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Mini Review

Photosynthetically Active Radiation Dynamics: Implications for Grassland Productivity, Phenology, Carbon Cycling and Ecosystem Management

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Abstract: Ecosystem functioning depends on an integrated system of environmental factors that are directly or indirectly influenced by photosynthetically active radiation (PAR). The objective of this review is to synthesize and analyze grassland productivity dynamics as influenced by PAR as the primary factor influencing grassland productivity. The methodology followed a conceptual gap analysis of related literature. A PAR-Water-Structure framework was developed to propose how the grassland ecosystem drivers interact cohesively to explain the hierarchy of efficiency for Gross Primary Production (GPP). The key findings include confirmation that PAR seasonal variations are influenced by vegetation structure, water availability and PAR utilization efficiency. The narrative approach used in the study allowed conceptualization to provide a holistic understanding that can be used to relate PAR- ecosystem interactions in grassland ecosystems to other biomes. Significantly, the study also highlights the importance of alignment of management practices such as grazing and restoration with PAR ecophysiology regimes. It is recommended that the PAR-Water-Structure framework is essential for understanding existing models and contributes new perspectives to the understanding PAR dynamics in the context of sustainable grassland ecosystem management. The new perspective is important to inform strategies for changing climatic conditions affecting grassland ecosystems and other biomes.

Keywords: photosynthetically active radiation; grasslands, productivity; ecosystem dynamics; climate variability

1. Introduction

The ecological significance of grasslands can be demonstrated by the extensive area cover on Earth. According to the different classification criteria, approximately 20–40% of the terrestrial land surface is constituted by grassland biomes (Knapp et al., 2008; Monteith, 1972; Running et al., 2004). This is an indication of the crucial role of grassland ecosystems in conservation of biodiversity. In the context of this study, it is important to note that the role can be linked to the soil-plant-atmosphere sustainability. For example, carbon sequestration contributes to soil stabilization. Consequently, plant water and energy use efficiencies can influence gross production potential. Sustainable livelihood benefits can be measured in terms of optimum rangeland and agriculture production systems.

Grassland ecosystem resilience is not enough to protect it from vulnerabilities associated with climate change, poor land use practices (NASA Earthdata). In this context, it is notable that variations in solar radiation are important. Photosynthetically active radiation (PAR) represents a small fraction of solar energy (400-700). However, it represents the primary role in its influence on photosynthesis (Monteith, 1977; Stocker et al. 2020). The influence places PAR in a position of the central driver of grassland ecosystem performance, which is characterized by integration of energy capture (e.g., radiation use efficiency), plant canopy structure (e.g., leaf area index), water use efficiency, carbon assimilation and overall ecosystem productivity. Evidence of such integration can be explained by using well-established crop simulation models. For example, the Monteith model can be used to show a significant relationship between energy source (PAR) and gross production potential (GPP) in a linear fashion when growth conditions are not limiting (Monteith, 1977). However, grassland ecosystem environmental conditions do not occur in a constant linear integration. The natural spatial and temporal variability requires consideration of multidimensional models to predict ecosystem response to constant environmental changes. This creates the special need to understand PAR as a primary factor in ecosystem modelling.

The seasonal and terrestrial variables influencing solar radiation intensity and duration affect energy availability in ecosystems (Field et al., 1995). Research has established that photosynthetic activity is related to day length and solar angles, which explains seasonal variability in ecosystem productivity. Events are mainly due to physiological processes (e.g., respiration, transpiration) and shown as phenological changes (e.g., germination, leaf emergence, vegetative growth stages, flowering, senescence) (Knapp et al., 2002; Noy-Meir, 1973; Pei et al., 2022; Potter et al., 1993). The integrated phenomena determine ecosystem species composition, function and sustainability. Adaptation to changes by different plant species can be explained by availability and intensity of light. Since PAR is sensitive to minor variations, it becomes necessary for plants to use short-term niches of energy availability effectively to avoid serious impacts of seasonal change. In this context, interaction of species and typical community structure can be used to explain ecosystem stability and resilience. Optimum use of soil and atmospheric resources under different climatic conditions become major indicators of ecosystem classification within a biome, despite major patterns in climatic variations. Since PAR is influenced by complex interactions with climate and other processes of the ecosystem, it is necessary to consider integrated methods of explaining its relevance in grassland ecosystem management.

Existing empirical evidence can benefit future research. Hence, this study is designed as a narrative review. The approach is suitable for examining a broad base of research topics with a directed focus on PAR dynamics in grassland ecosystems in the context of identifiable management options. The approach is well grounded in literature in that it creates opportunities for flexible interpretation of existing frameworks to establish new models on a robust theoretical basis. The important aspect of valid contribution to new knowledge can be explained on the basis of critical themes and gaps in knowledge due to the diversity of sources of information (Xiao et al., 2004; Zhao et al., 2005). It is important to realize that a narrative review provides the advantage of integration of empirical, theoretical and methodological studies to establish a comprehensive understanding of complex phenomena which prevail in ecological systems. The heterogeneity of research and multiple disciplines related to PAR include many disciplines such as plant physiology, land use, climatology, ecology and remote sensing. Hence, the choice of standardized quantitative synthesis is not feasible for creating conceptual relationships required to understand ecosystem dynamics and establishment of new model foundations (Mercado et al., 2009; Medlyn et al., 2011; Bonan et al., 2014; Ball et al., 1987).

Therefore, the aim of this study was to develop a grassland management and productivity understanding that is informed by synthesis of established PAR dynamics. Reliance on findings from relevant research and their integration using ecological theory is the principal proposition to support the suitability of narrative synthesis methodology.

2. Methodology

A structured narrative synthesis was used to determine evidence of relevant literature from a multidisciplinary perspective. The study used a search string approach to identify literature from reliable sources using Scopus, Web of Science, Google Scholar and ScienceDirect databases. Targeted disciplines included ecology, environmental science, climatology, remote sensing, crop modelling and ecosystem modelling. The study focused primarily on publications from 2000–2026. The search string used a combination of keywords—Photosynthetically active radiation, PAR, Radiation Use Efficiency, Grassland productivity, Carbon cycling, Remote sensing, Biomes, Ecosystems, Light Use Efficiency, Phenology. This approach led to a large literature capture. Consequently, priority was given to studies addressing the five thematic fields (Figure 1).

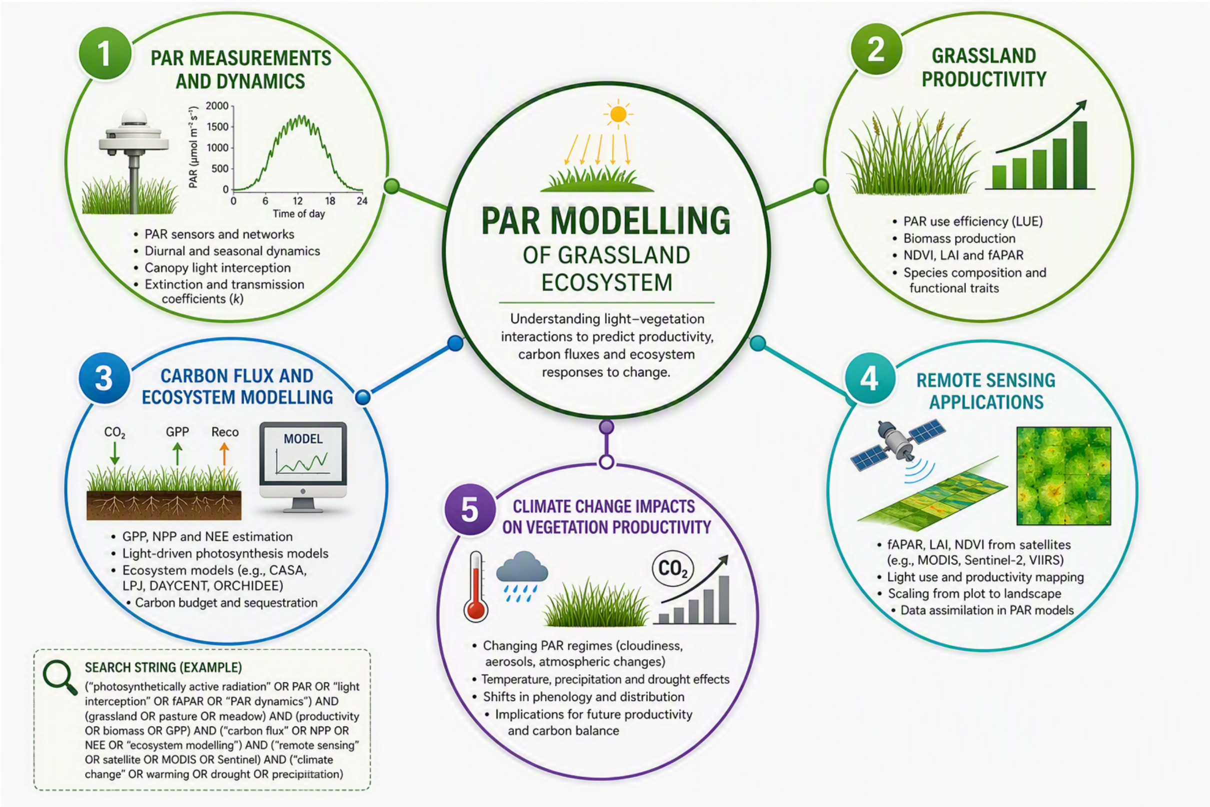

Figure 1. Five research domains of literature search strategy for PAR modelling in grassland ecosystems based on primary data sources: field measurements, flux tower observations, satellite remote-sensing products, climate databases, and vegetation surveys. Source: AI adaptation from the PAR productivity framework of Monteith (1972, 1977), integrating concepts from MODIS-based productivity modelling (Running et al., 2004), ecosystem carbon flux theory (Baldocchi, 2003), and climate change impacts on grassland ecosystems (Fang et al, 2023).

The study screened 230 publications. For qualitative synthesis, 118 studies were selected for qualitative synthesis. Results were clustered as findings to create thematic categories (Figure 1). Instead of aggregating the studies statistically, the thematic categories were evaluated based on context: ecosystem applicability, environment context, spatial scale, and methodological approaches. The method allowed for establishment of the review focus explained in a conceptual gap-analysis framework to identify areas where knowledge remains incomplete, particularly regarding PAR-water-carbon interactions within grassland ecosystems.

3. Results and Discussion

3.1. Seasonal Dynamics of Photosynthetically Active Radiation

Seasonal variability affects photosynthetically active radiation (PAR). In the context of South Africa the changes are influenced by both atmospheric and plant components, including geographical position and ecosystem-specific vegetation structure. South Africa encompasses nine biomes: Savanna, Grassland, Fynbos, Nama Karoo, Succulent Karoo, Forest, Thicket, Desert, and Albany Thicket. Each biome has significantly distinct PAR regimes which influence d ecological responses (Midgley et al., 1997; Mucina and Rutherford, 2006; Van Rooyen et al., 2008; Vlok et al., 2003). Summer (October–March) is the period when the majority of biomes have elevated PAR due to higher solar energy intensity and long days. The Savanna and Grassland biomes, experience a high PAR coinciding with the rainy season. This results in high gross primary productivity (GPP) (Mucina and Rutherford, 2006). Winter (May–August) has reduced PAR, associated with shorter day-length and lower GPP. Therefore, seasonal variability affects biome sustainability in terms of primary production levels in response to PAR.

However, radiation effects must be considered from the perspective of an integrated ecosystem performance drivers. This approach justifies why South African biomes (Figure 2) can be viewed collectively in terms of the interaction of solar energy, water availability and vegetation structure (Figure 2; Table 1). A clear explanation of this view can be provided by considering the Fynbos biome. It is characterized by high incident PAR in summer, representing Mediterranean-type ecosystems, but its photosynthetic efficiency is reduced by persistent seasonal drought. This causes a decoupling of light availability and carbon assimilation (Midgley et al., 1997; Mucina and Rutherford, 2006; de Oliveira et al., 2025). Radiation-rich environments are found in the Succulent Karoo and Desert biomes globally, but GPP is low due to significant water. Hence, ecosystem performance is characterized by Crassulacean Acid Metabolism (CAM) and succulence, which are useful for water-use efficiency, but light capture is compromised. This leads to underutilization of PAR (Mercado et al., 2009; Ball et al. 1987). By comparison, the Forest biome shows stable above-canopy PAR inputs. Dense vertical vegetation structure causes significant light penetration pathways. This enhances the capacity of leaf area index (LAI) to regulate light penetration and improve GPP. The drivers of high ecosystem performance include efficient canopy stratification and water availability, which is associated with tropical and temperate forest biomes (Reinermann et al., 2025). The Albany Thicket biome should be viewed as an intermediate system. It is characterized by an evergreen canopy structure which mitigates the negative effects of seasonal variation on PAR while preventing significant water limitation. The consequence is that GPP performance is relatively stable and compares well with subtropical biomes, where structural complexity is important for resilience (Running et al., 2004). The Nama Karoo biome has a pulse-driven productivity where a high PAR effect can be diminished by erratic rainfall. The consequence is a significant interannual variability in GPP. This reflects non-equilibrium dynamics which are similar to those that are found in semi-arid rangelands (Siad et al., 2019; Tolomio and Casa, 2020; Larcher, 2003). Desert and Karoo biomes are arid systems that can maintain long-term high PAR levels due to low cloud cover and atmospheric moisture. Their productivity is limited by low water availability. Forest biomes are characterized by minimal variability associated with canopy interception and internal light stratification. This biome has high summer PAR. Its photosynthetic output is reduced due to drought stress (Allen et al., 1998).

When considered together, the South African biomes demonstrate important ecological principles

(i) Ecosystems that have a coincidental occurrence of high energy and water limitation (e.g., Succulent Karoo) have a productivity constraint due to hydrological deficits.
(ii) Structurally complex ecosystems are rich in water availability (e.g., Forest), however, their productivity is significantly controlled by PAR partitioning within canopies.
(iii) Seasonally dry ecosystems (e.g., Fynbos), have temporal misalignment of radiation and water availability, which can reduce carbon gain.
(iv) There are transitional ecosystems (e.g., Thicket and Nama Karoo), where buffering and variability dynamics influence ecosystem stability.

This finding is significant because it explains the importance of patterns that influence the integrated water–energy–structure interactions in ecosystems. This is important for ecosystem function and resilience under changing climatic conditions.

Table 1. Comparative light-water constraints on photosynthetic productivity across South African biomes. PAR = Photosynthetically Active Radiation. MAP = Mean Annual Precipitation. LAI = Leaf Area Index. GPP = Gross Primary Productivity.

Biome	GPS (Lon, Lat)	PAR (μmol m^{-2} s^{-1})	MAP (mm yr^{-1})	LAI (m^2 m^{-2})	GPP (gCm^{-2} yr^{-1})	Water Limitation	Structural Characteristic
Fynbos	18.5° E, 33.5° S	High (summer peak)	250–600	1–3	Moderate	Strong seasonal drought	Sclerophyll shrubland
Succulent Karoo/Desert	19.5° E, 30.5° S	Very high (annual)	<200	<1	Low	Extreme	Sparse, succulent-dominated
Nama Karoo	23.5° E, 29.0° S	High, variable	100–400	<2	Variable	Highly variable rainfall	Open shrubland (non-equilibrium)
Albany Thicket	26.5° E, 32.0° S	Moderate	300–700	3–5	Moderate–high	Moderate	Dense evergreen canopy
Forest	30.0° E, 26.0° S	Moderate (filtered)	800–1200+	5–8	High	Low	Closed, stratified canopy

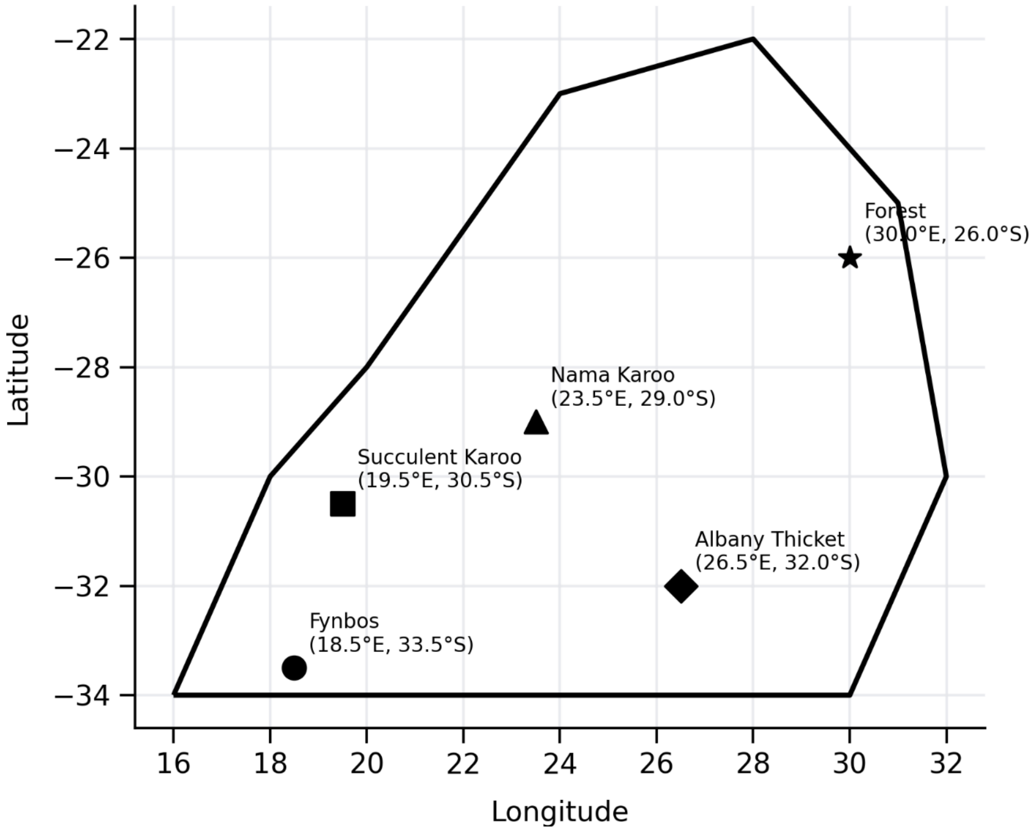

Figure 2. Spatial distribution of major South African biomes for comparative analysis of ecological processes across climatic and structural gradients. Redesigned (MODIS GPP and NPP algorithms).

3.2. Potential Effects of PAR on Grassland Productivity

Research on productivity frameworks identifies PAR as the primary determinant of photosynthesis and biomass production. Evidence synthesized across South African biomes shows that radiation availability alone cannot explain observed variations in ecosystem productivity. Hence, ecosystem functioning must be explained by interactions among three critical controls: energy availability (PAR), water availability, and vegetation structure. It is on this fundamental basis that this study proposes the PAR-Water-Structure (PWS) framework shown in Figure 3. The emphasis is that ecosystem productivity is regulated by simultaneous interactions of these three controls and the PAR effect alone is not useful.

The framework should be viewed as extending traditional PAR-productivity relationships by integrating hydrological and structural controls. This approach provides a mechanistic basis for understanding productivity differences across South African biomes for grassland ecosystem modelling. The study suggests that the PWS framework extends the classical Monteith Light Use Efficiency concept by explicitly incorporating water limitation and structural ecosystem controls. This is a new perspective that offers a more mechanistic understanding of ecosystem functioning by providing a conceptual basis for research in next-generation grassland productivity models.

The significance of an integrated explanation of ecosystem performance (Figure 3) recognises that PAR has a fundamental control on vegetation growth, ecosystem productivity, and biogeochemical carbon cycling (Table 2). This is clear from the ecosystem scale perspective of modelling. Gross primary production (GPP) is generally modelled using light-use efficiency (LUE) attributes where productivity is expressed as a function of incident PAR. In this context, the fraction of PAR absorbed by vegetation (FPAR), and the efficiency with which plants convert absorbed light into biomass are fundamental. The phenology of vegetation, timing of leaf emergence, plant growth and maturation, play a critical role in terms of regulatory components of the process. They determine canopy structure (e.g., leaf area index), control radiation interception and carbon exchange dynamics. These phenological processes are significantly sensitive to climate change drivers such as temperature and radiation variability.

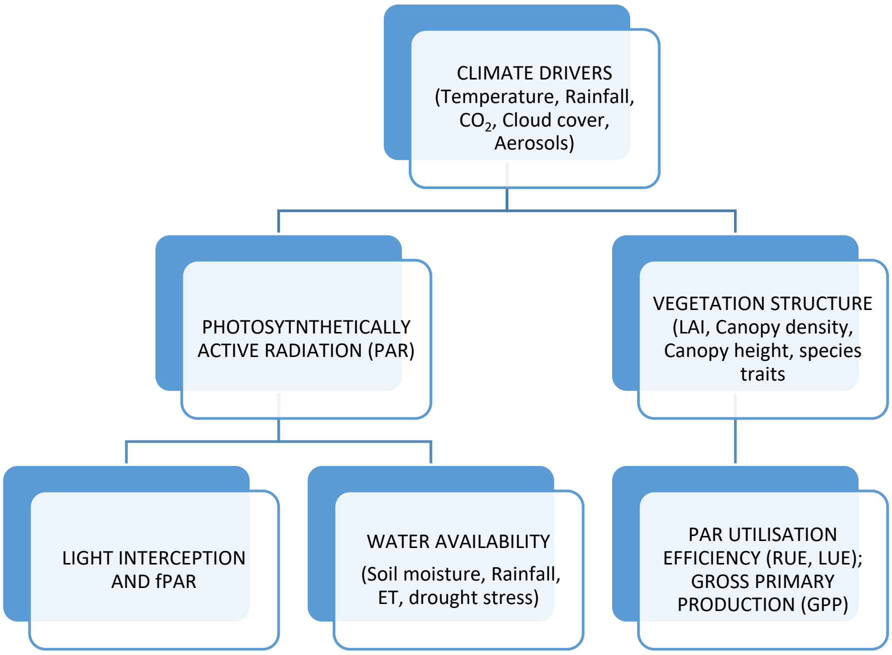

Figure 3. Proposed PAR-Water-Structure (PWS) framework for grassland ecosystem functioning. PAR provides the energy required for photosynthesis. Water availability determines the ability of plants to utilize intercepted radiation through regulation of stomatal conductance and carbon assimilation. Vegetation structure controls canopy light interception, radiation distribution, and overall light-use efficiency through parameters such as leaf area index (LAI), canopy height, and canopy stratification. Source: Author-generated Microsoft Word SmartArt design.

Table 2. Crop and Water Relations Models Justification.

Descriptor	PAR Role	Processes	Integration Approach	Expected Outputs	Models
Grassland Plant Phenology	PAR regulates photosynthesis timing and seasonal growth transitions (budburst, flowering, senescence)	Leaf emergence, canopy expansion, flowering cycles, senescence	Couple PAR with temperature (Growing Degree Days, GDD) and photoperiod within phenology sub-models; integrate remote sensing FPAR/NDVI	Start/end of growing season, LAI, phenological stages	Phenology models, MODIS LAI/FPAR products
Ecosystem Carbon Dynamics	PAR drives Gross Primary Production (GPP) through Light Use Efficiency (LUE) frameworks	Photosynthesis, autotrophic & heterotrophic respiration, Net Ecosystem Exchange (NEE)	Implement PAR × FPAR × LUE formulations with environmental stress scalars (temperature, VPD, soil moisture)	GPP, NEE, carbon sequestration, carbon balance	CASA, VPM, P-model
Grassland Productivity (Biomass)	Determines energy input for photosynthesis and biomass accumulation	Biomass growth, dry matter accumulation, forage production	Radiation Use Efficiency (RUE) or APAR-based models linking biomass to absorbed PAR (APAR)	Aboveground biomass, yield, pasture productivity	RUE models, APSIM pasture
Climate Change Interactions	PAR variability from clouds, aerosols, and atmospheric changes affects productivity and phenological sensitivity	Phenological shifts, extended growing seasons, stress responses, acclimation	Integrate PAR with climate drivers (CO_2, temperature, precipitation, soil moisture) in DGVMs and Earth System Models	Changes in phenology, productivity trends, resilience, feedbacks	DGVMs (LPJ, ORCHIDEE), Earth System Models
Water–Carbon Coupling	PAR influences transpiration indirectly via stomatal conductance and photosynthetic demand	Evapotranspiration, stomatal regulation, water-use efficiency (WUE)	Link PAR-driven photosynthesis with stomatal conductance models (e.g., Ball–Berry, Medlyn) and soil moisture modules	Evapotranspiration (ET), WUE, drought response indicators	Coupled photosynthesis–hydrology models, SPA, CLM

Dominant environmental constraints and objectives are important in model selection. Their consideration is crucial for integrating PAR with plant and environment components. Plant phenology influences canopy structure for radiation use efficiency. Carbon dynamics influence respiration and transpiration (aerial) and mineral and biological quality (soil). Water relations influence evapotranspiration. (Table 3). In environments which are characterized by water limitations, AquaCrop and

SWAT models are suitable. These models have strong representation of soil moisture dynamics, evapotranspiration, and hydrological processes, which are crucial in situations where water availability is the main driver of productivity. When integration of crop-climate-carbon modelling is the main objective, DSSAT and APSIM offer more robust frameworks. They are capable of simultaneous simulation of phenology, biomass accumulation, and soil–plant–atmosphere interactions. This enables comprehensive system-level analysis. The framework proposed in the current study suggests that when the focus is on PAR-driven productivity and phenology, WOFOST and APSIM are particularly valuable. They accurately incorporate radiation interception and light-use efficiency processes, which are central to biomass formation. SWAT is more suitable at broader spatial scales, particularly for landscape or watershed ecosystem analysis. Its applicability is associated with the capability to simulate interactions among hydrology, vegetation growth, and land-use change across heterogeneous terrains.

Table 3. Model integration layers for PAR-Crop-Water system nexus.

Layer	Purpose	Recommended models	Key variables integrated	Typical outputs
PAR–Phenology	Captures vegetation dynamics and seasonal development driven by radiation, temperature, and photoperiod	Remote sensing LAI/FPAR products (MODIS, Sentinel), process-based phenology models	PAR, FPAR, temperature (GDD), photoperiod	Phenological stages, LAI, growing season timing
Carbon (GPP/NEE)	Quantifies carbon assimilation and exchange using light-driven productivity models	Light Use Efficiency (LUE) models: CASA, VPM, P-model	PAR, FPAR/APAR, LUE, temperature, VPD, soil moisture	Gross Primary Production (GPP), Net Ecosystem Exchange (NEE), carbon balance
Biomass/ Productivity	Simulates crop/grassland growth and yield based on radiation interception and resource use efficiency	APSIM, WOFOST, RUE/APAR-based models	Absorbed PAR (APAR), radiation use efficiency (RUE), nutrients, water availability	Biomass accumulation, yield, forage production
Water	Estimates water balance, evapotranspiration, and drought responses interacting with plant growth	AquaCrop, FAO-56 ET model, SWAT	ET_0, soil moisture, rainfall, crop coefficients (Kc), PAR-driven transpiration	Evapotranspiration (ET), soil water balance, irrigation requirements
Integrated System	Combines carbon, water, and crop growth processes for whole-system simulation and decision support	DSSAT, APSIM–SWAT coupling frameworks, Earth system model linkages	PAR, climate variables, soil water, nutrients, CO_2	Crop yield, water productivity, system resilience, scenario analysis

Distinction between direct and diffuse radiation is emerging as a new PAR research area. Typical ecosystem productivity studies generally assume that all PAR contributes equally to photosynthesis. However, recent research demonstrates that diffuse radiation may enhance canopy-scale productivity. This is due to scattered light penetration deeper into vegetation canopies to reach shaded leaves and increase illumination. Diffuse radiation penetration improves whole-canopy photosynthetic efficiency without the need to increase total incoming PAR (Li et al., 2025; Li et al., 2026). The effect is important in grassland ecosystems that are characterized by spatially heterogeneous canopies and mixed species assemblages. Under predominantly cloudy conditions or moderate aerosol loading, increased diffuse radiation enhances light distribution throughout the canopy This has a potential to increase gross primary production and improve radiation-use efficiency (RUE). Most Grassland GPP models, including CASA and several light-use efficiency approaches, primarily utilize total PAR measurements and do not explicitly distinguish between diffuse and direct radiation components (Netsianda and Mhangara, 2025). There is uncertainty regarding how future changes in atmospheric composition, cloud dynamics, and aerosol concentrations may alter diffuse radiation fractions and influence grassland productivity under climate change. Incorporating diffuse PAR into ecosystem productivity models represents an important opportunity to improve predictions of carbon sequestration and ecosystem resilience (Deng et al., 2026).

3.3. Strategic Recommendation for the PAR–Grassland Framework

For PAR–grassland system that is developing, a hybrid modelling approach is recommended because it captures the complex interactions of radiation, phenology, carbon, and water dynamics. By combining WOFOST or APSIM with SWAT or AquaCrop modelling provides a complementary system and depiction of radiation-driven processes (PAR interception, phenology, biomass accumulation) is effectively coupled with water balance and hydrological realism (soil moisture, evapotranspiration, runoff). The integrated approach improves the capacity to simulate both productivity and resource constraints under climate variability. In addition, incorporating a light-use efficiency (LUE)-based carbon model, such as the P-model, allows for scaling ecosystem carbon fluxes (e.g., GPP and NEE) and improves representation of climate–carbon feedback mechanisms. This method supports strong analysis of grassland productivity, carbon sequestration, and water-use efficiency under conditions of changing climate variables.

For grassland ecosystems, it is important to align grazing periods with peak Photosynthetically Active Radiation (PAR) availability to ensure maximum plant growth improve forage utilization efficiency. This prevents overgrazing during periods of low productivity. For restoration, selecting plant species that are adapted to local light (PAR) regimes enhances successful establishment and improves resilience to environmental stress, which supports long-term ecosystem recovery. Combining remote sensing tools such as satellite data with field-based measurements improves monitoring systems and continuous tracking of seasonal productivity patterns and vegetation health. It is suggested that effective grassland management requires an integrated strategy that considers the interaction of PAR with climatic factors such as temperature and rainfall, as well as soil properties including nutrient availability and moisture. This is a holistic approach which helps to optimize ecosystem services, including carbon sequestration and biodiversity. It can be expanded for different purposes guided by comparison of existing models (Table 4).

Table 4. Critical comparison of modelling approaches. Sources: Khoza et al., 2026; Netsianda and Mhangara, 2025; Tolomio and Casa, 2020).

Model	**Main Application**	**Strengths**	**Limitations**	**Data Demands**	**Grassland Suitability**
CASA	Carbon productivity	Simple, scalable	Sensitive to FPAR uncertainty	Moderate	High
VPM	GPP estimation	Good physiological basis	Requires calibration	Moderate	High
P-model	Carbon cycling	Optimality-based approach	Newer model, limited validation in Africa	Moderate	Very High
APSIM	Productivity and management	Strong grazing simulations	High parameterization	High	Very High
DSSAT	Crop production	Mature platform	Less adapted for natural grasslands	High	Moderate
WOFOST	Radiation-use efficiency	Explicit PAR formulation	Limited ecosystem complexity	Moderate	High
SWAT	Hydrology and vegetation	Strong watershed integration	Weak physiology representation	High	Moderate
APSIM-SWAT	Integrated system	Water-carbon-productivity nexus	Computationally intensive	Very High	Excellent

It is shown in Table 4 that no single modelling approach is capable of adequately representing the complex interactions among photosynthetically active radiation (PAR), vegetation phenology, carbon dynamics, and water availability within grassland ecosystems. Light-use efficiency models (CASA, VPM, and the P-model) are effective for estimating gross primary productivity and carbon fluxes. They clearly incorporate PAR absorption and conversion into biomass. However, the performance of these models is influenced by uncertainties in fAPAR estimation and environmental stress parameters. Therefore, process-based models such as APSIM, WOFOST, and DSSAT provide a more detailed representation of plant physiological processes, phenological development, and management interventions, which makes them more suitable for evaluating grazing and productivity responses (Liu et al., 2025). Hydrological models such as SWAT excel are recommended for representing soil moisture dynamics, runoff, and catchment-scale water processes, although they simplify vegetation physiological responses. Hence, integrated modelling frameworks that combine ecosystem productivity, carbon cycling, and hydrological processes (e.g., APSIM-SWAT couplings) offer a better potential for grassland research because they capture the coupled effects of radiation, water limitation, and vegetation structure (Christofi et al., 2025; Cao et al., 2025). The model comparison highlights an important knowledge gap in current grassland modelling: the need for operational frameworks that simultaneously represent PAR utilization, hydrological constraints, and ecosystem structural characteristics, which forms the basis of the proposed PAR-Water-Structure framework developed in this review.

3.4. Knowledge Gaps and Research Priorities

The relationship between PAR and photosynthesis is well established, but there still significant certainties regarding the mechanisms through which changing radiation environments influence ecosystem functioning. Existing studies predominantly quantify total PAR and generally neglect the ecological importance of diffuse radiation. Evidence presented in the current study demonstrates that diffuse PAR can enhance canopy-scale photosynthesis through improved light penetration, although this process remains poorly represented in most production models (Christofi et al., 2025). Current remote sensing products estimate productivity indirectly through vegetation indices rather than direct physiological measurements. The current study suggests that Sentinel-2 and machine learning approaches have improved biomass estimation accuracy substantially, however, uncertainties remain in transferring models across heterogeneous grassland systems (Pei et al., 2022). Despite their ecological and socio-economic significance, African grasslands remain underrepresented in global productivity studies (Deng et al., 2026). Therefore, future research should prioritize integrated monitoring frameworks by linking PAR, fAPAR, GPP, biomass, carbon sequestration, and ecosystem services for improved interpretation.

3.5. From Descriptive Relationships to Mechanistic Understanding

This review contributes an important insight that PAR does not function as an independent driver of productivity. Productivity is a result of a three-way interaction between energy availability (PAR), water availability and vegetation structure. Comparison of biomes shows that similar PAR levels can generate markedly different productivity outcomes. These can be explained in the following contexts:

(i) Succulent Karoo receives abundant PAR but exhibits low productivity because water limits photosynthesis.
(ii) Forest systems exhibit lower within-canopy PAR but achieve higher GPP through efficient canopy stratification.
(iii) Grasslands occupy an intermediate state where productivity depends strongly on synchronization between PAR and rainfall.

The synthesis presented in this study provides a view showing that ecosystem functioning should be explained through a PAR-Water-Structure framework rather than radiation alone.

4. Future Research Directions

Substantial advances in understanding photosynthetically active radiation (PAR) and ecosystem functioning exist, but more scientific and methodological challenges remain unresolved. A significant shift in future research should move beyond simple radiation-productivity relationships and to integrated assessments that simultaneously consider PAR dynamics, water availability, vegetation structure, and climate variability. New direction is recommended.

4.1. Quantifying Diffuse and Direct PAR Separately

Existing research continues to use total PAR as the primary predictor of productivity. However, there is evidence that diffuse radiation can contribute disproportionately to canopy photosynthesis by improving light penetration into lower canopy layers and reducing light saturation in upper leaves. Aerosol concentrations, cloud cover, and atmospheric scattering alter the balance between direct and diffuse radiation, but these mechanisms are poorly represented in grassland productivity models. Future research should quantify how diffuse PAR affects light-use efficiency across contrasting grassland systems and environmental conditions.

4.2. Integration of New Remote Sensing Technologies

Recent research on satellite platforms provides new opportunities for monitoring PAR-driven ecosystem processes. For example, Sentinel-2, GEDI LiDAR and solar-induced chlorophyll fluorescence (SIF) datasets allow direct estimation of photosynthetic activity instead of relying solely on vegetation indices. Future research should integrate these products into operational monitoring frameworks for grassland ecosystems. Improved performance in biomass estimation, productivity assessment and grassland classification has been shown in machine learning models.

4.3. Development of PAR-Water-Carbon-Ecosystem Models

Current modelling approaches are less integrated. They generally represent carbon, vegetation, and hydrological processes separately. Future research should shift towards integrated modelling systems that are capable of simulating feedbacks among PAR, photosynthesis, soil water, biomass accumulation, and ecosystem resilience. The benefit will be a better understanding of semi-arid grasslands, because they are predominantly characterized by a productivity that depends on interactions between energy supply and moisture availability rather than either factor alone.

4.4. Addressing Geographic Biases in Global PAR Research

Predominantly, PAR-related ecological research is conducted in North America, Europe, and East Asia, while African grassland ecosystems remain comparatively understudied. To extend knowledge, long-term monitoring networks across South African grasslands could improve understanding of climate change impacts on productivity, phenology, and carbon sequestration. The major benefit would be the development of datasets that validate global productivity models under diverse ecological conditions.

4.5. Climate Change and Phenological Mismatches

Climate change decouples seasonal PAR peaks from periods of optimal temperature and rainfall. This creates phenological mismatches which alter productivity, forage availability, and ecosystem resilience. Future studies should be designed to evaluate whether grassland communities can adapt to changing seasonal synchrony among radiation, moisture, and temperature drivers.

5. Conclusions and Perspectives

Photosynthetically active radiation is a fundamental determinant of grassland ecosystem structure, productivity, and resilience. Seasonal variability is central in developing integrated models to better understand the complexity of grassland ecosystems. This study provides a new insight by demonstrating that PAR is not only central in photosynthetic processes and biomass production, but also controls phenological patterns, species interactions, and carbon cycling dynamics across diverse grassland ecosystems. However, the ecological influence of PAR is significantly mediated by interactions with temperature, soil moisture, and nutrient availability. This emphasizes the need for integrated approaches to understanding ecosystem responses. The study also demonstrates that effective grassland management should incorporate seasonal PAR dynamics together with climatic and edaphic factors. For management, it is suggested that strategies which synchronize grazing with peak radiation periods, select species adapted to local light regimes, and implement advanced monitoring systems can enhance ecosystem productivity and sustainability. Future research should prioritize the development of integrated, multi-scale models that couple PAR with climate and hydrological processes. Such advances will improve predictive capacity and support adaptive management frameworks, particularly in the context of climate change, where shifts in radiation patterns may alter ecosystem functioning and service provision. The major contribution of this study to knowledge is the development of the PAR-Water-Structure framework. This serves to explain ecosystem productivity through interactions between energy availability, hydrological constraints, and vegetation structure. The framework is presented as a new foundation for mechanistic future ecosystem models and adaptive grassland management strategies in response to climate change.

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Conflicts of Interest

The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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