earth (pre-land vegetation)	Extended via algae/cyanobacteria	Ocean surface biosignatures	O'Malley-James & Kaltenegger, 2019

Terrestrial Analogues and Extraterrestrial Ecosystem Frameworks. Extrapolating from terrestrial ecosystems to potential extraterrestrial environments requires understanding both the spectral signatures of diverse photosynthetic organisms and the ecological contexts that produce them. Murakami et al. (2025) proposed that floating vegetation on water-rich planets with limited land should be considered alongside or even in place of terrestrial vegetation as a biosignature target, because the naturally low reflectance of water enhances detection sensitivity for floating plants, whose red edge was found to be equivalent to or more pronounced than that of terrestrial plants. This finding broadens the range of planetary surface types where vegetation biosignatures could be detectable, particularly for ocean worlds where land vegetation is absent.

Meurer et al. (2024) argued for an "astroecology" framework that integrates ecological theory into astrobiology, noting that ecology is largely overlooked in astrobiological research despite its relevance for evaluating whether Earth-like life could survive in extraterrestrial environments. They proposed that organismal ecology provides niche modeling for extraterrestrial habitability, community ecology informs the concept of vacant habitats, and biosphere ecology addresses whether stabilized near-optimal planetary conditions analogous to Earth's Gaia-like feedback could operate on other inhabited worlds. The distinction between "strong" biospheres like Earth and "weak" biospheres like Mars raises the question of whether ecosystem-level feedback is necessary for the long-term persistence of biosignatures (Meurer et al., 2024).

Schultz et al. (2026).emphasized that extreme terrestrial environments serve as essential analog sites for validating life-detection methods and biosignature preservation, with the Atacama Desert, McMurdo Dry Valleys, and Rio Tinto providing well-established Mars and icy moon analogues, and Saudi Arabian extreme environments offering additional pristine sites including volcanic craters that mimic Enceladus's ocean chemistry and Red Sea systems with complex metabolic landscapes relevant to icy moon habitability. Howells et al. (2025) argued that astrobiology should function as a bidirectional science, where knowledge gained from biological systems and Earth study sites that guide planetary investigation can simultaneously inform strategies for carbon capture, low-carbon energy, and biotechnology on Earth.

The interpretation of any detected biosignature must also account for the possibility of prebiotic chemistry producing life-like signatures. Barge et al. (2021) demonstrated that complex organic chemical systems exhibiting life-like properties can be produced abiotically in the laboratory, and that the "biosignature threshold" distinguishing abiotic from biotic chemistry varies by environment and can shift over time, particularly if life emerges and diversifies on a given world. They advocated for involving experimental prebiotic samples as analogues when generating comparison libraries for life-detection instruments, because on Earth, biology has suppressed most abiotic organic chemistry and overprints geologic records of prebiotic processes (Barge et al., 2021). Chandru et al. (2024) further challenged the assumption that all life must use the same building blocks as terrestrial life, proposing that non-biomolecules may have played essential roles at the origin of life and could serve as agnostic biosignatures indicative of extraterrestrial life with fundamentally different biochemistry. These considerations imply that vegetation-like spectral signatures, while compelling, represent only one class of potential biosignature, and that the absence of a red edge feature on an exoplanet would not constitute a meaningful null result for life (Seager et al., 2005).

Conclusions. The vegetation red edge remains a compelling surface biosignature because it arises as a general physical consequence of photosynthetic pigment systems rather than from any single metabolic pathway. Observations of Earth as an unresolved point source have established that the feature is detectable at the few-percent level, yet its amplitude is modulated by cloud cover, viewing geometry, and the fractional area of photosynthetically active surface. Temporal variability associated with seasonal cycles supplies an essential test against static mineral reflectance edges, while complementary signals, circular polarization induced by molecular homochirality, and chlorophyll or bacteriochlorophyll fluorescence, add orthogonal constraints that strengthen any claim of biogenicity.

Extrapolation beyond present-day Earth reveals both opportunities and limitations. Early photosynthetic communities (cyanobacteria, algae, lichens) could have generated a detectable red edge for a far greater fraction of planetary history than land plants alone. On ocean-dominated or land-scarce worlds, floating aquatic vegetation may produce an equally or more pronounced spectral discontinuity against a dark water background. Model calculations for tidally locked M-dwarf planets and for future direct-imaging observatories indicate that VRE-like features, or analogous sharp edges at wavelengths tuned to the local stellar spectrum, are in principle recoverable within practical exposure times under moderate cloud conditions. Nevertheless, the precise wavelength, strength, and temporal behavior of any extraterrestrial edge cannot be assumed a priori; search strategies must therefore remain open to time-variable discontinuities across a broad spectral range.

Ultimately, the absence of a red-edge signature does not constitute a null result for life, nor does its presence alone constitute definitive evidence. Robust remote biosignature assessment will require the simultaneous consideration of multiple spectral, polarimetric, and temporal diagnostics, informed by a deeper integration of ecological theory and by careful comparison with both biotic and abiotic laboratory analogues. Continued refinement of these multi-messenger approaches will be essential for interpreting the spectra of terrestrial-planet candidates expected from the next generation of space- and ground-based observatories.

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