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Calculation of intercepted photosynthetically active radiation (IPAR) for traditional crops in Castilla y León, Spain

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TOPIC: RENEWABLE ENERGIES, ENVIRONMENTAL IMPACT AND CIRCULARITY

1. Introduction

Agriculture is one of the most important economic activities in the Castilla y León region (Spain), approximately one-third of the land area is destined for this use. The role of agriculture in rural areas is essential from a territorial perspective, where rural depopulation is originating a crisis in the countryside. Moreover, climate change is having a major impact on agricultural productivity as a consequence, among others, of the increase in the frequency and the severity of extreme events, especially in Mediterranean regions [1]. For these reasons, it is essential to highlight the vision of agriculture as a multifunctional activity. Besides good management, productivity depends on many other factors, such as soil properties or climatic factors. A decisive climatic variable, which is often not considered in the planning and management of the crops, is the Photosynthetically Active Radiation (PAR), specifically, the Intercepted Photosynthetically Active Radiation (IPAR).

The Photosynthetically Active Radiation (PAR) is a component of the global solar radiation located in the visible spectrum, between 400 and 700 nm. It is a term that refers to the flux of photons ($\mu mol \cdot m^{-2} \cdot s^{-1}$) or the energy ($W \cdot m^{-2}$) capable of electron transport from the photosynthetic process [2]. It plays a central role as the only source of energy for photosynthesis. PAR measurements are scarce, despite some few initiatives such as the Active Radiation Monitoring Network, recently established in Spain [3]. In the development of these networks, there are some factors such as the type of sensors [4], their correct calibration, or their strategic location [5] that are very important to obtain reliable measurements. For this reason, some authors estimate the PAR by establishing a constant relationship with the Global Horizontal Irradiance (GHI), generally between 0.45-0.5 [6], modelling through meteorological indices, applying neural networks [7] or by satellite observations for a specific state of the atmosphere [8].

The IPAR is involved in many processes such as photosynthesis and water exchange [9]. It is usually estimated from an approach of Beer's Law [10] defined in Eq. 1, which depends on the light extinction coefficient (k) and the leaf area index (LAI).

$$IPAR = PAR \cdot (1 - e^{-k \cdot LAI}) \tag{1}$$

The light extinction coefficient (k) is a parameter that describes the efficiency of light interception in plant canopies. The calculation of this factor is very complex, as it is influenced by plant canopy characteristics (development stage [11], leaf shapes, or inclination angles) and by the spectral properties of solar radiation [12].

The Leaf Area Index (LAI) is the leaf area per unit ground projection area (m^2/m^2). It can be measured, analysed, and modelled at different spatial and time scales. These factors make it a reliable indicator of the state and evolution of vegetation over time [13]. LAI is usually estimated by direct (harvested leaves and leaf litters) or indirect optical methods carried on with numerous commercial instruments (digital hemispherical photography (DHP), the LAI-2200 plant canopy analyser (LI-COR Inc., Lincoln, Nebraska, USA), or the AccuPAR LP-80 ceptometer (Decagon Devices Inc., Pullman, Washington, USA). In recent years, other methodologies have been developed, such as the processing of remote sensing data with machine learning [14].

The main purpose of this study is to calculate and represent an estimation of IPAR values for the most characteristic crops of Castilla y León.

2. Materials and method

The Castilla y León community is one of the largest regions in Europe with an area of 94,224 km² (approximately 20% of Spanish national territory). Located in the inland northwest of Spain, the region is distinguished by a broad plateau with an average altitude of 800 metres. The climate is temperate, characterised by quite long cold winters and short dry summers. Its orography is also distinctive because it is surrounded by three mountain systems (Cordillera Cantábrica to the north, Cordillera Central to the south, and Sistema Ibérico to the east).

The "Mapa de Superficies Naturales de Castilla y León 2021" (MSNCyL), elaborated every year by the "Instituto Tecnológico Agrario de Castilla y León" (ITACyL) [15], was used to identify the different types of crops and the area of land used for each of them. Four different groups of arable crops were considered for this study: cereals (wheat, barley, oat, rye, and maize), tubers (potatoes), industrial crops (sugar beet, sunflower, and rapeseed), and forage crops (alfalfa and vetches). Vineyards were also included as the most representative woody crop in Castilla y León. The total area covered by each of the considered crop groups is shown in Table 1. Note that industrial crops were independently considered due to their morphological differences compared to the other crops.

Table 1. Area destined for arable crops in Castilla y León in 2021.

Crop	Area (ha)
Forage crops	216419
Rapeseed	33810
Vineyard	66368
Cereal crops	2117431
Sunflower	242432
Potatoes	15556
Sugar beet	18422

The experimental dataset included 14 years (2007-2020) of data collected at 46 stations from Castilla y León, provided by the SiAR network [16]. In addition, 49 stations belonging to all the neighbouring regions (SiAR network, ADRASE, Air Quality Control Network in Cantabria, and SOLARGIS) had been included. The initial data were processed to obtain the annual daily mean value of GHI (MJ/m²) at each weather station. They were also spatially represented in QGIS 3.16 software with the ordinary kriging geostatistical method as it is the spatial interpolation technique that best works with the GHI data [17, 18].

As already mentioned in the introduction, PAR databases are spatially and temporally limited. In addition, making field measurements is a very technical and time-consuming process. For these reasons, PAR was calculated by setting a constant relationship with the GHI, for which data were measured at most weather stations. In this case, a coefficient of 0.48 [19, 20] was applied to the GHI map of Castilla y León.

The k and LAI values were established after a literature review of different studies performed on these crops in several locations and under a wide range of environmental, physical, and chemical conditions. IPAR was obtained for each type of crop through the application of Eq. 1.

Table 2. Light extinction coefficient (k) and Leaf Area Index (LAI) estimated values for each crop.

Crop	k	LAI (m^2/m^2)	References
Forage crops	0.670	1.794	[21, 22]
Rapeseed	0.718	1.609	[21, 23]
Vineyard	0.507	1.574	[24, 25]
Cereal crops	0.579	2.903	[11, 12, 21]
Sunflower	0.738	4.416	[26, 27]
Potatoes	0.681	3.090	[28, 29]
Sugar beet	0.694	4.420	[30, 31]

3. Results and discussion

All the GHI data from the weather stations of Castilla y León and neighbouring Communities were used, employing the ordinary kriging interpolation method, to represent a GHI map of the Community. A coefficient of 0.48 was applied to this GHI map to obtain the PAR map of the Community. This map showed PAR values ranging between 5.69 and 8.35 MJ/m². These values increase as we move southwards in the region (Figure 1).

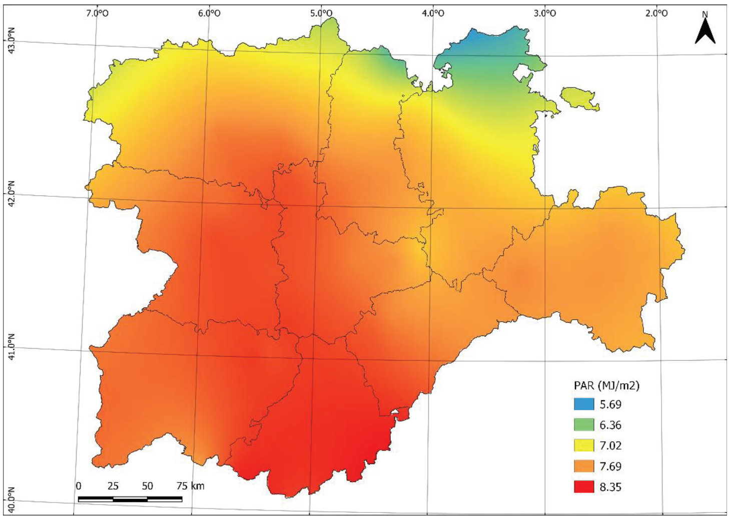

Figure 1. Estimated annual daily average PAR (MJ/ m²) values in Castilla y León.

Once the PAR map of Castilla y León was represented, LAI and k values (Table 2) were also needed to apply Beer's law and obtain the IPAR maps for each crop. The expressions (Eq. 1) used to calculate the IPAR for each crop and the range of values obtained in each map are detailed in table 3.

Table 3. Ranges of IPAR values estimated for each crop in Castilla y León.

Crop	Beer's law	IPAR (MJ/m²)
Forage crops	$PAR\ map \cdot (1 - e^{-0.607 \cdot 1.794})$	4.08-5.81
Rapeseed	$PAR\ map \cdot (1 - e^{-0.718 \cdot 1.609})$	4.07-5.62
Vineyard	$PAR\ map \cdot (1 - e^{-0.507 \cdot 1.574})$	3.70-4.59
Cereal crops	$PAR\ map \cdot (1 - e^{-0.579 \cdot 2.903})$	4.80-6.78
Sunflower	$PAR\ map \cdot (1 - e^{-0.738 \cdot 4.416})$	5.73-7.89
Potatoes	$PAR\ map \cdot (1 - e^{-0.681 \cdot 3.090})$	5.11-6.92
Sugar beet	$PAR\ map \cdot (1 - e^{-0.694 \cdot 4.420})$	5.93-7.74

These values provide a general idea of the IPAR, i.e., approximate values of the intercepted PAR by each crop in Castilla y León. The IPAR ranges are quite similar for forage crops and rapeseed due to their similar leaf morphology. For the same reason, potatoes, sugar beet, and sunflowers have the highest IPAR ranges. They can intercept more solar radiation than other crops because of their planophile leaves. Figure 2 shows the case of cereals.

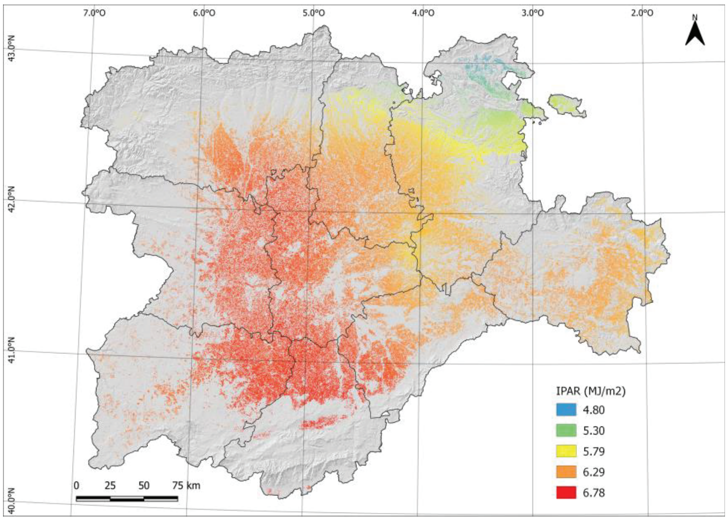

Figure 2. Estimated IPAR (MJ/ m²) values in cereal crops.

In addition to industrial crops, the vineyards of Castilla y León are especially relevant and are widely recognised worldwide, as they have managed to stand out due to the high quality of their wine production. One of the most renowned designations of origin with the largest surface area is Ribera del Duero. The vineyards of this appellation belong to four provinces (Soria, Burgos, Segovia, and Valladolid). Figure 3 shows the estimated IPAR in Ribera del Duero vineyards in southern Burgos. As can be seen, this study can be more detailed to analyse the individual plots.

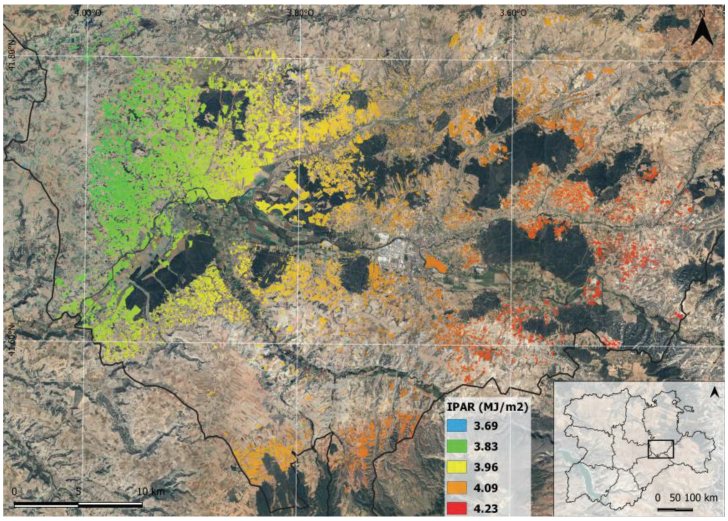

Figure 3. Estimated IPAR (MJ/ m²) values in vineyard in southern Burgos.

Value ranges presented in Table 3 show that canopy light interception is positively related to changes in LAI average values (Table 2). PAR interception usually increases sharply with increasing leaf area up to values of 2 [32]. It then increases at a slower rate up to a leaf area of 5. When this LAI value is reached, the percentage of incoming radiation intercepted can be as high as 95% [33]. Once the maximum LAI is attained in the mid to late growing season, the IPAR starts to decrease linearly to a final mean PAR interception value of 25% [34].

Many authors express the cumulative IPAR (CIPAR) over a complete growing season. They take days after sowing as a reference to make their IPAR measurements and put them all together at the end of the crop cycle [34, 35]. Daily IPAR measurements throughout the growth cycle indicate that IPAR could be dependent on plant age due to the observed differences in growth stages [36, 37].

Other influential factors are the sowing date and the plant density. [33] observed that IPAR values in wheat plots during two consecutive seasons decreased as the sowing date was delayed. Early sowing intercepted 19.8% to 25.7%, more PAR than late sowing, probably due to the longer duration. They also studied the effect of plant density on IPAR. They were higher in plots with higher plant density.

4. Conclusions

The data presented here emphasise the importance of using detailed studies on the relationship between IPAR and the relative efficiencies of different crops. The ability of the canopy to intercept PAR has a positive impact on biomass accumulation and grain production, but estimating IPAR from instantaneous measurements is complicated. Therefore, high yields require agronomic techniques that produce both a high level of radiation interception and a high conversion rate of IPAR into the grain. This information has a potential application in agronomic management and improving crop production efficiency. Determining the best sowing date, optimal rotation crops, row spacing, or seeding density can be easier with this application.

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