

Mapping of Average DLI Obtained over 17 Years in Different Regions of Côte d'Ivoire: A Sustainable Agricultural Decision-Making Tool

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Abstract

Plants require a certain amount of photosynthetic active radiation (PAR) every day to grow efficiently. The total amount of daily photosynthetic light or the daily light integral (DLI), comes from global solar radiation and may sometimes be insufficient or in excess to grow specific plants in certain regions. Indeed, DLI, a performance factor directly linked to the photosynthetic activity of crops, has an effect on the development, growth, quality and yield of these crops. It is, therefore, of great importance for producers to know the average DLI in their regions to strategically design their agricultural risk management and mitigation plans. However, this major factor of crop performance is very little or almost not integrated into farm management in West Africa. In this context, the objective of this study is to present a mapping of DLI averages over 17 years in the main regions of Côte d'Ivoire. First, we determined the PAR/Global Radiation ratio, and then the DLI was calculated from the global solar radiation data obtained over the period from 2004 to 2020. The results revealed that the DLI varies between $28.73 \pm 0.62 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ and $52.47 \pm 0.53 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ across the country depending on the region. The lowest DLIs are recorded in the months of June, July, August, and September; and the peaks are observed during the months of March, April, and May. Through these results, one can easily select the appropriate region and the adequate growing period for growing plants with known daily photosynthetic active radiation requirements. Decisions to integrate compensation techniques such as supplemental artificial lighting to increase photosynthetic active radiation for certain areas or throughout certain periods can be made. These results may also explain the low yields obtained for certain crops, and furthermore trig-

ger a positive change in the habits of farmers for a successful adaptation to climate change.

Keywords

Photosynthetic Active Radiation, Daily Light Integral, Sustainable Agriculture, Climate Change Adaptation, Côte d'Ivoire

1. Introduction

For most African countries, agriculture remains one of the main sources of economic income, and its development has had a considerable impact on food security and poverty reduction [1]. However, in recent decades, it has been observed that the increase in agricultural production is rather due to an expansion of agricultural land and very little to a change in production techniques and an improvement in yield. Currently, one in four people suffer from malnutrition; and this situation is likely to deteriorate over the years because it is estimated that there will be a 20% reduction in growing periods by 2050 in West and South Africa, which will lead to a drop in the yield of certain crops [1]. In addition, it should not be forgotten that the world population is projected to increase by 2.4 billion between 2013 and 2050, half of which will occur in sub-Saharan Africa [2]. Agriculture in African countries must, therefore, feed an ever-growing population while in recent years, we have observed a strong urbanization in these regions leading to a decrease in arable land [3]; thus, new practices have emerged to increase the efficiency of agricultural production, among which we can cite the intense use of pesticides. However, this practice, although supposed to prevent pests, is often criticized for its harmful effect on health and the environment [4]. In addition, Africa is suffering from the adverse effects of climate change, which threatens the stability and yield of agricultural production. Indeed, we observe an irregularity of growing seasons, formerly well-known and controlled; and projections of extreme climatic conditions such as heavy rains, downpours, often long and intense periods of sunshine, soil erosion causing nutrient drainage [5]. In Côte d'Ivoire, there is a shortening and shift in growing seasons [6]: over the period 1951-2000, the growing season was reduced by 30 days [7]. Thus, it is necessary to make a significant transformation in agriculture in Africa so that it can meet the challenges related to the implementation of sustainable solutions in response to climate change and food insecurity [8]. To do this, new cultivation techniques could be integrated in which the climatic environment of the plant is controlled to avoid extreme external conditions. In this sense, important factors such as irrigation, nutrient supply, temperature, humidity and the plant's light environment must be controlled to ensure optimal production. Light is an important and essential factor for plant development; through different processes such as photosynthesis, photomorphogenesis, photoperiodism and phototropism, light acts on the development, growth,

secondary metabolisms of plants; and thus on the quality and quantity of agricultural production [9]. To assess the light environment in agricultural production, global radiation is very often used as a performance indicator; this indicator is part of the parameters measured and evaluated in agri-meteorology bulletins (intended for agricultural production) regularly presented by national meteorological agencies as is the case in Côte d'Ivoire [10]. However, the spectral distribution of global solar radiation measured at the earth's surface has a broad band ranging from 280 nm to 3000 nm. And only a portion of the global radiation between 400 and 700 nm, defined as photosynthetically active radiation by the International Commission on Illumination, is actually used by plants for their growth, development, physiology and metabolism; and this is done through plant photoreceptors such as chlorophylls, phytochromes, cryptochromes, phototropins that use the captured energy from light to mediate various important biological processes [11] [12]. The DLI constitutes the daily integral of this photosynthetically active radiation; in other words, the DLI describes the daily number of photosynthetically active photons delivered to a given area during a day [13]. The concept of DLI was introduced in the 1980s when Armitage *et al.*, on an experiment conducted on Geranium seeds, demonstrated in their work that minimum DLIs of $1.94 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ and $3.25 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ are necessary to initiate flowering and flower development respectively [14]. In 2002, a DLI map of 48 states of the United States was published by Korczynski *et al.*, then updated in 2018 by Faust and Logan [13] [15]; The DLI concept initially little used by producers in the United States has gradually integrated the jargon of horticulturists thanks to strong awareness and training programs dedicated to professionals; and this has ultimately contributed to improving the management of the light environment in commercial agricultural production of a wide variety of crops [13]. In 2021, a DLI mapping of the Nordic and Baltic countries was carried out by Hernandez [16]; then in 2024, András Jung *et al.*, proposed in a first publication a DLI mapping of Hungary, and in a second publication that of Spain [17] [18]. Knowing the DLI for a given area, growers can optimize their crop management strategy, such as selecting the most suitable crops at the DLI level, determining optimal growing periods, and selecting the best location for their crops [17]. DLI has also proven to be a very useful and reliable tool for greenhouse cultivation, allowing growers to assess their light requirements and determine the need for supplemental lighting or shading to reach a certain DLI threshold [16]. In addition, several studies have shown the influence of DLI on plants. An experiment conducted on cucumber showed that a DLI of $30 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ reduced the growth period compared to $10 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ and $5.5 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ [19]. Gavhane *et al.* have also demonstrated, in iceberg lettuce culture, that DLI affects physiological (photosynthesis rate, transpiration rate, stomatal conductance), morphological (leaf width, root size of the plant) and nutritional (antioxidant, total phenol, vitamin C) parameters [20]. In addition to this, research on tomato has shown that DLI influences fresh mass; there is an increase in fresh mass when going from a DLI of $10.4 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ to a DLI of $18.4 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ [21]. Experi-

ments carried out on leafy vegetables such as lettuce, chicory, basil and arugula confirm the influence of DLI on fresh biomass [22]. Visual appearance is also influenced by DLI; It was found in a study conducted on lettuce that an increase in DLI deteriorates the visual appearance of lettuce and reduces the photosynthetic quantum yield of PSII as well as the light use efficiency [23]. Thus, global radiation, although proportionally linked to DLI, has a high proportion not used by plants; it therefore reflects less of the production activity of plants compared to DLI which turns out to be a more effective performance indicator for plants. DLI should be monitored, regularly evaluated, and integrated into agricultural management systems as an essential decision-making tool. In this context, our objective is to propose a mapping of DLI in the main regions of Côte d'Ivoire with the aim of making it a decision-making tool in the management of agricultural production; this tool, once integrated, could enable farmers to optimize their production.

2. Material and Method

2.1. Site Presentation

Côte d'Ivoire is a country in West Africa bordered to the north by Mali and Burkina Faso, to the west by Liberia and Guinea, to the east by Ghana and to the south by the Gulf of Guinea. It has an area of 322,462 km² and is located in the intertropical zone between longitudes -2° and -9° and latitudes 4° and 11° . With an economy mainly based on agriculture, Côte d'Ivoire experiences different growing seasons varying from the south to the north of the country; note that the definition of these seasons is essentially based on rainfall data widely used by scientists to determine the beginning and end of growing seasons [7]. Thus, the north of the country has a single growing season that begins in the months of April to May and ends in the months of October to November with a season duration varying from 80 to 120 days maximum. On the other hand, the south of the country benefits from two growing seasons: the first season begins in the months of March to May and ends in the month of July with an average duration of 80 to 120 days (with a variation that can go from 60 to 240 days); the second season starts from the month of August and ends in the months of November to December with a duration of 60 to 140 days, shorter than the first growing season. Furthermore, the locality of Tabou is an exception with a growing season that begins in April and ends beyond the month of December [7].

2.2. Data Collection

Data from the World Meteorological Organization's Global Agrometeorological Information Service country database were collected. These data contain global radiation information for 14 regions of Côte d'Ivoire from 2004 to 2020 regularly collected and reported on a ten-day basis (every 10 days) by the national meteorological agency as an agro-meteorological information bulletin.

2.3. DLI Calculation

The global radiation data initially in $\text{cal}\cdot\text{cm}^{-2}\cdot\text{day}^{-1}$ were converted into quantum units. Radiometric units such as the calorie and the joule evaluate the amount of energy contained in the radiation and are therefore useful for assessing the impact of solar radiation in applications such as heating and cooling greenhouses, irrigation, evapotranspiration; however, these units are not suitable for assessing biological processes related to plant growth. Indeed, most of the photoreceptors located inside the leaves, such as chlorophyll, are active elements that are responsible for capturing photons and converting their energy into chemical energy. This is what happens during the process of photosynthesis where the rate of photosynthesis has a strong correlation with the amount of photons per unit area per second on a leaf. Therefore, the amounts of light in the PAR are expressed in quantum units by the number of moles or micromoles of photons with 1 mole corresponding to Avogadro's number which is 6.023×10^{23} [15]. Therefore, the recommended and commonly used unit of measurement to evaluate the DLI is $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ [13] [15] [17]. The conversion of the data from $\text{cal}/\text{cm}^2/\text{day}$ to $\text{mole}/\text{m}^2/\text{day}$ was done in two steps: the first step consisted of converting calories to moles of photons using 4.1868 joules/calories and 4.57 $\mu\text{mol}/\text{joules}$ [24]; The second step consisted in determining the ratio $\alpha = \text{PAR}/G$ which is the share of photosynthetic active radiation in global solar radiation. For the Ivory Coast, we have $\alpha = 1.04 \cdot \text{PAR}_0/G_0$ where PAR_0/G_0 is the ratio of PAR to global radiation at the top of the atmosphere [25]. We obtain $\alpha = 0.52$ by assuming $\text{PAR}_0/G_0 = 0.5$ [26]-[30]. Finally, the DLI was calculated from the radiometric data by estimating 9.94951152 $\mu\text{mol}/\text{cal}$. Besides, some studies have been conducted to determine PAR/G ratio in some regions: 0.47 ± 0.03 is recommended in Akure, Nigeria [31]; 0.51 ± 0.01 under clear skies in Dar es Salaam, Tanzania and 0.63 ± 0.02 under cloudy skies [32].

2.4. Data Analysis

Microsoft Excel software was used to perform data processing and analysis. All DLI averages presented were calculated over 17 years, from 2004 to 2024. For the calculated averages, the standard error is specified. For each region, the DLI averages per month were presented in the form of a histogram to illustrate the difference between the different months, the maxima and the minima; to analyze the evolution of the DLI throughout the months, a polynomial trend curve of degree 6 was used due to the fluctuation of the data and the R^2 coefficient specified for each trend curve allows to evaluate the adjustment of the trend curve to the data.

3. Results

Results obtained, as illustrated in **Table 1** and **Table 2**, give DLIs that vary between 28.73 ± 0.62 to $52.47 \pm 0.53 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ across the country depending on the region and the time of year. The lowest DLIs are recorded around the month of August and the peaks are observed during the months of March-April. The north

of the country, precisely the regions of Korhogo and Odienné give the highest DLI values and the regions of Adiaké and Tabou in the south give the lowest values. In terms of spatio-temporal variation, the highest DLIs are observed in the north of the country in the regions of Korhogo and Odienné in the month of March (respectively 52.47 ± 0.53 and 50.18 ± 0.83 mol·m⁻²·d⁻¹); and the lowest DLIs appear in the southern regions of Tabou and Adiaké in August (respectively 28.92 ± 0.57 and 28.73 ± 0.62 mol·m⁻²·d⁻¹).

Table 1. Mean \pm SE of DLI in mol·m⁻²·d⁻¹ per month per region over the period 2004-2020.

	Korhogo	Odienne	Bondoukou	Bouake	Daloa	Man	Dimbokro	Yamous-soukro	Gagnoa	Adiaké	Abidjan	Sassandra	San-pedro	Tabou
January	49.45 \pm 0.56	45.43 \pm 1.39	46.13 \pm 0.54	44.38 \pm 1.53	40.87 \pm 0.91	44.71 \pm 0.86	43.16 \pm 0.65	43.85 \pm 0.57	40.18 \pm 0.54	38.79 \pm 0.89	40.34 \pm 0.95	41.66 \pm 0.56	41.22 \pm 0.69	39.45 \pm 0.8
February	48.48 \pm 1.08	45.21 \pm 1.13	45.62 \pm 0.6	46.92 \pm 1	41.4 \pm 0.48	43.32 \pm 1.25	43.54 \pm 0.47	43.99 \pm 0.67	39.74 \pm 0.42	39.63 \pm 0.58	41.44 \pm 0.57	41.09 \pm 0.47	39.83 \pm 0.62	40.29 \pm 0.53
March	52.47 \pm 0.53	50.18 \pm 0.83	47.31 \pm 0.41	46.72 \pm 1.51	43.69 \pm 0.44	46.11 \pm 1.16	46.61 \pm 0.53	45.8 \pm 0.78	42.47 \pm 0.63	43.56 \pm 0.5	44.14 \pm 0.74	43.77 \pm 0.58	43.53 \pm 0.72	42.48 \pm 0.55
April	51.47 \pm 0.76	47.38 \pm 1.01	46.62 \pm 0.41	48.04 \pm 0.96	44.25 \pm 0.41	43.08 \pm 0.87	47.77 \pm 0.43	47.25 \pm 0.55	42.97 \pm 0.46	43.73 \pm 0.44	45.1 \pm 0.58	44.42 \pm 0.61	43.82 \pm 0.64	41.26 \pm 0.51
May	50.25 \pm 0.67	47.83 \pm 0.73	46.16 \pm 0.45	44.22 \pm 0.95	42.18 \pm 0.41	41.17 \pm 0.75	46.14 \pm 0.33	45.79 \pm 0.45	39.78 \pm 0.46	39.43 \pm 0.54	40.2 \pm 0.52	39.71 \pm 0.52	38.81 \pm 0.58	36.23 \pm 0.58
June	44.42 \pm 1.51	44.62 \pm 0.89	40.22 \pm 0.47	37.14 \pm 1.16	35.66 \pm 0.44	34.14 \pm 1.22	40.1 \pm 0.52	39.6 \pm 0.71	33.5 \pm 0.5	31.36 \pm 0.53	33.35 \pm 0.61	32.71 \pm 0.61	32.21 \pm 0.61	29.78 \pm 0.6
July	41.92 \pm 0.81	41.34 \pm 0.83	36.18 \pm 0.44	34.32 \pm 0.53	32.71 \pm 0.39	31.88 \pm 0.93	36.03 \pm 0.36	36.32 \pm 0.47	31.93 \pm 0.46	31.06 \pm 0.47	34.82 \pm 0.62	34.52 \pm 0.65	34.08 \pm 0.82	30.72 \pm 0.69
August	41.13 \pm 0.95	40.68 \pm 0.79	35.09 \pm 0.47	34.12 \pm 0.81	30.71 \pm 0.43	31.17 \pm 0.6	34.16 \pm 0.43	34.29 \pm 0.5	30.29 \pm 0.49	28.73 \pm 0.62	32.56 \pm 0.75	33.03 \pm 0.71	31.82 \pm 0.71	28.92 \pm 0.57
September	41.43 \pm 1.42	42.97 \pm 1.08	37.43 \pm 0.39	32.56 \pm 1.17	34.73 \pm 0.37	34.4 \pm 0.93	37.47 \pm 0.28	37.61 \pm 0.33	33.91 \pm 0.4	30.8 \pm 0.51	35.14 \pm 0.54	36.21 \pm 0.52	35.24 \pm 0.6	30.39 \pm 0.59
October	48.28 \pm 1.09	46.31 \pm 0.75	42.49 \pm 0.59	40.14 \pm 1.11	38.72 \pm 0.46	37.29 \pm 0.69	43.43 \pm 0.57	42.27 \pm 0.51	39.59 \pm 0.47	38.5 \pm 0.8	39.63 \pm 0.9	41.25 \pm 0.49	40.54 \pm 0.58	38.66 \pm 0.72
November	46.92 \pm 0.87	45.16 \pm 0.58	44.1 \pm 0.31	43.22 \pm 0.86	39.15 \pm 0.39	40.41 \pm 0.41	44.78 \pm 0.37	42.89 \pm 0.51	38.95 \pm 0.37	42.81 \pm 0.48	43.82 \pm 0.44	42.23 \pm 0.4	41.19 \pm 0.45	41.06 \pm 0.45
December	47.75 \pm 1.02	45.1 \pm 0.9	43.41 \pm 0.56	42.31 \pm 2.52	38.17 \pm 0.56	42.1 \pm 1.19	40.93 \pm 0.41	41.23 \pm 0.36	37.94 \pm 0.41	40.05 \pm 0.53	40.8 \pm 0.7	40.75 \pm 0.55	39.11 \pm 0.69	39.24 \pm 0.47

Table 2. DLI averages (in mol·m⁻²·d⁻¹) by region over the period 2004 to 2020.

	Korhogo	Odienne	Bondoukou	Bouake	Daloa	Man	Dimbokro	Yamous-soukro	Gagnoa	Adiaké	Abidjan	Sassandra	San-pedro	Tabou
Mean DLI \pm SE	46.85 \pm 0.43 (n = 137)	45.1 \pm 0.34 (n = 138)	42.46 \pm 0.23 (n = 489)	40.85 \pm 0.56 (n = 138)	38.46 \pm 0.24 (n = 488)	38.83 \pm 0.5 (n = 138)	41.96 \pm 0.23 (n = 488)	41.69 \pm 0.26 (n = 382)	37.53 \pm 0.23 (n = 488)	37.22 \pm 0.29 (n = 489)	39.13 \pm 0.27 (n = 483)	39.16 \pm 0.24 (n = 489)	38.34 \pm 0.26 (n = 488)	36.4 \pm 0.28 (n = 483)

3.1. Evaluation of Monthly Variations in DLI

In almost all regions, the same trend of DLI evolution is observed over the months

of the year. The evolution curve throughout the months, as presented in **Figure 2**, shows an increase in DLI at the beginning of the year to reach a peak in the months of March and April, then a decrease in DLI after April to reach its lowest level around August. From September, we have seen a new increase in DLI, which reached its second peak around November. The DLI is at its highest level (peaks) in the months of March and April.

3.2. Assessment of Regional Variations in DLI

The mapping in **Figure 1** gives us higher DLIs in the northern part of the country compared to the southern regions. The highest DLI values are reached in Korhogo region with an average of $46.85 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ with a maximum of 55.02; while the lowest values appear in Tabou region with a DLI of $36.40 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ and a minimum of 18.55. Furthermore, the central regions such as Yamoussoukro and Dimbokro give a DLI of 41.69 and $41.96 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ respectively, which is approximately the average between the DLI of Korhogo and that of Tabou. The DLI, therefore, evolves gradually from SOUTH to NORTH.

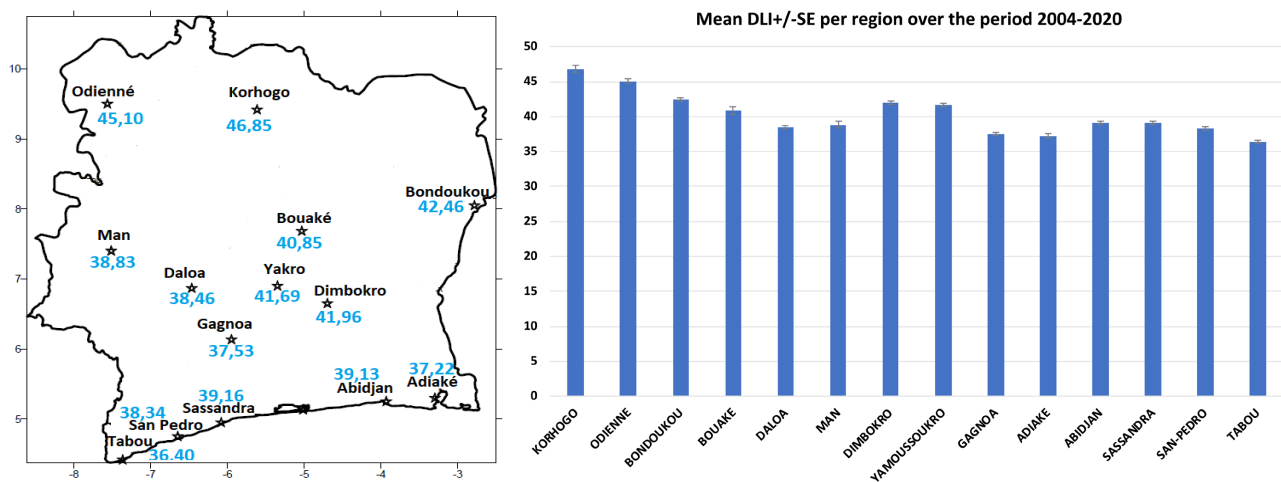


Figure 1. Average DLI in $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ per region obtained over the period 2004-2020. The bars indicate the standard error.

3.3. Evaluation of Seasonal Variations in DLI

In the north of the country, which has a single growing season, the season begins in April-May, when the DLI begins to decline from its March peak but is still at its highest level ($47 - 52 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), and ends in October-November, when the DLI increases to its second peak ($45 - 49 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$). For the example of the Odienné and Korhogo regions located in the far north, the average DLI does not fall below $40 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ throughout the growing season.

In the south, the first growing season begins in March-May, when the DLI at its highest level begins to decline; this season ends in July when the DLI reaches its lowest levels. The second period of growth begins in August, the month when the DLI level is lowest, and ends in November-December, the period when the second peak of the DLI appears. These trends are illustrated in **Figure 2**.

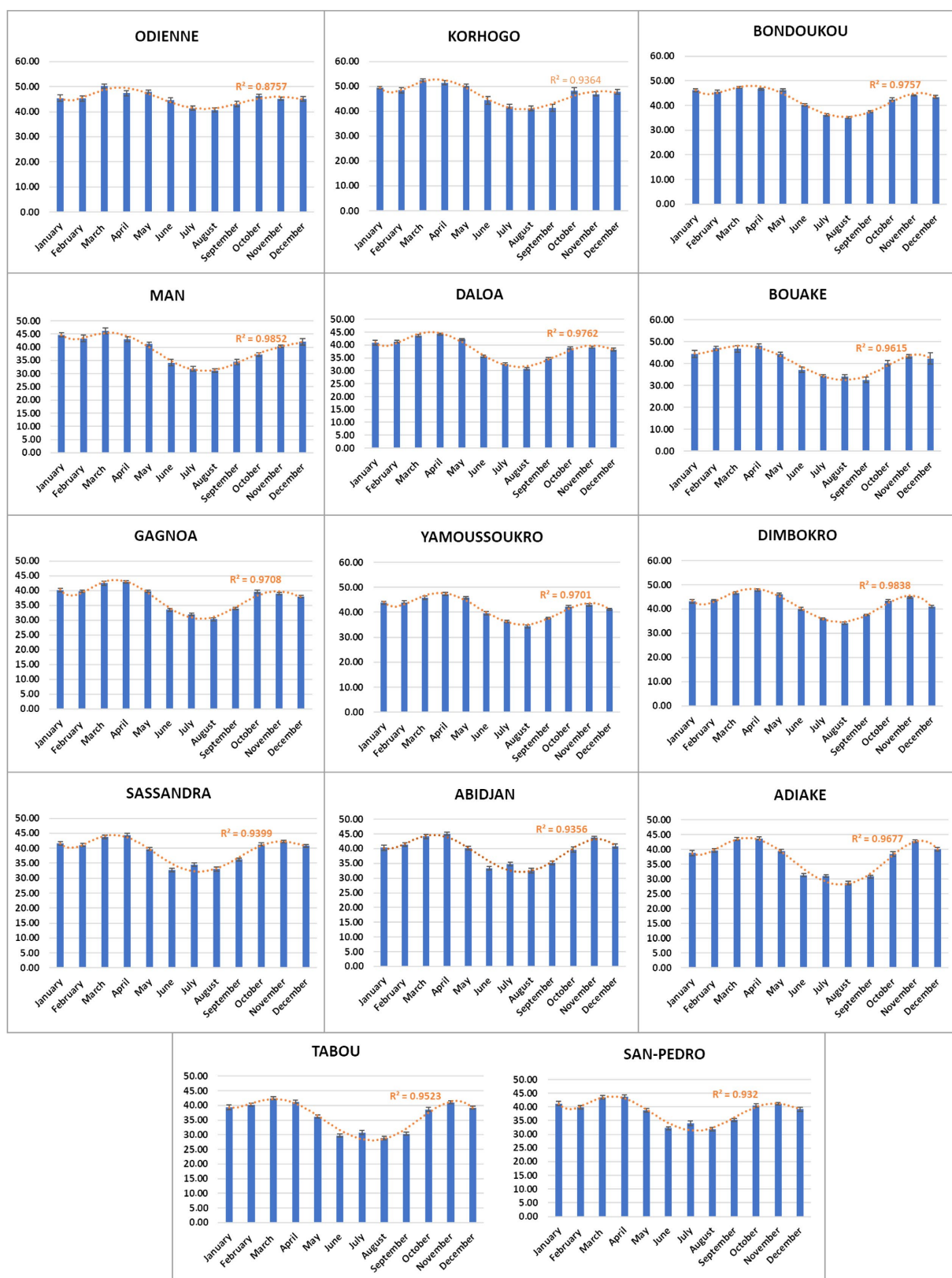


Figure 2. Annual average DLI (in $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) evolution per region obtained over the period 2004-2020. The bars indicate the standard error. A polynomial trend curve of degree 6 was used due to the fluctuation of the data and the R^2 coefficient specified for each trend curve allows to evaluate the adjustment of the trend curve to the data.

4. Discussion

In the United States of America, DLI ranges from 5 - 10 mol·m⁻²·d⁻¹ in the north of the country in December to 55 - 60 mol·m⁻²·d⁻¹ in the southwest of the country in May-July [15]; this map has been updated with a new peak of 60 - 65 mol·m⁻²·d⁻¹ appearing in the southwestern United States only in June, and a minimum of 0 - 5 mol·m⁻²·d⁻¹ in the north of the country due to the inclusion of Alaska on the map [13]. In Hungary, in Central Europe, DLI ranges from 4-5 mol·m⁻²·d⁻¹ in winter to 46 - 47 mol·m⁻²·d⁻¹ in summer [17]. The DLI in Spain, a southwestern European country, ranges from 5 mol·m⁻²·d⁻¹ in winter to 55 mol·m⁻²·d⁻¹ in summer [18]. The DLI results obtained for Côte d'Ivoire, ranging from 28.73 ± 0.62 to 52.47 ± 0.53 mol·m⁻²·d⁻¹, show a much smaller variation gap and, therefore, a certain relative stability compared to the regions mentioned above.

Furthermore, several studies have shown that DLI has effects on plant growth, and recommendations have been made on appropriate DLI values for the cultivation of certain species (as shown in **Table 3**). For greenhouse cultivation of lettuce, tomato, sweet pepper, and cucumber, the minimum required DLIs are 12, 12 - 14, 20 - 30, and 30 mol·m⁻²·d⁻¹, respectively [19] [33]-[35]. An experiment conducted on cucumber seedlings showed that an increase in DLI by 1% using supplemental artificial lighting resulted in an increase in cucumber shoot dry mass by 1.2% - 1.8%; the growth and morphology of these cucumber plants were significantly improved under a solar DLI of 16.2 ± 5.3 mol·m⁻²·d⁻¹ compared to a DLI of 5.2 ± 1.2 mol·m⁻²·d⁻¹ [36]. Similarly, according to Dorais, one way to estimate the effects of light on production is to use the 1% rule, which states that a 1% reduction in light will also result in a 1% reduction in production [19]. For hydroponic spinach cultivation, a DLI of 17.3 mol·m⁻²·d⁻¹ is recommended, which yields the highest net photosynthesis rates [37]. For vertical farming of leafy vegetables such as lettuce, basil, chicory, and arugula, a DLI of 14.4 mol·m⁻²·d⁻¹ is recommended [22].

Clearly, the preceding paragraphs demonstrate the importance of DLI in plant growth and development. The DLI trends obtained across the country could also explain the definitions of growing seasons in the north and south of the country. Indeed, in the north of the country, during the entire growing season which begins in April-May and ends in October-November, the DLI is maintained at a relatively high level which does not fall below 40 mol·m⁻²·d⁻¹; and therefore, one could assume that the cultivated plants do not experience a DLI deficit during this period. While in the south of the country, there are two growing seasons separated by a period where the DLI has its lowest level, that is to say during the months of July-August with a DLI which falls below 30 mol·m⁻²·d⁻¹ in some regions of the south; in order to avoid a DLI deficit in crops, the interruption of growth at this time could prove necessary for a recovery at a time when the DLI rises to higher values, acceptable for the plants; Hence the definition of these two growth periods in the south, which takes on its full meaning with a justification by the DLI.

It should also be noted the increasing use of agricultural greenhouses in Africa. De Bon *et al.*, in their expert report on market gardening in Côte d'Ivoire, recom-

mends the use of greenhouse shelters to achieve better yields and obtain quality products available year-round [38]. Indeed, in greenhouses, the light transmission rate inside varies from 35% to 70% [13]; and this reduction is due to the greenhouse infrastructure, the glazing materials, or the quality of the polyethylene covers used and the shade curtains. This significantly reduces the DLI for crop growth: for example, for the Adiaké region which has an average DLI of $30.8 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in the month of September, greenhouse cultivation could lower this DLI to between 10.78 and $21.56 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$; in this case, DLI mapping could be used to assess the missing DLI gap to reach the minimum DLI required by the plant to grow optimally and artificial lighting can be used as a supplement to fill this gap. In this sense, one could rely on various studies that evaluate the impact of artificial lighting on food crops such as okra [39]-[41]. In addition, it is noted that some regions of the country could face certain challenges related to excess light that could be managed by advanced techniques for reducing environmental lighting of the plant such as shading. This is the case of the northern regions of Ivory Coast, such as the Korhogo region whose average DLI reaches $52.47 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in the month of March at the beginning of the growing season; this DLI could be saturated and inappropriate for the optimal growth of certain crops. The use of a greenhouse shelter with a transmission rate of 70% could reduce this DLI to $36.73 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. The shading technique is quite complex because, using a spectral filter, it modifies both the quantity of light but also its spectral quality; which has an impact on different microclimatic factors such as humidity, photosynthetic activity, production of secondary metabolites, enzymatic process and in the end, affect plant production [18].

Table 3. Recommended DLI in $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$.

Type of vegetable	Growing condition	Optimal DLI	Reference
Iceberg lettuce	Indoor vertical hydroponic system	11.5	[20]
Lettuce	Greenhouse production	Minimum 12 - 14	[33]
Cucumber plug seedlings		6.35	[42]
Red_leaf lettuce	Indoor cultivation	6.5 to 9.5	[43]
Tomato	Greenhouse production	Minimum 30	[19] [34]
Sweet pepper	Greenhouse production	Minimum 12, 20 - 30	[19] [35]
Cucumber	Greenhouse production	Minimum 30	[19]
Tomato seedlings	Greenhouse production	4.8 to 6	[19]
Lettuce, Chicory, Basil, Rocket	Vertical farming	14.4	[22]

5. Conclusions

This study presented the average DLI values in the main regions of Côte d'Ivoire over a 17-year period. Monthly averages for different regions were also determined, as well as their variations throughout the year. In addition, an analysis of DLI levels during different growing seasons was performed. This analysis provides farmers with an idea of the light environment in these regions to facilitate decision-making in their agricultural management processes.

Furthermore, this study highlights several possibilities for using DLI mapping in Côte d'Ivoire: 1) as an agricultural management tool to decide on the location and appropriate time to start growing a specific crop. 2) During certain periods in locations where the DLI is high enough for cultivation, provide shading systems or agricultural greenhouses with a low transmission rate to control the DLI and reduce it to a lower level acceptable for crops. 3) For periods and regions where the DLI is low for the crops under consideration, greenhouse cultivation methods should be considered, incorporating artificial lighting in addition to natural light to increase the DLI. 4) This could be a tool in investigating the causes of low or high production during certain periods of the year or in certain regions; a link should then be made between the plant's exposure to a certain DLI (optimal or not) and the quantity and quality of the resulting production.

Integrating DLI as an agricultural management tool requires various measures that should be included in our transformation process towards sustainable agriculture resilient to climate change, namely: 1) continuous assessment of DLIs in agricultural premises using measuring instruments. 2) Promoting scientific research to determine optimal DLIs for strategic crops for local consumption or export. 3) Awareness of the integration of the lack of control of DLI as one of the potential causes of the advent of a certain quality and quantity of production of our crops, alongside other parameters such as rainfall, soil quality.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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