UNIVERSIDADE FEDERAL DE LAVRAS

LÍDIA RAIZA SOUSA LIMA CHAVES TRINDADE

COMPORTAMENTO BIOFÍSICO EM CULTIVARES DE CAFÉ ARÁBICA

LAVRAS-MG
2023

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COMPORTAMENTO BIOFÍSICO EM CULTIVARES DE CAFÉ ARÁBICA

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Engenharia Agrícola, na área de concentração em Sensoriamento Remoto e Geoprocessamento, para obtenção do título de Doutor.

Prof. Dr. Marcelo de Carvalho Alves
Orientador

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Ao Bolt,

Por me ensinar o verdadeiro significado do amor genuíno.

Dedico.

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“Toda árvore possui por baixo da terra uma versão primeva de si mesma. Por baixo da terra, a árvore venerável abriga ‘uma árvore oculta’, feita de raízes vitais constantemente nutridas por águas invisíveis. A partir dessas radículas, a alma oculta da árvore empurra a energia para cima, para que sua natureza mais verdadeira, audaz e sábia viceje a céu aberto.”

Clarissa Pinkola Estes

RESUMO GERAL

O café é uma das bebidas mais apreciadas e populares globalmente. No Brasil, o maior produtor e exportador desse grão, a cafeicultura desempenha um papel crucial como atividade agrícola, principalmente no cultivo do café arábica (*Coffea arabica* L.). Embora o cafeeiro tenha se adaptado bem ao cultivo em pleno sol, é uma espécie nativa dos sub-bosques das florestas tropicais. A variabilidade climática no país é apontada como a principal responsável pelas oscilações e quedas de produtividade nas regiões produtoras tradicionais. A interação entre as culturas e os fatores ambientais, representados por diferentes elementos meteorológicos, afeta o crescimento e o desenvolvimento em várias fases da cultura. Portanto, fatores ambientais, como a radiação solar, desempenham um papel fundamental nos processos de acúmulo de energia derivada da radiação solar de ondas curtas. É essencial, portanto, realizar estudos sobre o desenvolvimento dessa cultura em diferentes regiões de cultivo, além de selecionar cultivares mais adaptáveis e produtivas. Assim, o objetivo deste estudo foi analisar a influência da radiação fotossinteticamente ativa (PAR), refletância (r), transmitância (t), fração absorvida da radiação fotossinteticamente ativa (f_{APAR}) e índice de área foliar (LAI) ao longo do ciclo fenológico de cultivares de café arábica (*Coffea arabica* L.), a fim de estabelecer a relação entre vegetação e clima. O experimento foi conduzido em um painel de cultivares de café localizado na Universidade Federal de Lavras (UFLA), em Minas Gerais. A área experimental foi dividida em três blocos, cada um contendo parcelas com 10 plantas de cada cultivar de café arábica, totalizando 30 cultivares diferentes e 900 plantas, sendo 20 delas utilizadas neste estudo. Os dados foram medidos entre 10h e 14h (GMT-4) utilizando um ceptômetro (AccuPAR LP-80, Decagon Devices Inc.). Todas as análises e mapas foram realizados no software R, considerando um nível de significância de 5%. Foi possível observar o comportamento temporal dos parâmetros biofísicos, indicando se houve recuperação ou degradação das cultivares após a colheita, além de selecionar as cultivares que apresentaram melhor recuperação após a fase reprodutiva, bem como sua relação com a produtividade. Além disso, por meio da análise dos dados climáticos da região, foi possível identificar as cultivares com maior tolerância às adversidades climáticas.

Palavras-Chave: Cafeeiro. Ceptômetro. Grandezas radiométricas. Índice de área foliar. Mudanças Climáticas. Radiação Solar. Tolerância à seca.

GENERAL ABSTRACT

Coffee is one of the most appreciated and popular beverages globally. In Brazil, the largest producer and exporter of this commodity, coffee farming plays a crucial role as an agricultural activity, primarily focused on the cultivation of Arabica coffee (*Coffea arabica* L.). Although the coffee plant has adapted well to full-sun cultivation, it is a species native to the understory of tropical forests. The climatic variability in the country is considered the main driver of fluctuations and productivity declines in traditional coffee-producing regions. The interaction between crops and environmental factors, represented by various meteorological elements, affects growth and development at different stages of the crop. Therefore, environmental factors such as solar radiation play a fundamental role in the accumulation processes of energy derived from shortwave solar radiation. It is essential, therefore, to conduct studies on the development of this crop in different growing regions, as well as to select more adaptable and productive cultivars. Thus, the objective of this study was to analyze the influence of photosynthetically active radiation (PAR), reflectance (r), transmittance (t), fraction of absorbed photosynthetically active radiation (f_{APAR}), and leaf area index (LAI) throughout the phenological cycle of Arabica coffee cultivars (*Coffea arabica* L.) in order to establish the relationship between vegetation and climate. The experiment was conducted in a coffee cultivar panel located at the Federal University of Lavras (UFLA), in Minas Gerais. The experimental area was divided into three blocks, each containing plots with ten plants of each Arabica coffee cultivar, totaling 30 different cultivars and 900 plants, of which 20 were used in this study. Data were measured between 10 am and 2 pm (GMT-4) using a ceptometer (AccuPAR LP-80, Decagon Devices Inc.). The temporal behavior of the biophysical parameters was observed, indicating whether there was recovery or degradation of the cultivars after harvesting, as well as selecting the cultivars that showed better recovery after the reproductive phase, and their relationship with productivity. Additionally, through the analysis of climatic data from the region, it was possible to identify the cultivars with higher tolerance to climate adversities.

Keywords: Coffee plant; Ceptometer; Radiometric variables; Leaf area index; Climate change; Solar radiation; Drought tolerance.

SUMÁRIO

1. INTRODUÇÃO GERAL

O café é uma das bebidas mais apreciadas e populares do mundo. No Brasil, um dos maiores produtores e exportadores de grãos de café, a cafeicultura é uma das atividades agrícolas mais importantes, especialmente o cultivo do café arábica (*Coffea arabica* L.), que é muito apreciado pela qualidade da bebida e por sua grande participação no mercado. Estima-se que um terço da população mundial consuma café diariamente. Além disso, a produção de café proporciona, principalmente nos países em desenvolvimento, emprego para milhões de pessoas (SEMEDO *et al*., 2018).

Embora tenha se ajustado com sucesso às condições de cultivo sob pleno sol no Brasil, é importante lembrar que o cafeeiro é, originalmente, uma espécie nativa dos sub-bosques de florestas tropicais. No país, a variabilidade climática tem sido apontada como a principal responsável pelas oscilações e retrocessos das safras nas áreas tradicionais de produção brasileira (CAMARGO, 2010). Neste contexto e diante do cenário esperado de mudanças climáticas globais, com potencial impacto sobre a produtividade em áreas produtoras, torna-se relevante a realização de estudos visando avaliar as variáveis climáticas para a manutenção da cultura do café.

Dentre as variáveis climáticas que afetam o crescimento e a produtividade do *Coffea arabica* L., destacam-se como as mais relevantes a variação da temperatura média anual, a disponibilidade de luz e a disponibilidade hídrica (CAMARGO, 2010). De acordo com o quinto relatório do Intergovernmental Panel on Climate Change (IPCC, 2013), essas são coincidentemente as variáveis mais propensas a serem alteradas no futuro, o que constitui um risco para a cafeicultura brasileira.

A cultura do café tem à disposição diversas cultivares com características produtivas distintas e épocas de maturação diferenciadas. No entanto, essas cultivares são classificadas de acordo com o tempo de amadurecimento dos frutos, considerando as condições climáticas nos locais escolhidos, e sabe-se que, embora o amadurecimento dos frutos seja controlado geneticamente, é fortemente influenciado pelo clima da região (PETEK *et al.*, 2009). Portanto, as cultivares de café podem se comportar de maneira diferente em termos de áreas de cultivo e apresentar diferenças climáticas entre os anos. Como resultado, pode haver casos em que a diferença esperada no amadurecimento dos frutos não seja alcançada. Variedades com diferentes características de tempo de maturação em um local de origem podem se tornar idênticas em outros locais devido às interações entre genótipo e ambiente.

A quantidade de radiação incidente nas plantas de café afeta diretamente a fotossíntese, um processo vital para a geração de biomassa vegetal e a produtividade das culturas (STEENBOCK; VEZZANI, 2013). De acordo com Coelho *et al.* (2010), a falta de pesquisas sobre as interações entre o componente arbóreo e as plantas de café, especificamente em relação à radiação fotossinteticamente ativa incidente nas plantas, dificulta a determinação adequada da ordem de plantio e da densidade correta. Portanto, são necessários estudos sobre o desenvolvimento dessa cultura em diferentes regiões de cultivo, assim como a seleção de genótipos mais adaptáveis às adversidades climáticas e com maior produtividade.

1.1 Hipótese

Partindo da hipótese de que as cultivares com melhores parâmetros radiométricos são mais resistentes e produtivas, é esperado que essas cultivares também possuam mecanismos de recuperação mais eficientes e sejam capazes de se adaptar rapidamente às mudanças ocorridas durante o período da colheita. Além disso, espera-se que essas cultivares sejam mais tolerantes a períodos de seca e possuam maior eficiência fotossintética.

1.2 Objetivo geral

Analisar a influência da radiação fotossinteticamente ativa (PAR), refletância (r), transmitância (t), fração absorvida da radiação fotossinteticamente ativa (f_{APAR}) e índice de área foliar (LAI) em função das cultivares de café arábica (*Coffea arabica* L.) ao longo do seu ciclo fenológico, relação entre a vegetação e o clima. No intuito de identificar cultivares que possuam características mais adaptáveis às condições climáticas e com maior produtividade.

1.3 Objetivos específicos

- Análise do comportamento dos parâmetros biofísicos das cultivares, antes e pós-colheita, tal como sua relação com a produtividade;
- Selecionar as cultivares com melhor recuperação após fase reprodutiva;
- Análise temporal da PAR, r, t, f_{APAR} e LAI em função das diferentes cultivares, durante seu ciclo reprodutivo e vegetativo;
- Seleção de cultivares tolerantes à seca, a partir da análise da variação sazonal dos parâmetros radiométricos, em relação aos dados climáticos da região.

1.4 Organização da tese

Esta tese segue as normas exigidas pela Universidade Federal de Lavras (UFLA) para a elaboração de trabalhos acadêmicos, de acordo com o modelo estrutural de artigo científico. Seguindo esse modelo, a tese está dividida em duas partes, conforme descrito a seguir:

A primeira parte consiste na introdução geral, na qual reúne as principais ideias dos três artigos científicos que compõem a tese e como esse conteúdo se relaciona entre si. Essa parte é subdividida em hipótese, objetivo geral, objetivos específicos e organização da tese.

Na segunda parte, estão incluídos os três artigos científicos elaborados durante o período de realização da pesquisa. Cada um desses artigos segue a estrutura exigida pelas normas dos periódicos selecionados para a publicação, respeitando as diretrizes editoriais do periódico correspondente.

O primeiro artigo, intitulado ***"Cultivars of Arabica coffee: characterization and interception of solar radiation"***, apresenta uma revisão da literatura sobre as características e hábitos de crescimento do cafeeiro. Considerando as variações entre as espécies de café, o estudo discute informações agronômicas específicas de diferentes cultivares de café arábica (*Coffea arabica* L.). Além disso, é abordado o ciclo fenológico, que é uma análise importante para compreender o comportamento temporal da planta ao longo do ciclo vegetativo e reprodutivo. O artigo também discute as grandezas radiométricas utilizadas para analisar a interceptação solar na planta, incluindo a radiação fotossinteticamente ativa (PAR), fração absorvida da radiação fotossinteticamente ativa (f_{APAR}), transmitância, refletância e Índice de Área Foliar (LAI).

No segundo artigo, intitulado ***"Temporal behavior of biophysical parameters in different Arabica coffee cultivars"***, foi analisada a relação entre os parâmetros biofísicos ao longo do ciclo fenológico das cultivares de café arábica. O estudo também investigou a influência desses parâmetros na produtividade. Foi possível identificar as cultivares que apresentaram melhor recuperação após o período de colheita, conhecido como senescência, bem como aquelas que levaram mais tempo para atingir o vigor vegetativo ideal para o crescimento e desenvolvimento da planta. Além disso, o estudo examinou se essas cultivares mais resilientes são também as mais produtivas.

No terceiro artigo, intitulado ***"Identification of Arabica coffee cultivars tolerant to climatic adversities"***, o objetivo foi identificar as cultivares de café Arábica com maior tolerância aos períodos de seca, levando em consideração a variação sazonal dos parâmetros radiométricos e os dados climáticos da região ao longo do ciclo fenológico do cafeeiro, como temperatura, umidade relativa e precipitação. O estudo tem como propósito auxiliar os cafeicultores na seleção de cultivares que sejam mais adaptáveis às diferentes condições climáticas específicas de cada região.

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SEGUNDA PARTE - ARTIGOS

Nesta seção, são apresentados os artigos obtidos durante o período de realização da tese, os quais foram estruturados de acordo as diretrizes editoriais específicas de cada periódico selecionado para submissão e publicação.

O primeiro artigo apresentado, intitulado *“Cultivars of Arabica coffee: characterization and interception of solar radiation”* foi aceito e está em tramitação para publicação no periódico CAB Reviews - Perspectives in agriculture, veterinary science, nutrition and natural resources, ISSN: 1749-8848.

O segundo artigo, intitulado *“Temporal behavior of biophysical parameters in different Arabica coffee cultivars”*, foi submetido e está em tramitação no periódico Agricultural Systems, ISSN: 0308-521X.

O terceiro, intitulado “*Temporal analysis of radiometric parameters in identifying climate-adaptive Arabica coffee cultivars”*, foi submetido e está em tramitação no periódico Agriculture, Ecosystems & Environment, ISSN: 0167-8809.

PAPER 1 - CULTIVARS OF ARABICA COFFEE: CHARACTERIZATION AND INTERCEPTION OF SOLAR RADIATION

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ABSTRACT

The importance of coffee crop in the global agricultural scenario goes beyond economic aspects, also encompassing political and sociocultural factors. Brazil stands out in this scenario as the largest producer and exporter of coffee in the world, with a particular emphasis on the state of Minas Gerais. Coffee production is mainly focused on the *Coffea arabica* L. species. However, several factors directly impact coffee crop productivity, resulting in significant losses. Among the most relevant factors are adverse climatic conditions, nutritional deficiencies, and the presence of pests and diseases. Therefore, it is essential to seek an efficient metabolic response from coffee crop in the face of biotic and abiotic stresses, developing plants that are more resistant to climate variations. Based on the literature, this review is structured as follows: firstly, the characteristics and growth habits of coffee crop are presented; secondly, eighteen cultivars of Arabica coffee analyzed in the study are discussed, providing specific agronomic information for each of them; subsequently, the coffee's phenological cycle and productivity are addressed; finally, radiometric variables such as photosynthetically active radiation (PAR), fraction of absorbed photosynthetically active radiation (f_{APAR}), transmittance, reflectance, and leaf area index (LAI) are treated. The evidence gathered in this review unanimously points to the need for intensified studies on solar radiation interception and LAI in different cultivars of arabica coffee. The literature highlights the importance of using field-obtained datasets to complement information on the characteristics and growth patterns of varieties, as well as their phenological cycle, in order to understand the plant's behavior before and after harvesting and its relation to productivity.

KEYWORDS: Coffee crop; Phenological cycle; Radiometric variables.

Review methodology:

The objective of this study is to present a literature review on the agronomic characteristics and growth habits of different cultivars of Arabica coffee. Additionally, the biophysical parameters that can help understand the temporal behavior of the plant throughout its phenological cycle were discussed. The research was conducted using various databases, including Scopus (Elsevier), Web of Science (WoS) from Clarivate Analytics, Google Scholar, ScienceDirect (Elsevier), DOAJ (Directory of Open Access Journals), Springer Science and Scientific

Electronic Library Online (SciELO). The article was organized into topics that address the characteristics and growth habits of the plant, different cultivars of Arabica coffee, the coffee's phenological cycle and productivity, as well as issues related to radiation, radiometric variables such as transmittance, reflectance, photosynthetically active radiation (PAR), and fraction of absorbed photosynthetically active radiation (f_{APAR}), in addition to the leaf area index (LAI). Additionally, the references from the articles were used to identify additional relevant material. This strategy allowed for the aggregation of complementary and relevant information related to the subject at hand.

INTRODUCTION

The coffee crop (*Coffea arabica* L.) originates from the mountainous forests of Ethiopia, southeastern Sudan, and northern Kenya [1]. Its domestication took place in Yemen, and its spread to Asia and Latin America occurred during the Renaissance period (1300-1700), leading to the expansion of coffee cultivation throughout Europe and the Americas [1]. Coffee was introduced to the country in 1727, starting in the state of Para, from where it spread across the entire national territory [2].

The habit of drinking coffee was transmitted by the arabs, and its importance in the global agricultural scenario goes beyond just economic aspects, encompassing political and sociocultural factors as well [1]. Coffee is one of the most consumed and appreciated products worldwide, making a significant contribution to the economies of coffee-producing and exporting countries [3]. Brazil stands out in this scenario, being considered the largest producer and exporter of coffee in the world. In 2023, coffee cultivation spans a total area of 2.24 million hectares in Brazil, with 1.88 million hectares dedicated to active plantations, marking a 1.9% increase from the previous year, while 362.5 thousand hectares are under development. In the current harvest, the production of Arabica coffee in the country is projected to reach 38.16 million bags, representing 70.2% of the total, which signifies a 16.6% increase compared to the 2022 harvest. This growth is the result of a 2.4% expansion in the cultivation area, along with an anticipated 13.9% increase in productivity, thanks to more favorable weather conditions compared to the last two harvests [4].

For 2023, there was an increase of 28.8% in comparison to the total quantity harvested in the previous harvest, which can be explained by a 6.5% expansion in the cultivation area, a substantial 21% increase in production efficiency, and, above all, due to the improvement in the conditions of the plantations after the last harvests, which were affected by unfavorable weather conditions [4].

Coffee cultivation in Minas Gerais is responsible for over 50% of the national production and is present in four main regions: Cerrado (Triângulo Mineiro/Alto Paranaíba), Sul de Minas (Southern/Southwestern), Chapadas de Minas (Vale do Jequitinhonha/Mucuri), and Matas de Minas (Zona da Mata/Rio Doce) [4].

The coffees produced in Minas Gerais have distinct flavor and aroma characteristics, influenced by the peculiarities of climate, altitude, and production systems adopted in each region [5]. Coffee belongs to the *Coffea genus*, and two species stand out in the global market: *Coffea arabica* and *Coffea canephora*, which have distinct characteristics.

In Minas Gerais, coffee production is primarily focused on cultivating Arabica coffee, which represents approximately 69% of the national production of this type of coffee. The state has a coffee-growing area of 1,210 thousand hectares [4]. Arabica coffee beans are highly valued in the market due to their balance of desirable chemical compounds and their ability to offer a beverage of superior quality, making them more appreciated by consumers [6].

Several causes directly impact coffee crop productivity, leading to significant losses. Among the most relevant factors are adverse climatic conditions, nutritional deficiencies, and the presence of pests and diseases [7]. Some of the significant coffee diseases include orange rust caused by *Hemileia vastatrix* Berk. & Br., cercospora leaf spot caused by *Cercospora coffeicola* Berk & Cooke, coffee berry anthracnose caused by *Colletotrichum kahawae* Waller & Bridge (considered a quarantine pest A1 in Brazil), *Meloidogyne* spp., Phoma spot caused by *Phoma tarda* (Stewart) Boerema & Bollen, and aureolate spot caused by *Pseudomonas syringae* pv. *garcae* Young, Dye & Wilkie, among others [8, 9].

The climatic conditions of the environment where coffee crop are cultivated can affect productivity due to variations in photosynthetic activity [10]. There are numerous coffee genotypes cultivated in different countries worldwide. The selection of plants adapted to different conditions has been crucial for choosing the varieties used [11]. The *Coffea arabica* L. genus exhibits high phenotypic plasticity, enabling its adaptation to diverse climatic conditions, including temperature and radiation.

According to the fifth report of the IPCC (Intergovernmental Panel on Climate Change), the global average temperature has increased by 0.61°C since pre-industrial time, and this increase is expected to continue in the coming years [12]. The projected climate changes would have severe impacts on coffee bean production and quality, especially for the species *Coffea arabica* L. [13, 14], which is adapted to average annual temperatures of 18°C to 22°C [15, 16], and experiences a water deficit of less than 100 mm annually [17].

In Minas Gerais, the climatological average of monthly rainfall totals varies from 70 to 310 mm, with average minimum and maximum temperatures ranging from 16 to 18°C and 32 to 34°C, respectively. In the mountainous regions of the state, the average minimum and maximum temperatures range from 16 to 18°C and 26 to 29°C. The occurrence of dry spells in the months of January, February, and March has been common, especially in the Central North and East regions of the state [4]. Climate zoning studies have shown that the increase in global temperature may render many regions, especially in southeastern Brazil, unsuitable for the cultivation of *Coffea arabica* L., or require the adoption of irrigation practices [18-20].

A 38% reduction in bioclimatic areas favorable for Arabica coffee production is predicted by 2080 in Ethiopia due to the climate changes that have occurred in recent decades. The rise in temperature, changes in the distribution of rainfall throughout the year, and increased carbono dioxide (CO_2) emissions have impacted commercial coffee farming [21]. In recent years, global minimum temperatures have increased twice as much as maximum temperatures, posing a threat to tropical crops like arabica coffee [22]. It is necessary to seek an excellent metabolic response from coffee crop to biotic and abiotic stresses, developing more resilient plants to climate variations [1].

Based on this perception, there is a clear research need that the current study aims to address: to analyze existing research that explores the characteristics and behavior of different Arabica coffee cultivars regarding solar radiation interception. This knowledge gap is crucial, both from a productive and ecological perspective, as understanding the impact of solar radiation throughout the coffee phenological cycle is essential to maintain and optimize its productivity.

This study, structured based on the literature, specifically addresses this research need. Initially, the characteristics and growth habits of the coffee crop are presented. Next, different cultivars widely used commercially are analyzed in the study, detailing the agronomic information and characteristics of each. Subsequently, the focus shifts to the coffee's phenological cycle and its productivity, with the aim of thoroughly understanding the various stages of plant development and growth over time. Finally, radiometric variables, including Photosynthetically Active Radiation (PAR), Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}), transmittance, reflectance, and Leaf Area Index (LAI), are meticulously explored to unravel how solar radiation interception influences plant growth and development, as well as the relationship of these variables with climatic factors and productivity.

Characteristics of the plant and growth habits

The coffee crop is a perennial tropical dicotyledonous shrub with a more upright stem structure. Its height can vary from four to six meters without pruning or from two to three meters with pruning [23].

Regarding carbon metabolism, coffee is considered a C3 plant, and most of these plants show photosynthetic saturation between 600 and 800 µmol m^{-2} s^{-1}. According to [24], when atmospheric CO_2 concentrations increase above the compensation point without saturation, photosynthesis is stimulated, and the photon flux occurs linearly in relation to the photosynthetic rate and biomass, resulting in an increase in plant productivity. Coffee reaches its maximum yield about four years after planting. It is worth noting that crops are typically renewed every 16 years, although some plantations remain productive for decades [25].

There are differences among coffee genotypes, which can manifest as small bushes or large trees with hard and thick stems. All species in the *Coffea* genus are diploids, except for *C. arabica*, which is tetraploid and the only species with four sets of the genus's basic chromosomal number (n = 11), totaling 44 chromosomes. The stem is woody, rigid, and erect, with *C. arabica* having a single stem (monocaul) and *C. canephora* having multiple stems (multicaul), with diameters ranging from eight to ten centimeters [26].

There is dimorphism in the growth pattern of the branches, known as orthotropic branches when they grow vertically and plagiotropic branches when they grow horizontally. The leaves have short petioles, are elliptical, and typically range from dark green to greenish-brown, with nine to twelve veins and a leaf surface area of 12 to 20 cm^2 in mature plants [27].

The coffee plant's root system consists of a taproot that can reach up to one meter deep. Additionally, there are auxiliary roots that can extend up to three meters deep. The coffee crop has several lateral roots parallel to the ground, located about two meters from the trunk, as well as root hairs. Approximately 75% of the secondary and adventitious roots are less than 30 cm deep and are concentrated in the protruding regions of the canopy, performing functions of plant support and water and nutrient absorption [28].

The coffee fruit has an oval shape and usually contains two seeds. The maturation of the fruit occurs over a period of 7 to 9 months, and the seeds have a dark red or yellow color when ripe. The fruit is composed of the peduncle, crown, exocarp, mesocarp, endocarp, and seed. The seed is surrounded by an inner shell called parchment, which is coated with the endosperm (silver skin), mesocarp (pulp), and exocarp (skin). The seed consists of the embryo, endosperm, and tegument [27].

Years of low productivity are associated with the allocation of photosynthetic resources to branching [29]. Genetic variation is one of the determining factors for differences among coffee varieties [30, 31]. However, there is a growing demand for genotypes that can adapt to specific conditions and demonstrate satisfactory productive results.

It is known that the coffee crop has a significant adaptive capacity, leading to physiological, biochemical, morphological, and anatomical changes [32]. Therefore, there is an increasing demand for cultivars adapted to different environmental stress conditions, climatic factors, and resistance to pests and diseases, as global climate change and increased atmospheric carbon dioxide may pose risks to coffee cultivation [33].

Arabica coffee cultivars

Brazil is a country known for its diversity of Arabica coffee cultivars available for commercial use. Currently, there are 142 cultivars registered in the National Registry of Varieties (RNC) of the Ministry of Agriculture, Livestock, and Supply (MAPA), which is responsible for the registration and protection of these cultivars. However, only about 40 cultivars are widely used commercially. This is partly due to a lack of understanding of the benefits, agronomic performance, and characteristics of the new cultivars available for cultivation [34].

It is essential to know the characteristics and agronomic information of Arabica coffee cultivars to make an appropriate decision in choosing the most suitable variety for planting. Table 1 presents some characteristics, such as productivity, plant size, canopy diameter, vegetative vigor, maturation period, seed size, and tolerance to water deficit, of the cultivars used in this study. This information is valuable in assisting coffee growers in selecting the most suitable cultivar for their needs and environmental cultivation conditions.

Table 1. Characteristics and agronomic information about Arabica coffee cultivars.

Characteristics	**Acaua**	**Acaua Novo**	**Aranas RV**	**Araponga MG1**
Plant Size	Low	Low	Low	Low
Canopy Diameter	Medium	Medium	Medium	Medium
Color of Young Leaves	Bronze	Green	Green/Bronze	Green/Bronze
Fruit Color at Maturity	Red	Red	Red	Red
Seed Size	Medium	Medium	Large	Medium
Maturation Period	Late	Med./Late	Med./Late	Medium
Rust Resistance	Resistant	Resistant	Part. resist	Resistant
Nematode Resistance	Resistant to *M. exigua*	Resistant to *M. exigua*	Resistant to *M. exigua*	Susceptible
Other Diseases	None	None	None	None
Vegetative Vigor	High	High	High	High
Cup Quality	Regular	Regular	Regular	Regular
Productivity	High	High	High	Medium

Characteristics	**Catigua MG1**	**Catigua MG2**	**Catigua MG3**	**Catucai Amarelo 2SL**
Plant Size	Low	Low	Low	Low
Canopy Diameter	Medium	Medium	Medium	Medium
Color of Young Leaves	Bronze	Green/Bronze	Light Bronze	Green/Bronze
Fruit Color at Maturity	Red	Red	Red	Yellow
Seed Size	Medium	Small	Medium	Medium
Maturation Period	Medium	Med./Late	Medium	Medium
Rust Resistance	Resistant	Resistant	Resistant	Part. resistant
Nematode Resistance	Susceptible	Susceptible	Resistant to *M. exigua*	Susceptible
Other Diseases	None	Resistant to *Pseudomonas*	None	Partially to *Phoma* spot
Vegetative Vigor	High	High	High	High
Cup Quality	Regular	Distinguished	Regular	Regular
Productivity	Medium	Medium	High	High

Characteristics	**Iapar 59**	**IPR 100**	**IPR 102**	**IPR 103**
Plant Size	Low	Low	Low	Low
Canopy Diameter	Small	Medium	Medium	Medium
Color of Young Leaves	Bronze	Bronze	Green/Bronze	Bronze
Fruit Color at Maturity	Red	Red	Red	Red
Seed Size	Medium	Medium	Large	Medium
Maturation Period	Early/Medium	Late	Late	Late
Rust Resistance	Resistant	Susceptible	Resistant	Part. resistant
Nematode Resistance	Resistant to *M. exigua*	Resistant to *M. paranaensis* and *M. exigua*	Susceptible to *M. paranaensis* and *M. incognita.* Not tested for *M. exigua*	Susceptible to *M. paranaensis*, *M. incognita*. Not tested for *M. exigua*
Other Diseases	Partially to bacterial halo blight	None	Resistant to aureolate spot and *Phoma* spot	None
Vegetative Vigor	Low	High	Medium	High
Cup Quality	Distinguished	Regular	Regular	Regular
Productivity	High	Very high	High	Very high

Characteristics	**Rubi – MG 1192**	**Siriema**	**Saira**	**Arara**
Plant Size	Low	Low	Low	Low
Canopy Diameter	Medium	Small	Medium	Large
Color of Young Leaves	Bronze (predominant)	Green	Green/Bronze	Green
Fruit Color at Maturity	Red	Red/Yellow	Red	Yellow
Seed Size	Medium	Small	Medium	Large
Maturation Period	Medium	Early	Med./Late	Late
Rust Resistance	Susceptible	Part. resistant	Resistant	Resistant
Nematode Resistance	Susceptible	Susceptible	Susceptible	Susceptible
Other Diseases	None	Resistant to leaf miner in about 35% of plants	None	Resistant to *Pseudomonas*
Vegetative Vigor	High	High	High	High
Cup Quality	Regular	Regular	Regular	Distinguished
Productivity	Medium	Medium	High	Very high

Characteristics	**Guara**	**Pau Brasil MG1**
Plant Size	Low	Low
Canopy Diameter	Large	Small
Color of Young Leaves	Green/Bronze	Green
Fruit Color at Maturity	Red	Red
Seed Size	Large	Medium
Maturation Period	Medium	Medium
Rust Resistance	Part. resistant	Resistant
Nematode Resistance	Moderately resistant to *M. exigua*	Susceptible
Other Diseases	None	None
Vegetative Vigor	High	Medium
Cup Quality	Regular	Regular
Productivity	High	Very high

Source: Adapted from [34].

Phenological cycle of coffee and productivity

Most plants bloom in the spring and bear fruit in the same phenological year. Arabica coffee is a special plant that takes two years to complete its phenological cycle. First, during the months of long days, vegetative branches with axillary buds form at the nodes. In January, when the days start to shorten, the axillary vegetative buds are stimulated by photoperiods in the reproductive buds [35].

The second phenological year begins with flowering, and the small fruits precede the inflation of the beans until they reach their normal size. Then comes the grain filling and ripening phase. And finally, aging, death of terminal plagiotropic branches, and familiar self-pruning. In the spring of the following civil year, new vegetative buds germinate and begin to spread, allowing for new late growth production in the following year [36].

Figure 1 presents a detailed diagram of the phenological stages of Arabica coffee (*Coffea arabica* L.) according to [36]. For the tropical conditions of Brazil, the phenological cycle is divided into six distinct stages, two vegetative and four reproductive: 1. plant formation and leaf budding; 2. induction and maturation of floral buds; 3. inflorescence 4. grain filling; 5. fruit ripening; and 6. dormancy and aging of the third and fourth branches.

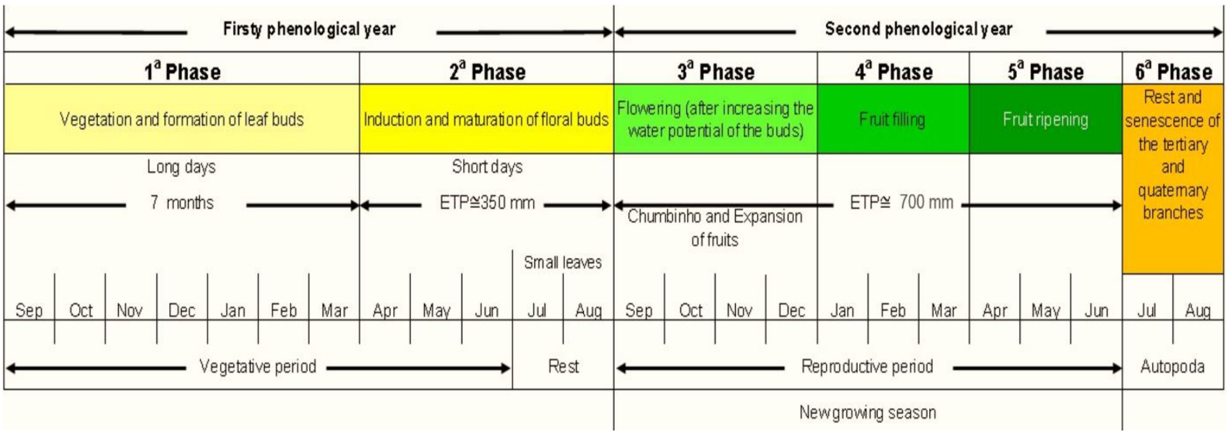

Figure 1. The six phenological stages of *Coffea arabica* L., over 24 months, in the tropical climatic conditions of Brazil. Source: Adapted from [36].

Studies conducted in Campinas [37] and Chinchiná, Colombia [38] have shown that arabica coffee fruits mature approximately in the 32nd week after anthesis. However, the time required to reach full maturity is influenced by climatic conditions and the genetic composition of the coffee crop [37].

Arabica coffee is native to shaded environments, where it exhibits lower photosynthetic rates, even under optimal cultivation conditions. However, the spatial and temporal fluctuations in photosynthesis and the reasons behind the low photosynthetic rates are not fully understood [39]. Therefore, it is of utmost importance to study the biophysical parameters and their impact on arabica coffee.

Radiation

The accumulation of dry matter in plants of different crops is directly related to solar interception, as pointed out by [40, 41]. The efficiency of light interception can be a crucial factor influencing crop performance under different climatic conditions, including within forests. The amount of solar energy captured by plants depends on the characteristics of the incident solar radiation and canopy properties. To understand and model crop growth and production, it is essential to use light interception or radiative transfer models, which combine vegetation characteristics with how radiation is attenuated by the canopy [42].

In general terms, interception can be understood as the process by which solar radiation strikes a certain surface. For the leaf surface to be intercepted at any point in the canopy, the solar radiation incident on the top of the canopy must be transmitted. Radiative transfer along the canopy depends on factors such as the type of radiation (direct or diffuse), optical properties of the plants, and canopy structure. According to [43], the optical properties of plants are characterized by the coefficients of reflection (ρ), transmission (τ), and absorption (α), as shown in the following equation:

$$\alpha = 1 - \rho - \tau \tag{1}$$

Furthermore, when it comes to radiation transfer, it is also common to use the term scattering coefficient (ω), which can be calculated using Equation 2:

$$\omega = \rho + \tau \tag{2}$$

Although the visual characteristics of leaves may vary with age, structure, and the presence of diseases, it is possible to create a generic idealization of the optical behavior of healthy green leaves (Figure 2).

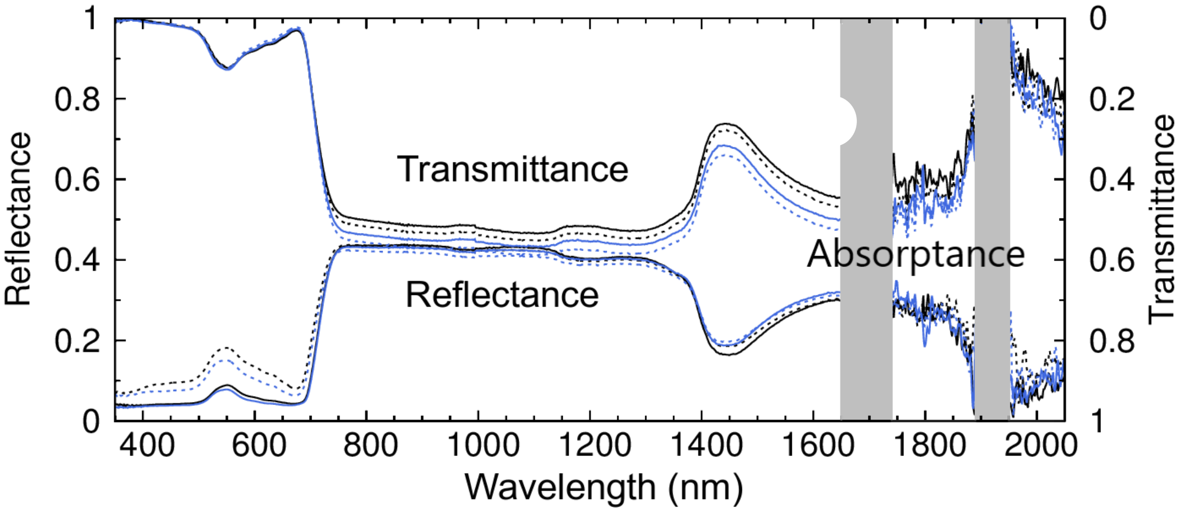

Figure 2. Relationship between reflection, transmission, and absorption of a green leaf systematized. Source: Adapted from [44].

Figure 2 shows a significant absorption of radiation in the visible range (0.4 to 0.7 µm), reaching around 90% absorption. From 0.7 µm, the absorption decreases drastically, reaching a minimum of 10% between 0.7 and 1.2 µm. From 1.2 µm, the absorption increases again, reaching values at 1.5, 2.1, and 2.5 µm [44]. In addition to optical properties, the transmission of radiation also depends on the canopy structure. [45] defined "architecture" as the set of characteristics that define the shape, size, geometry, and external structure of a plant.

The calculation of solar radiation can be performed at any point in the Earth's outer atmosphere for each day of the year, based on the latitude and solar declination. However, gases and clouds cause changes in the amplitude and spectral composition of solar radiation. Empirical models are used to estimate global solar irradiance, which is a useful tool when parameters can be calibrated at different locations. These models have the advantage of using widely available meteorological data [46].

According to [47], crop reflectance has been studied in the visible region (400-700 nm) and near-infrared (760-1300 nm) for plant health detection. In healthy plants, in the visible region, chlorophyll absorbs higher amounts of blue and red radiation in the spectrum, while green is more reflected, giving healthy plants their natural green appearance. In the near-infrared, radiation is also strongly reflected due to the internal leaf structure.

Radiometric Quantities

Radiation measurements are essential when analyzing the interaction of electromagnetic radiation with the Earth's surface. The quantities that describe the radiation field resulting from the interaction with various surfaces are reflectance, transmittance, and absorption.

- Transmittance

Understood as the fraction of radiant energy that penetrates to reach parallel levels within the medium. It can also be defined as the ratio of the incoming solar radiation flux (Rad_o) within the canopy to the incoming radiation flux above the canopy (Rad_i), according to equation 3.

$$t = \frac{Rad_0}{Rad_1} \tag{3}$$

Transmittance is related to the canopy openness fraction and is directly affected by the zenith angle and the amount of diffuse radiation [48].

- Reflectance

Derived from the Latin word "reflectu + ância," it is a term in photometry that represents the ratio of the reflected luminous flux from a surface to the incident luminous flux, i.e., the ratio of the radiant flux reflected from the surface (Rad_r) to the incident radiant flux (Rad_i), according to equation 4.

$$r = \frac{Rad_r}{Rad_i} \tag{4}$$

Reflectance represents the fraction of the total incident solar radiation that is reflected by a surface. It is a variable used to study the interaction of solar radiation with the Earth. Changes caused by human activities in land cover and albedo have an impact on the proportion of solar radiation reflected back into space, making it an important radiative climate variable [49].

The albedo of vegetated surfaces varies according to solar elevation angle, vegetation type, atmospheric conditions, surface moisture, soil type, humidity, and cloud amount and type [50]. In the case of forest vegetation, when the foliage is clustered in the canopy, the canopy surface presents crevices and depressions, allowing the penetration of a significant amount of incident solar radiation before being reflected [51].

Photosynthetically Active Radiation (PAR)

It should be considered that a canopy consists of various elements of the plant itself, such as leaves, branches, fruits, flowers, among others. The radiation flux that strikes these elements will undergo processes of transmission and absorption. The spectral characteristics of leaves and multiple reflections between them result in a high degree of absorption of Photosynthetically Active Radiation (PAR) in the visible spectrum (0.4 to 0.72 μm) and moderate reflectance in the near-infrared region (0.72 to 4.0 μm). When the ground is not covered by vegetation, it generally shows a gradual increase in radiation reflectance between 0.4 and 4.0 μm [52].

The amount of PAR depends primarily on two factors at any given moment: the position of the sun and atmospheric transmissivity. The position of the sun follows a regular pattern of altitude, which can be used to estimate the maximum potential PAR for a given time and location under clear sky conditions [53].

Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR})

The evolution of terrestrial ecosystems is characterized by physical, biochemical, and physiological variables, some of which can be extracted from remotely sensed data collected from space, with a high level of acceptance. This makes the Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}) an excellent indicator of canopy status [54]. Thus, f_{APAR} is a reliable variable for determining the presence of vegetation on a global scale.

The amount of PAR absorbed by green leaves can be used to estimate carbon sequestration by the canopy [55]. Fortunately, vegetation remote sensing indices show a stronger correlation with f_{APAR} [56].

The determination of f_{APAR} depends on canopy structure, LAI, zenith angle, diffuse radiation rate, and soil albedo [57, 58]. Leaf Area Index (LAI) is often estimated, and f_{APAR} is calculated assuming that the standard canopy model is suitable [48].

According to [52], f_{APAR} is a key parameter in several ecosystem productivity models, as well as in global climate, hydrology, biochemical, and ecological models.

The study conducted by [59] emphasizes the importance of analyzing the absorption of photosynthetically active radiation in the context of parameterizing physiological models. The researchers examined the behavior of the LAI and the radiation extinction coefficient in coffee crop subjected to different irrigation levels, using in situ sensors. They observed significant variations related to the irrigation treatments and the plant canopy structure.

In the case of plants subjected to the L130% irrigation level, it was found that approximately 90% of photosynthetically active radiation (PAR) was absorbed in the upper canopy quadrants. In the middle and lower quadrants, these values were approximately 35%

and 4%, respectively. However, plants treated with L100%, i.e., with the ideal amount of water to fully meet the crop's needs, exhibited a similar pattern, with approximately 90% PARi absorption, comparable to the L130% treatment [59].

Another study, like that of [60], in the context of climate change, developed a method for predicting coffee production on a regional scale. In this study, f_{APAR} was used as one of the vegetation variables obtained through satellite remote sensing. The authors employed the Crop Growth Monitoring System Statistical Tool (CGMSstatTool - CST) to analyze these vegetation variables derived from satellite remote sensing (SPOT-VEGETATION and PROBA-V). They emphasized the significance of these variables in the accurate prediction of coffee production, which is crucial for all farmers in the coffee industry.

Leaf Area Index (LAI)

It is known that the leaf area of crops is an indicative parameter of yield, as photosynthesis depends on the capture of light energy and its conversion into chemical energy. According to [61], photosynthetic efficiency depends on the rate of photosynthesis per unit leaf area and the absorption of solar radiation, which is affected, among other things, by canopy structural characteristics and system size.

Thus, the leaf surface area of a plant is the basis for the potential yield of the crop. In addition, knowledge of the leaf area of the plant allows for the estimation of water loss, as leaves are the main organs involved in the transpiration process, responsible for gas exchange with the environment [62]. Therefore, understanding the temporal variation of leaf area index in perennial crops can be useful in evaluating various cultural practices such as pruning, fertilization, irrigation, spacing, and pesticide application, among others.

According to [63], the use of LAI in coffee cultivation was initially suggested by Castillo in 1961, in Colombia. However, [64] were the first researchers to conduct studies on this topic. [63] conducted a study correlating LAI with coffee productivity based on planting density. The results indicate that the highest crop productivity was achieved when LAI reached a value of eight, which occurred three years after planting for a population of 10,000 plants ha^{-1} and only after the 4th year following planting when the population was 5,000 plants ha^{-1}.

LAI is a variable of great importance used to estimate water, carbon, and energy fluxes. This index plays a relevant role in studies related to the understanding of phenomena at different scales, from the leaf to the canopy, as well as in the calculation of the Photosynthetically Active

Radiation Extinction Coefficient (kPAR), providing crucial information for the parametrization of physiologically based models [65].

It is expected that the agricultural sector will be substantially affected by climate change, due to the sensitivity of crops to increasing temperature and water scarcity [66, 67]. The negative effects are evident and include declines in crop production and quality, as well as increased pest and disease infestation, resulting in a reduction in global agricultural production [12].

[68] reported that, in 2006, about 57% of coffee producers suffered production losses, with 26% due to water stress and 27% due to excessive rainfall. These challenges represent significant difficulties for small-scale farmers, many of whom depend on rainfed cultivation and have limited access to financial and technical support [69, 70], which could help them cope with constantly changing weather conditions.

In the study conducted by [59], which aimed to assess the variation in LAI in coffee crop subjected to different irrigation levels using a linear radiation bar sensor (SunScan-Delta-T Devices Ltd, London), it was observed that the average LAI values (for the entire plant) were 4.7, 4.2, 3.7, and 3.5 for the L130, L100, L70, and L40 treatments, respectively. The average LAI values were higher in plants subjected to the L130 and L100 treatments compared to the values observed in coffee plantations receiving deficit irrigation levels (70% and 40%).

The study conducted by [71] monitored the evolution of the LAI in a coffee plantation. This monitoring was based on plant measurements derived from 3D point clouds generated in conjunction with the application of the SfM algorithm to digital images captured by a camera attached to an unmanned aerial vehicle (UAV). The results revealed LAI values exceeding 3.0 in various blocks during the months of January through May 2018.

The LAI is a crucial indicator of ecosystem services and management practices, as evidenced in a study conducted by [66] on a coffee agroforestry farm in Costa Rica. In this study, LAI results derived from MODIS showed seasonal variations ranging from 2.4 to 4.4 m^2 m^{-2}. The authors emphasized the significant role of LAI as an important co-predictor of production and discussed how it is influenced by natural factors such as phenology and climate, as well as management.

Research like the one conducted by [60] emphasized the importance of the LAI, revealing that the development of coffee production prediction models based on multiple linear regression of satellite-derived vegetation biophysical variables, such as LAI, resulted in coffee production forecast models with satisfactory accuracy.

CONCLUSION

Overall, the synthesis of evidence presented in this review unanimously points to the conclusion that there is an urgent need to deepen research on solar radiation interception and Leaf Area Index (LAI) in different Arabica coffee cultivars. This becomes particularly relevant considering that many coffee cultivation regions are already subject to climate variability, which may worsen in the future. Despite the abundance of studies addressing solar radiation and LAI, these analyses often focus on plantations as a whole, lacking, however, investigations that delve into the biophysical behavior of different cultivars.

A detailed understanding of solar radiation interception is essential not only to identify cultivars more resilient to climatic adversities but also to select the most suitable varieties for different regions. Although the literature includes various studies using in-situ sensors and satellite data, there is a clear need for research dedicated to evaluating the individual behavior of each cultivar. This effort aims to gain a comprehensive understanding of plant behavior both before and after harvesting, as well as its relationship with productivity.

By gaining knowledge of the temporal behavior of these varieties and their interactions with solar radiation, it is possible to potentially develop cultivars more resilient to periods of drought, better equipped to face adversities, and with higher productivity, with the goal not only of providing support to coffee producers in their practices but also playing a fundamental role in promoting food security.

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PAPER 2 - TEMPORAL BEHAVIOR OF BIOPHYSICAL PARAMETERS IN DIFFERENT ARABICA COFFEE CULTIVARS

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ABSTRACT

Concern about coffee has increased significantly due to its high sensitivity to climatic conditions. Environmental factors, such as solar radiation, play a fundamental role in the accumulation of energy from the short waves emitted by the sun. The range of solar radiation used by plants covers wavelengths between 400 and 710 nanometers (nm) and is called Photosynthetically Active Radiation (PAR). Crop productivity is related to the efficiency of PAR utilization. In this context, the aim of this study was to analyze the influence of PAR, reflectance (r), transmittance (t), fraction of absorbed Photosynthetically Active Radiation (f_{APAR}), and Leaf Area Index (LAI) in different cultivars of *Coffea arabica* L. throughout their phenological cycle. Additionally, we sought to select cultivars with better post-harvest recovery and investigate their relationship with productivity. The experiment was conducted with a panel of 30 cultivars located at the Federal University of Lavras (UFLA), Minas Gerais. PAR (µmol m^{-2} s^{-1}) was measured using a ceptometer (AccuPAR LP-80, Decagon Devices Inc.), which allowed the estimation of the other indices. Trend analyses, such as the Nemenyi Test and the non-parametric method of monotonic trend by Mann Kendall, were used to evaluate the temporal behavior of biophysical parameters. The cultivar Siriema showed the best performance in all analyzed biophysical parameters, followed by the cultivar IPR 100. Cultivar IPR 103 also performed well in most parameters. Among the cultivars with higher productivity, those that were able to recover vegetative vigor in a shorter time after harvesting stood out. These cultivars include Acaua Novo, Clone 224, Clone 312, Guara, Catigua MG-1, Saira II, Siriema, IPR 100, and Arara. It can be stated that there was a relationship between the analyzed biophysical parameters and coffee productivity. Cultivars that presented better radiometric indices, such as reflectance, transmittance, f_{APAR}, and LAI, were more resistant and, at the same time, more productive.

Keywords: Fraction of Absorbed Photosynthetically Active Radiation; Reflectance; Transmittance; Leaf Area Index; Mann Kendall; Productivity.

1. Introduction

Coffee is a beverage produced from coffee beans obtained from perennial and tropical plants. These beans exhibit morphological variations, showing different shapes, colors, and sizes (Souza et al., 2022). Globally, Arabica (*Coffea arabica* L.) and Robusta (*Coffea canephora*) coffee types represent about 99% of the world's coffee production (Jayakumar et al., 2017). Arabica coffee, often used in specialty coffee production, develops best at temperatures between 18 and 22 °C, while lower-quality Robusta coffee is more resilient and productive at temperatures between 22 and 28 °C (Magrach and Ghazoul, 2015).

Coffee is the second most traded commodity globally, after oil (Davis et al., 2012). Brazil is responsible for approximately 36% of the world's production, followed by Vietnam (17%), Colombia (8%), and Indonesia (6%) (ICO, 2019). According to FAO estimates (FAO, 2018), total global coffee production could reach 273.6 million sacks by 2050, with a productivity of 38.3 sacks per hectare, considering 60 kg sacks of peeled coffee.

The total area devoted to coffee cultivation in Brazil in 2023, encompassing Arabica and Conilon varieties, amounts to 2.25 million hectares, representing a 0.3% increase compared to the previous year's crop area. Among this area, 1.87 million hectares are dedicated to producing crops, with a 1.7% growth (CONAB, 2023).

Arabica species represent more than three-quarters of the total production in Brazil, being cultivated in almost 80% of the coffee cultivation area in the country, and 70% of this production is concentrated in the state of Minas Gerais (CONAB, 2022). With a 69.3% share of coffee production in the country, for the current crop, an estimated 37.93 million sacks of Arabica coffee are expected to be harvested. The result represents a growth of 15.9% over the 2022 crop. This growth is due to a 1.9% increase in the production area, combined with an estimated gain of 13.7% in productivity, substantiated by more favorable climatic conditions compared to the last crops of the previous year (CONAB, 2023).

Concern about coffee has grown significantly, as this crop is cultivated by more than 25 million farmers, most of whom are small-scale producers, in more than 60 countries in the tropics (Jayakumar et al., 2017). Furthermore, coffee is highly sensitive to local climatic conditions (Damatta and Ramalho, 2006). Due to climatic adversities in various coffee-producing regions in Brazil, such as low rainfall, long periods of drought, and above-average temperatures during much of its development, the year 2022 had low productivity despite being a year of positive bienniality for the crop (CONAB, 2023).

Crops interact with environmental factors, represented by various climatic elements, and affect growth and development in different ways during different stages of the life cycle

(Camargo et al., 1986). Thus, environmental factors, such as solar radiation, play a fundamental role in all processes of energy accumulation from the short waves emitted by the sun. The range of solar radiation used by plants covers wavelengths between 400 and 710 nanometers (nm) and is called Photosynthetically Active Radiation (PAR) (Angelocci, 2002). Through the absorption of PAR, plants convert light energy into chemical energy necessary for their vital processes.

Crop productivity is related to the efficiency of Photosynthetically Active Radiation (PAR) utilization (Barradas and Fanjul, 1986). The main selection criterion in coffee trees is productivity, and for cultivar recommendation, it is essential to observe the genotype's interaction with the environment (Matiello et al., 2016). Genetic variability is a determining factor for the differences found among different types of coffee (Kitzberger et al., 2014). Genetic divergence among Arabica coffee cultivars can be decisive in adapting to environmental climatic conditions, with some cultivars showing greater resistance to pests, diseases, abiotic factors, water deficit, among others.

In this context, the aim of this study was to analyze the influence of Photosynthetically Active Radiation (PAR), reflectance (r), transmittance (t), fraction of absorbed Photosynthetically Active Radiation (f_{APAR}), and Leaf Area Index (LAI) in different cultivars of Arabica coffee (*Coffea arabica* L.) throughout their phenological cycle. Additionally, we also aimed to select cultivars that presented better post-harvest recovery, as well as investigate their relationship with productivity.

2. Materials and methods

2.1 Location and characterization of the study area

The experiment was conducted in a panel of Arabica coffee cultivars located at the Federal University of Lavras (UFLA), in the state of Minas Gerais, Brazil. The geographical coordinates of the site are 21° 14' 43 S and 44° 59' 59 W, with an altitude of 919 m. The panel was established on March 30, 2015, by the National Institute of Coffee Science and Technology (INCT do Café), with a total of 30 cultivars, planted at a spacing of 3.5 x 0.7 meters (Fig. 1).

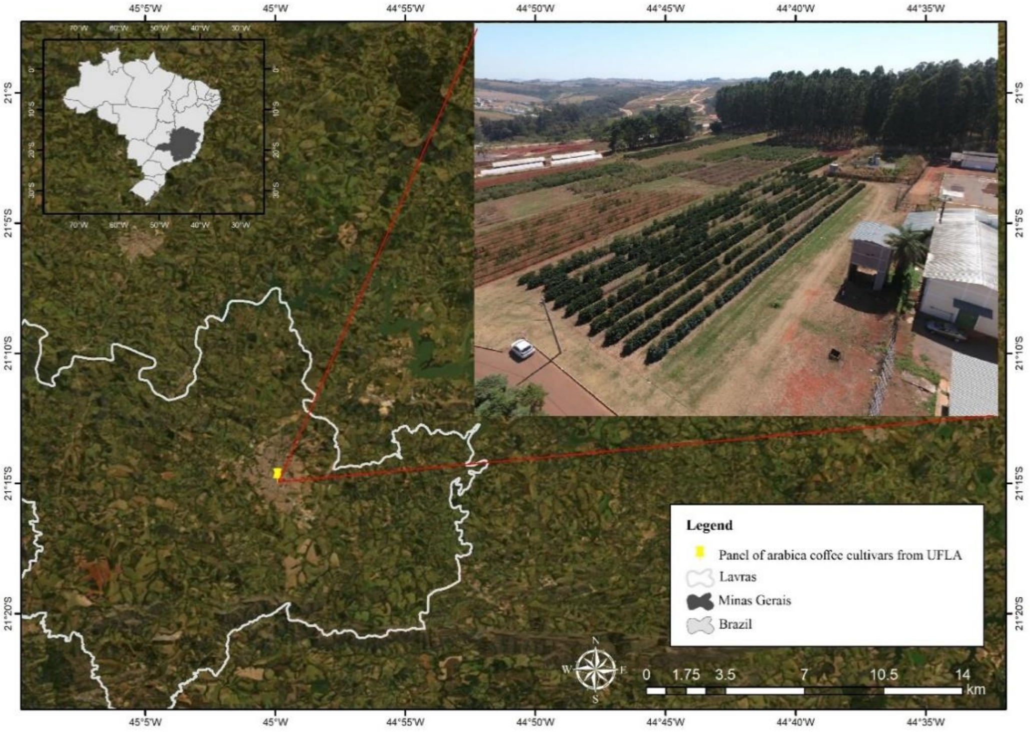

Fig 1. Location of the panel of Arabica coffee cultivars at the Federal University of Lavras (UFLA), in the city of Lavras, Minas Gerais, Brazil.

(Table 1) shows the hydroclimate data for the city of Lavras, Minas Gerais, Brazil.

Table 1. Hydroclimatic data for the city of Lavras, Minas Gerais, Brazil.

Parameter	Value
Annual Mean Temperature	20.4°C
Minimum Temperature in July	7.1°C
Maximum Temperature in February	22.8°C
Annual Accumulated Precipitation	1460 mm
Maximum Precipitation in January	321 mm
Minimum Precipitation in July	7 mm
Potential Evapotranspiration (ETP)	956 mm
Actual Evapotranspiration (ETR)	873 mm
Water Deficit (DEF)	83 mm
Water Excess (EXC)	587 mm
Water Index (Ih)	61.4
Aridity Index (Ia)	8.7
Moisture Index (Iu)	56.2
Summer Potential Evapotranspiration/ Annual Potential Evapotranspiration (ETPv / ETP)	31%
Climate (Thornthwaite)	B3 r B'3 a'
Köppen Climate Classification	Cwa

Source: Dantas et al. (2007).

2.2 Experimental Design

The experiment was conducted in an area divided into three blocks, each containing plots with ten plants of each of the thirty cultivars of Arabica coffee, totaling 900 plants. In this panel, cultural and phytosanitary treatments relevant to the conventional management system were applied. However, for this study, twenty cultivars were considered as shown in (Table 2). For the analyses, the fifth plant from each plot was selected, totaling sixty sampling points as illustrated in (Fig. 2).

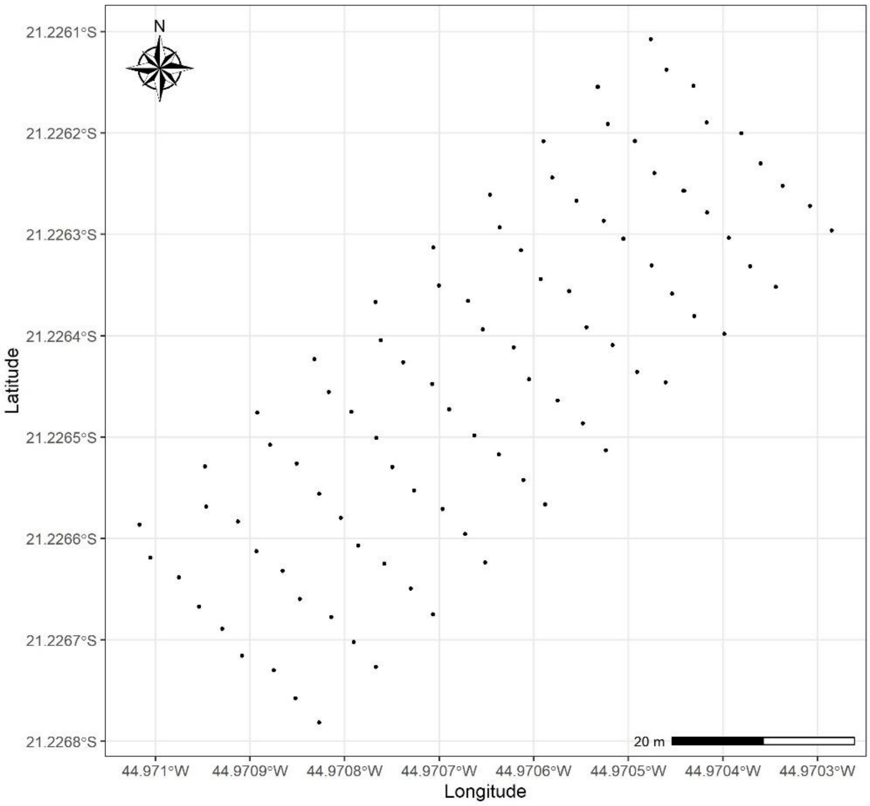

Fig. 2. Experimental design of Arabica coffee cultivars at the Federal University of Lavras (UFLA).

Table 2. Arabica coffee cultivars, divided into three blocks, totaling 60 plants.

Block 1	Block 2	Block 3
Acaua Novo	Catigua MG 3	Iapar 59
IPR 103	IPR 103	Pau Brasil MG 1
Catigua MG 1	Catigua MG 2	Arara
Catucai Amarelo 2SL	Acaua	Clone 224
Pau Brasil MG 1	IPR 100	Clone 312
IPR 102	Iapar 59	Catucai Amarelo 2SL
Siriema	Catucai Amarelo 2SL	Acaua Novo
IPR 100	Rubi MG 1192	Acaua
Catigua MG 3	Aranas RV	Guara
Saira II	Arara	Saira II
Iapar 59	IPR 102	Rubi MG 1192
Rubi MG 1192	Pau Brasil MG 1	Catigua MG 3
Catigua MG 2	Catigua MG 1	Siriema
Acaua	Guara	Araponga MG-1
Araponga MG-1	Saira II	IPR 102
Clone 224	Siriema	IPR 103
Arara	Clone 224	Catigua MG 1
Aranas RV	Acaua Novo	Catigua MG 2
Guara	Araponga MG-1	IPR 100
Clone 312	Clone 312	Aranas RV

2.3 Measurement of Photosynthetically Active Radiation (PAR)

The photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}) was measured using a ceptometer (AccuPAR LP-80, Decagon Devices Inc.). This instrument consists of a data processor and a microprocessor-controlled sensor. The sensor has 80 independent photodetectors spaced at 1 cm intervals. These photodetectors can measure PAR in the frequency range of 400 to 700 nm, which is the wavelength range used by plants for photosynthesis. The AccuPAR can operate in a wide temperature range, from 0 to 50 ºC, and at relative humidities of up to 100%. It allows for manual or autonomous data collection, providing flexibility in data collection (Devices, 2003).

The ceptometer is a sensor that allows for quick and non-destructive data collection. In the context of this study, measurements of Leaf Area Index (LAI) and spectral reflectance were obtained using this in situ sensor. These measurements can be used to calibrate LAI and spectral reflectance data collected by a remote sensing system located on an aircraft or satellite (Jensen et al., 2005).

For the specific case of photosynthetically active radiation (PAR), it was measured using a bar ceptometer. The reading procedure was conducted above the canopy of each plant, with the sensor oriented in the North-South direction. The value obtained corresponds to incident PAR (PARi) on the plant in the full-sun cultivation system. To obtain reflected PAR (PARr), the sensor was positioned with its sensitive face pointing downward, above the canopy.

In the study, a conical shape was adopted to represent the coffee canopy, considering the first pair of plagiotropic branches as the starting point (Assmann, 1970). Based on this representation, measurements of PARi were initially taken. Then, measurements of PARr were taken above the top of the plant, i.e., in the upper section of the canopy. Additionally, measurements were taken in the middle and lower areas of the canopy, as well as at ground level, to obtain transmitted PAR (PARt) or the entire plant (Fig. 3).

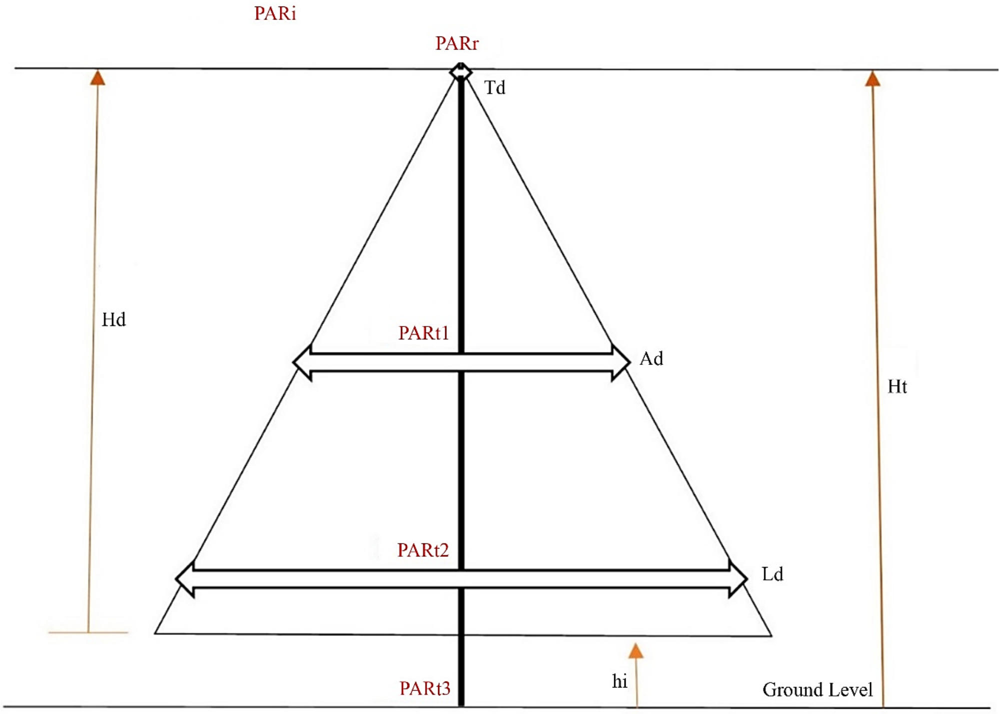

Fig. 3. Coffee plant architecture variables: ht: plant height (m), Hd: canopy height (m), hi: height (m) of the insertion of the first pair of plagiotropic branches. Di: diameter (m) of the lower canopy section, Dm: diameter (m) of the middle canopy section, and Ds: diameter (m) of the upper canopy section. And analyzed radiometric parameters: incident PAR (PARi), reflected PAR (PARr), and transmitted PAR (PARt), in the upper, middle, and ground level sections. Source: Adapted from Favarin et al. (2002).

The data were collected at sixty sampling points, with five measurements taken at each point. The collections were made monthly, from March 2020 to May 2021, except for April, where two collections were made due to the proximity to the harvest date. All measurements were taken between 10 a.m. and 2 p.m., as this is the time of highest solar radiation incidence. At this time, the sun forms a 45° solar angle with a reference point on Earth, indicating the maximum angular displacement of the sun and, therefore, the highest availability of solar radiation at that specific point (Cunha and Volpe, 2010).

To minimize external influences on the variables, days with little or no cloudiness and no rain were chosen. In this way, ideal weather conditions were sought for data collection, in order to obtain more accurate and representative results.

2.4 Estimation of Leaf Area Index (LAI)

The Leaf Area Index (LAI) of the canopy was estimated using the Lambert-Beer law for light extinction, as modified by Monsi and Saeki (1953). This method considers the extinction coefficient of the canopy and the stratum, which is reasonably homogeneous and solely dependent on the solar angle.

The method of Monsi and Saeki (1953) integrates the photosynthetically active radiation data, taking into account the daily radiation above and below the canopy. Then, the fraction of intercepted radiation was calculated using equation 1.

$$f_c = \frac{(PAR_o - PAR_{or}) - PAR}{(PAR_o - PAR_{or})} \times 100 \tag{1}$$

Where, fc is the fraction of intercepted radiation calculated by Monsi and Saeki (1953) (%); PARo is the daily incident photosynthetically active radiation at the top of the canopy (mol m-2 s-1); PARor is the daily reflected photosynthetically active radiation by the canopy (mol m-2 s-1); PAR is the daily transmitted photosynthetically active radiation through the canopy (mol m-2 s-1).

The Leaf Area Index (LAI) was calculated from the intercepted fraction, according to equation 2.

$$LAI = \frac{\ln(1 - f_c)}{-K} \tag{2}$$

Where LAI is the Leaf Area Index (m2 m-2), fc is the fraction of intercepted radiation calculated by Monsi and Saeki (1953), and K is the extinction coefficient of the canopy (m2 m-2).

The reflectance (r) was calculated as the ratio between PARr and PARi over the canopy. For this purpose, the measurements of photosynthetically active radiation (PAR) obtained by the ceptometer were used. The ceptometer was positioned with its sensitive face pointing upwards at the height of the canopy top, recording the values of PARi. Then, the sensor was placed with its sensitive face pointing downwards, measuring PARr.

From the values of PARi and PARr, the reflectance (r) and transmittances between different heights of the plant were estimated. These transmittances are denoted as t1, t2, and t3, corresponding respectively to the transmittance between the canopy top and the plant's middle height, between the canopy top and the plant's lower height, and between the canopy top and the ground.

The fraction of absorbed photosynthetically active radiation (f_{APAR}) was estimated using equations 3 and 4. These equations consider that the PAR reflected by the ground surface (PARrsolo) is negligible, as indicated by equation 3.

$$f_{\mathrm{APAR}} = \frac{\left[\left(\mathrm{PAR_i} - \mathrm{PAR_r}\right) - \left(\mathrm{PAR_o} - \mathrm{PAR_{rsolo}}\right)\right]}{\mathrm{PAR_i}} \quad (3)$$

Which can be rewritten as Equation 4.

$$f_{\mathrm{APAR}} = 1 - \mathrm{r} - \mathrm{t_{topo-o}} \quad (4)$$

2.5 Estimation of the Zenith Angle (Z)

The position of the sun in the sky is described in terms of its altitude (β, elevation angle relative to the horizon) or zenith angle (Z, measured from the vertical) and its azimuth angle (AZ, angle from true north or south measured in the horizontal plane).

The zenith angle Z is reported as β = 90 - Z (degrees), which depends on the time of day, local latitude, and time of the year, calculated by equation 5:

$$\cos Z = \sin\beta = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\left[15\left(t - t_o\right)\right] \quad (5)$$

In which, φ is the latitude of the study location, δ is the solar declination, *t* is the time, and t_o is the time of sunset.

The Earth takes 24 hours to complete 360º, giving fifteen conversion factors of hours into degrees. The time *"t"* is the local time, ranging from 0 to 24. Since the solar declination varies from +23.45º in winter to -23.45º in summer (relative to the equator), the solar declination can be calculated using equation 6:

$$\sin\delta = 0{,}39785\,\sin\left[278{,}97 + 0{,}9856\,J + 1{,}9165\,\sin(356{,}6 + 0{,}9856\,J)\right] \tag{6}$$

2.6 Coffee Yield Assessment

The quantification of coffee yield was carried out in May/June 2020, based on the collection of produced fruits. After the harvest, sub-samples of fruit mass were sent for drying until reaching a moisture content between 12% and 13%. Subsequently, they were processed to obtain productivity values in liters per plant, liters per plot, and sacks per hectare of the processed coffee beans.

Coffee yield was quantified in May/June 2020, following the fruit harvest. Sub-samples of fruit mass were collected and dried until reaching a moisture content between 12% and 13%. Afterwards, these sub-samples were processed to obtain productivity values in liters per plant, liters per plot, and sacks per hectare of the processed coffee beans.

2.7 Statistical Analysis

To assess the temporal behavior of the biophysical parameters in coffee plants, trend analysis was employed. By monitoring the behavior of the plants, it is possible to observe whether there was recovery or degradation of the species throughout its phenological cycle.

Two methods were used for time series analysis: the Nemenyi Test (Nemenyi, 1963) and the non-parametric method of monotonic trend by Mann Kendall (Mcleod, 2011).

The Mann Kendall method involves analyzing the continuous increase or decrease of the observed value of a particular parameter over a specific period of time (Goossens and Berger, 1986). This approach to vegetation trend analysis has been applied to sensors to assess their relationship in different land covers (Lamchin et al., 2020), track ecological restoration or degradation (Zhou et al., 2021), and monitor changes in natural vegetation cover (Zoungrana et al., 2018).

The Nemenyi test is a non-parametric analysis of variance for a single contrast factor that allows comparisons between multiple independent samples to assess whether performance differences are statistically significant. It is used to perform comparisons among all samples. In this procedure, it is considered that the performance of two samples is significantly different when their average ranks show a difference greater than a certain critical distance. This critical distance depends on the number of parameters, the number of data sets, and the critical value corresponding to a specific level of significance. The calculation of this critical distance is based on the Studentized range statistic and can be found in statistical manuals. The critical distance is calculated for a significance level of 0.05 (Kocev et al., 2009).

The analyses and maps related to the Nemenyi Test were performed using RStudio software (RStudio, 2023), with a significance level of 5%. The analyses using the Mann Kendall method were conducted in Python software (Python, 2023).

3. Results and discussion

The temporal behavior of the biophysical parameters of the different analyzed coffee cultivars throughout their reproductive and vegetative cycles was observed, allowing us to assess whether there was recovery or degradation of the species after harvest (Fig. 4).

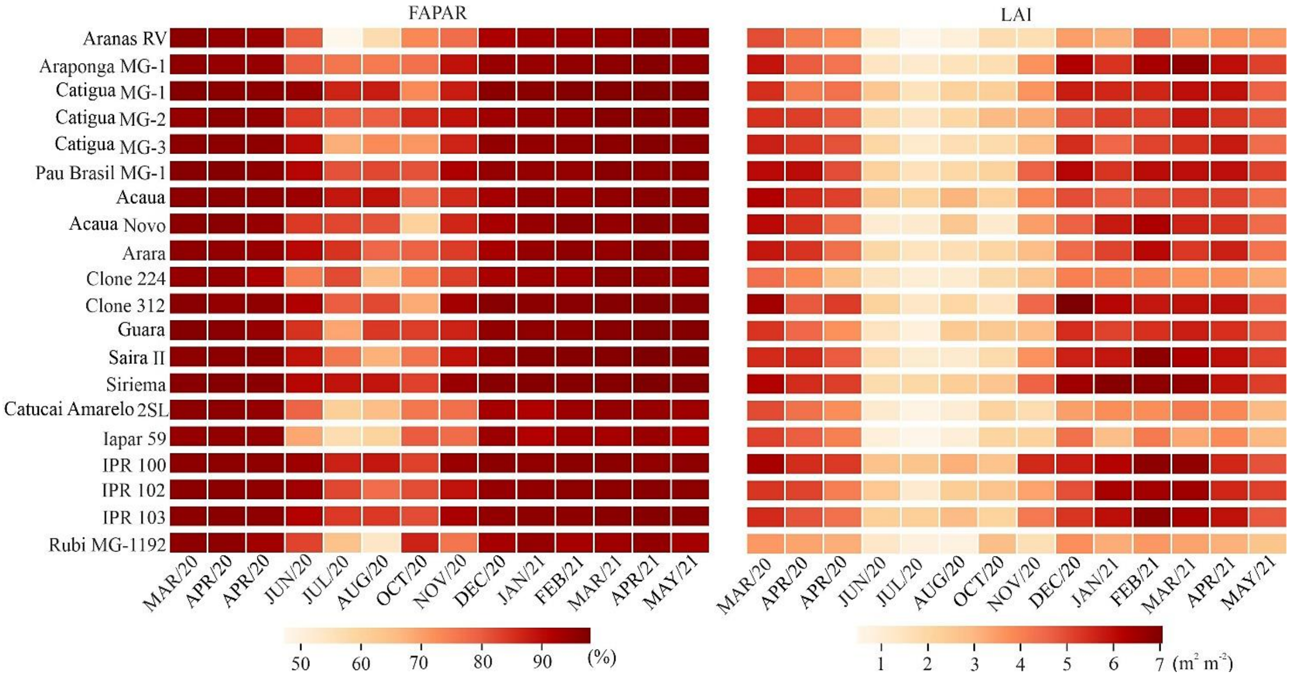

Fig. 4. Temporal behavior of the fraction absorbed of photosynthetically active radiation (f_{apar}) and leaf area index (lai) of different arabica coffee cultivars.

The f_{APAR} is an excellent indicator of the canopy state, and all the analyzed cultivars showed high values of f_{APAR} during the period from March to April 2020, which corresponds to the fruit ripening months and is a reproductive period preceding the harvest. During this period, solar radiation plays a crucial role in the maturation process of coffee fruits, as well as in other plants. The coffee plant utilizes the energy from solar radiation to produce carbohydrates, which are responsible for fruit development and ripening.

Throughout the maturation phase, coffee fruits go through various stages of development, during which changes occur in size, texture, color, and chemical composition. Solar radiation influences this development, as it synthesizes chlorophyll pigments, contributing to the initial green color of the fruits and their evolution into yellow, orange, or red colors, which are characteristic of ripe fruits, thanks to the presence of carotenoids.

Additionally, solar radiation drives fruit filling through hormonal regulation that controls processes such as tissue elongation and cell division.

From May, a reduction in f_{APAR} was observed in almost all cultivars, which extended until October 2020. This period is known as senescence, during which the non-primary productive branches naturally fall, dry, and die. This limits the vegetative growth of the plant and results in a decrease in the fraction of photosynthetically active radiation absorption by the plant canopies.

Only in November 2020, five months after the harvest, the cultivars began to enter a recovery phase, where f_{APAR} increased again, indicating higher vegetation and the formation of leaf buds. This recovery phase is crucial for reestablishing healthy plant growth, where coffee plants direct their resources to repair the damage incurred during the harvesting process. Therefore, this phase is marked by important physiological and biochemical processes for restoration and resumption of vegetative growth.

The recovery time of each coffee plant may vary depending on the extent of damage and specific conditions. Among the cultivars that showed better recovery after the harvest, Araponga MG-1, Catigua MG-1, Catigua MG-2, Catigua MG-3, Pau Brasil MG-1, Clone 312, Siriema, IPR 100, IPR 102, and IPR 103 stood out. It was observed that the Siriema and Pau Brasil MG-1 cultivars presented a higher fraction of absorbed photosynthetically active radiation throughout their reproductive and phenological cycle, even during the senescence period.

According to Sellers et al. (1997), the fraction of absorbed photosynthetically active radiation (f_{APAR}) is a key parameter in various models used to estimate ecosystem productivity, as well as in global climate, hydrology, biochemical, and ecological models.

The f_{APAR} data correspond to LAI data, and the periods with lower f_{APAR} also showed lower LAI values. These periods correspond to the post-harvest phase, known as senescence, during which the plant enters a stage of gradual decline, leading to the eventual shedding of leaves. This process is natural and results in the reduction of the plant's photosynthetic activity, preparing it for the resting period. This reduction in photosynthetic activity explains the lower values of f_{APAR} and LAI since a lower Leaf Area Index implies a smaller leaf surface exposed to solar radiation, resulting in a lower fraction of radiation absorbed by the plant.

The absorption of photosynthetically active radiation by crops is influenced by various factors, such as leaf area index, leaf geometry and size, plant arrangement, sowing rate, sun position, temperature, season, type of crop, climatic conditions, and management practices adopted.

Even during the senescence period, some cultivars showed better biophysical parameters compared to others. The Siriema and IPR 100 cultivars stood out by presenting the highest LAI values, which were consistent with the f_{APAR} results. Next, the Pau Brasil MG-1 and Clone 312 cultivars also showed significant values. From November 2020 onwards, an increase in these parameters was observed. This increase is related to the fact that, during this period, the plants exit the dormant or resting period, known as the off-season, and resume their metabolic activity, resulting in the production of new shoots.

In the absence of stress or water and nutrient restrictions, plants are capable of reaching the ideal leaf area index, where all leaves actively contribute to biomass production. Based on the f_{APAR} and LAI data, the Siriema, IPR 100, Pau Brasil MG-1, and Clone 312 cultivars exhibited more efficient post-harvest leaf recovery. This indicates that these cultivars have more efficient regeneration mechanisms and adapt better to changes caused by the harvesting process, initiating the sprouting phase and resuming their phenological cycle earlier compared to other cultivars analyzed in this study.

The Aranas RV, Catucai Amarelo 2SL, IAPAR 59, and Rubi MG-1192 cultivars showed slower recovery, as their LAI values increased only in December 2020 to January 2021, seven to eight months after the harvest phase. Several factors may be associated with this delayed recovery of these cultivars. It is possible that the plant's resources were depleted during the harvesting process, resulting in a limited reserve of nutrients and energy. As a consequence, the plant may exhibit reduced vigor and difficulties in recovery, requiring more time to initiate the sprouting phase and resume its phenological cycle.

Studies conducted by Shibles and Weber (1965), Jahn (1979), Flénet et al. (1996), Maddonni and Otegui (1996), Collino et al. (2001), and Silva et al. (2006) found that the attenuation of solar radiation is directly related to the leaf area index, i.e., the number of leaves in the plant. These studies showed that an increase in photosynthetically active radiation (PAR) is always associated with an increase in LAI, indicating that a greater leaf quantity results in higher radiation absorption. Sinclair and Horie (1989) demonstrated that coffee plants use radiation less efficiently when they have a lower LAI, as most leaves are photosynthesized by the radiation.

LAI, being a parameter that describes the interaction between the plant and the atmosphere, plays a fundamental role in various models aiming to predict and quantify spatial distribution, health, photosynthesis, transpiration, and energy transfer in ecosystems (Running, 1990). Additionally, accurate estimation of LAI is increasingly important for some crops, especially as an indicator of productivity. This is because photosynthesis depends on the capture of electromagnetic radiation by the plant and its conversion into energy (Favarin et al., 2002).

Another parameter that allows analyzing plant behavior is reflectance. Changes in surface coverage affect the fraction of solar radiation reflected back into space by the canopy. Physiological properties, such as photosynthetic efficiency, plant nutrition, and health status, can be evaluated by analyzing leaf reflectance.

A complementary measure to reflectance is transmittance. Through it, it is possible to observe the fraction of radiant energy that penetrates the lower layers of the plant. Through this parameter, one can infer the concentration of chlorophyll, a compound related to plant vigor, as well as provide information about changes in leaf cell structure, water stress, and nutrient accumulation that influence fruit growth and development.

In general, the quantity and quality of leaf reflectance and transmittance can provide information about biomass production and plant photosynthetic efficiency. (Fig. 5) represents the temporal behavior of the cultivars in relation to these parameters, from the top of the plant to its average diameter.

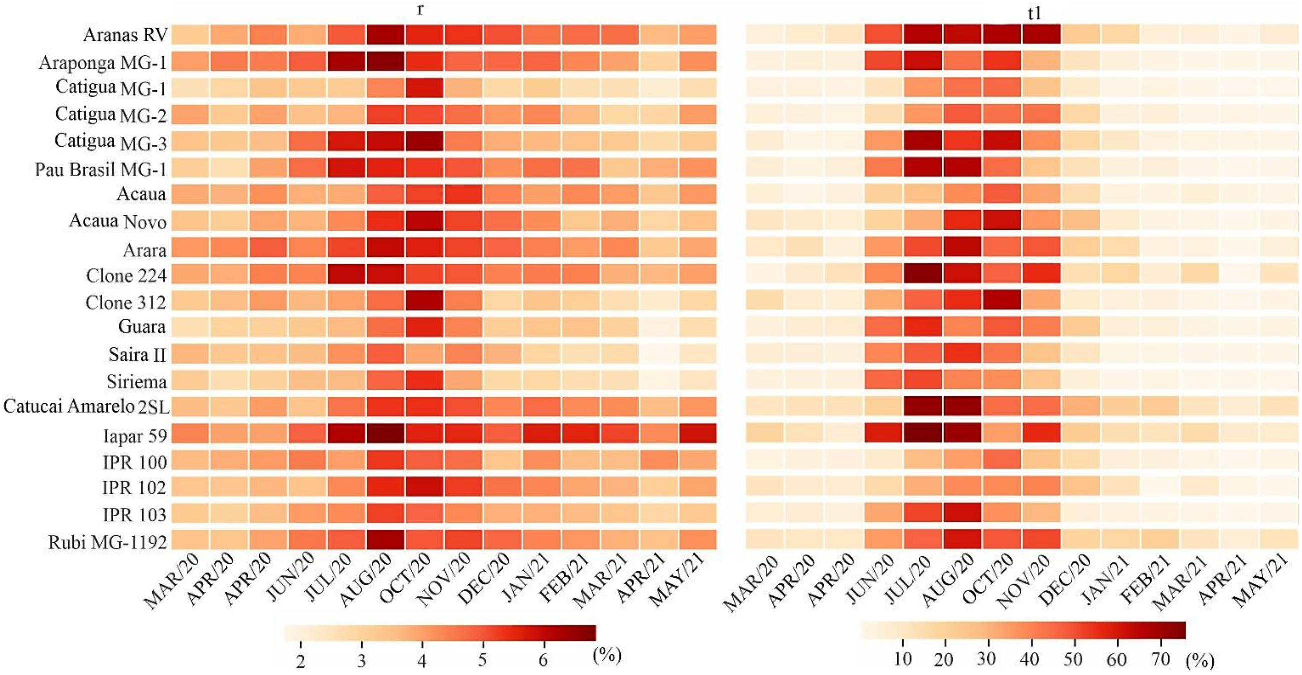

Fig. 5. Temporal behavior of reflectance (r) and transmittance (t) from the top to the middle diameter, of different arabica coffee cultivars.

From June to November, a higher reflectance was observed among the cultivars. This occurred due to physiological changes in the plant in response to fruit removal during the harvesting process and the redistribution of resources such as nutrients and energy. As a result, some older leaves fall off, and new leaves emerge over the days. All these factors are a response to the stress generated during the harvesting procedure. Possible damages to leaf tissues and fruit removal result in a decrease in the leaf area index, leading to increased exposure of leaves to sunlight. Consequently, there is an increase in reflectance due to reduced radiation absorption.

Starting from December, a decrease in plant reflectance was observed as the number of leaves and leaf coverage increased during the vegetative phase. With the development of a denser canopy and a leaf area index closer to the ideal, there was greater sunlight absorption, resulting in a reduction in reflectance during this period.

Despite the stress conditions imposed on the plants during harvesting, it was observed that some cultivars exhibited lower reflectance values than others. It is important to emphasize that the same management practices were adopted for all plants included in the study. Thus, the cultivars that showed lower reflectance during the senescence period were Siriema, IPR 100, Saira II, and Catigua MG-1. On the other hand, the cultivars Aranas RV, Araponga MG-1, Iapar 59, and Catigua MG-3 presented higher reflectance values for the same period, indicating lower leaf area index and f_{APAR}.

During the post-harvest period, the plant's radiation transmittance is also affected, and the months from June to November correspond to a period of higher transmittance from the top of the plant to its median diameter. This is due to the smaller number of leaves present in the plant, which influences the passage of light to the lower parts of the canopy.

In the period from December to January, when the plant is in full growth and development, there is an increase in chlorophyll concentration, the primary pigment responsible for radiation absorption. Additionally, with the increased leaf structure, the plant can absorb more solar radiation, resulting in decreased transmittance, especially in the lower parts of the canopy. This indicates higher radiation absorption efficiency by the plant during this growth stage.

Cultivars IPR 100, IPR 102, Catigua-MG1, Siriema, and Acaua exhibited lower transmittance values during the post-harvest period. After December 2020, with the increase in leaf area, transmittance decreased progressively, indicating greater radiation absorption efficiency by the leaves. This is related to the increased vegetative vigor of the plant, resulting from the development of a larger number of leaves.

Moreira (2005) highlights the importance of ground sensor systems for obtaining data of reflected and/or emitted radiation from objects on the Earth's surface. This data is essential for understanding the spectral behavior of these objects. For example, field radiometry is used in studies that seek to relate the spectral behavior of plants to abnormalities caused by stress, such as nutrient deficiencies. Additionally, field radiometry is employed in the study of estimating biophysical parameters such as the leaf area index, which are important for crop growth models.

Studies by Papa (2009) and Goergen et al. (2009) observed that during the senescence phase, older leaves have higher reflectance in the visible spectrum and lower reflectance in the infrared spectrum compared to green leaves. This higher reflectance in the visible spectrum is a result of pigment degradation, especially chlorophyll, which is responsible for energy absorption in this region of solar radiation. The degradation of leaves during the senescence process leads to a decrease in chlorophyll content, resulting in a reduction in the intensity of the absorption band in the 45 to 65 nm range, leading to a simultaneous increase in reflectance in these spectral ranges.

As mentioned by Silva et al. (2009), there is a significant correlation between reflectance measurements and crop productivity. This is because productivity is directly related to the amount of solar radiation absorbed by the crop, while reflectance is associated with the amount of active leaf tissue capable of absorbing this radiation per unit area. This relationship between reflectance and productivity is supported by previous studies, such as that of Canteri et al. (1999).

To better understand the process by which light passes through the leaves along the canopy, transmittance was also evaluated in the lower parts of the plant, from the canopy top to the lower diameter and from the canopy top to ground level, as observed in (Fig. 6).

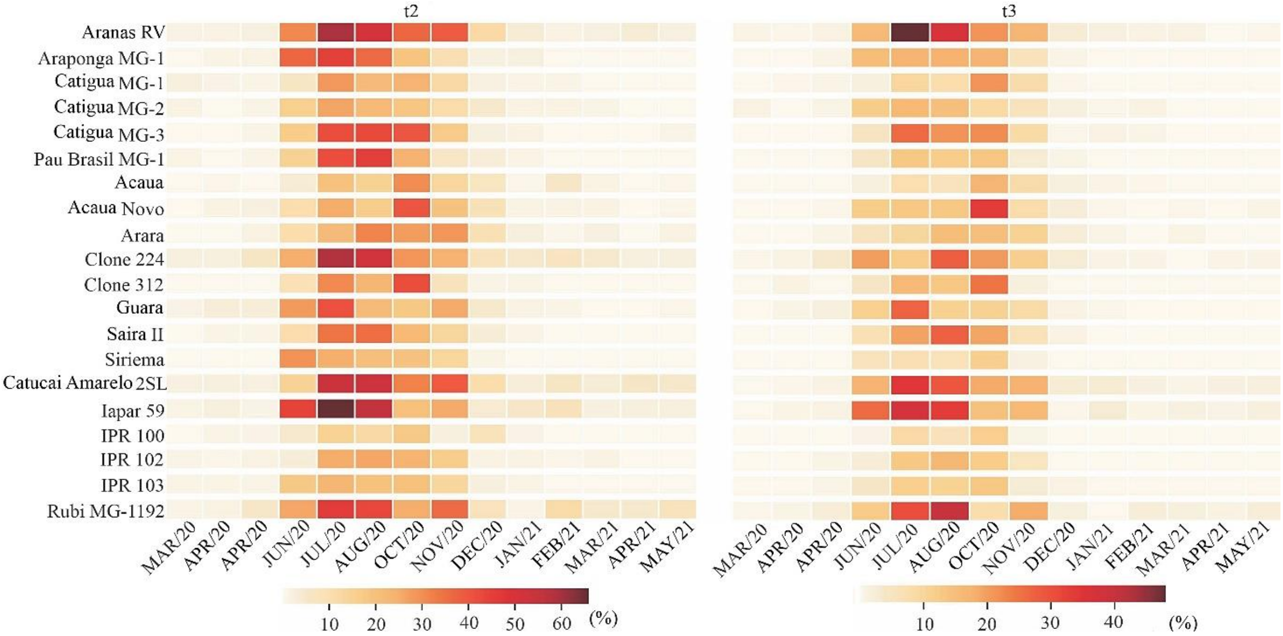

Fig. 6. Temporal behavior of transmittance (t) from top to bottom diameter, and transmittance from top to ground level of different arabica coffee cultivars**.**

The plants that showed good transmittance, even in the post-harvest period when the leaf surface is considerably smaller, were 'Catigua MG-1', 'Siriema', 'IPR 100', 'IPR 102', and 'IPR 103'. Transmittance decreases as one enters the canopy because the closer to ground level, the greater the amount of radiation absorbed by the plant, due to various factors such as shading effects, the presence of other plants, foliage, and the conical architecture of the canopy.

Leaves located in the upper part of the plant generally absorb and reflect a portion of the incident radiation, gradually reducing transmittance to the leaves located in the lower parts of the canopy, as observed in (Fig. 8 and 9). Additionally, it is important to consider reflection and absorption by the soil. In dark soils and in the presence of vegetative cover, even if reduced, the absorption of part of the solar radiation is even higher.

Dry mass and leaf surface area are higher in the lower part compared to the upper part. This is because the upper leaves receive more light, which does not require the development of such an extensive leaf area. Therefore, the upper leaves tend to be smaller. On the other hand, the lower leaves grow more due to shade and the need to maximize light capture, as reported by Matos et al. (2019).

Based on the biophysical parameters analyzed, it was possible to select the cultivars that showed better recovery after the reproductive phase, as well as those with poorer performance. (Fig.7) illustrates the cultivars with the best results regarding f_{APAR} and LAI.

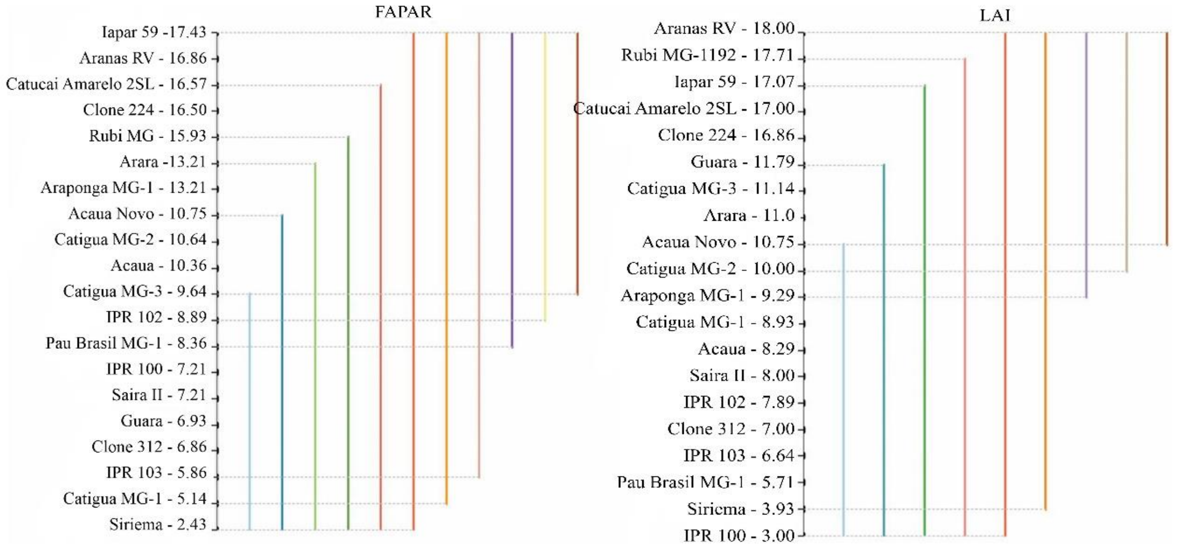

Fig. 7. Placement among cultivars, in relation to Fraction of Photosynthetically Active Radiation (f_{APAR}) and Leaf Area Index (LAI).

The cultivar Siriema obtained the best result regarding f_{APAR}, followed by the cultivars Catigua MG-1, IPR 103, and Clone 312. According to Carvalho (2022), the Siriema cultivar is the result of hybridization between coffee plants of the species *Coffea arabica* (Blue Mountain cultivar) and *C. racemosa*, backcrossed with Mundo Novo, carried out at the Agronomic Institute of Campinas (IAC) in the 1970s, with the aim of developing resistance to the coffee leaf miner (bicho-mineiro).

The Siriema cultivar is known for its tolerance to drought periods and early fruit maturation, making it a valuable option for genetic improvement in the development of other cultivars. Moreover, it is praised for the superior quality of its beverage, which is characterized by pleasant aroma and flavor. Regions with warmer climates that are susceptible to attacks from the coffee leaf miner are particularly suitable for cultivating Siriema due to its smaller canopy size. Densely planting the crop and adopting organic management practices are recommended for this cultivar (Carvalho, 2022).

As for the Catigua MG-1 cultivar, despite its good performance, it has not been widely recommended for commercial use. However, it is worth noting that this cultivar exhibits good resistance to coffee rust and has shown field resistance to *Pseudomonas*, as mentioned by Carvalho (2022).

The IPR 100 cultivar is considered a good option for areas infested with *M. paranaensis* and *M. incognita* nematodes, and it also exhibits good drought tolerance. It has been widely planted recently in the Cerrado Mineiro region. However, there are still no large commercial coffee plantations with more than ten years of age using this cultivar. In terms of productivity, IPR 100 shows a high fruit production capacity with good fruit setting rates, contributing to satisfactory yields during harvests, as reported by Carvalho (2022).

Regarding the Leaf Area Index (LAI), the cultivars IPR 100, Siriema, Pau-Brasil MG-1, IPR 103, and Clone 312 showed the best indices over time and better foliar recovery after harvesting. It is important to note that these plants maintained abundant foliage throughout the year.

The Pau-Brasil MG-1 cultivar is highly adapted to the main coffee-producing regions in Minas Gerais and other Brazilian states. Due to its compact size, it is recommended for planting with row spacings of 2 to 3.5 meters and plant spacings within rows of 0.5 to 1 meter. This characteristic facilitates both manual and mechanized harvesting of coffee plants, allowing for higher planting densities. Additionally, Pau-Brasil MG1 is an excellent option for organic coffee production as it has resistance to coffee leaf rust, which is the main disease affecting the crop, as pointed out by Carvalho (2022).

While the Pau-Brasil MG1 cultivar is still not widely used for commercial purposes, the IPR 103 cultivar is extensively disseminated, mainly due to its characteristics. IPR 103 has good tolerance to heat and drought and shows greater tolerance to soils with low fertility levels. Moreover, 'IPR 103' demonstrates adaptability in various coffee regions and has high productivity, especially in the early harvests. However, in some experiments conducted on plantations over ten years old, the phenomenon of branch drying and leaf impoverishment has been observed, as reported by Carvalho (2022).

As for the Clone 312 cultivar, which is a result of the cross between 'Siriema' and 'Catucai Amarelo 2SL', there are still few available studies. However, in this experiment, the cultivar showed good results in terms of f_{APAR} and LAI, ranking among the top-performing ones. These results align with the research conducted by Souza et al. (2017), which investigated cultivars with drought tolerance and rust resistance, and found that the Clone 312 cultivar showed a higher tendency for susceptibility to drought periods.

The (Fig. 8) illustrates the cultivars with the best performance in terms of reflectance and transmittance, from the top of the plant to the average diameter.

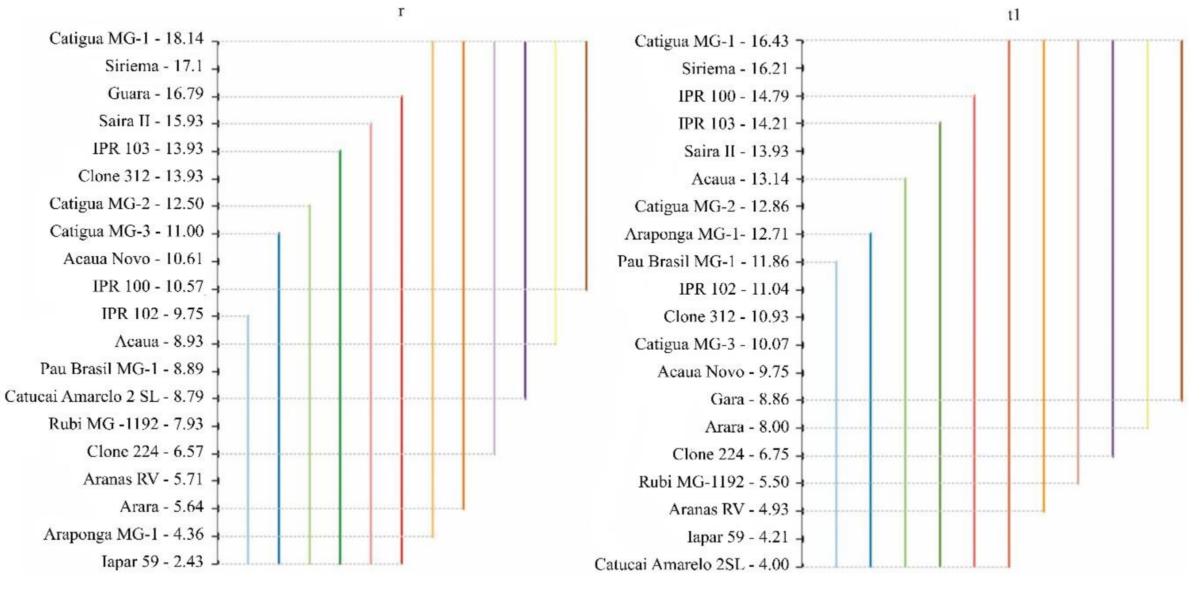

Fig. 8. Placement among cultivars with respect to reflectance (r) and transmittance between the top of the coffee tree and the average diameter in a panel of cultivars.

The cultivars Catigua MG-1, Siriema, Guara, Saira II, and IPR 100 were the ones that showed the best reflectance values, even during the senescence period.

As mentioned by Carvalho (2022), the Guara cultivar demonstrates high agronomic performance in the Cerrado Mineiro and Southern Minas Gerais regions. It has low fruit drop during the maturation period, even in the dry stage. Additionally, the Guara cultivar is known for its high productivity and partial resistance to coffee leaf rust and moderate resistance to *M. exigua* nematodes. It is recommended especially for areas characterized by a hot and dry climate, common in cerrado regions.

The Saira II cultivar is one that, despite showing high productivity and long-lasting resistance to coffee leaf rust, is still not widely disseminated commercially (Carvalho, 2022). However, in this study, 'Saíra II' obtained good results concerning reflectance.

The Saira II cultivar has demonstrated good performance in various coffee-producing regions, with productivity comparable to the Catucai cultivar. It can be grown in both wide and dense spacing. However, it is recommended to initially plant it on a small scale to evaluate its potential within the specific management system of the property, as mentioned by Carvalho (2007).

In the analysis of transmittance from the top of the plant to its average diameter, the cultivars that showed higher radiation absorption were Catigua MG-1, Siriema, IPR 100, IPR 103, and Saira II. These cultivars also stood out in the other analyzed biophysical parameters. In the analyses conducted to evaluate transmittance from the top of the canopy to its lower part and from the top of the plant to ground level, it was possible to observe the cultivars that presented better transmittance values, as represented in (Fig. 9).

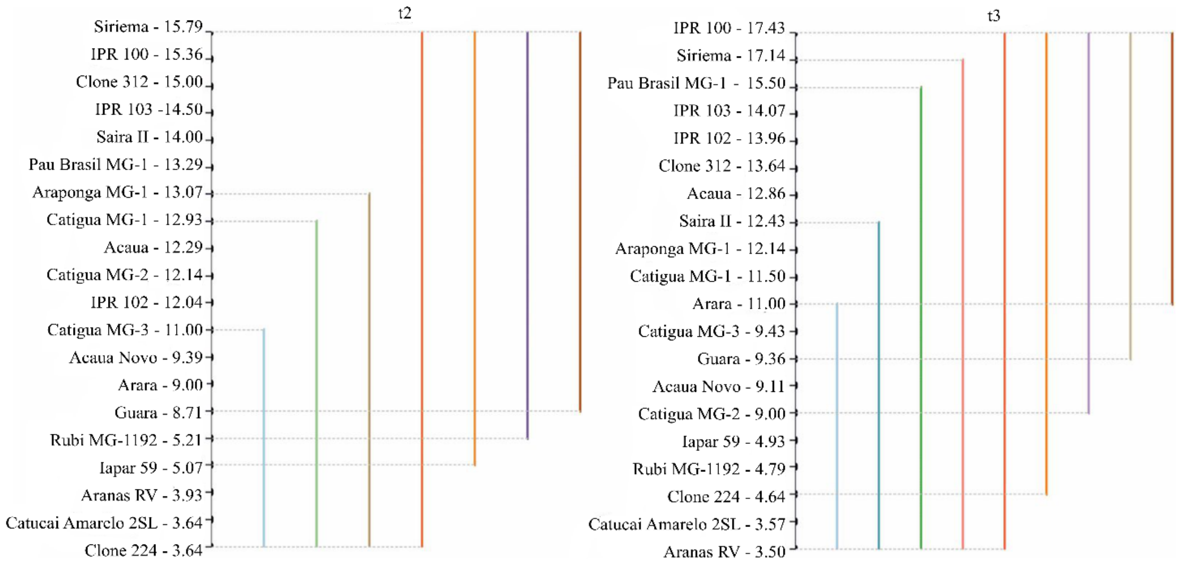

Fig. 9. Placement among cultivars with respect to transmittance (t2) from top to bottom diameter and transmittance (t3) at ground level in a panel of cultivars.

The cultivars that showed better transmittance from the top of the plant to the lower part were Siriema, IPR 100, Clone 312, IPR 103, and Saíra II. Regarding radiation absorption from the top of the plant to ground level, the cultivars with better performance were IPR 100, Siriema, Pau Brasil MG-1, IPR 103, and IPR 102, even during the post-harvest period.

The IPR 102 cultivar, despite its high productivity, is still cultivated on a small scale due to its recent commercial cultivation. It is highly recommended for plantations in areas with severe difficulties related to leaf spot, as it is resistant to this disease, as well as to Phoma spot. Another relevant feature is its resistance to coffee leaf rust, one of the main diseases affecting the coffee crop (Carvalho, 2022). A distinctive characteristic of IPR 102 is its good adaptation to different altitudes, making it suitable for cultivation in areas with low, medium, and high altitudes, which makes it a versatile option for growers.

(Table 3) demonstrates the cultivars that performed best in relation to the analyzed biophysical parameters in the study.

Table 3: Best cultivars in relation to biophysical parameters.

CULTIVARS	f_{APAR}	LAI	r	t_1	t_2	t_3
Siriema	■	■	■	■	■	■
IPR 100		■	■	■	■	■
IPR 103	■	■		■	■	■
Catigua MG-1	■		■	■		
Clone 312	■	■				
Saira II			■	■	■	
Pau - Brasil MG-1		■				■
IPR 102						■
Guara			■			

The Siriema cultivar performed the best in almost all of the analyzed biophysical parameters, followed by the IPR 100 cultivar, which showed the best results in most parameters, except for f_{APAR}. The IPR 103 cultivar also ranked well in almost all radiometric parameters, except for reflectance. Additionally, the Catigua MG-1, IPR 102, Clone 312, Pau-Brasil MG-1, Guara, and Saira II cultivars stood out in relation to the analyzed biophysical parameters.

(Fig. 10) displays the productivity data of the cultivars and the number of months they took to recover their vegetative vigor after the harvest period, showing the cultivars with better recovery and those that were more degraded and took longer to recover after the reproductive phase.

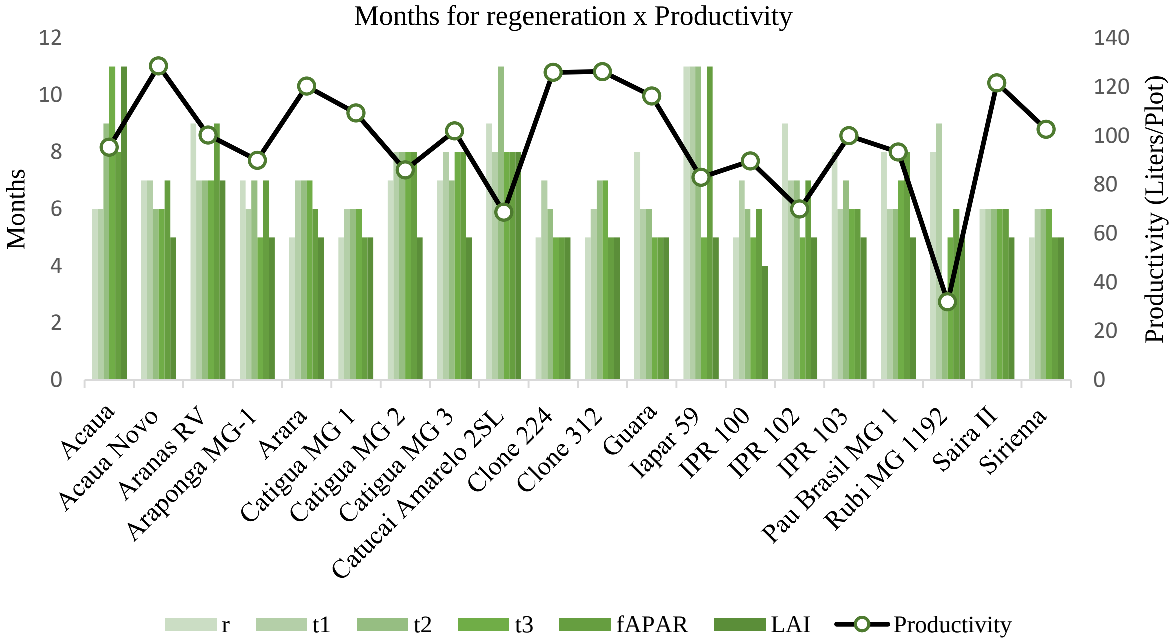

Fig. 10. Months of recovery of post-harvest vegetative vigor and productivity of different Arabica coffee cultivars**.**

The varieties that showed better productivity were those that were able to recover their vegetative vigor in a shorter period after the harvest phase. These varieties include Acaua Novo, Clone 224, Clone 312, Guara, Catigua MG-1, Saira II, Siriema, IPR 100, and Arara, which took four to seven months to recover their leaf area. For instance, the 'Clone 224' variety, which had high productivity, took only five months to present better values of transmittance, f_{APAR}, and LAI. However, more in-depth studies are needed on the 'Clone 224' variety.

The Acaua Novo cultivar, which achieved higher productivity, stands out for its green buds and early maturation compared to the Acaua cultivar. It also has a lower percentage of defective beans and a less dense canopy. It is highly recommended for regions like the South of Minas and Cerrado Mineiro, especially in areas infested with the nematode *Meloidogyne exigua*. The cultivar also exhibits resistance to rust, which is a significant disease affecting coffee plants (Carvalho, 2022).

Among the cultivars with good productivity, six of them also showed good parameters of reflectance, transmittance, f_{APAR}, and LAI. These cultivars are Clone 312, Guara, Catigua MG-1, Saira II, Siriema, and IPR 103. After harvest, they took four to seven months to reach values similar to the pre-harvest biophysical parameters. Most of the cultivars managed to recover their vegetative vigor during this period, demonstrating their ability to bounce back after the reproductive phase.

It's important to highlight that the productivity of a vegetated area is directly related to various factors, including the fraction of photosynthetically active radiation absorbed by the vegetation. Previous studies (Myneni and Williams, 1994; Mariscal et al., 2000; Nouvellon et al., 2000) have demonstrated this relationship. The productivity of a crop is influenced by a variety of biotic and abiotic factors that affect its growth period. Therefore, the final yield is the result of the interaction of these factors with the plant, and its evaluation can be used to analyze different practices and technologies. Additionally, productivity may have been influenced by the environmental conditions in the previous months.

In a study by Moreira (2015), it was found that microclimatic variables have a significant influence on coffee productivity, with photosynthetically active radiation being one of the variables most related to increased productivity. These variables have a significant impact on the growth and productivity of Arabica coffee, as mentioned by Camargo (2010). Ponzoni and Shimabukuro (2007) state that it is possible to use radiation data to predict crop productivity by estimating the number of leaves at a specific growth stage and relating it to yield through a specific mathematical model.

It's important to note that cultivars with low productivity also showed a longer period of vegetative vigor recovery. These cultivars, such as Acaua, Rubi MG-1192, IAPAR 59, and Catucai Amarelo 2SL, took up to eleven months to begin showing signs of improvement in the analyzed biophysical parameters. This result indicates a relationship between productivity and the plant's ability to recover after harvest.

Another factor that should be mentioned is that cultivars such as Rubi MG-1192 exhibit susceptibility to rust, while Catucaí Amarelo 2SL is partially resistant, a factor intrinsically linked to low productivity and delayed recovery of vegetative vigor in plants. The Rubi MG-1192 cultivar, classified as susceptible to rust, tends to show greater vulnerability to the disease. This results not only in periods of low productivity but also in a significant delay for the plant to recover, as it can compromise the integrity and health of the leaves, interfering with metabolic processes and the normal functioning of the plant.

Therefore, the relevance of proper management is emphasized, including practices such as palpation, which involves regularly checking the leaves for signs of infection, allowing for early and more effective intervention in rust control.

Furthermore, susceptibility to other diseases can have a substantial impact on the productivity and the ability to recover vegetative vigor in coffee plants. Another factor to consider is the high productivity that may have occurred in the previous harvest, as it usually means that the plant is investing a significant amount of energy in fruit production. This can result in a disproportionate allocation of resources, with the plant directing many nutrients and photoassimilates to the fruits, at the expense of vegetative growth.

In a study by Louzada et al. (2018), they evaluated whether the incidence of solar radiation received by the coffee crop affected the sensory quality of Arabica coffee. They concluded that lower solar radiation incidence, and therefore, lower radiation absorption by the plant, has a significant effect on the overall quality of Arabica coffee. This reinforces the importance of the environmental state, i.e., solar radiation, which can lead to alterations in internal metabolites, creating a condition of stress, and consequently generating different conditions for the development of microorganisms.

4. Conclusion

The Siriema cultivar demonstrated the best performance in all the bio-physical parameters analyzed, followed by the IPR 100 cultivar, which achieved the best results in almost all parameters, except for f_{APAR}. The IPR 103 cultivar also showed good performance in most parameters, except for reflectance. These results indicate that the Siriema, IPR 100, and IPR 103 cultivars are promising in terms of their bio-physical performance, excelling in different aspects of agronomic interest.

In addition to the Siriema, IPR 100, and IPR 103 cultivars, other cultivars that stood out in relation to the bio-physical parameters analyzed were Catigua MG-1, IPR 102, Clone 312, Pau-Brasil MG-1, Guara, and Saira II.

Among the cultivars with better productivity, those that were able to recover vegetative vigor in a shorter period after the harvesting phase stood out. These cultivars include Acaua Novo, Clone 224, Clone 312, Guara, Catigua MG-1, Saira II, Siriema, IPR 100, and Arara. These varieties demonstrated a faster recovery period, indicating an efficient capacity to resume growth and vegetative development after harvesting. This aspect is important to ensure an adequate productive cycle and high productivity in coffee cultivation.

It was observed that cultivars with low productivity also took a longer time to recover vegetative vigor after the harvesting phase. These cultivars, including Acaua, Rubi MG-1192, IAPAR 59, and Catucai Amarelo 2SL, took up to eleven months to show signs of improvement in the analyzed bio-physical parameters. This result suggests that these varieties faced greater challenges in recovering growth and vegetative development, which may have impacted productivity in the following year. Therefore, it is important to consider the capacity for vegetative vigor recovery when selecting cultivars to ensure satisfactory productivity in coffee cultivation.

The study revealed a relationship between bio-physical parameters and coffee tree productivity. It can be concluded that cultivars with better radiometric indices have greater resistance and, at the same time, higher productivity. This reinforces the importance of the environmental conditions for healthy growth and optimal productivity of arabica coffee cultivars.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this article.

Data Availability

The data will be available upon request.

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PAPER 3 - IDENTIFICATION OF ARABICA COFFEE CULTIVARS TOLERANT TO CLIMATIC ADVERSITIES

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ABSTRACT

The coffee crop is highly sensitive to conditions of excessive moisture, heavy rains, and very humid environments, as well as hot and dry conditions. Projections point to a possible global loss of up to 50% of favorable coffee cultivation areas by 2050, directly affecting major producers like Brazil. In this scenario, it becomes essential to implement adaptation measures to face these challenges. Among the promising strategies is the introduction of coffee cultivars with greater tolerance to climatic adversities. Considering that changes in temperature, precipitation, and humidity variables can substantially affect species suitability, this study aimed to analyze the influence of climatic factors on bio-physical parameters, such as reflectance (r), transmittance (t), fraction of absorbed photosynthetically active radiation (f_{APAR}), and leaf area index (LAI), in twenty arabica coffee cultivars (*Coffea arabica* L.) in the municipality of Lavras, Minas Gerais, Brazil. A ceptometer was used for measuring photosynthetically active radiation (PAR, µmol m^{-2} s^{-1}). All analyses were performed using RStudio software, considering a significance level of 5%. In summary, the study revealed that several arabica coffee cultivars show distinct responses in their bio-physical parameters due to climatic factors. Some cultivars stood out for their notable adaptation to adverse conditions, such as high temperatures and low water availability, with emphasis on the varieties 'Siriema', 'Saira II', 'IPR 100', 'IPR 102', 'IPR 103', and 'Clone 224'.

Keywords: Bio-physical parameters; Climate changes; Coffee plant; Humidity. Precipitation, Temperature.

1. Introduction

Climate change, including global temperature rise and water scarcity, will have a significant impact on the agricultural sector due to the sensitivity of crops to adverse conditions. Changes in these aspects can negatively affect agricultural production, as demonstrated in previous studies (Mendelsohn, 2008; Ramirez-Villegas and Challinor, 2012).

Among agricultural exports, coffee holds a prominent position as one of the world's largest commodities in terms of value (FAO, 2011; Pendergrast, 2009). Besides its significant contribution to the agricultural Gross

Domestic Product (GDP) in many countries, coffee production plays a crucial role in poverty reduction, mainly due to job creation. Over 70% of global coffee is produced by small farmers in various regions of the world, including Latin America (Chemura et al., 2016; Laderach et al., 2017; Fridell et al., 2008).

Coffee production is highly concentrated in countries of the "Global South," which are typically tropical and subtropical countries suitable for coffee cultivation. Among these countries, Brazil, Vietnam, Colombia, Indonesia, Ethiopia, and Honduras stand out. On the other hand, coffee consumption is predominant in countries of the "Global North," which are developed countries located at higher latitudes where the climate is less favorable for large-scale cultivation (Torga and Spers, 2020).

Coffee cultivation is widely recognized as a market-oriented cash crop, making coffee producers susceptible to price fluctuations and, consequently, exposed to cost shock risks. Among the factors affecting coffee prices, the impact of climatic variability has been prominent, reverberating throughout the product's value chain structure and influencing price volatility (Zhou et al., 2022; ICO, 2021).

The coffee crop demonstrates high sensitivity to conditions of excessive moisture, such as heavy rains and very humid environments, as well as hot and dry conditions (IPCC, 2022; IPCC, 2014; IPCC, 2007). Reports of harvest losses have been documented due to periods of drought and climate change, reaching up to 70%, especially in the Americas (Bacon et al., 2017). Projections indicate that by 2050, a general global loss of up to 50% of favorable coffee cultivation areas may occur, directly impacting major producers such as Brazil, Vietnam, Honduras, and India (Bunn et al., 2015).

Results of negative impacts arising from climate change have already been documented in studies such as that by Magrach and Ghazoul (2015), which point to an increase in pest distribution, such as the coffee berry borer. Diseases like coffee rust (*Hemileia vastatrix*), a fungal disease severely affecting coffee plants, have caused significant damage in various producing regions, including Colombia, Central America, and Nicaragua (Avelino et al., 2015; Bacon et al., 2017). The distribution and abundance of pollinators in the Latin American region may also be affected by rising temperatures and other climatic changes (Imbach et al., 2017). Moreover, negative impacts from climate change on coffee production may ultimately pose a threat of extinction to this valuable species (Moat et al., 2019).

In light of this context, the implementation of adaptation measures becomes essential to face these challenges. Promising strategies include the introduction of coffee cultivars with greater tolerance to high temperatures (Ovalle-Rivera et al., 2015), as well as the indispensable quantification of the evolving impact of climate change on coffee cultivation and production (Laderach et al., 2017).

Considering that climate change can substantially affect species suitability, especially concerning temperature, precipitation, and humidity variables, this study aims to analyze the influence of climatic factors on bio-physical parameters, such as reflectance (r), transmittance (t), fraction of absorbed photosynthetically active radiation (f_{APAR}), and leaf area index (LAI), in different arabica coffee cultivars (*Coffea arabica* L.) in the municipality of Lavras, Minas Gerais, Brazil. Thus, the study seeks to identify and select cultivars that are more resistant to drought periods, in light of projected climate change.

2. Materials and methods

The study was conducted in the cultivar panel of the Federal University of Lavras (UFLA), located in the municipality of Lavras, Minas Gerais, Brazil. The site is situated at an altitude of 919 m, with the following geographical coordinates: 21° 14' 43 S and 44° 59' 59 W. The panel is maintained under the supervision of the National Institute of Coffee Science and Technology (INCT do Café) (Fig. 1).

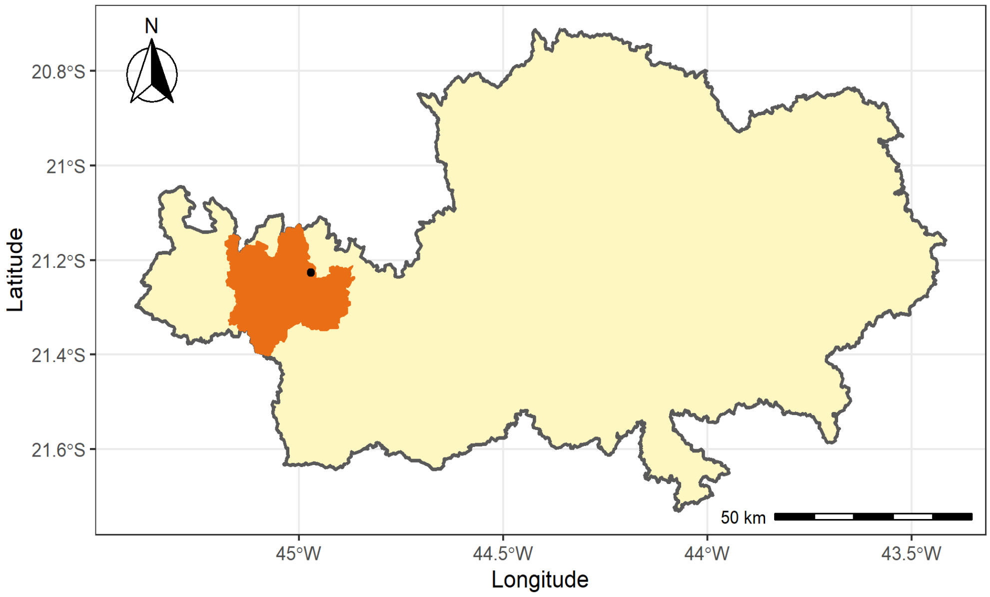

Fig. 1. Location of the panel of arabica coffee cultivars at the Federal University of Lavras (UFLA), municipality of Lavras, Minas Gerais, Brazil.

Hydroclimatic data for the municipality of Lavras, Minas Gerais, reveals an average annual temperature of 20.4 ºC, with a minimum record of 7.1 ºC in July and a maximum of 22.8 ºC in February. As for precipitation, the accumulated annual average is 1460 mm, with a peak of 321 mm in January and a minimum of 7 mm in July. According to the Thornthwaite classification, the climate in the region is categorized as B3 r B'3 a', characterized as humid with a slight water deficiency, and it is denominated mesothermal (Dantas et al., 2007).

2.1 Experimental Design

The experimental area was subdivided into three blocks, with plots composed of ten plants each, totaling thirty distinct cultivars of arabica coffee, resulting in a total of 900 plants. The selection of the twenty cultivars used in the study was based on the criterion of established plant productivity. The analyzed cultivars were as follows: Acaua Novo, IPR 103, Catigua MG 1, Catucai Amarelo 2SL, Pau Brasil MG 1, IPR 102, Siriema, IPR 100, Catigua MG 3, Saira II, Iapar 59, Rubi MG 1192, Catigua MG 2, Acaua, Araponga MG-1, Clone 224, Arara, Aranas RV, Guara, Clone 312.

2.2 Data Acquisition

For the measurement of photosynthetically active radiation (PAR, µmol m^{-2} s^{-1}), a ceptometer (AccuPAR LP-80, Decagon Devices Inc.) was used. This device consists of a photosensitive probe equipped with 80 independent sensors, properly spaced, allowing precise capture of incident solar radiation on the studied crop.

The conical shape of the coffee plant was taken into account during the measurement of photosynthetically active radiation (PAR). The sensor was positioned above the plant to measure incident PAR (PARi) reaching the plant. Then, the sensor was placed with the sensitive face down to measure reflected PAR (PARr) by the plant leaves. To measure transmittance, the sensor was positioned at three levels: medium, lower, and near the ground, to obtain transmitted PAR (PARt) to the lower canopy layers.

With the acquisition of PARr (reflected photosynthetically active radiation) and PARi (incident photosynthetically active radiation), reflectance (r) was calculated as the ratio between these two measurements. In turn, transmittance was measured from the ratio between PARt (transmitted photosynthetically active radiation) and PARi, being performed at three different levels of the plant: at the medium level of the plant, denominated as (t1); at the lower level of the canopy, denominated as (t2); and at ground level, denominated as (t3).

The fraction of absorbed photosynthetically active radiation (f_{APAR}) was estimated as the difference between 1 and the reflectance value minus the total transmittance value of the plant, taking into account that the contribution of photosynthetically active radiation (PAR) reflected by the soil surface (PARrsolo) is negligible. This estimate provides the fraction of photosynthetically active radiation that is absorbed by the plant and used in the photosynthesis process.

On the other hand, the Leaf Area Index (LAI) was estimated by applying the Lambert-Beer law for light extinction, as modified by Monsi and Saeki (1953). In this calculation, the extinction coefficients of the canopy and the stratum were considered, which depend on the solar angle. For obtaining climatic variables, the platform of the National Institute of Meteorology (INMET) was used, with data collected from the conventional station of Lavras (83687). The data covers the period from March 2020 to May 2021, allowing the calculation of monthly average temperature, monthly precipitation, and relative humidity.

2.3 Statistical Analyses

To understand the variations of climatic variables over time and their relationships with bio-physical parameters, time series graphs were created for each analyzed cultivar. To compare the bio-physical parameters among different cultivars and observe the median and dispersion of the data, boxplots were constructed. In order to assess the linear relationship between climatic variables and bio-physical parameters of cultivars, the Pearson correlation was applied. All analyses and graph creation were performed using RStudio software (RStudio, 2023), considering a significance level of 5%.

3. Results and discussion

Data on Leaf Area Index (LAI), fraction of absorbed photosynthetically active radiation (f_{APAR}), reflectance (r), and transmittance (t), together with monthly data on temperature, precipitation, and humidity, were observed throughout the phenological cycle of the coffee plant and presented in time series graphs. These graphs allow visualization of seasonal patterns and variations over time for each analyzed cultivar.

3.1 'Aranas RV'

For the Aranas RV cultivar, LAI was 4.9 $m^2.m^{-2}$ in the first measurement month (March). As the harvest date approached, there was a decrease in LAI, being 4.1 $m^2.m^{-2}$ at the beginning of April and 3.7 $m^2.m^{-2}$ at the end of April, as can be observed in (Fig. 2).

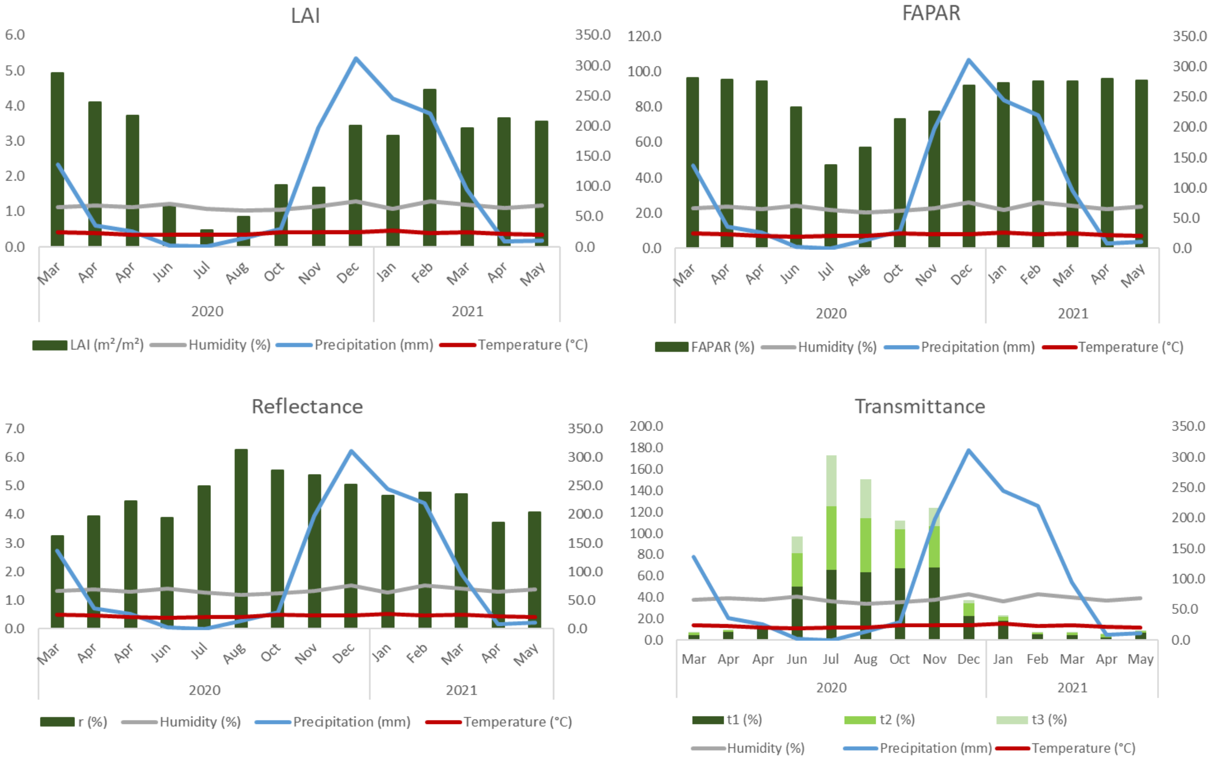

Fig. 2. Leaf Area Index (LAI), fraction of absorbed photosynthetically active radiation (f_{APAR}), reflectance (r), and transmittance (t) of the cultivar Aranas RV.

The values found for the Leaf Area Index (LAI) in March and early April were considered ideal for a healthy coffee plant in development, ranging from 4 to 6 m².m^{-2}, indicating a good vegetative development of the plant during this period. However, the LAI decreased as the harvest date approached, which is a natural phenomenon in various crops. This is because the plant directs its resources, such as energy and nutrients, towards the formation and development of fruits, which contain the coffee beans responsible for the plant's productivity (Taugourdeau et al., 2014).

After the harvest, in May 2020, the LAI significantly decreased to 1.2; 0.5; and 0.9 m².m^{-2} in June, July, and August, respectively. This decrease is related to the post-harvest period, known as senescence, in which the plant experiences defoliation and a decrease in photosynthetic capacity due to cell degradation.

Even after the harvest period, the Aranas RV cultivar took about seven months to recover the LAI equivalent to the pre-harvest state, reaching an LAI value of 4.5 m².m^{-2} only in February 2023. In December and January, there was an increase in the LAI value (3.4 and 3.2 m².m^{-2}, respectively), possibly due to higher precipitation volumes in those months (311.7 and 245.0 mm). However, despite the increment, it was still not enough to reach the LAI observed before the harvest.

Regarding the Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}) for the Aranas RV cultivar, March and April had high values (96.3% and 95.3%, respectively), indicating that the plant captured a significant amount of solar radiation during this period. In July and August, the f_{APAR} values were the lowest (47.1% and 57.1%, respectively), increasing in October and November, but reaching values close to the pre-harvest period only in February 2021 (94.4%).

The reflectance values were 3.3%, 3.9%, and 4.5% in March, early and late April 2020, respectively. These values increased significantly during the harvest period, reaching 5.0%, 6.3%, and 5.5% in July, August, and October. After the harvest, the reflectance values remained high throughout the year, decreasing only in April 2021 (3.9%), suggesting that the plant might not be maximizing its photosynthetic capacity.

Regarding transmittance, the highest values were observed for t1 (from the top of the plant to the middle part) due to the fact that the upper leaves receive more direct sunlight than the leaves in the lower parts of the plant, which are less exposed. Additionally, the conical shape of the coffee plant contributes to a higher concentration of leaves in the lower part of the plant, resulting in higher transmittance in the upper part.

In March, early, and late April, transmittance was relatively low, being 4.9%, 7.5%, and 10.8%, respectively, due to higher absorption of solar radiation during this period for fruit filling and growth. From July to November, transmittance increased significantly, reaching maximum values of 66.1%, 63.5%, 67.1%, and 67.9%. The values decreased only in December (22.4%), seven months after the harvest period.

Transmittance decreased along the canopy of the coffee plant, with the lowest value observed before the harvest period, in April (1.4%) for t2 (from the top of the plant to the lower part of the canopy). From July to December, the values increased, with July standing out with a t2 transmittance of 59.2%. Even with the increase in the number of leaves, transmittance remained high in this section.

Regarding t3 (from the top of the plant to the ground level), the values were lower, reaching the lowest value in March (0.4%) and the highest in July and August (48.0% and 36.6%, respectively). Like t1 and t2, t3 only decreased starting from December, when there was an increase in LAI, resulting in a higher total area of green leaves per unit area and consequently, a greater photosynthetic capacity of the plant.

3.2 'Araponga MG-1'

The values of LAI, f_{APAR}, reflectance, and transmittance corresponding to the Araponga MG-1 cultivar, as well as the climatic variables of the region, can be observed in (Fig. 3).

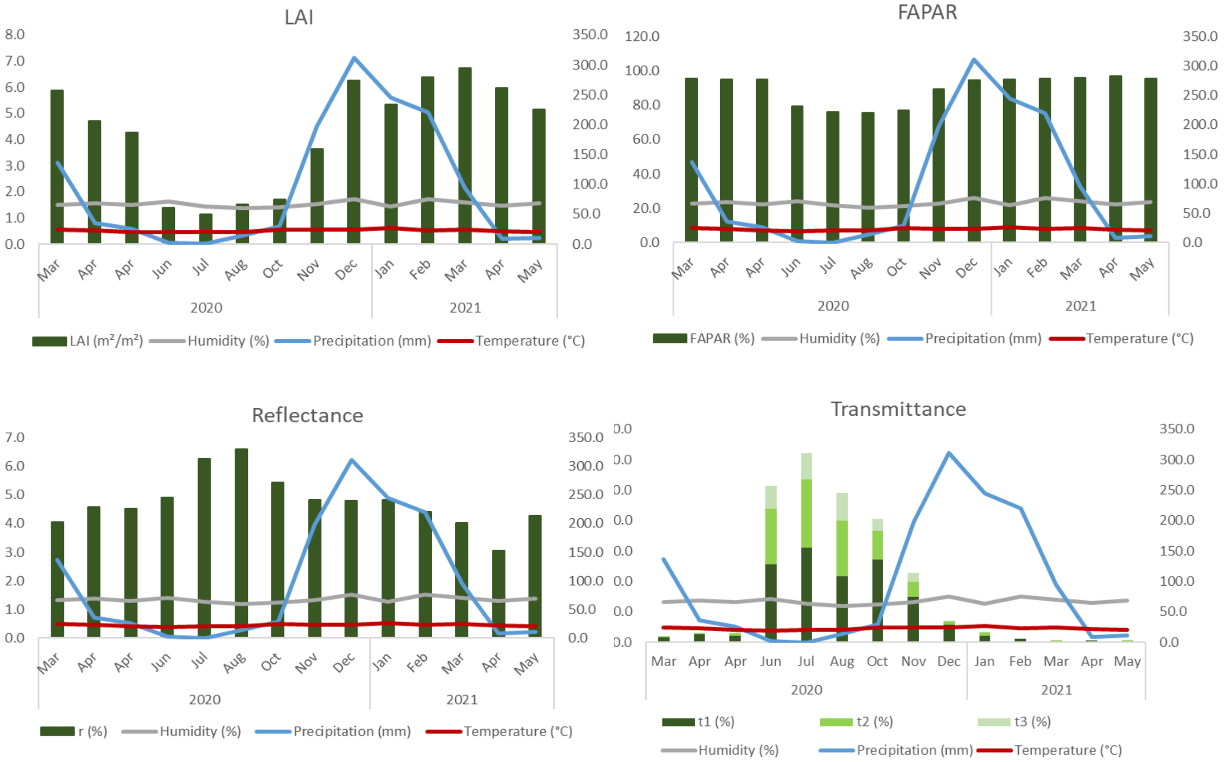

Fig. 3. Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}), reflectance (r), and transmittance (t) of the Araponga MG-1 cultivar.

For the Araponga MG-1 cultivar, the LAI showed high values in the months preceding the harvest, March, early and late April, with 5.9; 4.7; and 4.3 m².m^{-2}, respectively, decreasing in the post-harvest period, reaching the lowest value in July (1.1 m².m^{-2}). Subsequently, the LAI started to increase in November (3.6 m².m^{-2}), doubling its value in December (6.2 m².m^{-2}), a month with the highest precipitation of the year and high humidity (75.7%). The greater water availability allowed the plants to maintain hydrated leaves, enabling further leaf development and expansion. In the following months, the LAI reached even higher values, peaking in March 2021 (6.7 m².m^{-2}).

Regarding f_{APAR}, the values were high in the months before the harvest, with 95.8, 95.1, and 94.9 m².m^{-2} in March, early and late April, respectively, decreasing during the harvest period to 79.5, 76.1, and 75.4% in June, July, and August. Despite the reduced values, f_{APAR} remained relatively high compared to other cultivars that showed lower values for the same period.

Reflectance was 4.1, 4.6, and 4.5% for the first three months of measurement, increasing after the harvest period to 4.9, 6.3, 6.6, and 5.4% in June, July, August, and October, respectively, and decreasing only in February 2021, returning to values similar to the pre-harvest period.

Transmittance (t1, t2, and t3) showed very high values during the senescence period, reaching the highest value in July (62.2%). The values started to decrease from January 2021 (4.1%). The values of t2 and t3 were lower compared to t1, as expected. T2 reached its highest value in July (44.6%), decreasing in December (2.4%). T3 reached values of 15.5, 17.6, and 18.0% for the months of June, July, and August, and obtained the lowest values in December (0.5%). It is important to highlight that t3 reached very low values as LAI increased, reaching near-zero values in the months of February, March, April, and May 2021, when LAI reached its maximum value.

3.3 *'Catigua MG1'*

For the Catigua MG1 cultivar, the values of the biophysical parameters, as well as the data on humidity, precipitation, and temperature can be observed in (Fig. 4).

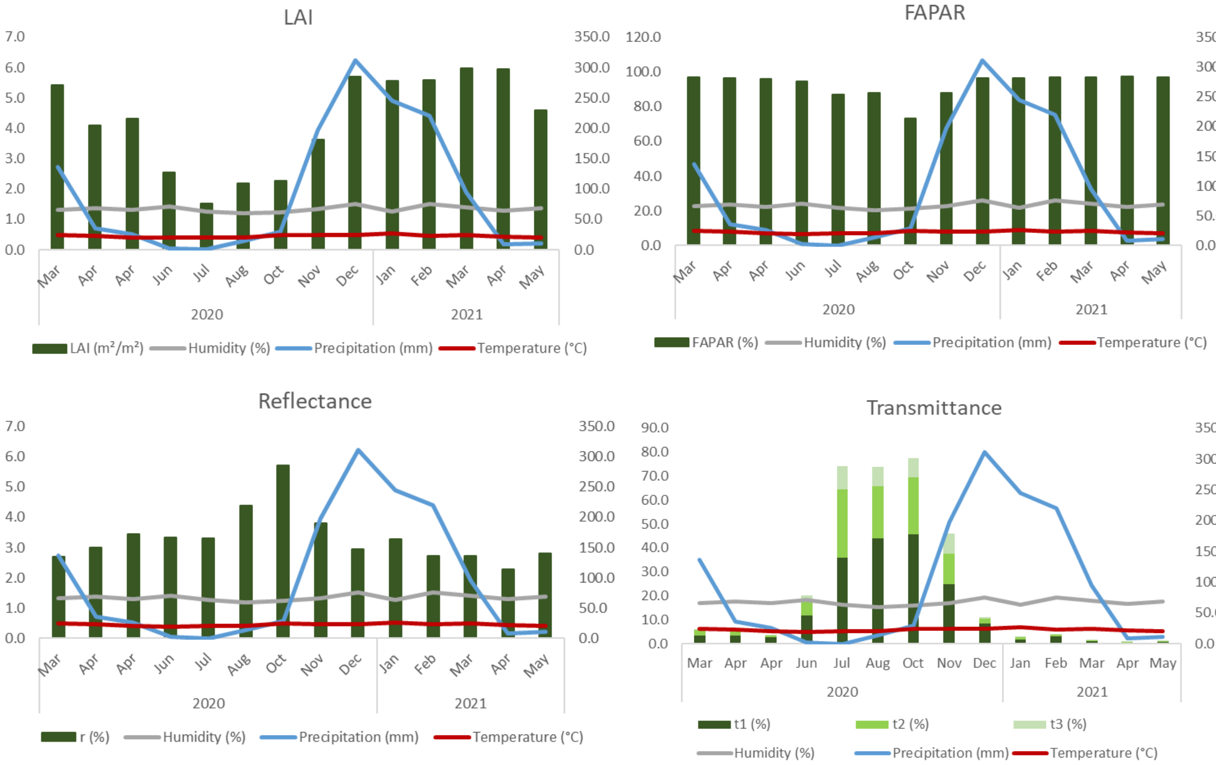

Fig. 4. Leaf Area Index (LAI), fraction of absorbed photosynthetically active radiation (f_{APAR}), reflectance (r), and transmittance (t) for the Catigua MG-1 cultivar.

The cultivar Catigua MG1 showed satisfactory biophysical parameters, even during the senescence period. The LAI of the cultivar exhibited high values in the months preceding the harvest, reaching its maximum value in March (5.4 $m^2.m^{-2}$) and decreasing as the fruits grew and the harvest month approached. The lowest LAI value was observed in July (1.5 $m^2.m^{-2}$), while in the other months of the senescence period, the index remained above 2 $m^2.m^{-2}$. From November, LAI values began to increase, reaching values above 5 in December and continuing to grow until April 2021.

The cultivar demonstrated good absorption of solar radiation, as indicated by the high f_{APAR} values throughout most of the year, even with lower values during the senescence period. The lowest f_{APAR} value was recorded in October (73.1%), but in the months following the harvest, f_{APAR} remained above 80%. From December, f_{APAR} exceeded 96%, even during months of low precipitation and low humidity, such as April and May, highlighting the plant's excellent photosynthetic capacity under water scarcity conditions.

The reflectance of the cultivar showed low values, including during the senescence period, with the maximum value in October (5.7%) and decreasing in November (3.8%), fluctuating around similar values in the following months.

Regarding transmittance, the values found were relatively low, even for t1, which in many other cultivars showed high values. The t1 values increased during the senescence period, reaching the highest values in August and October, 43.9% and 45.6%, respectively. In January, when the plant recovered its vegetative vigor, the t1 values were at their minimum, reaching the lowest value in April 2021 (0.5%).

For t2, the values were low in the first months preceding the harvest, increasing during the senescence period and reaching the minimum value in December (1.9%), decreasing even further in the following months. As for t3, the highest value was recorded in July, the post-harvest period (9.8%), decreasing to 0.6% in December, when the plant's vegetative vigor increases, and the absorption of solar radiation by the leaves is also higher.

3.4 ‘Catigua MG2’

For the cultivar Catigua MG2, the LAI values also showed a significant reduction in the post-harvest period, compared to the values presented in the early months of data collection, which were close to 5 $m^2.m^{-2}$. In the months of June, July, August, and October, the LAI values were 1.8, 1.4, 2.0, and 2.9 $m^2.m^{-2}$, as shown in (Fig. 5).

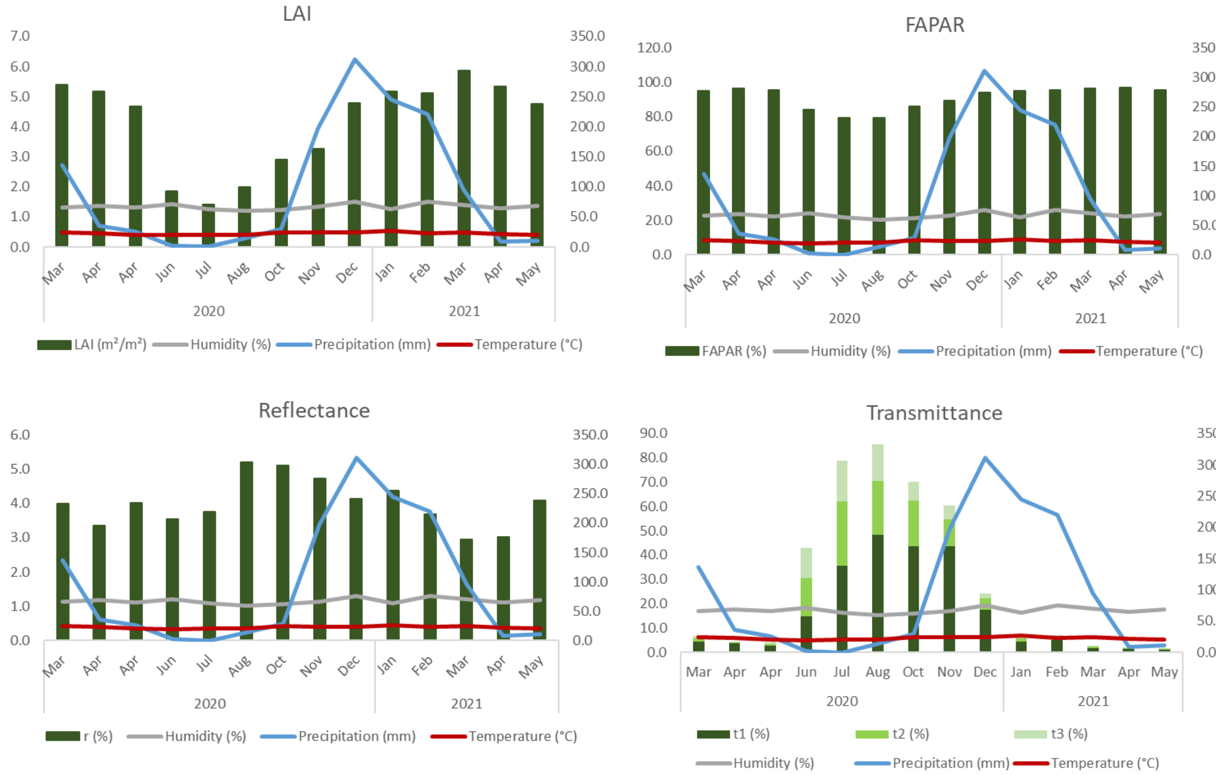

Fig. 5. Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}), Reflectance (r), and Transmittance (t) of the cultivar Catigua MG2.

For the Catigua MG2 cultivar, Leaf Area Index (LAI) values showed an increase starting from December, reaching 4.8 $m^2.m^{-2}$ and remaining even higher in the following months. Overall, Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}) values remained high even in the months after harvesting, with the lowest value occurring in July and August (79.6%). In December, f_{APAR} values increased again, reaching above 90% for all subsequent months, indicating that the cultivar has a good capacity for photosynthesis even in unfavorable periods.

Reflectance was quite high in the months following harvest, particularly in August, October, and November, with values of 5.2%, 5.1%, and 4.7%, respectively. Reflectance values decreased starting from December, reaching their lowest point in March and April 2021 (3.0%).

Transmittance values were low in the months preceding harvest when the LAI of the plant was high. During the senescence period, transmittance values increased significantly, reaching t1 values of 48.3%, 43.7%, and 43.5% for August, October, and November, respectively, decreasing in December and reaching their lowest value in May (1.0%). T1 values were considerably higher than t2, with t2's maximum values occurring in July and August

(26.3% and 22.1%), also decreasing in December. T3 had its highest value in July (16.7%) during senescence, reaching its lowest values in April and May 2022 (0.2%).

The Catigua MG2 cultivar, in general, took more time to recover vegetative vigor, presenting biophysical parameter values similar to its pre-harvest state, one to two months longer than the Catigua MG1 cultivar, for example.

3.5 'Catigua MG 3'

For the Catigua MG3 cultivar, LAI values during the fruit maturation period were quite high, reaching values close to 6 m².m^{-2}, as can be observed in (Fig. 6).

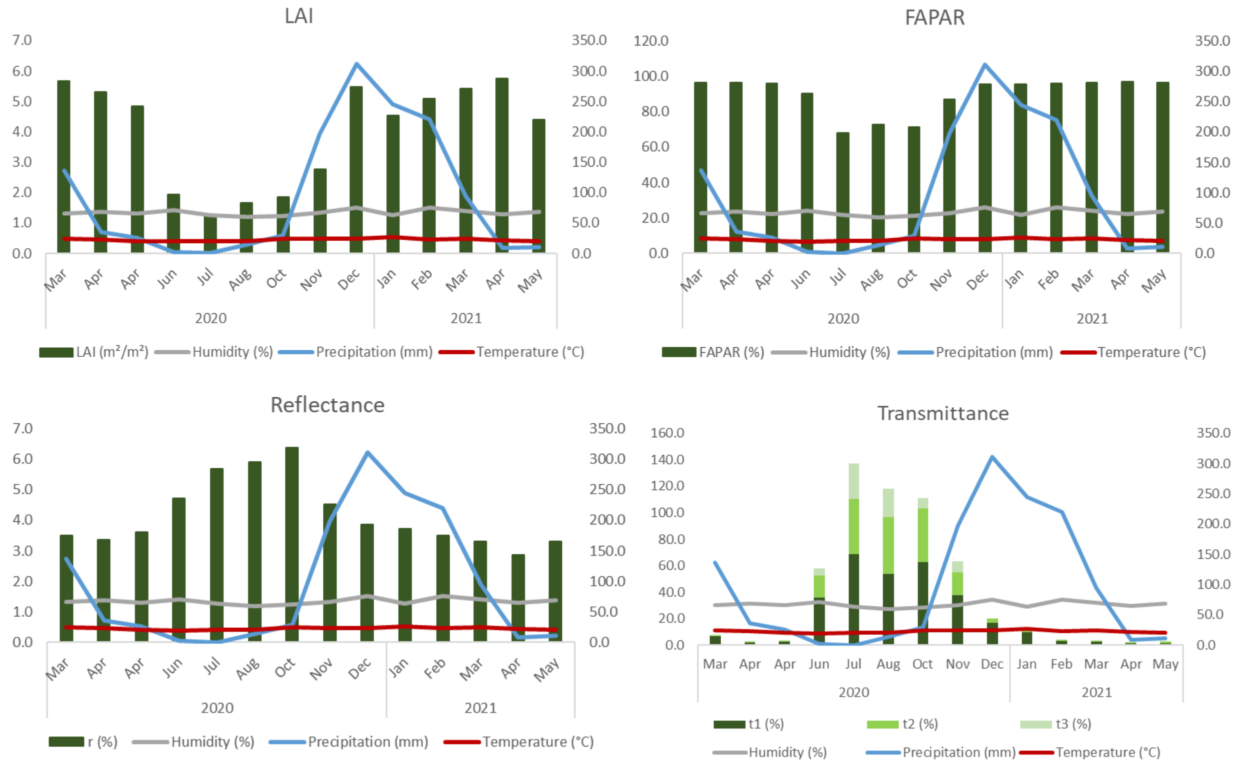

Fig. 6. Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}), Reflectance (r), and Transmittance (t) of the Catigua MG3 cultivar.

The Leaf Area Index (LAI) values for the Catigua MG3 cultivar showed a decrease during the harvest period, reaching its lowest value in July (1.2 m².m^{-2}), but subsequently increasing and oscillating between 5 and 6 m².m^{-2}, peaking in December.

The f_{APAR} of the cultivar remained high for most of the year, with an exception during the senescence period, where values were lower, recording 68.0%, 72.9%, and 71.3% for the months of July, August, and October, respectively. In December, the f_{APAR} increased again, reaching values above 95%.

The reflectance of the cultivar was high during the senescence period, reaching its maximum value in October (6.4%) and decreasing in December, reaching its lowest value in April 2021 (2.9%).

Regarding transmittance, the values were low, including for t1, which reached values of 6.5%, 1.9%, and 2.7% for the months of March, early and late April, respectively. Even during the post-harvest period, the transmittance values were not as high compared to other cultivars. The highest value for this period occurred in October, with t1 reaching 68.7%, and then decreasing in December to 1.6%. The values of t2 were similar to t1, indicating that there was no significant difference in the absorption of solar radiation by the leaves between the middle and lower parts of the plant. The highest values of t2 occurred during the senescence period, peaking in August (42.9%) and decreasing in December to values below 1%. T1 also remained high during the post-harvest period but already exhibited low transmittance in December, with values below 0.8%.

The Catigua MG3 cultivar showed a temporal behavior similar to Catigua MG2, both taking longer to recover vegetative vigor compared to the Catigua MG1 cultivar.

3.6 'Pau Brasil MG1'

The LAI for the Pau Brasil MG1 cultivar was high throughout the year, with values close to or above 6 $m^2.m^{-2}$. The lowest values were observed during the senescence period, between June and October. However, the values increased in November, reaching the annual peak in December (6.1 $m^2.m^{-2}$), as can be observed in (Fig. 7).

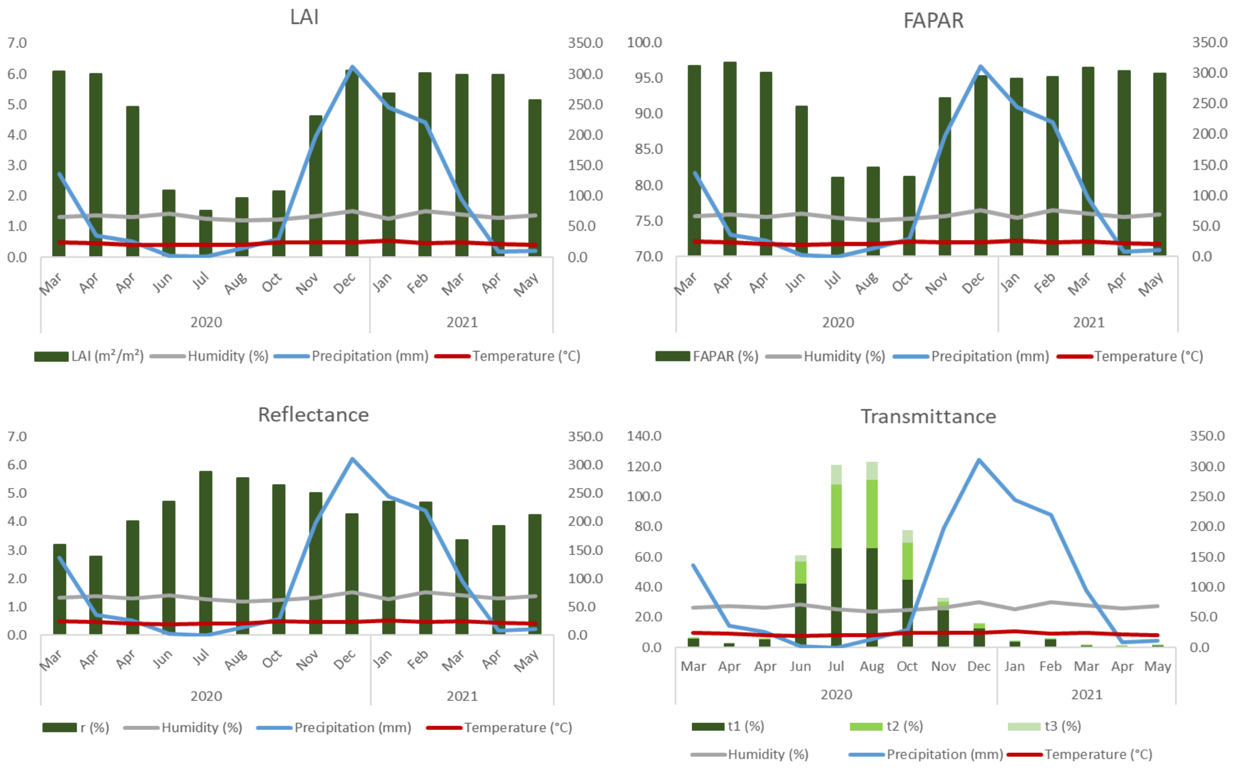

Fig. 7. Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}), reflectance (r), and transmittance (t) of the Pau Brasil MG1 cultivar.

The f_{APAR} of the cultivar remained high throughout the year, with values above 95%. There was a slight reduction during the senescence period, but f_{APAR} remained above 80%, indicating good performance of the cultivar even in the post-harvest period.

Regarding reflectance, the highest values occurred in the post-harvest period, with values of 5.8%, 5.6%, and 5.3% in July, August, and October, respectively. These values decreased in December, with fluctuations in the following months.

The cultivar exhibited low transmittance, even in the months of June to August. The highest values found for t1 were 66.1% in August, while in January, after the increase in LAI, the cultivar showed t1 of 3.8%. As for t2, the highest value was recorded in August (45.4%), and in January 2021, it reached 0.7%, decreasing in the following months. The t3 showed reduced values, even during the senescence period.

3.7 ‘Acaua’

The cultivar showed a good LAI in the months leading up to harvest, with values of 6.3, 5.5, and 5.2 $m^2.m^{-2}$ in March, early April, and late April, respectively. However, there was a significant reduction during the harvest period, with values ranging from 2 to 3 m².m^{-2}, as observed in (Fig. 8).

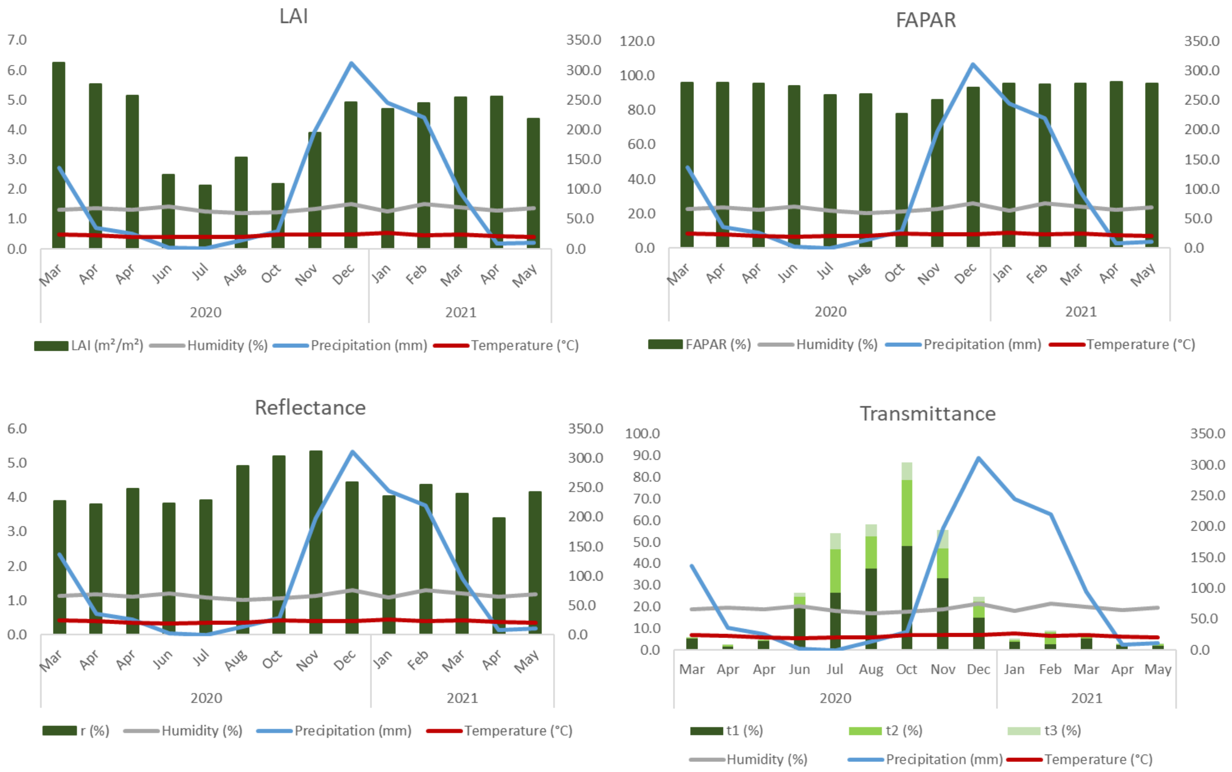

Fig. 8. Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}), reflectance (r), and transmittance (t) of the Acaua cultivar.

The LAI started to increase again in December, but the cultivar only reached values similar to the pre-harvest state in March 2021 (5.1 m².m^{-2}). The f_{APAR} for the cultivar was significant throughout most of the year, with the lowest values occurring during the senescence period, reaching 77.9% in October and values above 90% starting from December.

Regarding reflectance, the highest values were observed in August, October, and November, at 4.9%, 5.2%, and 5.3%, respectively, decreasing in December and fluctuating in the subsequent months.

The transmittance was low, even during the harvesting period, with the highest values found in August and October, at 37.8% and 48.3%, respectively. The transmittance progressively decreased, reaching lower values in January 2021 and in the following months. Both t2 and t3 followed the same pattern, presenting relatively low values for t3, even during the senescence period.

Overall, the cultivar took longer to recover its vegetative vigor after the harvest, compared to its state before May 2020.

3.8 ‘Acaua Novo’

For the Acaua Novo cultivar, the LAI was greatly reduced during the post-harvest period, ranging between 2 and 3 m².m^{-2}. However, there was an increase in LAI values in December, and in the following months, the values approached 5 m².m^{-2} (Fig. 9).

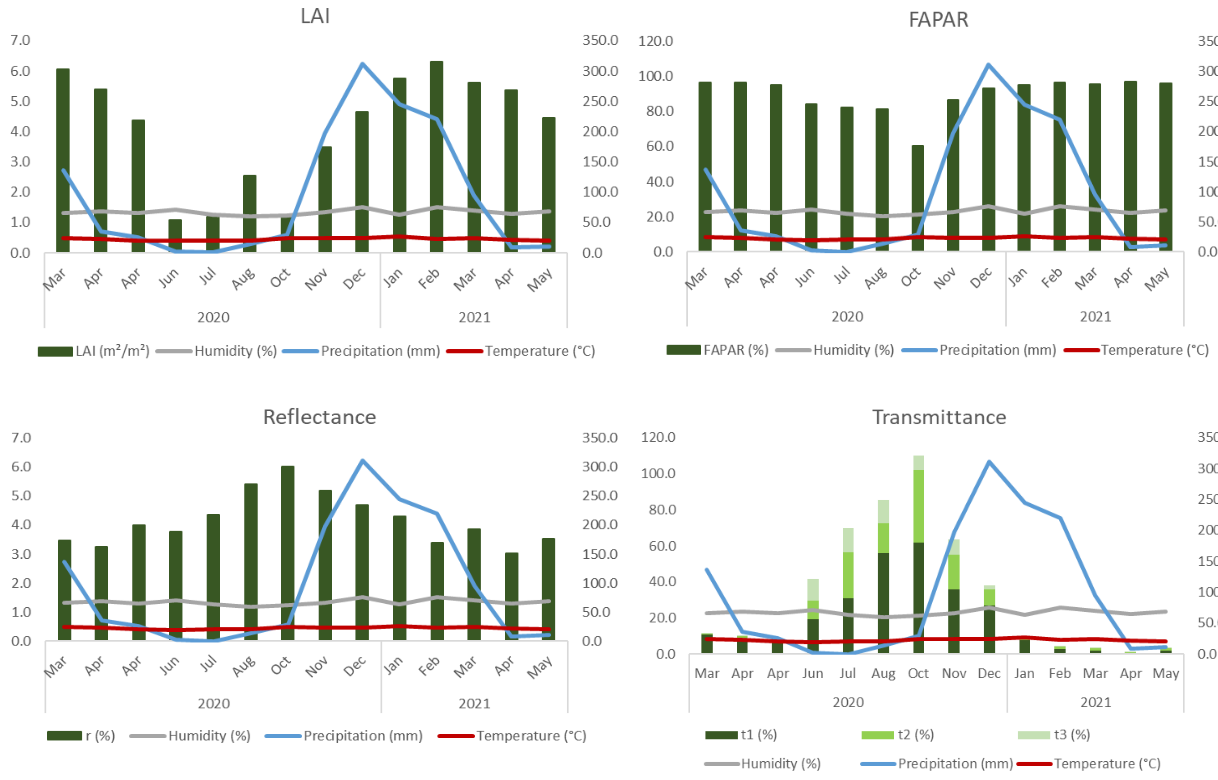

Fig. 9. Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}), reflectance (r), and transmittance (t) of the Acaua Novo cultivar.

The f_{APAR} for the mentioned cultivar was high throughout the year, except for the month of October when it experienced a drop to 77.9%.

Reflectance showed values below 4% during most of the growth cycle, except for the period of senescence, where it increased in the months of August, October, and November (4.9%, 5.2%, and 5.3%).

The t1 recorded higher values in August, October, and November (56.0%, 61.9%, and 35.9%), decreasing significantly in January (7.9%). As for t2, it reached its peak value in

October (40.3%), also decreasing in January 2021. The t3 showed its highest values in July and August (13.3%), decreasing in January, with values below 0.7%.

3.9 ‘Arara’

The LAI was significantly reduced for the cultivar during the post-harvest period, with the lowest values recorded in July and August (1.5 and 1.7 $m^2.m^{-2}$). However, from December onwards, the LAI values started to increase, reaching its peak in February 2021 with a value of 6.1 $m^2.m^{-2}$, as illustrated in Fig. (10).

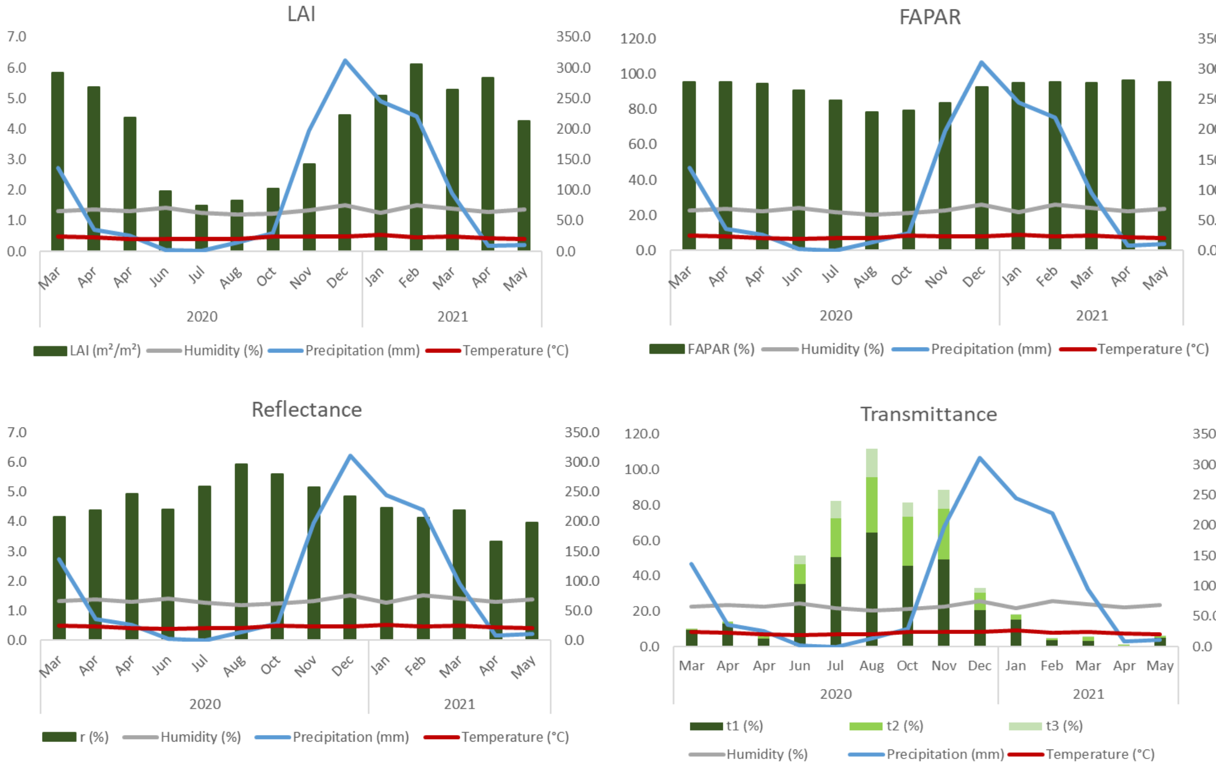

Fig.10. Leaf Area Index (LAI), Fraction of Photosynthetically Active Radiation Absorption (f_{APAR}), reflectance (r), and transmittance (t) of the Arara cultivar.

The f_{APAR} presented values above 80% for most of the year, except for the months of July and August, where values ranged from 78.4% to 79.2% during the senescence period.

The reflectance values were close to 4%, except for the post-harvest months, such as July, August, and October, where values of 5.2%, 5.9%, and 5.6%, respectively, were observed.

Regarding transmittance, the values of t1 were considerably higher than those of t2 and t3, with high values in July and August (50.6% and 64.4%), decreasing again in December, with values below 3% from January 2021. t3 was generally low, except in July, where it reached 15.7%. From January onwards, the values remained below 0.5%.

3.10 'Clone 224'

The LAI values for Clone 224 were relatively lower compared to other cultivars, presenting an atypical behavior. In the month before harvest, at the end of April, the LAI was equal to 2.8 m².m^{-2}, as shown in (Fig.) 11.

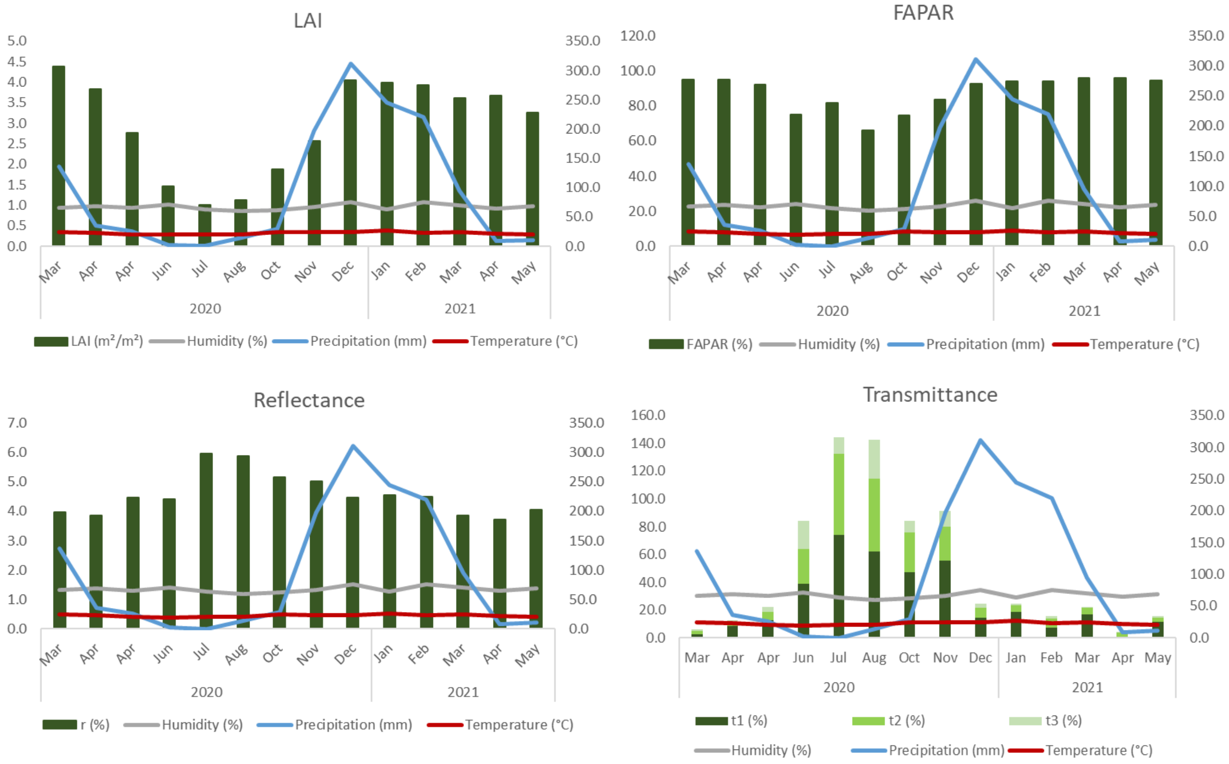

Fig. 11. Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}), Reflectance (r), and Transmittance (t) of Clone 224 cultivar.

During the senescence period, the LAI decreased even further, reaching values of 1.5, 1.0, 1.1, and 1.9 m².m^{-2}. Although the LAI values increased in December, they did not exceed 4 m².m^{-2}.

The f_{APAR} remained above 90% for most of the cycle, but during the post-harvest period, these values were lower, reaching a minimum in August (66.0%).

The reflectance values fluctuated throughout the cycle, being higher in the months after harvesting. In December, reflectance obtained even lower values.

The values of t1 fluctuated during the months from June to November, and in December, these values decreased as the plant's vegetative vigor increased. The t2 showed a similar behavior. The t3 presented moderate values during the senescence period, reaching its highest value in August (28.1%), decreasing to 2.7% in December.

3.11 ‘Clone 312’

The cultivar showed good LAI throughout the cycle, but the values were reduced in the post-harvest period, reaching the lowest value in July (1.3 m².m^{-2}). Unlike most cultivars, Clone 312 achieved a rapid recovery of LAI already in November, further increasing the LAI, reaching 7.1 m².m^{-2} in December, which is the month with the highest precipitation of the year (Fig. 12).

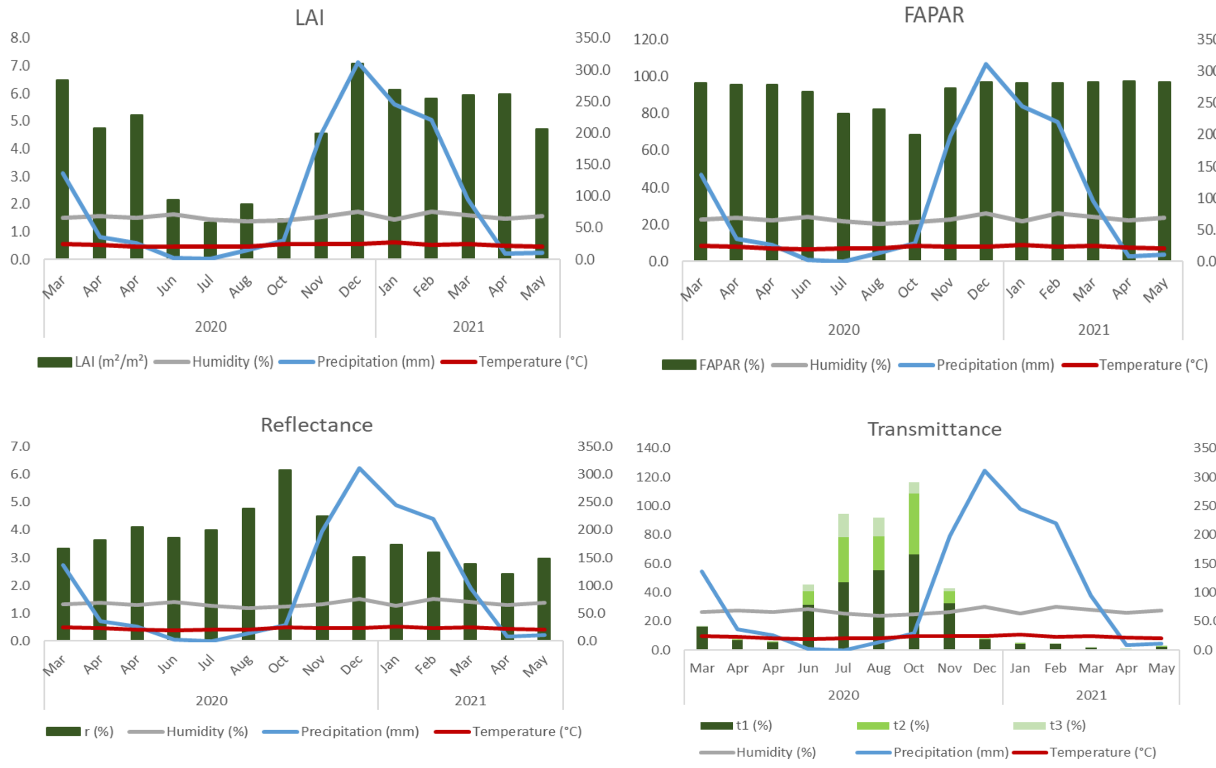

Fig. 12. Leaf Area Index (LAI), Fraction of Photosynthetically Active Radiation Absorption (f_{APAR}), Reflectance (r), and Transmittance (t) of Clone 312 cultivar.

The f_{APAR} remained high throughout most of the year, staying above 80%, except for October, when it dropped to 68.4%. The months of July and August also showed lower f_{APAR} values.

The reflectance values fluctuated throughout the cycle, with higher values in August, October, and November (4.8%, 6.2%, and 4.5%, respectively), decreasing in December.

For the t1 parameter, the cultivar showed relatively low values, with the highest values occurring in July, August, and October (47.2%, 55.5%, and 66.5%, respectively), while in December, the values started to decrease, reaching the lowest value in April (0.4%). The t2 followed a similar pattern, with lower values, and the highest value was recorded in October (42.2%). Overall, throughout the year, the t3 values were low, with the lowest values observed from December onwards, with t3 not exceeding 0.2%.

3.12 'Guara'

The LAI values decreased as the fruits filled up due to nutrient competition. The lowest values were observed during the senescence period. However, in December, with increased precipitation, the LAI reached its maximum value in the year 2020. In the following months, the LAI remained above 5 m².m^{-2} (Fig. 13).

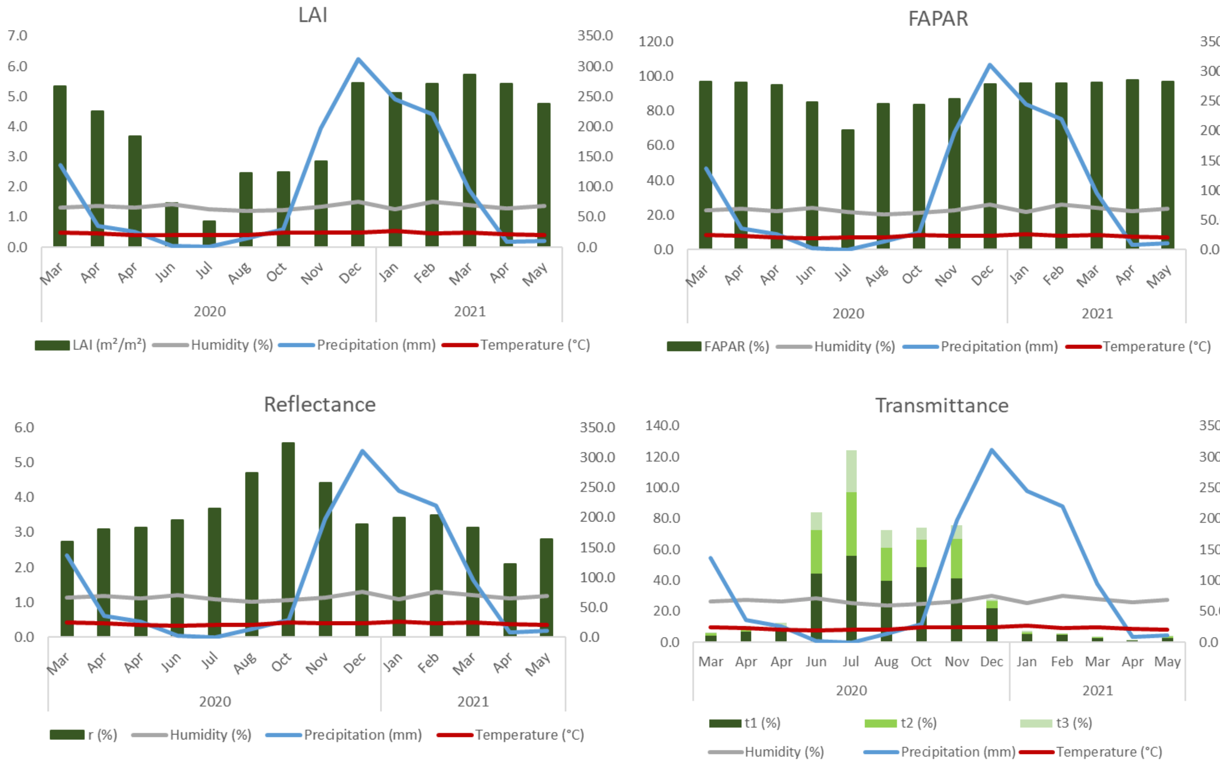

Fig. 13. Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}), Reflectance (r), and Transmittance (t) of Guara cultivar.

The values of f_{APAR} did not show much variation throughout the cycle, except for the month of July, which had the minimum value of 69.2%. All other months had f_{APAR} values above 80%.

For reflectance, the highest values were 4.7%, 5.6%, and 4.4% in the months of August, October, and November, respectively, during the post-harvest period. Only in December did the reflectance decrease, fluctuating between 2% and 3% in the following months.

The values of transmittance were good, except during the senescence period, with the highest values for t1 occurring between June and November. Transmittance decreased only in December (4.5%), decreasing even further over the months. The same occurred for t2, which had the highest value in July (41.4%). As for t3, the highest value was recorded in July (27.2%), with values below 1% from January 2021 onwards.

3.13 ‘Saira II’

The LAI values were very close to 6 m².m^{-2} in the months leading up to harvest, decreasing during the senescence period, with values of 1.7, 1.1, and 1.2 m².m^{-2} in June, July, and August, respectively. The LAI values increased again already in the month of November (Fig.14).

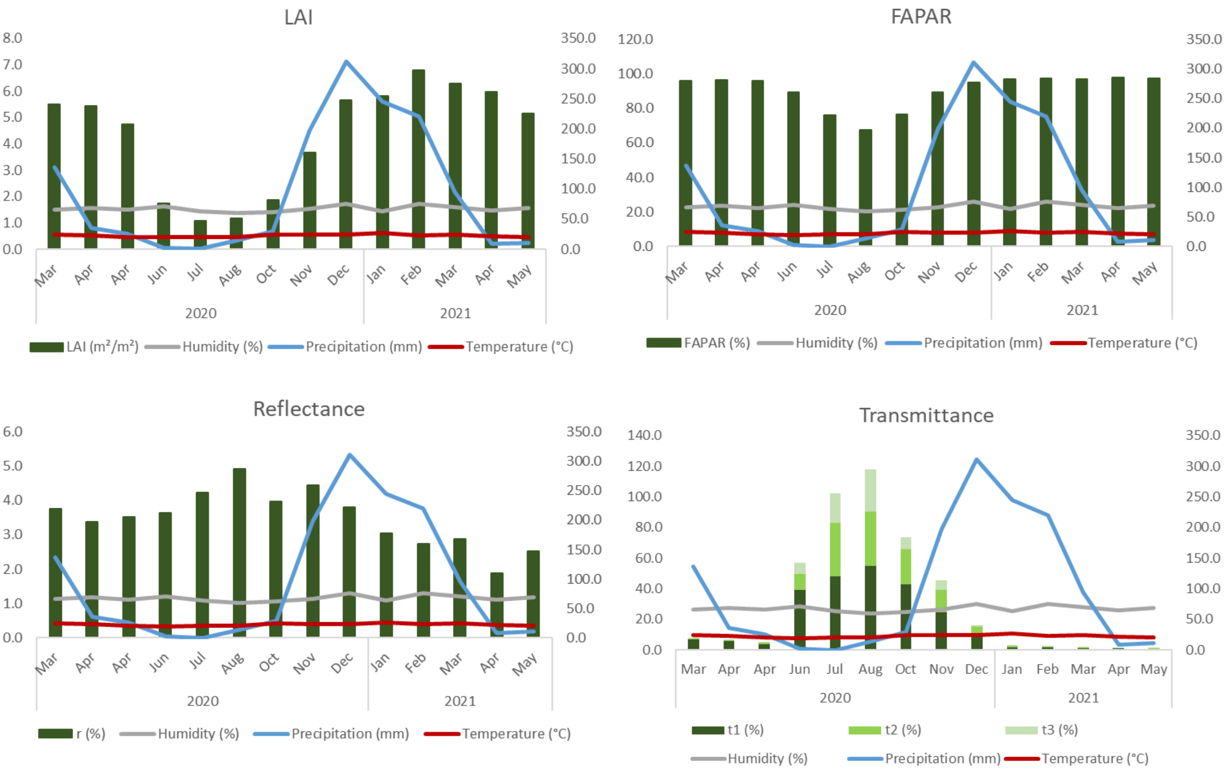

Fig. 14. Leaf Area Index (LAI), Fraction of Photosynthetically Active Radiation Absorption (f_{APAR}), reflectance (r), and transmittance (t) of the Saira II cultivar.

From December onwards, the LAI values were close to 6 m².m^{-2}, with a peak in February reaching an LAI of 6.8 m².m^{-2}.

The lowest f_{APAR} values were recorded in July, August, and October (76.2%, 67.4%, and 76.8%, respectively). In the other months, f_{APAR} exceeded 80%, with a notable peak in April 2021, reaching 98.1%.

Overall, the cultivar showed low reflectance values during fruit maturation, with the highest value observed in August (4.9%). Reflectance values decreased from December and January onwards.

Transmittance values were higher during the senescence period when the LAI was also lower. Even in December, t1 values remained relatively high but increased significantly to 1.9% in January, and then decreased further. The t2 followed a similar pattern, with values below 1% starting from January. The t3 showed higher values during senescence compared to other cultivars but decreased from December.

3.14 'Siriema'

Siriema is among the cultivars with the highest LAI throughout the cycle. During fruit maturation, the LAI values were 6.2, 5.4, and 5.2 m².m^{-2} in March, early April, and late April, respectively, decreasing as the fruits ripened, as shown in (Fig. 15).

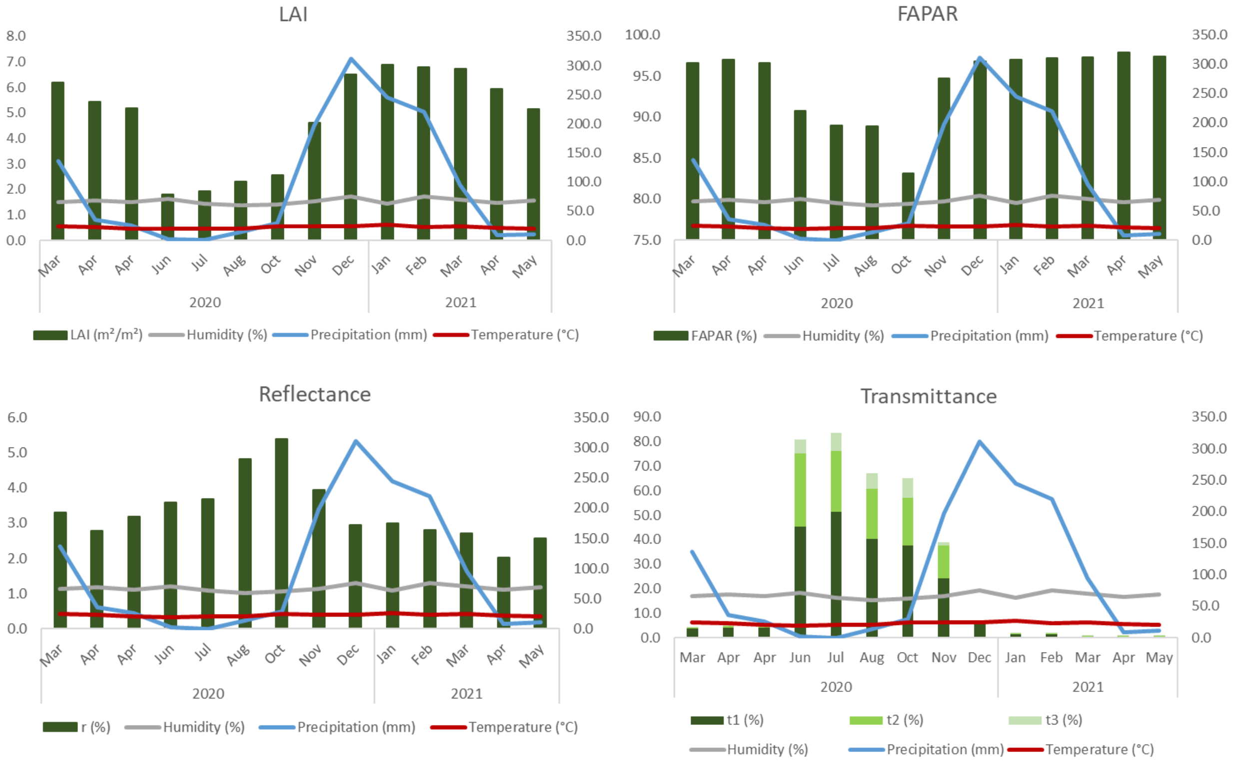

Fig. 15. Leaf Area Index (LAI), Fraction of Photosynthetically Active Radiation Absorption (f_{APAR}), Reflectance (r), and Transmittance (t) of the Siriema cultivar.

The LAI values during senescence were 1.8, 1.9, and 2.3 m².m^{-2} in June, July, and August, respectively. From November, the values increased, reaching values above 6 m².m^{-2} in December and remaining close to 7 m².m^{-2} until March 2021.

The cultivar obtained the highest f_{APAR} values throughout the year, even during senescence, with values close to 90%. The lowest value was recorded in October (83.2%), still relatively high.

Reflectance values were also low, with October showing the highest value (5.4%), decreasing further from December.

Regarding transmittance, overall, the values were very low, except during the post-harvest period when they were higher between July and October for t1, t2, and t3. From December, the values became even lower, with transmittance values close to zero, indicating the plant's good ability to absorb solar radiation even under adverse conditions.

3.15 'Catucai Amarelo 2SL'

The cultivar showed lower LAI values compared to other cultivars, with the lowest values recorded in June, July, and August, corresponding to 1.2, 0.7, and 1.0 m².m^{-2}, respectively. The LAI values only reached values closer to their pre-harvest state in January (3.8 m².m^{-2}), with similar values in the subsequent months (Fig. 16).

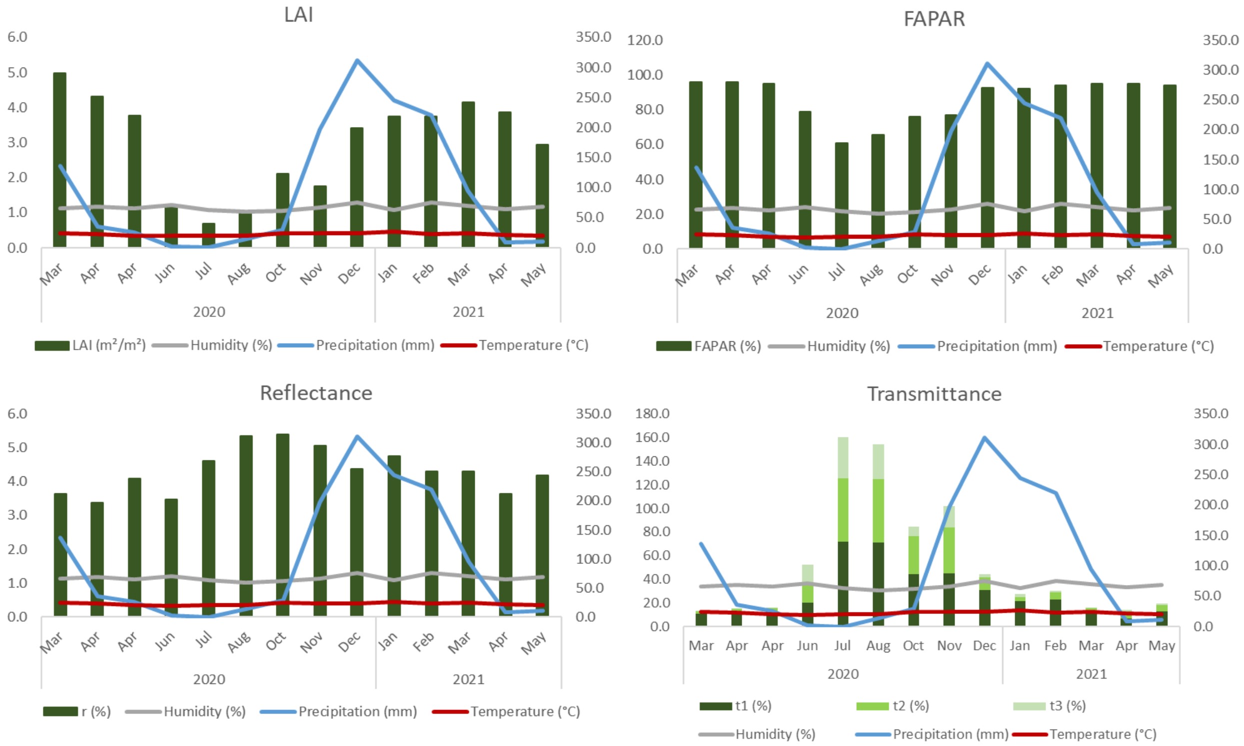

Fig.16. Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}), Reflectance (r), and Transmittance (t) of the cultivar Catucai Amarelo 2SL.

The f_{APAR} values were generally high for the cultivar, except during the senescence period, where the minimum values reached 60.9% and 65.5% in July and August, respectively.

The reflectance values fluctuated throughout the year, with lower values after the harvest, although the difference was not significant, remaining above 4% even during the period when the plant regained vegetative vigor.

The transmittance of the cultivar was high in all three canopy sections measured, with values even lower for t3. In July and August, t1 reached high values of 71.7% and 71.5%, indicating the low LAI during that period.

The cultivar took longer compared to other cultivars to return to values closer to its pre-harvest state.

3.16 'Iapar 59'

The LAI values for the cultivar were low compared to other cultivars, especially during the senescence period, where the values were less than 1 $m^2.m^{-2}$. The highest value was recorded in December (4.3%), and in the following months, the values fluctuated between 3 and 4 $m^2.m^{-2}$, as shown in (Fig. 17).

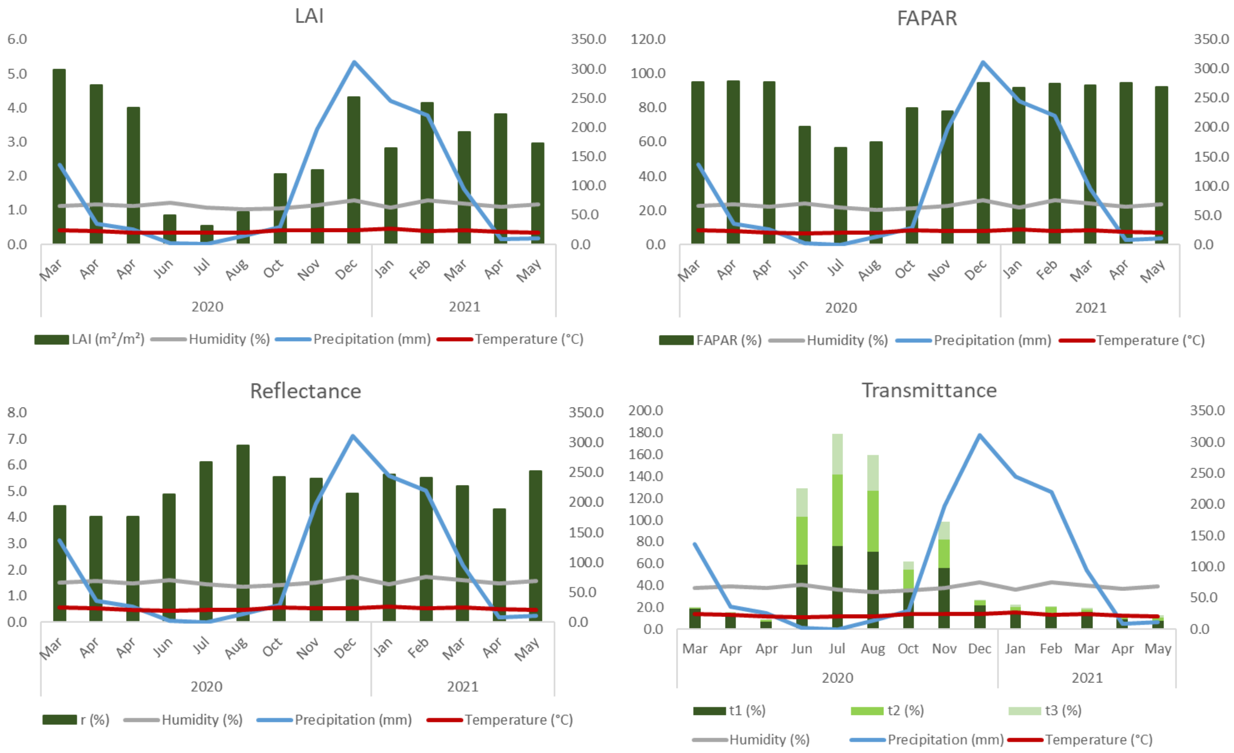

Fig. 17. Leaf Area Index (LAI), Fraction of Photosynthetically Active Radiation Absorption (f_{APAR}), Reflectance (r), and Transmittance (t) of the Iapar 59 cultivar.

Over the period from June to November, the f_{APAR} values were lower, with July being the month with the lowest value (56.8%). Starting from December, the f_{APAR} increased significantly and remained above 90% in the following months.

Regarding reflectance, the values were relatively high, even after the senescence period, remaining above 5% even after December when the plant was in the vegetative phase.

The values of transmittance were high as well. The t1 reached 75.9% and 70.6% in the months of July and August, respectively, decreasing only in December and reaching the lowest value in May 2021 (7.5%). The t2 remained high throughout the cycle, returning to values similar to the pre-harvest state only in March 2021. As for t3, the values fluctuated between 1% and 2% even during the plant's vegetative period.

3.17 'IPR 100'

The LAI values for the cultivar were high, remaining close to 6 $m^2.m^{-2}$, except during periods of senescence, where the LAI was lower, but still compared to other cultivars, the values were not as low, staying around 3 $m^2.m^{-2}$. In November, the cultivar already managed to recover its LAI to the pre-harvest state (5.5 $m^2.m^{-2}$), and the values increased in the following months, reaching 6.8 $m^2.m^{-2}$ in February 2021 (Fig. 18).

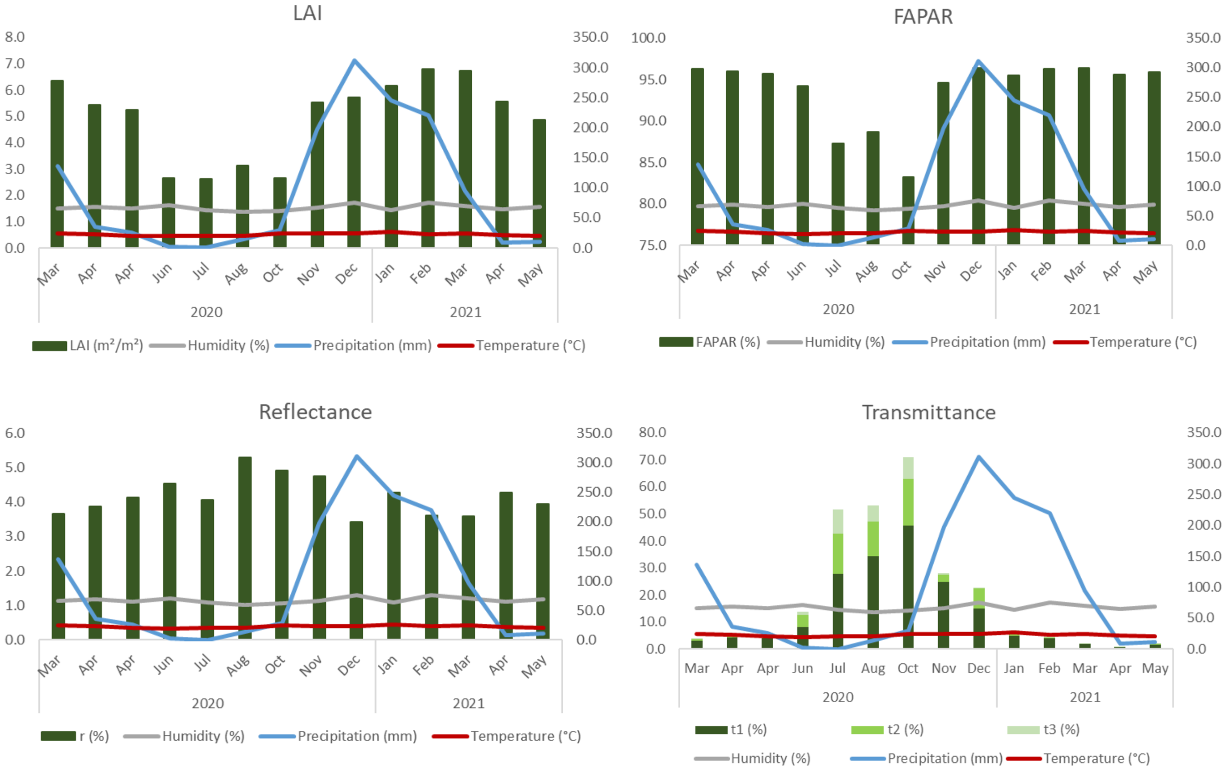

Fig. 18. Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}), Reflectance (r), and Transmittance (t) of the IPR 100 cultivar.

The f_{APAR} showed high values, even during the senescence period, with the lowest value recorded in October (83.3%). In November, the cultivar already exhibited f_{APAR} values above 90%, increasing further in the following months.

The reflectance of the cultivar remained close to 4% throughout the cycle, with an increase during the senescence period, especially in August, when the parameter reached 5.3%.

The values of transmittance were lower, particularly compared to other cultivars. For t1, the highest value was 45.6% in October, decreasing in December and reaching the lowest value in April (0.6%). The values of t2 were even more reduced, with t2 being less than 2% as early as January, and the highest value also in October. The t3 was higher in July (8.7%), but in November, it already showed low values, decreasing in the subsequent months, with t3 values close to zero.

3.18 'IPR 102'

The cultivar presented high LAI values throughout the cycle, with the lowest value found in July (1.2 m².m^{-2}). In December, the LAI started to increase, reaching values greater than 6 from January 2021 onwards (Fig. 19).

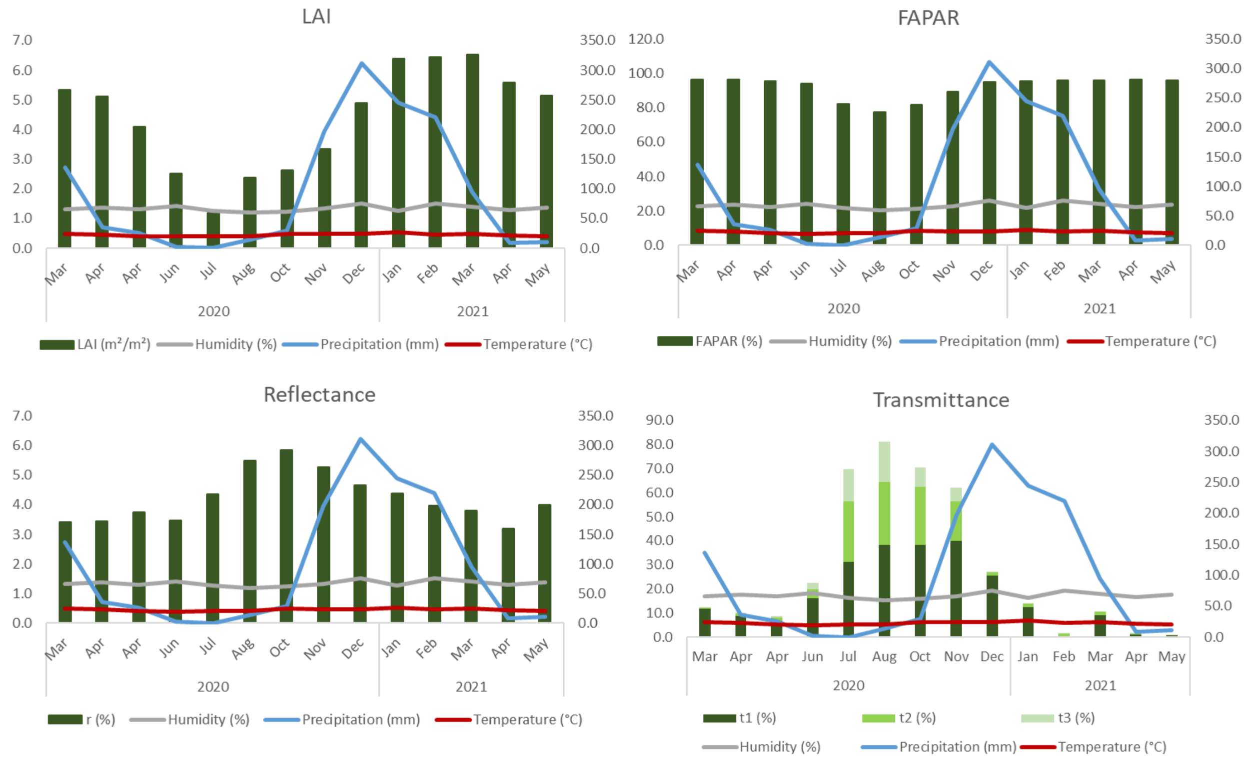

Fig. 19. Leaf Area Index (LAI), Fraction of Photosynthetically Active Radiation Absorption (f_{APAR}), Reflectance (r), and Transmittance (t) of the IPR 102 cultivar.

The f_{APAR} obtained values above 90% during the cycle, except for the senescence period, where these values ranged between 70% and 83%.

The reflectance of the cultivar remained between 3% and 4.5% during the cycle, increasing during the harvest period and reaching 5.9% in October. Reflectance values only approached the pre-harvest state in February 2021.

For transmittance, the values were low, even for t1, which usually presents higher values. The months of August, October, and November showed the highest values, decreasing in January 2021 and oscillating in the subsequent months. The t2 exhibited a similar behavior, with noticeably lower values. The t3 already in December had a transmittance of 0.4%, decreasing even further in the following months.

3.19 'IPR 103'

The LAI values for the cultivar were high throughout the cycle, ranging between 5 and 6 $m^2.m^{-2}$ after December (vegetative period), with a peak in February, reaching a value close to 7 $m^2.m^{-2}$. The lowest values were recorded between June and October, in the post-harvest period (Fig. 20).

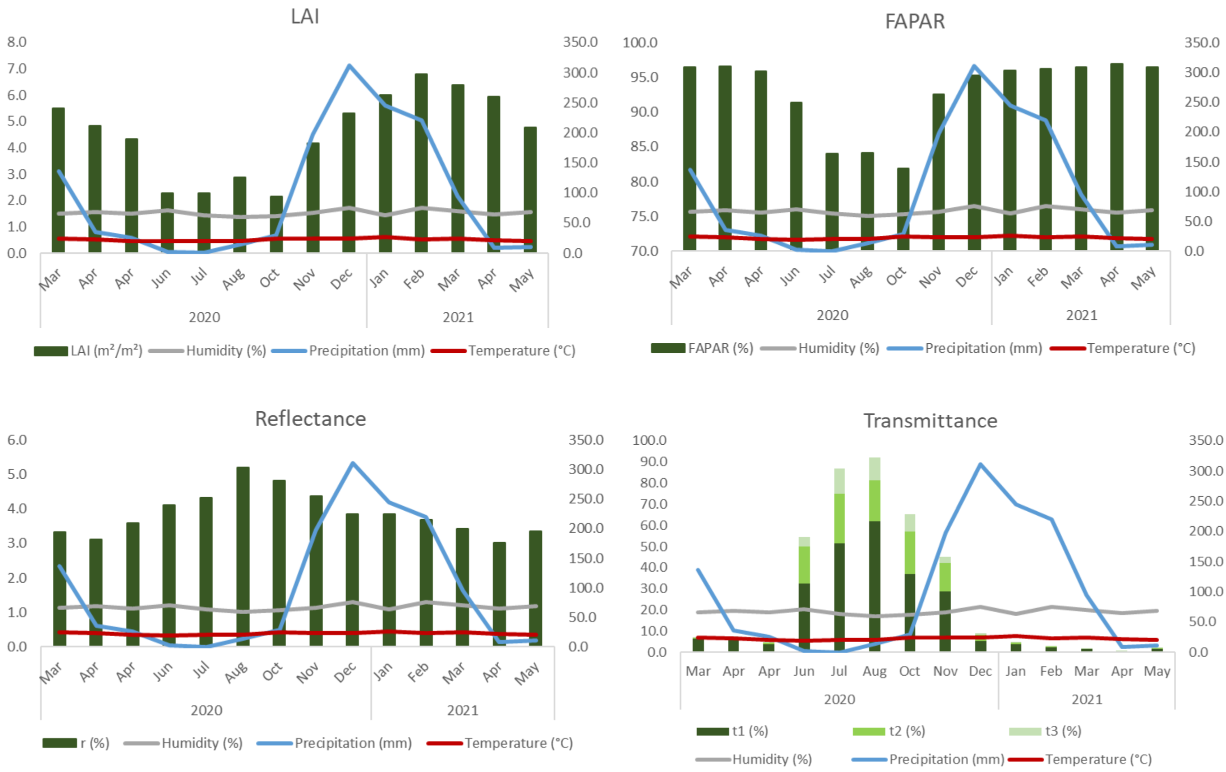

Fig. 20. Leaf Area Index (LAI), Fraction of Photosynthetically Active Radiation Absorption (f_{APAR}), Reflectance (r), and Transmittance (t) of the IPR 103 cultivar.

The f_{APAR} performed well throughout the analyzed cycle, with values above 95%. The lowest values were recorded in July, August, and October, still remaining above 85%.

The reflectance decreased as the months passed after harvest, being significantly lower in December and the following months.

The transmittance at the top of the canopy was higher than in other parts of the plant; however, in December, these values decreased considerably, with t1 at 5.3%, decreasing even further in the following months. Both t2 and t3 showed lower values, with t2 reaching 3% in December, and t3 reaching the same value as early as November.

Cultivars IPR 100, 102, and 103 exhibited similar behaviors regarding the analyzed biophysical parameters throughout the cycle.

3.20 'Rubi MG 1192'

The cultivar showed lower LAI values compared to other cultivars, even after the harvest period. The highest LAI value was recorded in February 2021, reaching 3.6 $m^2.m^{-2}$. During the senescence period, the values were even lower, not exceeding 1.3 $m^2.m^{-2}$ (Fig. 21).

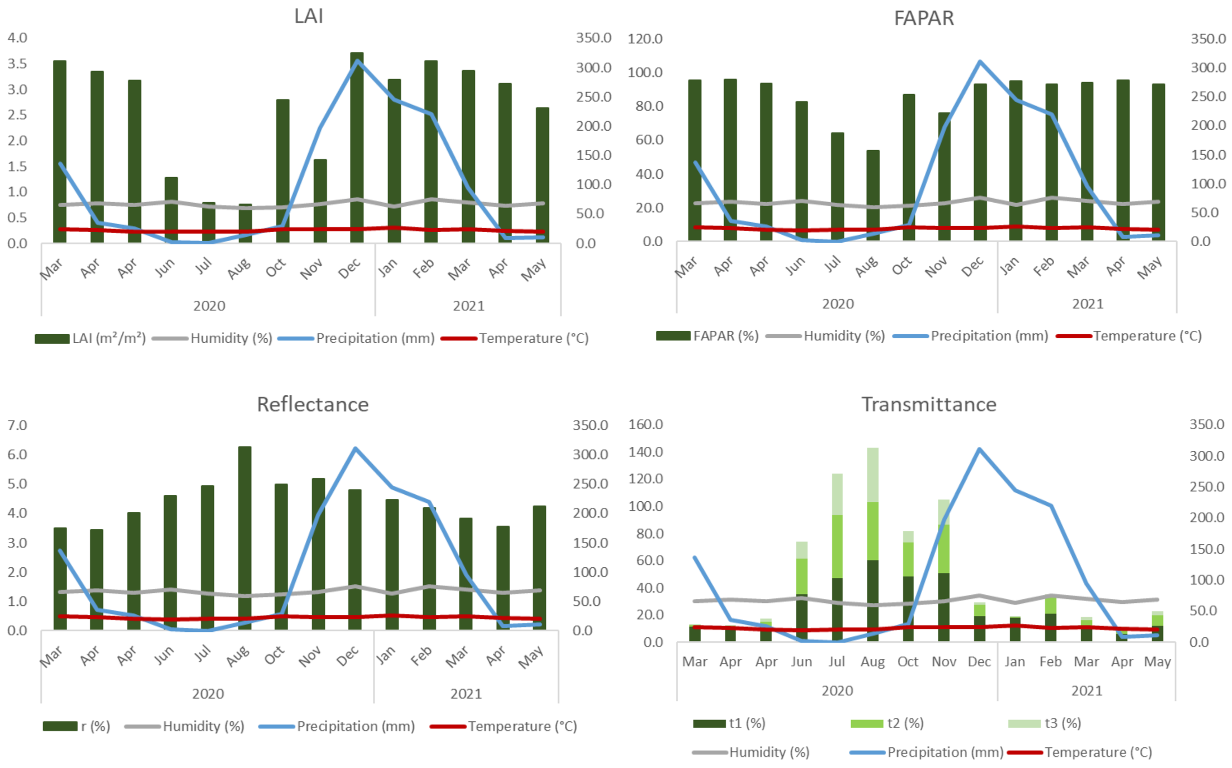

Fig. 21. Leaf Area Index (LAI), fraction of absorbed photosynthetically active radiation (f_{APAR}), reflectance (r), and transmittance (t) of the Rubi MG 1192 cultivar.

The f_{APAR} values were lower during the months of June, July, and August, with a spike in October. In December, the values already exceeded 90%.

In general, reflectance for the cultivar was high, especially in August (6.3%), decreasing only in December, ranging between 3% and 4.5%.

The transmittance, overall, did not show very high values, except during the senescence period, with the highest value of t1 recorded in August (60.4%). From December, the values decreased but remained above 10%. The t2 showed similar behavior, with significantly lower values, oscillating between months. The t3, although more reduced, still presented high values compared to other cultivars, ranging from 0.4% to 2.5% from December to April 2021.

Overall, the cultivars showed an increase in LAI and f_{APAR} values in December, which can be explained by higher precipitation (311.7 mm) and humidity (75.7%), also influencing reflectance and transmittance. In environments with adequate humidity, plants can develop more leaves, increasing LAI and the plant's photosynthetic capacity to absorb more solar radiation, resulting in decreased reflectance and transmittance for lower sections of the canopy.

There was a decrease in LAI in the first months of data collection as the fruits grew, ripened, and harvest time approached. This phenomenon is natural in agricultural systems, where leaves and fruits compete for available resources, such as energy and nutrients for growth and maturation. As fruits grow, the available resources in the leaves are redistributed to fill the fruits, resulting in a decrease in LAI.

Taugourdeau et al. (2014) obtained similar results in their study, where the decrease in LAI occurred during the fruit ripening period before harvest due to natural competition and energy translocation from leaves to fruits, resulting in leaf fall.

Overall, the analyzed parameters followed the seasonal distribution of the climate. The region has a well-defined seasonal climate with distinct dry and rainy seasons. Therefore, the decrease in LAI and f_{APAR} and the increase in reflectance and transmittance in the drier and cooler months, associated with the fruit ripening period, is notable. On the other hand, there is an increase in LAI and f_{APAR} and a decrease in reflectance and transmittance in the rainy and hot months.

For the state of Minas Gerais, which has a long and intense dry season, the succession of coffee crop phenological stages is well-defined over time, resulting in periods of flowering, fruiting, harvest, and leaf fall each year, leading to greater variation in biophysical parameters (Taugourdeau et al., 2014). This succession of phenological stages of the coffee crop can be defined as a well-defined temporal pattern.

Silveira and Carvalho (1996) highlight some factors that can also influence the leaf lifespan of the coffee plant, such as latitude and elevation, in addition to seasonal climate. During dry periods with reduced water availability, the leaf lifespan decreases. Under conditions of adequate irrigation or during milder and more humid periods, the leaf lifespan is prolonged.

Additionally, it is important to consider that pruning practices can also influence the variation in leaf lifespan. Pruning can modify the plant's architecture and how fruits are harvested, which, in turn, can affect the leaf fall rate and reduce LAI and f_{APAR} (Taugourdeau et al., 2014).

The harvesting method used in the panel of cultivars was manual, where fruits are removed all at once. This practice can result in the removal of green fruits, leading to a more intense leaf fall, especially the older leaves, and consequently, a decrease in LAI and f_{APAR}, along with an increase in reflectance and transmittance, as observed from June to October. To mitigate these effects, selective harvesting is recommended, removing only ripe fruits (Taugourdeau et al., 2014). Additionally, other factors such as fertilization practices and pest control in the plantations can also influence leaf lifespan.

The data on biophysical parameters obtained in specific months throughout the coffee crop phenological cycle, as obtained in this study, are valuable indicators for analyzing leaf health, as well as for predicting coffee productivity. They can also provide essential information to producers to adjust factors related to plant development, such as ideal management practices and selection of cultivars most suitable for the climatic conditions of each environment, enabling strategic decision-making to maximize crop productivity.

3.21 Boxplot of Biophysical Parameters

The distribution of data and statistical measures of the analyzed parameters can be observed in the boxplot graphs, with information on median, quartiles, minimum and maximum values, and potential outliers.

The cultivars that showed higher LAI values compared to the median were Siriema, Saíra II, Pau Brasil MG1, IPR 100, Clone 312, and Araponga MG1, as seen in (Fig. 22).

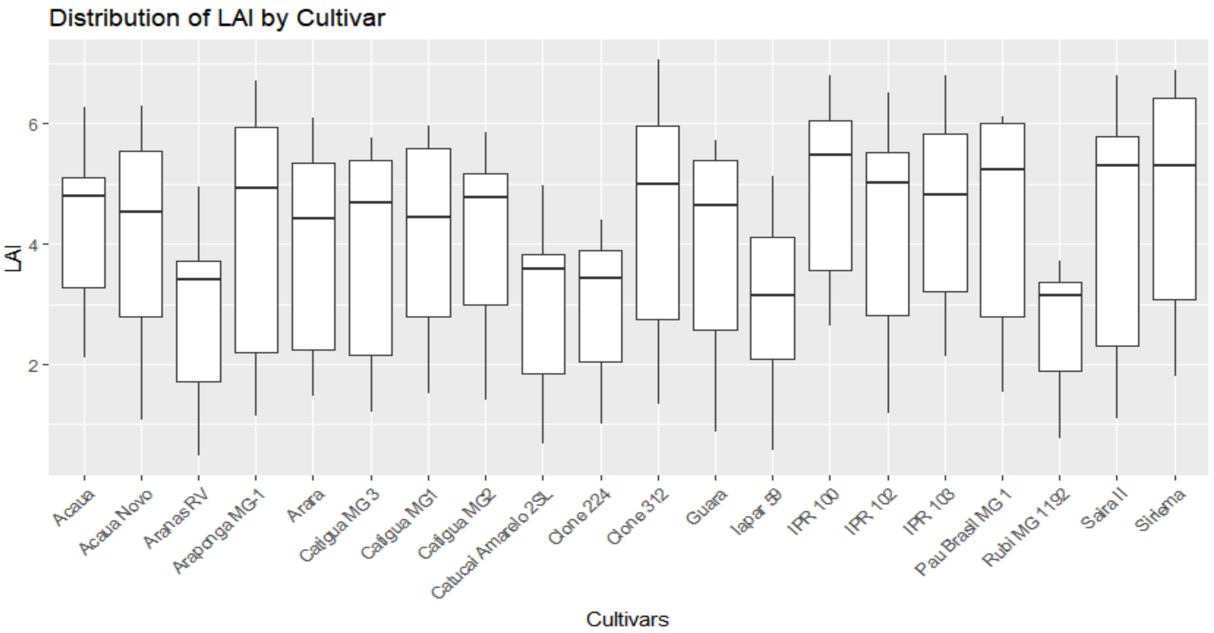

Fig. 22. Boxplot of Leaf Area Index (LAI) for different Arabica coffee cultivars throughout their phenological cycle.

The cultivars that showed higher LAI generally have better foliage development, which is associated with increased growth and vigor of the plant, especially after the harvest period. This may indicate greater resistance to environmental stresses and higher productivity potential.

Most cultivars had a median LAI above 4 m².m^{-2}, except for Aranas RV, Catucai Amarelo 2SL, Clone 224, Iapar 59, and Rubi MG1192. These cultivars had the lowest LAI values, equal to or below 1 m².m^{-2}. These lower LAI values may indicate a lower photosynthetic capacity of the plant due to reduced leaf coverage, which could result in less vigorous crop growth and increased susceptibility to diseases and other environmental stresses.

It is important to note that no outliers were found in the LAI values, indicating a more homogeneous and symmetric distribution around the median for this parameter. In other words, there were no extremely discrepant values compared to the rest of the data, suggesting a more consistent sample and reliable analysis of LAI values for the studied cultivars. Overall, LAI is a good indicator of coffee vigor and energy and gas exchange in the species.

The leaf area index (LAI) can vary due to various factors, including coffee variety, climatic conditions in the region, agronomic practices adopted in the plantations, and the stage of plant development. In general, an appropriate LAI for coffee plantations is one that allows for efficient interception of solar radiation, promoting effective photosynthesis and contributing to the healthy development of the plant. A higher LAI can be beneficial for optimizing sunlight capture, but excessively high values may lead to leaf competition for light, resulting in shading and potential phytosanitary issues.

In a study conducted by the authors Santos et al. (2020), aimed at monitoring the development of LAI in the same coffee plantation addressed in this study, a LAI greater than 3.0 was observed in specific areas of the crop, particularly in blocks located in the central and mid-western regions, during the period from January to May 2018.

Costa et al. (2019) conducted research that obtained average LAI values of 4.7 and 4.2 for the irrigation treatments L130 (corresponding to 130% of the ideal water quantity to meet the plant's water needs) and L100 (ideal conditions, where plants were irrigated with the exact amount of water required), respectively. For the L70 and L40 treatments (lower levels of deficit irrigation), the average LAI values were 3.7 and 3.5. These results provide additional support to the LAI findings in this study, indicating similar patterns in situations of considered normal irrigation.

The distribution of f_{APAR} for the cultivars is shown in (Fig. 23).

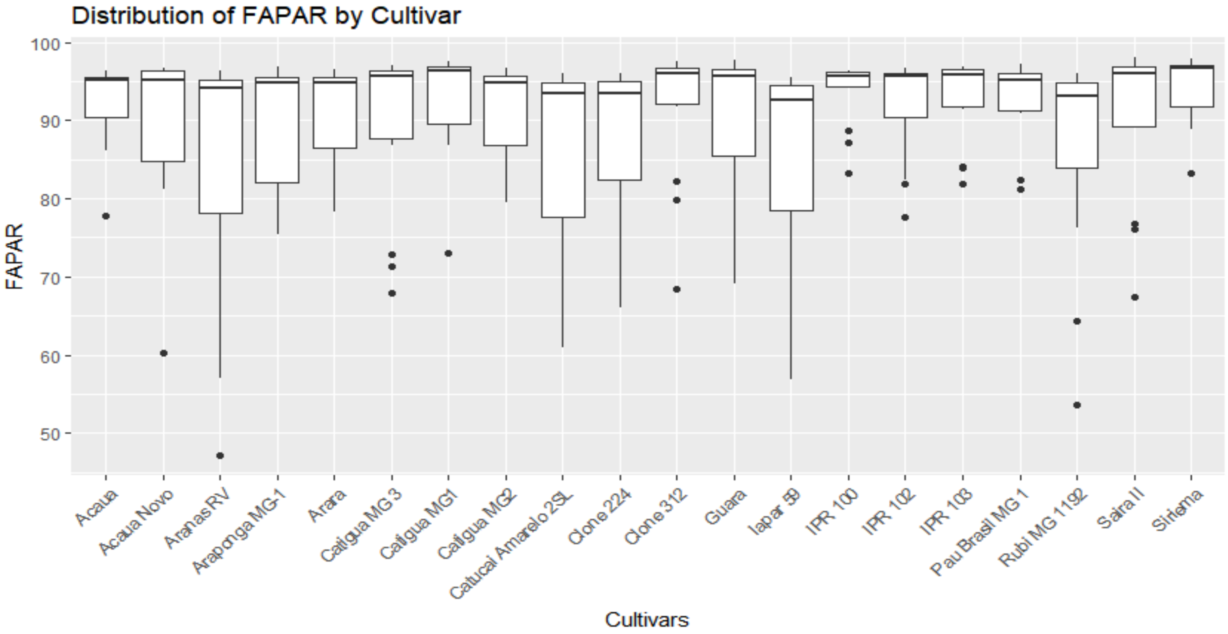

Fig. 23. Boxplot of Fraction of Absorbed Photosynthetically Active Radiation (f_{APAR}) for different cultivars of Arabica coffee throughout their phenological cycle.

In general, all analyzed cultivars showed median values of f_{APAR} above 90%, with most of the values concentrated in the first quartile. Cultivars with the highest median f_{APAR} were Siriema, Saira II, Pau Brasil MG1, IPR 100, 102, 103, Guara, Clone 312, Catigua MG1, and MG3. Cultivars with higher median f_{APAR} indicate a greater capacity to capture solar radiation and convert that energy into photosynthesis. These cultivars also exhibited high LAI values.

However, some cultivars displayed lower f_{APAR} values, such as Aranas RV, Catucai Amarelo 2SL, Iapar 59, and Rubi MG 1192, with medians around 60%.

Moreover, some outliers can be observed with greater discrepancy in certain cultivars, such as Aranas RV, Acaua Novo, and Rubi MG 1192. For instance, Aranas RV presented a minimum value below 50%, being an atypical value significantly distant from the rest of the data. Lower FAPAR values can indicate reduced photosynthetic efficiency of the cultivars, leading to limited vegetative growth of the plant.

Other cultivars that showed high median values also presented discrepancies in some values, such as Saira II, Clone 312, IPR 100, 102, 103, Catigua MG1, and Catigua MG3. This can be explained by the senescence period, during which the cultivars exhibited lower f_{APAR} values due to leaf removal, resulting in a significant reduction of LAI.

The study conducted by Costa et al. (2019) focused on evaluating the radiation extinction coefficient in coffee plants under different irrigation levels. In the treatment designated as L100%, representing optimal conditions where plants receive irrigation or rainfall in an amount that fully meets their water requirements, researchers identified a pattern similar to the results found in the present study. Under these favorable conditions, the radiation extinction coefficient reached approximately 90%, suggesting efficient absorption and utilization of solar radiation by coffee plants when adequately supplied with water.

Regarding the distribution of reflectance for the cultivars, it can be observed that the cultivars with the lowest medians were Siriema, Saira II, IPR 101, 102, 103, Guara, Clone 312, Catigua MG1, and MG3 (Fig. 24).

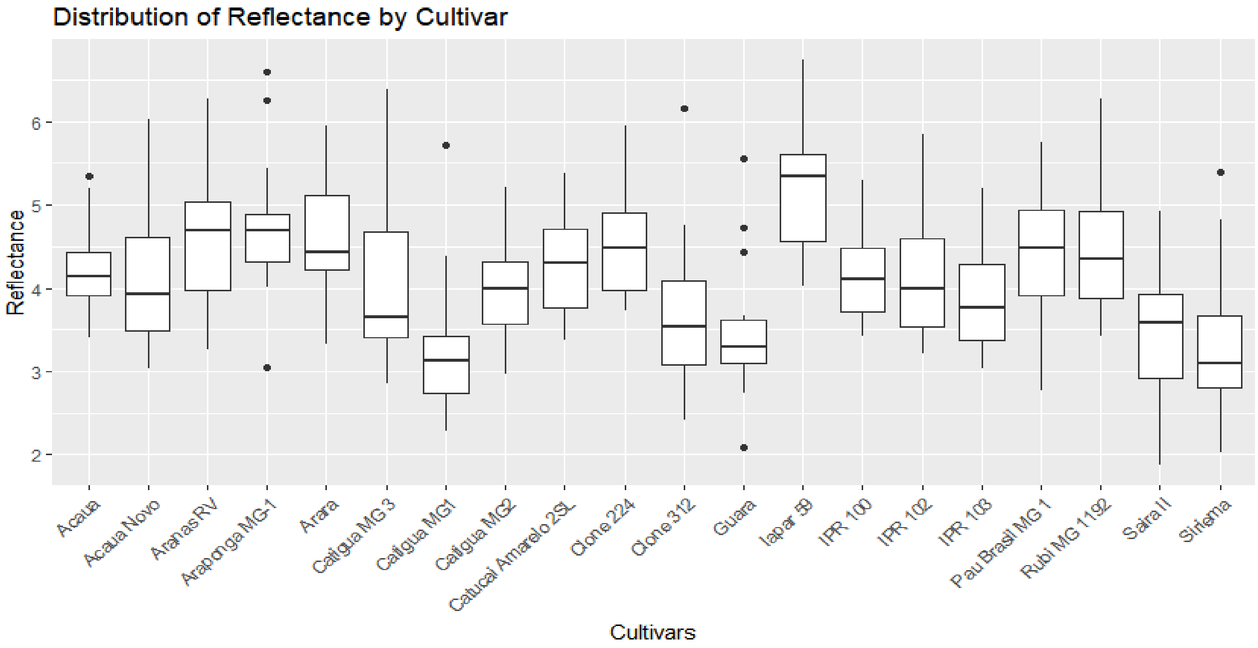

Fig. 24. Boxplot of reflectance for different cultivars of Arabica coffee throughout their phenological cycle.

It is important to emphasize that in the case of reflectance, lower values indicate that the coffee plant is healthy and well-developed, as it is absorbing more light than it is reflecting, especially during the vegetative period.

Cultivars with higher median reflectance values were Iapar 59, Aranas RV, and Araponga MG1, indicating that these cultivars are reflecting a higher proportion of light compared to the amount absorbed. This could be indicative of a lower rate of vegetative growth or some specific genetic characteristic of these cultivars that influences reflectance.

Some reflectance values were inconsistent compared to others for certain cultivars, which can be explained by some high values found in the post-harvest period. It's possible that during this period, physiological and morphological changes in the plants occur, which could affect reflectance. For instance, leaf drop or the formation of new shoots might influence the parameter values.

Regarding the transmittance (t1) of the upper canopy of the plant, the data distribution shows that cultivars with lower median values were: Siriema, Saíra II, Pau Brasil MG1192, IPR 103, IPR 100, Guara, Clone 312, Catigua MG1, MG2, and Acaua, with medians below 10%. This indicates that the foliage of the upper section of these cultivars is absorbing a higher proportion of the incident light upon them, as can be observed in (Fig. 25). This characteristic could be associated with an adaptation strategy of these plants to optimize the capture of light energy in environments with high light competition, resulting in better growth and development.

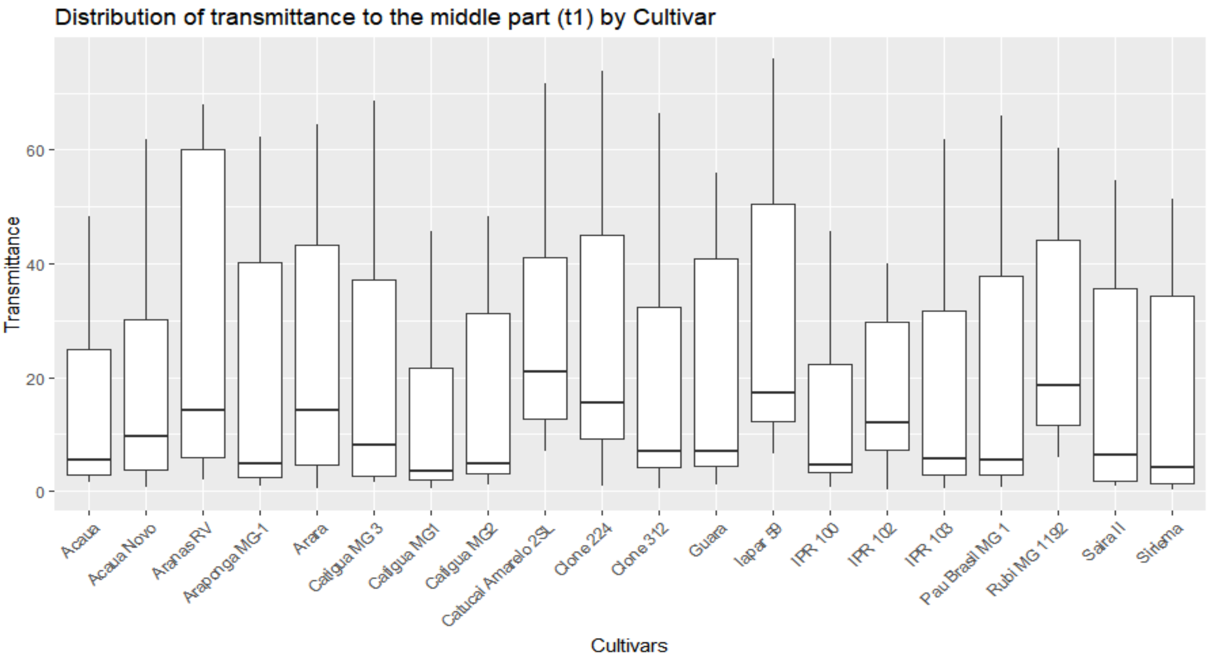

Fig. 25. Boxplot of transmittance (t1) for different cultivars of Arabica coffee throughout their phenological cycle.

The cultivars that showed higher values of t1 were Rubi MG1, Iapar 59, Catucai Amarelo 2SL, Clone 224, Arara, and Aranas RV. With the exception of Rubi MG1, the other cultivars presented maximum t1 values close to or above 70%, indicating that these cultivars allow more light to pass through to the lower layers of the canopy (t2 and t3), absorbing less energy through the leaves.

For the transmittance in the middle part of the plant (t2), the medians were below 10% for all cultivars. Siriema, Saira II, Pau Brasil MG1, IPR 102 and 103, Clone 312, and Catigua MG3 presented values very close to 5%, which were the lowest medians concerning t2. This indicates that the transmittance in the middle part of the plant is absorbing more solar radiation than transmitting to the lower layers of the canopy, as indicated in (Fig. 26).

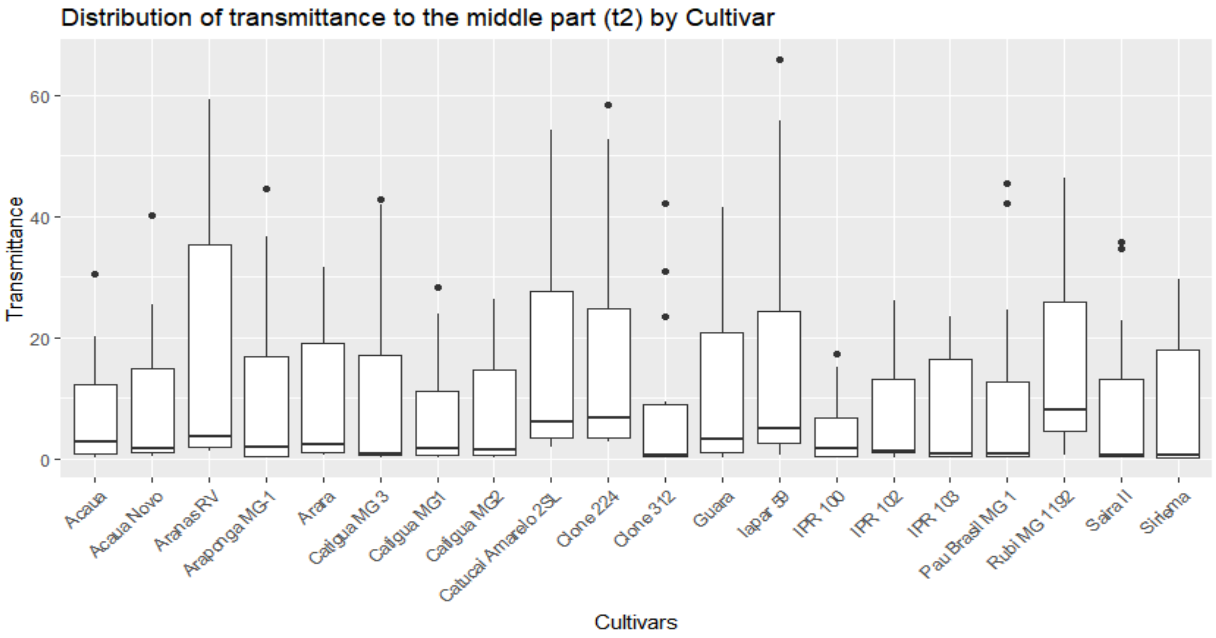

Fig. 26. Boxplot of transmittance (t2) for different Arabica coffee cultivars throughout their phenological cycle.

Some cultivars showed high values of transmittance compared to others, such as Aranas RV, Catucai Amarelo 2SL, Clone 224, and Iapar 59, with t2 values above 65%. This indicates that a larger amount of solar radiation is being transmitted to the lower layer of the plant, resulting in less energy absorption. Additionally, some cultivars displayed outlier values of transmittance, which might have occurred during the senescence period of the crop.

Finally, the transmittance at the bottom of the plant (t3), at ground level, can be observed in (Fig. 27).

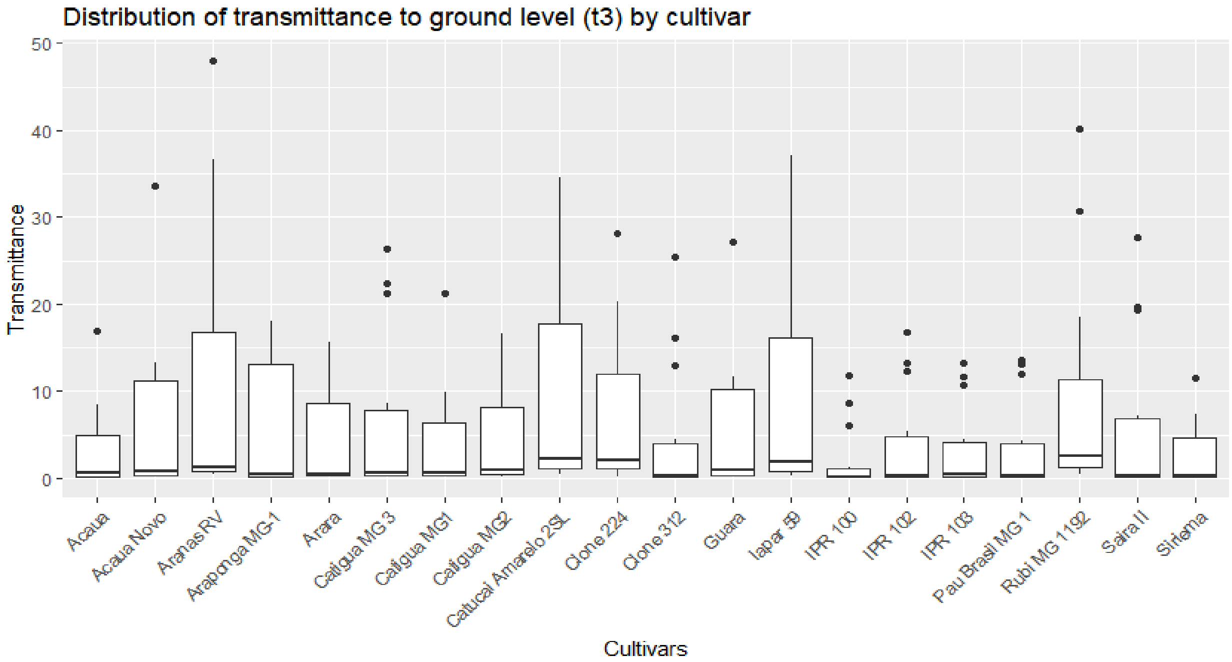

Fig. 27. Boxplot of transmittance (t3) for different arabica coffee cultivars throughout their phenological cycle.

Overall, the median values for t3 were low, close to zero, indicating high absorption of solar radiation throughout the canopy by the leaves, resulting in minimal radiation transmitted to the ground. However, some cultivars still showed high values for t3, such as Aranas RV, Catucai Amarelo 2SL, Iapar 59, and Rubi MG 1192. These cultivars also exhibited lower LAI and f_{APAR} values, suggesting that the reduced leaf area and more spaced leaves allow more light to pass through to the lower layers of the plant, reducing interception.

These results can be relevant for understanding the behavior of different coffee cultivars regarding sunlight capture and radiation distribution within the plant canopy. Lower LAI and f_{APAR} values, as well as higher reflectance and transmittance values, may indicate some health issues in the plant, such as nutritional deficiencies and water stress, factors that can negatively affect coffee plant development and productivity.

At the plant scale, the cultivars showed seasonal variations throughout the phenological cycle, which can be explained by abiotic factors, including water availability, which can influence the occurrence of dry periods, shading, and temperature. In addition to abiotic factors, biological factors, diseases, pests, and even overproduction can affect leaf health and vigor, influencing the amount of light reaching the lower layers of the plants (Taugourdeau et al., 2014).

As observed, transmittance decreases along the canopy as it approaches the ground. The percentage distribution of PARi in different canopy thirds reflects the amount of incident solar radiation effectively reaching the plant. Transmittance is associated with the ability of a medium to allow the passage of solar radiation. Therefore, when there is a higher percentage of PARi in the upper third compared to the middle and lower thirds, it indicates that more solar radiation is being transmitted and reaching the leaves in that specific part of the canopy, as reported by Costa et al. (2019), whose results demonstrated a superiority in the percentage of PARi compared to the middle and lower thirds.

This relationship is also consistent with the findings of Marin et al. (2003) and Righi et al. (2008), who identified irradiance gradients in the plant canopy. The vertical gradient observed by Marin et al. (2003) suggests that the attenuation of solar radiation along the height of the canopy influences transmittance, allowing more light in the upper parts. Similarly, the horizontal gradient identified by Righi et al. (2008) is related to leaf dimensions and the angle of incidence of solar radiation, which also affects transmittance in different parts of the canopy.

3.22 Pearson correlation between biophysical parameters and climatic data

The relationship between LAI and precipitation over time for different coffee cultivars can be visualized in (Fig. 28). It is possible to observe how LAI varied in response to changes in precipitation patterns throughout the analyzed period.

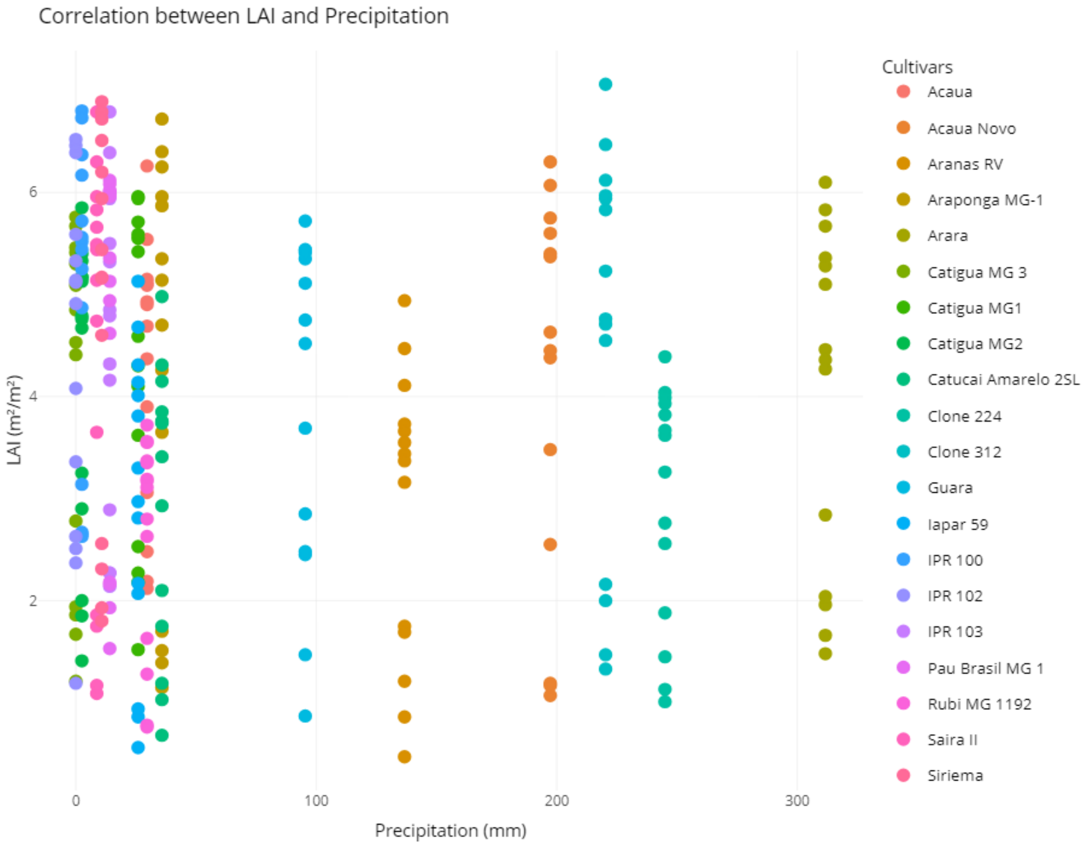

Fig. 28. Pearson correlation between LAI and precipitation over time for different Arabica coffee cultivars.

In conditions of low precipitation, the cultivars that managed to maintain high LAI values were Siriema, Saira II, IPR 100, IPR 102, IPR 103, Catigua MG2, Catigua MG3, Pau Brasil MG1, Araponga MG1, and Acaua. Even with precipitation below 50 mm in some periods, these cultivars were able to exceed 6 m².m^{-2} in some months.

On the other hand, to achieve the same LAI values, cultivars such as Arara, Clone 312, and Acaua Novo required greater water availability, reaching higher values only when precipitation approached or exceeded 200 mm.

When there is greater water availability in the soil, plants tend to exhibit better foliar development. Therefore, the cultivars that, even under water scarcity conditions, showed a good LAI response indicate good resistance to periods of water stress, suggesting greater adaptation to different climatic conditions.

The correlation between LAI and humidity over the months for different Arabica coffee cultivars can be observed in (Fig. 29).

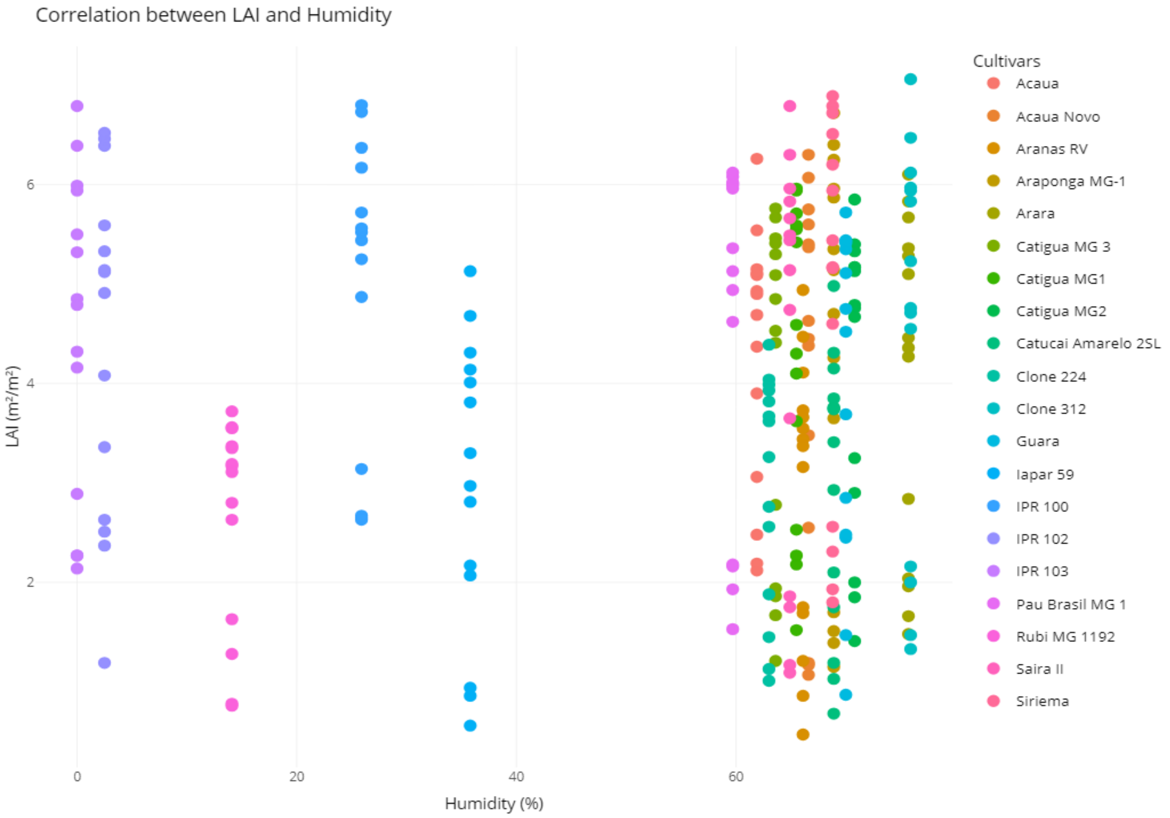

Fig. 29. Pearson correlation between LAI and humidity over time for different Arabica coffee cultivars.

Even under conditions of low humidity, some cultivars managed to maintain a good LAI, such as IPR 103 and IPR 102. In some periods with humidity below 3%, these cultivars showed most of the LAI values above 5 m².m^{-2}. Additionally, the IPR 100 cultivar also demonstrated good LAI values under humidity conditions between 20 and 30%.

On the other hand, cultivars like Acaua, Catigua MG3, Saira II, Catigua MG1, Acaua Novo, Siriema, Araponga MG1, Catigua MG2, Clone 312, Guara, and Arara only exhibited higher LAI (above 5 m².m^{-2}) in periods when the humidity was above 60%.

It is observed that the majority of cultivars presented a good LAI only under high humidity. Only the IPR 100, 102, and 103 cultivars demonstrated a positive response of LAI in periods of low humidity. Insufficient humidity can lead to the closure of stomata in leaves, reducing LAI (Levitt, 1980; Pitman et al., 1983). Therefore, cultivars that maintained a good LAI under these conditions indicate a good adaptation of the plant to drier environments.

The correlation between LAI and the different temperatures occurring in the region throughout the year can be observed in (Fig. 30).

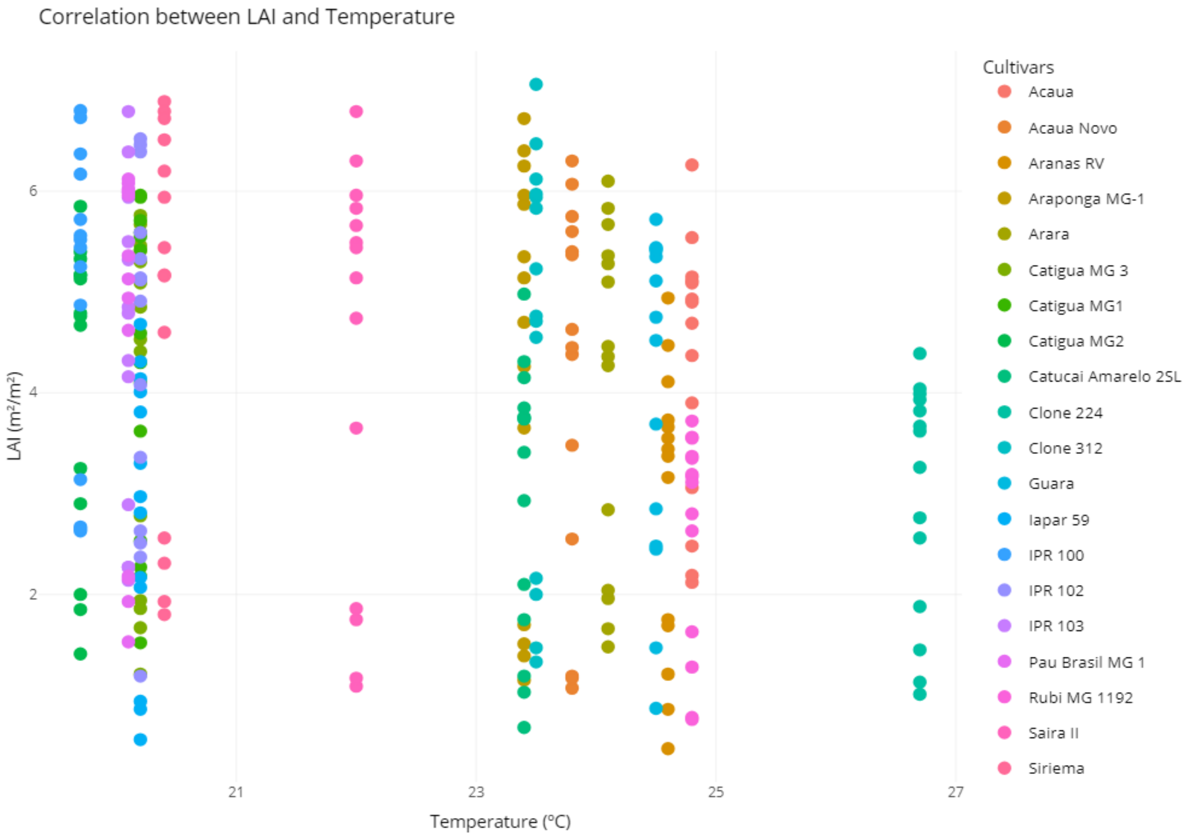

Fig. 30. Pearson correlation between LAI and temperature over time for different Arabica coffee cultivars.

In lower temperatures, below 23ºC, the cultivars that showed better LAI were IPR 100, IPR 103, Siriema, IPR 102, Catigua MG1, MG2, and MG3, Pau Brasil MG1, and Saira II, with values above 5 m².m^{-2}.

For temperatures between 23 and 25ºC, Clone 312, Araponga MG-1, Acaua Novo, Arara Guara, and Acaua performed better, with a significant portion of the data above 5 m².m^{-2}. With temperatures above 25ºC, only Clone 224 stood out, recording good LAI values at temperatures close to 27ºC. Considering that the ideal temperature for Arabica coffee cultivation is between 18ºC and 23ºC (Mesquita et al., 2016), Clone 224 achieved a good LAI result at a temperature higher than what is considered ideal for the species.

The correlation between f_{APAR} and precipitation throughout the coffee cycle can be observed in (Fig. 31).

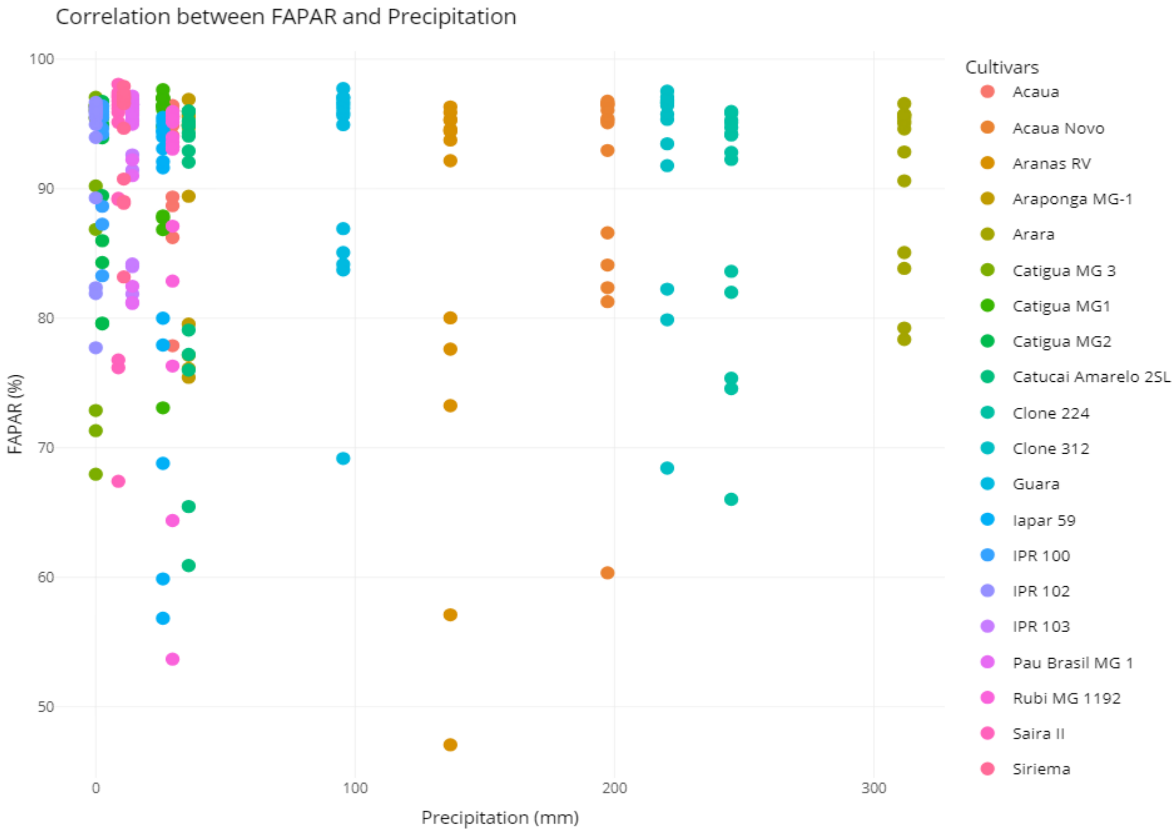

Fig. 31. Pearson correlation between f_{APAR} and precipitation over time for different cultivars of Arabica coffee.

In conditions of low precipitation, with values lower than 40 mm, the cultivars that showed good f_{APAR} were IPR 100, IPR 102, IPR 103, Catigua MG1, Catigua MG2, Catigua MG3, Saira II, Siriema, Pau Brasil MG1, Iapar 59, Rubi MG1192, Araponga MG1, Catucai Amarelo 2SL, and Acaua.

Among precipitation levels ranging from 90 to 200 mm, the cultivars Guara, Aranas RV, and Acaua Novo showed better correlation with f_{APAR}. With precipitation above 200 mm, we have Clone 312, Clone 224, and Arara.

The relationship between f_{APAR} and precipitation depends on various factors, making this relationship complex. Some plants have physiological and morphological characteristics that allow them to have a good photosynthetic capacity during periods of low precipitation, such as a deeper root system. In general, many cultivars showed a good correlation between periods of low precipitation and f_{APAR}, indicating a good light absorption even in moments of lower water availability. This capacity can be an indicator of good development of cultivars even in locations with irregular rainfall.

In (Fig. 32), the relationship between f_{APAR} and humidity over time can be observed.

Fig. 32. Pearson correlation between f_{APAR} and humidity over time for different cultivars of Arabica coffee.

In conditions of low humidity, below 20%, the cultivars that showed the best f_{APAR} were IPR 102, IPR 103, and Rubi MG1192. However, the latter mentioned cultivar exhibited very low f_{APAR} values at some points throughout the cycle.

For humidity levels between 20% and 40%, the cultivars IPR 100 and Iapar 59 stand out, although the latter also showed low f_{APAR} values over the months. As for humidity levels between 40% and 60%, the cultivar Pau Brasil MG1 achieved better performance. All other cultivars exhibited high f_{APAR} values with humidity above 60%.

Therefore, considering the high f_{APAR} values throughout the cycle of the cultivars IPR 100, IPR 102, and IPR 103, even during the senescence period, and the good correlation under low humidity conditions, the potential of these cultivars in limited water availability conditions is highlighted. This is relevant, especially considering that the ideal relative humidity for the cultivation of Arabica coffee is around 70%. These cultivars demonstrate a greater capacity for adaptation and resistance to water scarcity conditions, which can be advantageous in environments with irregular or prolonged dry spells.

The correlation between f_{APAR} and temperature can be observed in (Fig. 33).

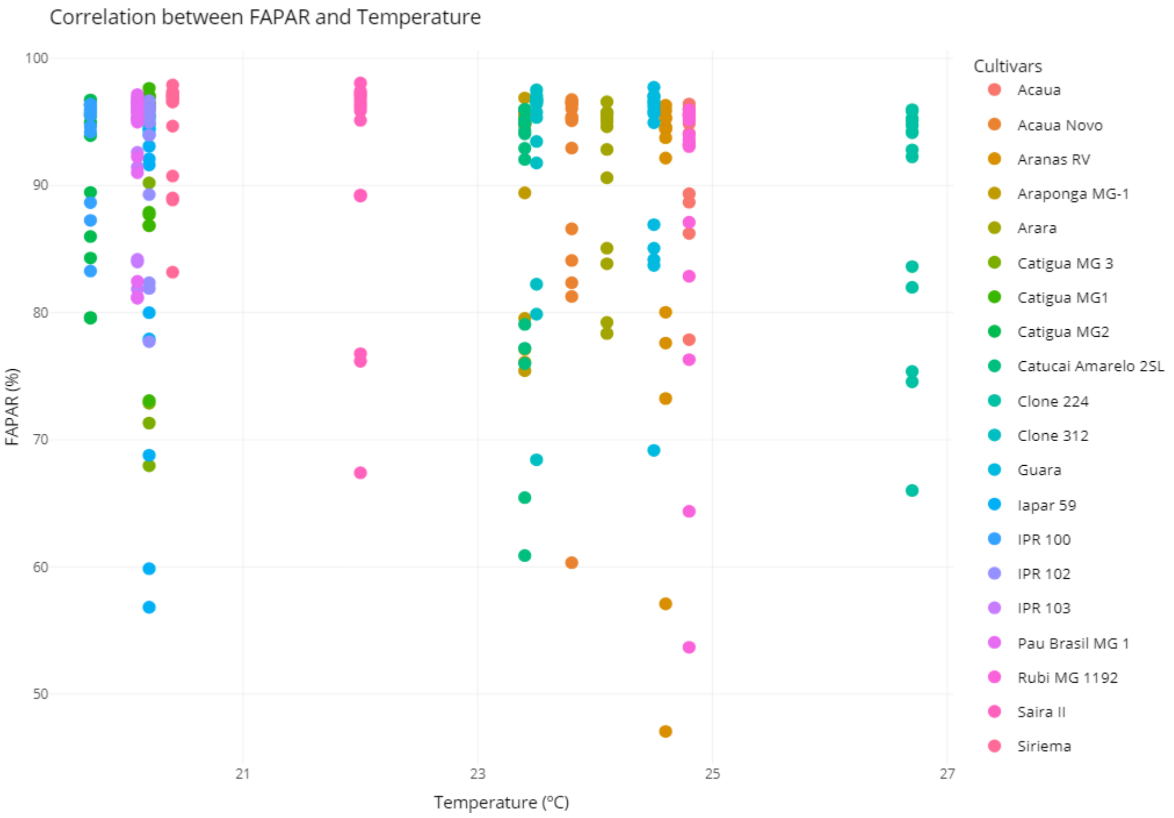

Fig. 33. Pearson correlation between f_{APAR} and temperature over time for different cultivars of Arabica coffee.

In conditions of low temperature (below 21°C), the cultivars that showed better f_{APAR}, with the majority of values above 90%, were IPR 100, IPR 102, Catigua MG1, Catigua MG2, Catigua MG3, Pau Brasil MG1, and Iapar 59.

For temperatures between 21°C and 23°C, only the cultivar Siriema displayed better f_{APAR}. However, all other cultivars achieved better f_{APAR} between temperatures of 23°C and 25°C.

Under higher temperatures, only the Clone 224 exhibited f_{APAR} values, with temperatures near 27°C. In addition to the good f_{APAR} results during the phenological cycle, Clone 224 also demonstrated a positive correlation with periods of high temperatures. This result indicates that the cultivar is well adapted to heat, maintaining its photosynthetic activity even during periods of thermal stress, representing an important adaptive mechanism in environments with high temperature variability throughout the year, a common characteristic in Brazilian regions. Furthermore, a cultivar that can maintain good f_{APAR} values under adverse high-temperature conditions is capable of developing mechanisms to withstand climatic adversities, which are becoming increasingly frequent worldwide.

Regarding reflectance and precipitation, the correlations can be observed in (Fig. 34).

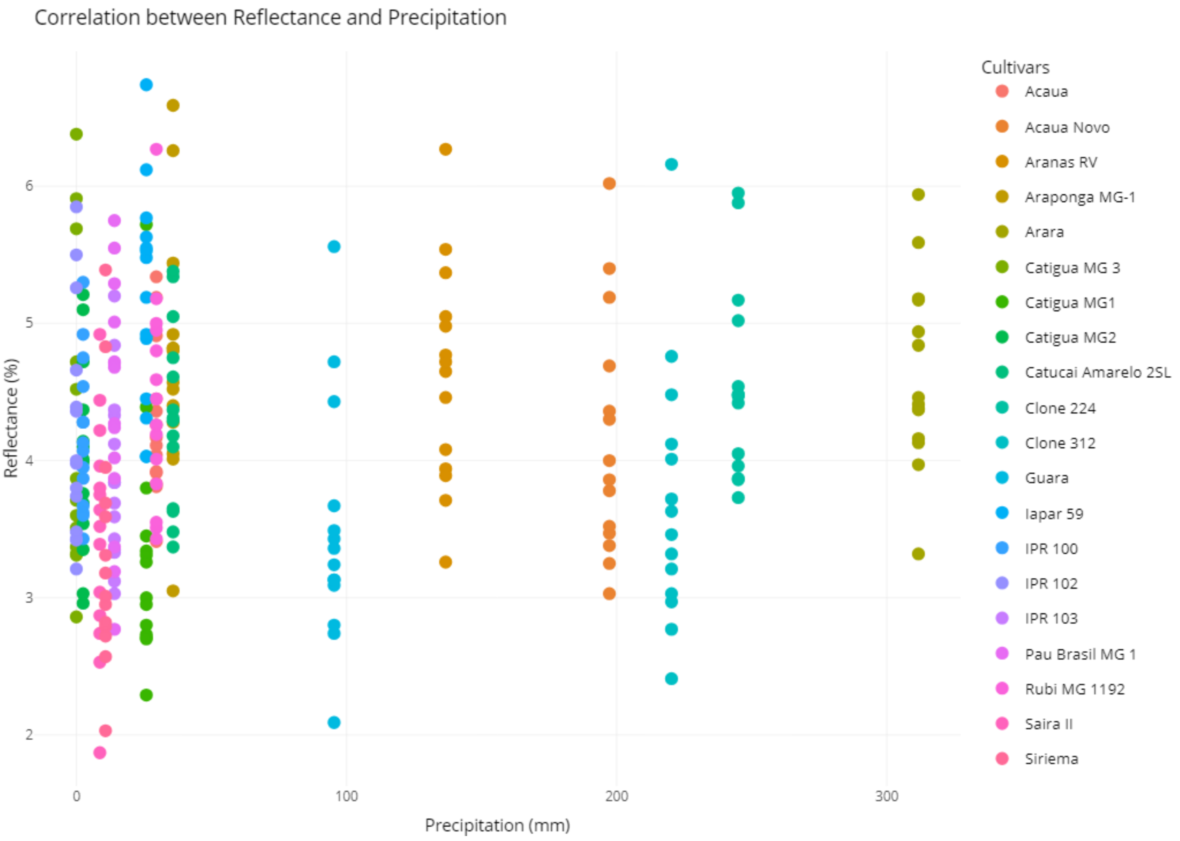

Fig. 34. Pearson correlation between reflectance and precipitation over time for different cultivars of Arabica coffee.

The cultivars that showed lower reflectance, with values below 3%, under low precipitation conditions (below 40 mm), were Catigua MG1, IPR 103, Saira II, Siriema, and Pau Brasil MG1. On the other hand, the Guara cultivar exhibited lower reflectance values between 50 and 100 mm of precipitation.

In general, low vegetation reflectance is associated with high precipitation because under conditions of good soil water availability, plants tend to absorb a larger amount of solar radiation, reducing the percentage of reflectance. However, some cultivars showed low reflectance not only throughout the phenological cycle but also during periods of drought.

For Arabica coffee plants, it is crucial for leaf absorption of solar radiation to be as high as possible, reducing the percentage of reflectance. Cultivars that exhibit a good correlation of this parameter with periods of low precipitation have an excellent ability to perform photosynthesis and minimize the negative effects resulting from low water availability, maintaining a larger quantity of healthy and well-developed leaves throughout the cycle. This mechanism influences the fruit maturation process and, consequently, the cultivar's productivity.

The correlation between reflectance and humidity over the cycle can be observed in (Fig. 35).

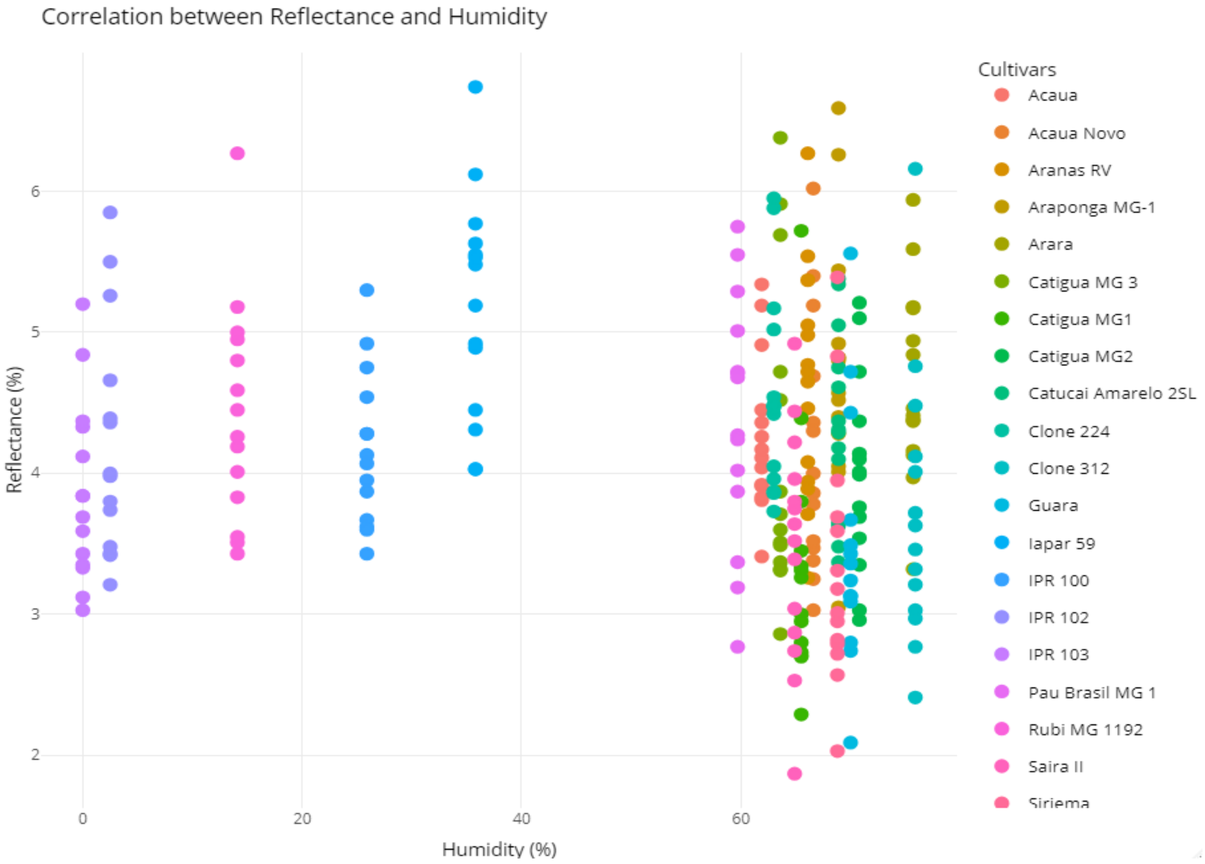

Fig. 35. Pearson correlation between reflectance and humidity over time for different Arabica coffee cultivars.

The majority of cultivars showed lower reflectance when humidity was high. Only the IPR 103 and IPR 102 cultivars exhibited lower reflectance under low humidity conditions. The Rubi MG1192 and IPR 100 cultivars also presented low reflectance values under low humidity conditions, between 10 and 30%. However, the IPR cultivars showed consistently lower reflectance values throughout the cycle compared to Rubi MG1192.

Under high humidity conditions, plants tend to reflect less light, resulting in lower reflectance. Conversely, under low humidity conditions, plants tend to reflect more light, leading to higher reflectance. Cultivars with lower reflectance, even during periods of low humidity, may possess hybrid characteristics, being more efficient in water use and showing greater adaptability to dry periods.

The correlation between reflectance and temperature over the Arabica coffee cycle can be observed in (Fig. 36).

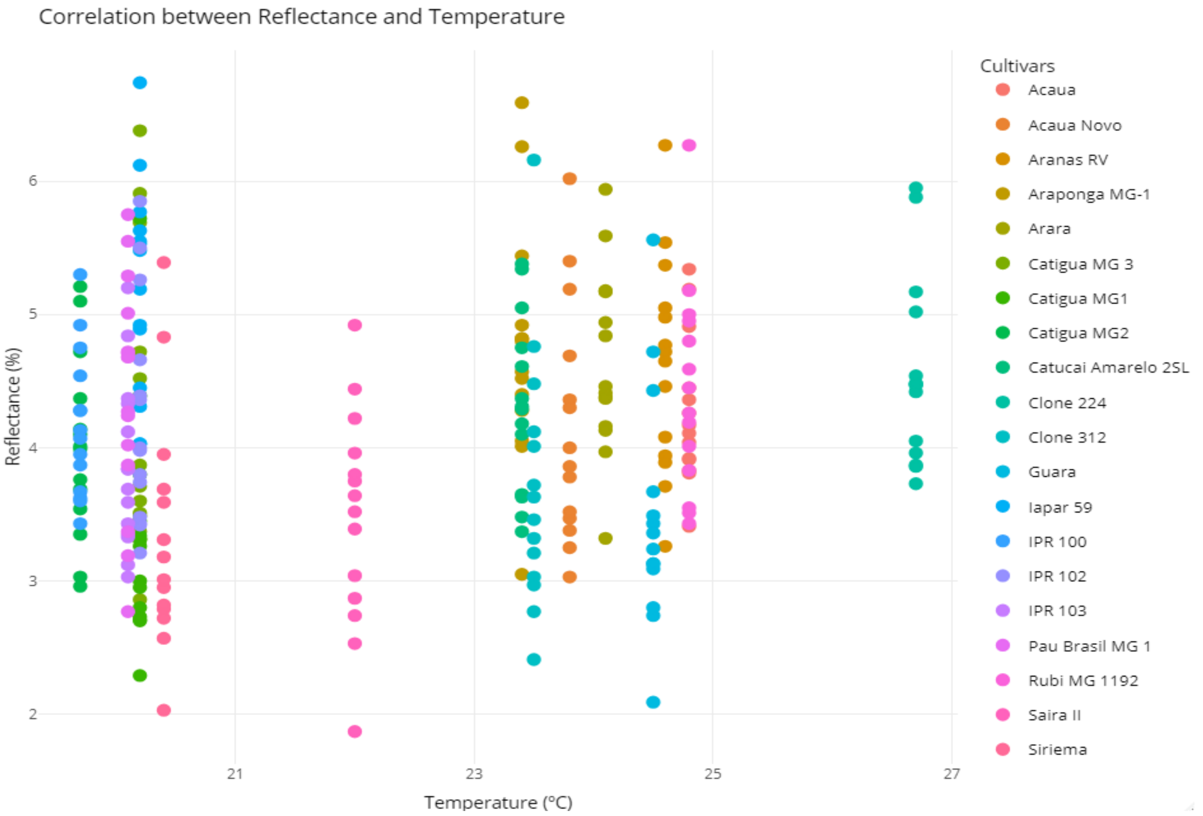

Fig. 36. Pearson correlation between reflectance and temperature over time for different Arabica coffee cultivars.

Overall, most cultivars showed lower reflectance values under low-temperature conditions. This is expected, as lower temperatures generally lead to reduced plant transpiration, resulting in less water loss. On the other hand, at higher temperatures, leaves tend to lose more water through transpiration in the form of water vapor, which can lead to higher reflectance values. Thus, most cultivars exhibited lower reflectance values under lower temperatures.

A noteworthy cultivar is Clone 224, which showed reflectance values at a temperature close to 27°C. This may indicate that this cultivar has adaptation mechanisms for regions with higher temperatures, demonstrating a good ability to absorb solar radiation even during warmer periods.

To analyze the canopy as a whole, the transmittance between the top and the bottom, at ground level (t3), was examined in relation to climatic data. The relationship between t3 and precipitation can be observed in (Fig. 37).

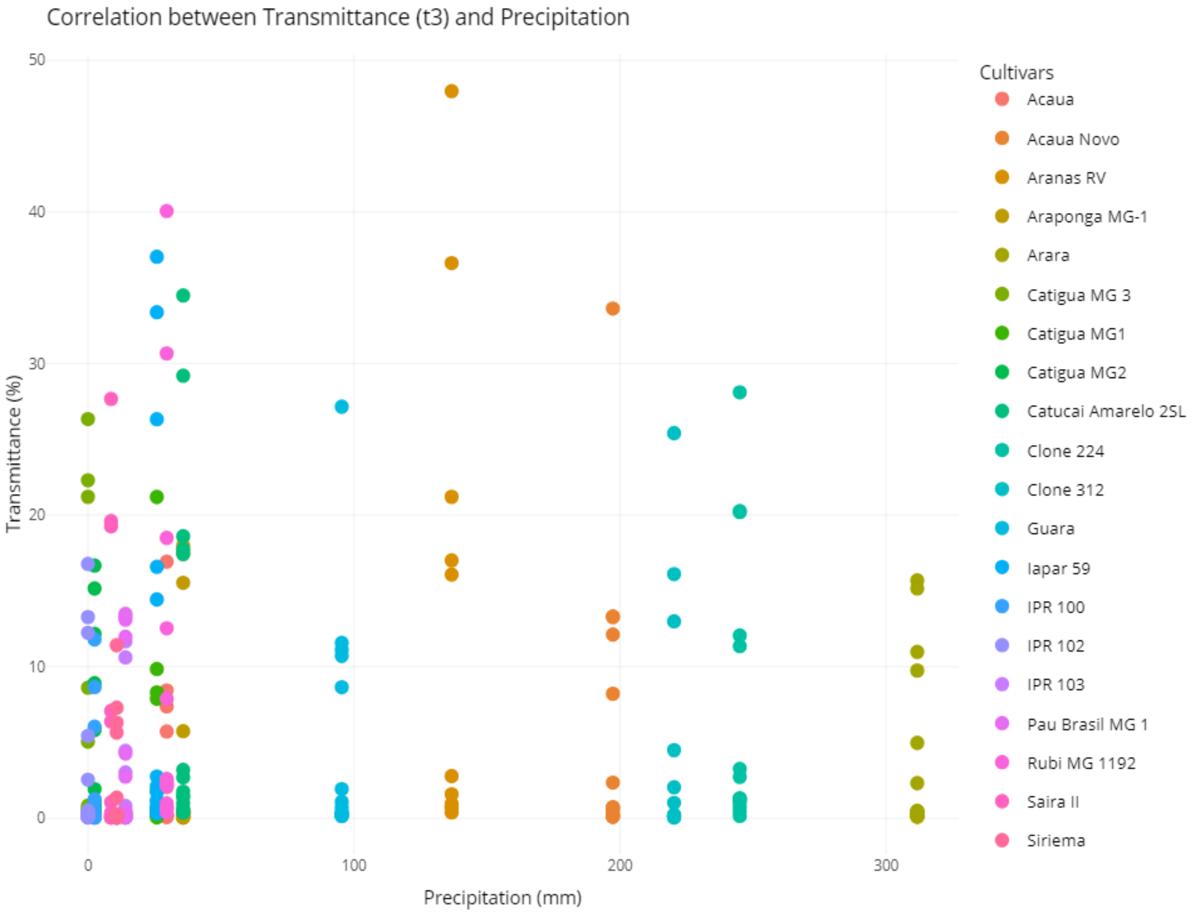

Fig. 37. Pearson correlation between t3 and precipitation over time for different arabica coffee cultivars.

The cultivars that showed lower transmittance under low precipitation conditions (below 40 mm) were: IPR 100, IPR 102, IPR 103, Catigua MG2, MG3, Saira, Siriema, Iapar 59, Rubi MG1192, Catucai Amarelo 2SL, Acaua, and Araponga MG1, and Catucai Amarelo 2SL. Near 100 mm of precipitation, the Guara cultivar also presented low transmittance values. On the other hand, the other cultivars showed lower t3 values when the precipitation volume was higher.

In general, most cultivars showed a good correlation with lower precipitation conditions, which may be related to the well-defined seasonality of precipitation in the municipality of Lavras, with higher volumes between November 2020 and March 2021, with a peak in December.

Under lower precipitation conditions, it is expected that the leaves are drier, which can influence transmittance, as there is less interference of water in the transmission of radiation to the lower layers of the canopy. Nevertheless, the good correlation of the cultivars may indicate that Arabica coffee plants are adapted to the precipitation seasonality of the region, suggesting that they have good resistance to periods of lower water availability.

The correlation between transmittance t3 and humidity over the months can be observed in (Fig. 38).

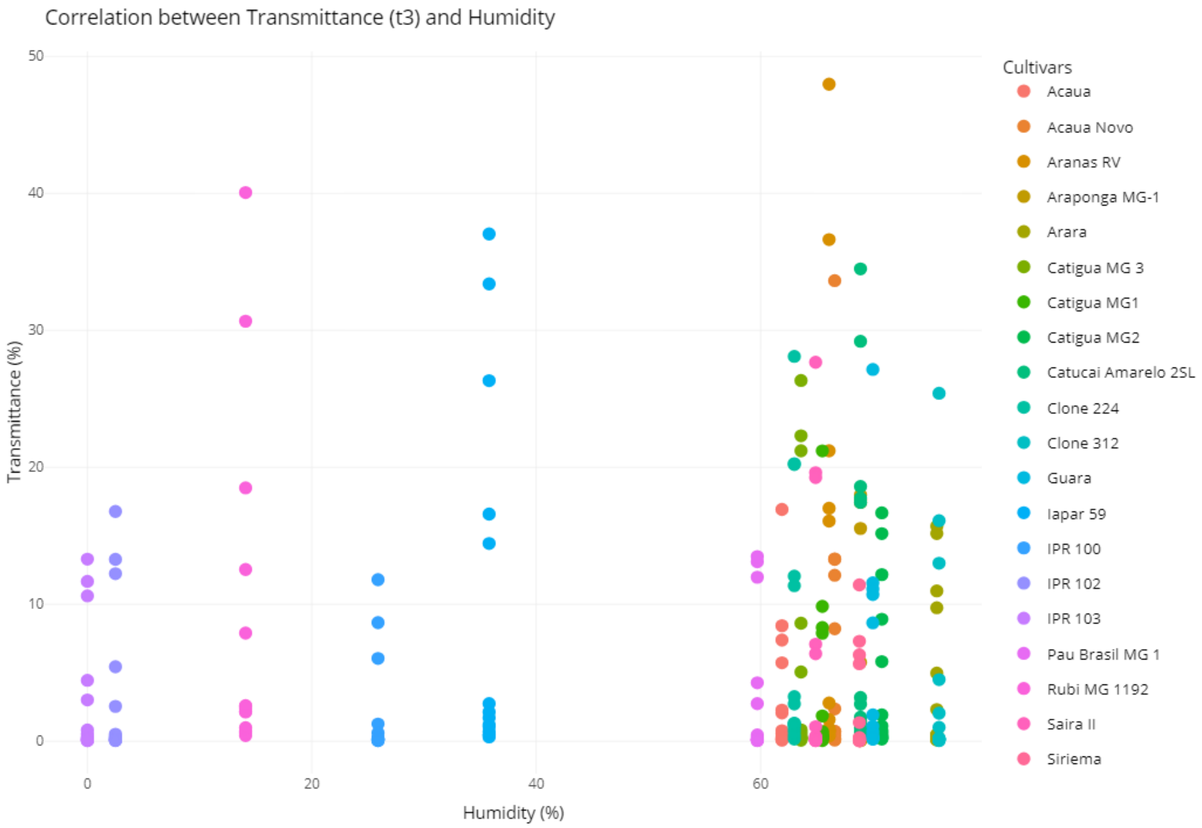

Fig. 38. Pearson correlation between t3 and humidity over time for different Arabica coffee cultivars.

In conditions of low humidity, the cultivars IPR 100 and IPR 102 showed lower values of transmittance. On the other hand, the cultivar IPR 103, in addition to presenting low transmittance values throughout the cycle, most of these values occurred under low humidity conditions, between 20 and 30%. This indicates a good behavior of the plant since in drier periods, the water availability in the leaves is expected to be lower, reducing the photosynthetic capacity and causing the leaves to absorb less radiation, increasing the transmittance to the lower layers of the plant. This phenomenon demonstrates the good capacity of these cultivars in adapting to drought periods and their ability to create mechanisms for better light absorption in drier environments.

Finally, it is important to analyze the relationship between transmittance and temperature, which can be observed in (Fig. 39).

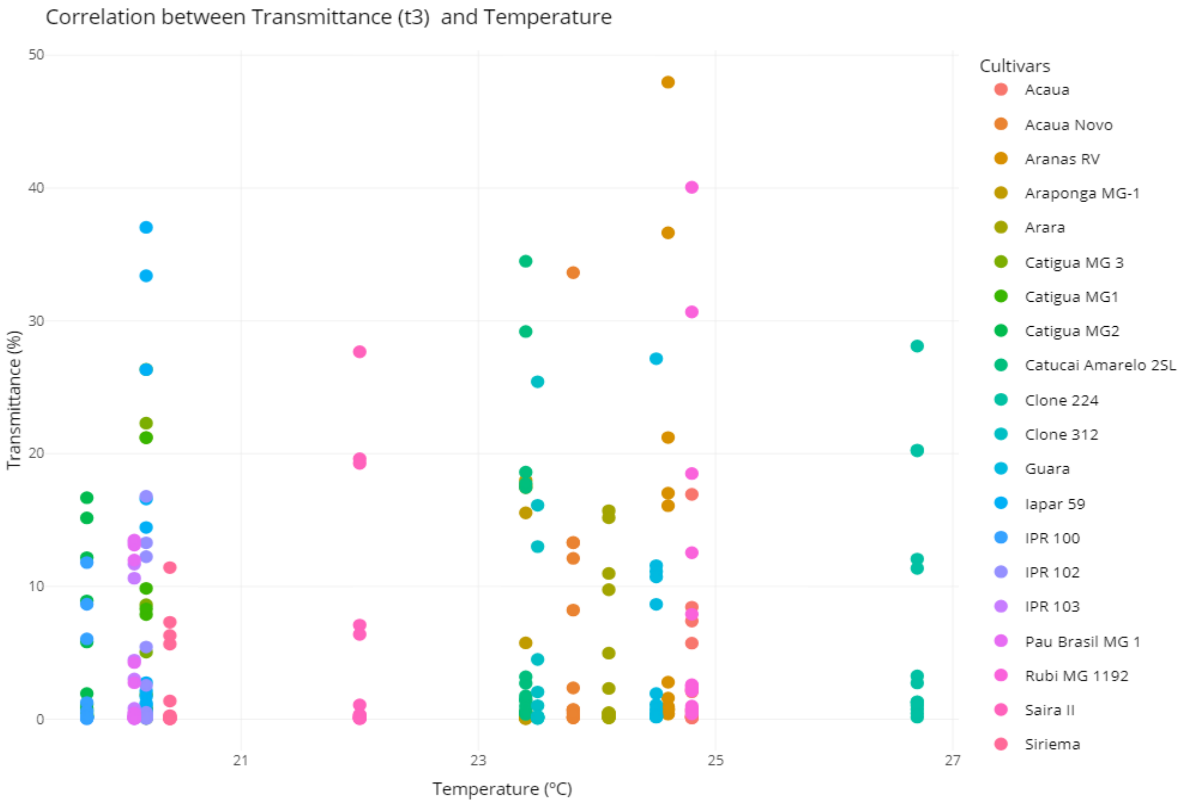

Fig. 39. Pearson correlation between t3 and humidity over time for different cultivars of Arabica coffee.

Most cultivars showed lower transmittance values between temperatures of 23 to 25°C. However, the Clone 224 cultivar exhibited better transmittance results at higher temperatures, close to 27°C.

In general, it is expected that under high-temperature conditions, the plant's photosynthetic capacity decreases, leading to lower radiation absorption due to potential damage to leaf cellular structures. Therefore, cultivars that demonstrate adaptation mechanisms to thermal stress environments are crucial, considering the global temperature rise due to climate change.

In this context, Clone 224 stands out for showing a good correlation even when the temperature exceeded what is considered ideal for Arabica coffee cultivation.

(Table 1) presents the cultivars analyzed in this study, as well as the correlation between biophysical parameters and climatic data during periods of low precipitation, low relative humidity, and high temperature for the municipality of Lavras throughout the period from 2020 to mid-2021.

Frame 1. Correlation between biophysical parameters and climatic data of different Arabica coffee cultivars.

	LAI ($m^2.m^{-2}$)
Precipitation (mm)	Siriema, Saira II, IPR 100, IPR 102 e IPR 103, Catigua MG2, Catigua MG3, Pau Brasil MG1, Araponga MG1 and Acaua
Humidity (%)	IPR 100, IPR 102 and IPR 103
Temperature (ºC)	Clone 224
	f_{APAR} (%)
Precipitation (mm)	IPR 100, IPR 102, IPR 103, Catigua MG1, Catigua MG2, Catigua MG3, Saira II, Siriema, Pau Brasil MG1, Iapar 59, Rubi MG1192, Araponga MG1, Catucai Amarelo 2SL and Acaua
Humidity (%)	IPR 102, IPR 103, Rubi MG1192 and IPR 100
Temperature (ºC)	Clone 224
	Reflectance (%)
Precipitation (mm)	Catigua MG1, IPR 103, Saira II, Siriema, Pau Brasil MG1 and Guara
Humidity (%)	IPR 103, IPR 102, Rubi MG1192 and IPR 100
Temperature (ºC)	Clone 224
	Transmittance (%)
Precipitation (mm)	IPR 100, IPR 102, IPR 103, Catigua MG2, MG3, Saira II, Siriema, Iapar 59, Rubi MG1192, Acaua, Araponga MG1, Catucai Amarelo 2SL and Guara
Humidity (%)	IPR 100, IPR 102 and IPR 103
Temperature (ºC)	Clone 224

In general, most cultivars showed a good correlation with precipitation, even during periods of drought, for all the biophysical parameters analyzed. This good correlation can be explained by some aspects of precipitation in the region, such as well-defined seasonality.

The temporal graphs of the biophysical parameters and climatic data showed two distinct periods in relation to precipitation in the municipality. One period with higher rainfall volumes occurring between November and March, defined as the rainy season (summer), and another period of low precipitation occurring between April and October, the dry season (winter).

This well-marked seasonality coincides with the phenological cycle of coffee. During the rainy season, which starts in November, the plants enter a period of vegetative recovery, as observed in the time series graphs, where most cultivars showed improvements from November onwards. This stimulus for vegetative growth occurs mainly from December when the highest rainfall of the year occurred. During this period, the LAI increased, consequently, f_{APAR} was also higher. With better photosynthetic capacity, reflectance decreased, and transmittance reduced as it reached the lower layers of the plant canopy.

On the other hand, during the dry season starting in April, when precipitation decreased, the plant showed its lowest vegetative vigor as it entered the senescence period, where the leaves were in a phenological resting state, conserving energy and water lost in the harvesting process that occurred in May.

According to CONAB (2020), the climatic conditions were favorable for the development of coffee plantations during most of the 2020 production cycle. Although the onset of rains was slightly delayed, starting in November 2019, the rainfall occurred regularly and in significant volumes, fully meeting the water needs of the crop for growth, formation, and grain filling, as well as ensuring adequate water availability in the soil.

It is important to note that besides favorable climatic conditions during the period, the 2020 harvest was marked by a positive biennial cycle of coffee. In the state of Minas Gerais, 34,647.1 thousand bags of coffee were harvested, representing an increase of 41.1% compared to 2019 and registering the highest production in the state's history. The Southern Minas Gerais and Central-West regions, which are the main producing regions, achieved 19,152.2 thousand bags, showing a growth of 37% compared to the previous harvest, and with a yield above the historical average of the locality (CONAB, 2020). These combined factors contributed to a robust and promising coffee crop sector.

High rainfall volumes persisted until March, but from April, the climate became predominantly dry, with precipitation volumes drastically reduced. This scenario was favorable for the harvesting and proper drying of coffee beans, contributing to obtaining a high-quality product. The scarcity of rain during this period allowed for more efficient harvesting, avoiding moisture accumulation in coffee beans and reducing the risk of storage problems and deterioration (CONAB, 2020).

Although the year 2020 was marked by good climatic conditions, it is important to highlight that periods of climatic adversity can alter the biennial cycle of coffee production, as occurred in 2014. Despite being a positive harvest year, severe water restrictions resulted in lower productivity compared to the previous year (CONAB, 2020). Approximately 25 million coffee farmers worldwide directly depend on rainfed production and are therefore susceptible to the adverse effects of climate variability and extremes (Orindi and Eriksen, 2005). According to Tavares et al. (2018), it is projected that the suitable land area for coffee production in Brazil may decrease from 20% to 60% by the end of the 21st century.

These unforeseen climatic events can have a significant impact on coffee production, as observed by Mukherjee et al. (2012), who reported how temperature extremes and erratic rainfall trigger outbreaks of pests and diseases in coffee. Iscaro (2014) explores how increased temperature and irregular rainfall affected Colombia and Ethiopia, leading to an increase in coffee leaf rust and a drastic increase in the population of coffee berry borer, harming productivity. Phenological cycle processes, such as flowering and grain filling, can also be interrupted by climate changes, resulting in reduced quality and quantity of production (Magrach and Ghazoul, 2015; Kifle and Demelash, 2015).

Special mention should be given to the Siriema, Saira II, and IPR 103 cultivars, which showed a good correlation with all biophysical parameters and precipitation.

Regarding humidity, most cultivars showed better correlation when humidity values were higher (above 60%). However, it is important to highlight the IPR 100, IPR 102, and IPR 103 cultivars, which showed good correlation between LAI, f_{APAR}, reflectance, and transmittance (t3) at low humidity values, well below the range of humidity considered favorable for Arabica coffee cultivation, which is around 70%. This indicates that these cultivars have efficient mechanisms for maintaining healthy and functional leaves, even under water stress conditions.

It is relevant to note that excessively high humidity can harm the coffee plant and beverage quality since it favors the incidence of pests, diseases, and undesirable fermentations. On the other hand, very low relative humidity can also be detrimental as it promotes the attack of some pests and reduces healthy coffee plant development (Mesquita et al., 2016).

Therefore, due to coffee's sensitivity, humidity levels should be monitored as they can affect both growth and grain quality. In 2006, a study conducted by Castellanos et al. (2008) showed that approximately 57% of coffee farmers experienced yield losses in their plantations. Among these losses, 26% were attributed to stress caused by humidity, while 27% were due to excessive rainfall.

Regarding temperature, the Clone 224 cultivar stood out, showing a better correlation under higher temperatures for all the biophysical parameters analyzed. This result may indicate that the cultivar possesses resistance and/or tolerance to periods of higher thermal stress.

Arabica coffee is particularly sensitive to temperature increases (Zullo et al., 2008). The average temperature suitable for Arabica coffee is between 18°C and 23°C (Mesquita et al., 2016). Outside of the ideal temperature range, the quality of the beans and the yield of both coffee species tend to decrease (Magrach and Ghazoul, 2015). This thermal variation can negatively affect plant development and grain formation, resulting in a lower quality and quantity of coffee production.

The study suggests that the analyzed climatic variables covaried and were associated with the biophysical parameters analyzed, and they cannot be dissociated when analyzing cultivars with resistance to drought periods. Cultivars that showed good biophysical parameters even during periods of low precipitation, low humidity, and high temperatures may have anatomical alterations that aim to protect and adapt leaves under stress conditions. In situations where plants face water scarcity, their tissues may undergo some changes to cope with this situation, such as the development of the protective layer called lignification, and they may also have smaller cells, more vascular tissue, and thicker cell walls (Levitt, 1980; Pitman et al., 1983). These alterations help plants adapt to water stress.

The effects of variations in biophysical parameters were inferred by climatic conditions, confirming the general rule already reported in the literature: under favorable temperature conditions, the healthy growth of leaves exhibits periodicity that closely follows the distribution of rainfall, and the development of sprouts tends to occur synchronously with the water availability from precipitation (Maestri and Barros, 1977; Rena et al., 1994).

It was observed that leaf expansion in Arabica coffee presents seasonal variations, being faster and resulting in larger leaves when expansion starts at the beginning of the rainy season and warmer temperatures, creating ideal conditions for the vegetative development of the plant (Rena and Maestri, 1985).

4. Conclusion

The analyzed parameters followed a seasonal pattern, varying according to climate changes throughout the year. In the drier and colder months, there was a decrease in LAI and f_{APAR} and an increase in reflectance and transmittance, associated with the fruit maturation period. In contrast, in the rainy and warmer months, there was an increase in LAI and f_{APAR} and a decrease in reflectance and transmittance.

In general, the cultivars showed good correlation under conditions of low precipitation, which may be related to the well-defined seasonality of the region that coincides with the phenological cycle of coffee. The cultivars Siriema, Saira II, and IPR 103 showed good correlation with all biophysical parameters during periods of low precipitation.

The cultivars IPR 100, IPR 102, and IPR 103 also showed good correlation between LAI, f_{APAR}, reflectance, and transmittance even under low humidity values, indicating good adaptability to water stress conditions.

Regarding temperature, the Clone 224 cultivar stood out, showing a better correlation with all biophysical parameters under higher temperatures (27°C), suggesting resistance and/or tolerance to periods of thermal stress.

In summary, the study revealed that several Arabica coffee cultivars have distinct responses in their biophysical parameters according to climatic factors. Some cultivars stood out for their remarkable adaptation to adverse conditions, such as high temperatures and low water availability, with emphasis on the varieties Siriema, Saira II, IPR 100, IPR 102, IPR 103, and Clone 224.

From an economic and social standpoint, understanding the extent of the impacts that climate change can have on coffee production is crucial in order to propose potential adaptation strategies, including irrigation, shading of plantations, or encouraging alternative sources of income for producers.

Moreover, it is important to consider that temperature, humidity, and precipitation variables play a significant role in the geographical distribution of suitable coffee cultivation areas. More accurately predicting future patterns of these variables and selecting drought-tolerant cultivars can improve projections of suitable cultivation areas. This, in turn, will allow the improvement of management practices and genetic improvement, aiming to maintain and increase coffee productivity and profitability, and consequently contributing to the food security of the families involved in production.

Declaration of Competing Interest

The authors state that they do not possess any identifiable conflicting financial interests or personal affiliations that might have impacted the research presented in this article.

Data Availability

The data will be available upon request.

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