Photosynthetically Active Radiation and Plant Light Use: Measurement, Physiology, and Canopy Dynamics

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***Abstract*—Photosynthetically active radiation (PAR), conventionally defined as electromagnetic radiation in the 400 to 700 nm waveband, is the primary energy input driving plant photosynthesis, biomass accumulation, and crop yield. Accurate characterisation of PAR interception and its fractional component (fPAR) is essential for predicting productivity across managed agricultural systems, from broadacre grain crops to orchard trees. This paper synthesises current understanding of PAR measurement techniques, canopy interception dynamics, and the physiological mechanisms by which plants convert intercepted photons into fixed carbon. Emerging research demonstrating that far-red photons (700 to 800 nm) can drive photosynthesis synergistically with conventional PAR wavebands has reopened debate about whether the 400 to 700 nm definition adequately captures the full photosynthetically useful spectrum. Evidence from controlled environment studies, canopy-level quantum yield experiments, and remote sensing retrieval methods is reviewed to assess the implications of an extended PAR definition for both measurement practice and agronomic modelling. The paper also addresses limitations in current fPAR retrieval methodologies, including the treatment of green and woody canopy components, and identifies the conditions under which spectral definitions, sensor technologies, and canopy models must be refined for reliable yield prediction and light use efficiency analysis.**

I. Introduction

Photosynthetically active radiation represents the portion of the solar spectrum that plant pigments absorb to drive the light-dependent reactions of photosynthesis, and it functions as the foundational energy currency linking solar input to biological productivity. In agricultural contexts, the fractional interception of PAR by a canopy (fPAR) is widely used as a predictor of crop yield, because the amount of incident radiation captured by leaf and canopy surfaces scales closely with the accumulation of dry matter over a growing season. A study on almond orchards demonstrated this relationship concretely: midday fPAR measured using a mobile lightbar platform correlated with dried kernel yield at approximately 57.9 lb per acre for every one percent increment in fPAR intercepted by the canopy at mid-season across multiple varieties [1]. This quantitative link between light interception and harvestable yield makes fPAR estimation a practical tool for crop management and precision agriculture, though it also exposes a dependence on measurement accuracy that becomes critical when low-cost or indirect sensing methods are substituted for direct quantum sensor arrays.

The measurement of PAR has evolved considerably from simple broadband quantum sensors toward a diverse toolkit that includes spectroradiometers, remote sensing platforms, and three-dimensional canopy models. In situ measurement using dedicated quantum sensors or spectroradiometers converts radiation in the 400 to 700 nm range into an electrical signal and expresses it as photosynthetic photon flux density (PPFD, in micromoles per square metre per second). This remains the mainstream approach in commercial and research applications because it accurately reflects the true radiation conditions at a measurement point with high temporal resolution [2]. However, in situ methods become impractical at spatial scales larger than individual plots, motivating interest in remote sensing retrievals and modelled estimates. Each approach carries its own sources of uncertainty, including sensor calibration drift, cosine response errors, and the difficulty of disaggregating sunlit from shaded canopy fractions, all of which propagate into yield estimates if not properly characterised.

Canopy architecture governs how PAR is spatially and temporally distributed across plant communities, and its effects cannot be fully captured by a single above-canopy measurement. Leaf area index (LAI), leaf angle distribution, vertical stratification of foliage, and planting density all interact to determine PAR transmittance at different depths within the canopy. Research in maize demonstrated that as LAI increased with higher planting densities, the upper canopy layers absorbed proportionally more radiation, reducing transmittance to lower strata, with minimum transmittance coinciding with peak LAI during the grain-filling period [3]. This vertical heterogeneity means that aggregate fPAR values, while useful for yield modelling, obscure within-canopy light competition, which influences both photosynthetic efficiency at the leaf level and the architectural strategies plants adopt to maximise photon capture. Understanding these dynamics is foundational before addressing the physiological question of which wavelengths plants can usefully convert to chemical energy.

II. Background and Scope

The conventional definition of PAR as radiation between 400 and 700 nm was established by McCree's action spectra work in the 1970s and has remained the operational standard for quantum sensors and photosynthesis models. However, accumulating evidence from controlled environment studies

has shown that far-red light (700 to 800 nm), while outside this boundary, is not photosynthetically inert. Far-red photons preferentially excite Photosystem I (PSI), and when delivered alongside shorter PAR wavebands that excite Photosystem II (PSII), they restore excitation balance between the two photosystems and measurably increase both quantum yield of PSII and net photosynthetic rate [4]. Experiments with lettuce demonstrated that supplementing a red-and-blue spectrum with far-red photons increased fresh mass and dry mass when the far-red photon flux density reached moderate levels, though the benefit was attenuated when red light was replaced entirely by far-red, because PSII excitation became limiting. This interaction reveals that far-red light acts through a synergistic rather than independent photosynthetic mechanism, which has direct implications for how controlled environment lighting systems should be designed and how PAR-based models should account for spectral quality beyond 700 nm.

The synergistic action of far-red photons has been examined at the canopy scale to determine whether their photosynthetic contribution is sufficient to warrant inclusion in an expanded PAR definition. Long-term studies comparing treatments in which far-red photons were substituted for an equivalent quantity of 400 to 700 nm photons found that canopy quantum yield for carbon dioxide fixation was equivalent between treatments, indicating that far-red photons absorbed by the canopy were equally efficient for photosynthesis when acting together with conventional PAR [5]. Critically, far-red light also increased total photon capture by the canopy, because it induced modest shade-avoidance responses that increased leaf expansion and canopy light interception area. The implication is that models relying solely on 400 to 700 nm photon counts may systematically underestimate the photosynthetic photon budget available to a canopy under natural or supplemented lighting conditions, particularly in the morning and evening hours when far-red wavelengths constitute a larger fraction of incident radiation.

The accumulated evidence from leaf-level and canopy-level studies has prompted formal calls to redefine the operational PAR waveband to include far-red radiation up to approximately 750 or 800 nm, giving rise to the concept of extended PAR (ePAR). Proponents of this redefinition argue that the 400 to 700 nm boundary is an artefact of historical sensor design and McCree's original action spectrum measurements on isolated leaves, and that it does not accurately represent the spectral sensitivity of an integrated plant canopy under field conditions [6]. Adopting ePAR as the standard would require recalibration of quantum sensors, revision of photosynthesis and crop growth models that use PAR as an input variable, and reinterpretation of long-term PAR datasets. The scope of this revision represents a significant practical barrier, and current consensus in the field has not yet converged on a single extended definition. This ongoing definitional debate sets the context for understanding why measurement methodology, canopy modelling, and physiological interpretation of light use efficiency all remain active areas of research.

III. Core Concepts and Mechanisms

The physiological response of plants to specific wavelengths within and adjacent to the PAR waveband is governed by the spectral absorption properties of the major photosynthetic pigments and the architecture of the two-photosystem reaction scheme. Chlorophyll a and b absorb strongly in the red (approximately 660 to 680 nm) and blue (approximately 430 to 450 nm) regions, while accessory pigments such as carotenoids extend absorption into shorter blue and ultraviolet wavelengths. The relative efficiency of different wavelengths in driving net carbon assimilation has been measured using action spectra and quantum yield curves, which show that red and orange wavelengths are most efficient on a per-photon basis, while blue photons, despite strong absorption, carry higher energy per quantum and drive photochemistry at somewhat lower quantum yields [7]. Green wavelengths, often assumed to be poorly used because of high leaf reflectance at the surface, penetrate more deeply into dense canopies than red or blue wavelengths and can drive photosynthesis in lower, shaded leaf layers, contributing meaningfully to whole-canopy light use efficiency. This wavelength-dependent penetration and absorption behaviour means that the spectral composition of incident radiation, not only its total quantum flux, influences how efficiently a canopy converts intercepted photons to fixed carbon.

Remote sensing provides a scalable means of retrieving fPAR across landscapes and agricultural regions, but the accuracy of these retrievals depends on how the spectral and structural complexity of real canopies is modelled. A persistent challenge is the contribution of non-green canopy components, including woody stems, branches, and senesced material, to the radiation interception signal. A remote sensing study demonstrated that algorithms which fail to account for woody and structural components can overestimate the fraction of PAR absorbed by green photosynthetically active tissue, leading to inflated estimates of canopy light use efficiency and potential errors in gross primary productivity models [8]. Spectral unmixing approaches that separate green, woody, and background signals improve retrieval accuracy but require either multi-spectral or hyperspectral imagery and more computationally demanding inversion procedures. The trade-off between retrieval accuracy and data and processing requirements constrains the operational deployment of high-fidelity fPAR products, particularly in heterogeneous or structurally complex canopies such as orchards, agroforestry systems, and sparse savanna vegetation.

LiDAR and hyperspectral sensing represent a convergent measurement frontier that addresses both the structural and spectral limitations of passive optical fPAR retrieval. LiDAR point clouds provide detailed three-dimensional canopy structure, enabling explicit modelling of light path geometry and shading within the canopy volume, while hyperspectral data resolve the spectral reflectance and absorptance properties of canopy components across narrow wavebands. Combining these two data sources to estimate fPAR has been shown to

outperform single-sensor approaches, with the structural constraint from LiDAR reducing the ill-posed nature of spectral inversion and improving the disaggregation of green from non-green absorbed radiation [9]. However, the cost and operational complexity of combined LiDAR-hyperspectral platforms remain barriers to routine agronomic use, and uncertainty propagation from individual sensor errors through the joint retrieval pipeline is not yet fully characterised. Reducing these barriers will require either cheaper sensor platforms, improved fusion algorithms, or validated empirical relationships between simpler proxy observations and full LiDAR-hyperspectral fPAR estimates across a range of crop species and growth stages.

IV. Evidence Synthesis

Taken together, the evidence from controlled environment physiology, canopy-scale quantum yield studies, and proposals for an extended PAR definition presents a consistent picture: the 400 to 700 nm waveband is a useful but incomplete description of the spectral range that plants convert to photosynthate. Research demonstrating that far-red light increases PSII quantum yield and whole-plant biomass when co-applied with red or blue light [4] aligns with canopy-level findings that substituting far-red for conventional PAR photons produces equivalent CO2 fixation per absorbed photon [5], and both bodies of evidence underpin the argument that ePAR, extending the definition to approximately 750 to 800 nm, is a more physiologically grounded standard than the classical 400 to 700 nm boundary [6]. This convergence across leaf, plant, and canopy scales strengthens the scientific case for reconsidering the PAR definition, though it does not yet resolve the practical and institutional challenges of updating the measurement infrastructure and modelling frameworks that agricultural science relies upon.

An important mechanistic nuance revealed by the experimental evidence is that the photosynthetic benefit of far-red light is strongly conditional on the concurrent supply of shorter PAR wavebands. When red light was eliminated and replaced entirely by far-red, lettuce fresh mass was not greater than in spectra lacking far-red, even though leaf expansion continued to increase [4]. This dissociation between leaf expansion and biomass accumulation illustrates that far-red acts primarily by enhancing PSI excitation and restoring the excitation balance between the two photosystems, rather than driving carbon fixation independently. The implication for the ePAR redefinition debate is that the photosynthetic value of far-red photons is context-dependent: it is high under natural or broad-spectrum lighting where conventional PAR photons are present, and it is low or absent when conventional PAR is severely limited. Models that treat ePAR photons as uniformly equivalent to 400 to 700 nm photons may overestimate productivity in conditions where spectral balance is skewed [5], and this caution should be incorporated into any revised quantum yield or radiation use efficiency framework.

The quantum yield equivalence observed at the canopy level for far-red substitution [5], combined with the theoretical argument that the ePAR definition better captures whole-canopy light use [6], suggests that crop models relying on radiation use efficiency (RUE) coefficients calibrated against conventional PAR measurements may require revision when applied to environments with altered spectral composition, such as glasshouses using LED supplemental lighting, or field crops under canopies with high far-red enrichment from neighbour shading. The magnitude of error introduced by using a 400 to 700 nm basis in such environments has not yet been systematically quantified across major crop species, representing a gap between the physiological evidence and its integration into operational agronomy.

V. Practical Implications and Limitations

The practical consequences of the PAR redefinition debate extend to the design of indoor and controlled environment agriculture systems, where growers routinely specify PPFD targets and light spectra for commercial plant production. If the ePAR concept is accepted, growers using LED systems that include far-red channels would need to reassess their PPFD setpoints and energy use calculations, because an ePAR-based PPFD figure would differ from a conventional 400 to 700 nm PPFD figure even for the same fixture [5]. The argument for ePAR also implies that lighting systems optimised solely on conventional PPFD may inadvertently undervalue the productivity gains achievable from modest far-red supplementation [6]. At the same time, the wavelength-specific physiological effects documented in the literature [7], including the role of red and far-red balance in regulating shade-avoidance responses, anthocyanin synthesis, and chlorophyll concentration, mean that growers cannot simply maximise ePAR photons without considering the spectral composition and its morphological consequences, such as reduced leaf pigmentation or excessive stem elongation in light quality-sensitive species.

For field-scale remote sensing and crop modelling, the limitations of current fPAR products impose constraints on the accuracy of productivity estimates, carbon flux calculations, and yield forecasts. The challenge of separating green absorbed PAR from non-photosynthetically active absorbed radiation in structurally complex canopies [8] becomes particularly acute in orchards, agroforestry systems, and sparse or mixed canopies, where woody area index is a significant fraction of total plant area index. Conventional vegetation indices used to infer fPAR from satellite imagery do not reliably distinguish green from woody components, and their performance varies with canopy cover, illumination geometry, and background soil reflectance. Addressing these limitations requires either more physically rigorous radiative transfer inversions constrained by structural data [9], or the development and validation of empirical correction factors specific to different canopy types, neither of which is yet available as a routine operational product for the full range of agricultural and ecosystem contexts where PAR-based productivity estimates are needed.

A further limitation is the spatial and temporal scale mismatch between the high-resolution measurements needed to resolve within-canopy PAR dynamics and the coarser resolution

of most operational remote sensing products. Research demonstrating that LAI-driven changes in vertical PAR distribution within maize canopies are closely tied to yield outcomes [3] implies that vertically integrated fPAR measurements can obscure productivity-relevant variation in light distribution across canopy layers. Validating remote sensing retrievals against ground-truth fPAR measurements therefore requires sampling designs that capture vertical canopy structure, not only above-canopy and below-canopy PAR differences, a requirement that increases measurement effort substantially and is rarely met in standard agronomic monitoring programmes. Closing this validation gap is a necessary condition for confident deployment of remote sensing fPAR products in precision agriculture decision systems.

VI. Conclusion

This paper has reviewed the measurement, physiological basis, and canopy dynamics of photosynthetically active radiation, drawing on evidence from quantum sensor technology, canopy interception studies, controlled environment physiology, and remote sensing retrieval methodology. The evidence consistently supports the view that PAR interception is a strong predictor of plant growth and yield, and that fPAR measured at the canopy scale provides a practical basis for agronomic management and productivity modelling. At the same time, the accumulated physiological evidence for far-red photon contributions to photosynthesis at both leaf and canopy scales challenges the adequacy of the classical 400 to 700 nm definition, and the case for an extended ePAR standard is scientifically grounded even if institutional adoption remains pending. Accurate fPAR retrieval from remote sensing platforms is constrained by structural canopy complexity, non-green component contributions, and the high cost of combined LiDAR-hyperspectral sensing, all of which limit the routine deployment of high-fidelity PAR-based productivity products.

The highest-value directions for future work include systematic quantification of the productivity error introduced by using conventional 400 to 700 nm PAR in models applied to LED-supplemented or far-red-enriched environments, development of operationally deployable fPAR retrieval algorithms that adequately account for woody and structural canopy components across major crop and ecosystem types, and multi-species validation studies that link within-canopy PAR distribution to yield at a resolution sufficient to inform precision management. Progress on these fronts would enable PAR-based models to serve with greater confidence across the range of environments, spectral conditions, and canopy architectures encountered in modern agriculture and land surface science.

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