**Appendix C**

This Appendix describes the application of SIMPLE crop model Zhao et al. (2019) and Steduto et al. (2012) formula to analyze the water stress impact on cocoa yield while defining the required amount of water to support the productivity. Then, while the SIMPLE supports crop yield estimation under different conditions, the Steduto formula allows determining the yield reduction regarding the water stress in the plantation to support the estimation of the factor. This study comprise the following steps based on the 2020 climatic behavior to determine the factor:

* Determine the cocoa crop yield under proper water conditions.
* Determine the cocoa crop yield under water stress conditions.
* Determine crop evapotranspiration under ideal water conditions.
* Determine crop evapotranspiration under water stress conditions.
* Estimate the factor based on yield loss ratio regarding water scarcity (evapotranspiration loss ratio).

In this sense, using such strategies, this study provides suitable water allocation and irrigation schemes, using the water resource properly to generate the irrigation before the cocoa crop reaches a yield detriment point. Appendix D details an Excel document whit all the calculations for estimating the factor.

1. **Cocoa crop yield estimation**

The SIMPLE model consists in three linked equations that determines the crop yield using the cumulative crop biomass:

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where is the daily biomass increment, is the cumulative biomass in the day, the cocoa crop yield when it reaches the maturity point, and is the potential harvest index (i.e., the relation between grain weight and total biomass weight). The model calculates as follows:

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where relates the daily solar radiation , is the solar radiation fraction intercepted by the cocoa crop canopy, is the radiation use efficiency . represents the impact of , temperature, the heat stress, and drought stress on biomass growth.

* + 1. **Radiation.** It relates the daily solar radiation .
    2. Represents the solar radiation fraction intercepted by the cocoa crop canopy.

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where represents the maximum fraction of solar radiation interception a crop canopy can reach. is “the cumulative temperature required for leaf area development to intercept 50% of solar radiation during canopy closure” and “the cumulative temperature required from maturity to 50% of radiation interception during canopy senescence” (Zhao et al., 2019). represents the optimal quantity of cumulative temperature required to harvest . The following expression allows to calculate that is the cumulative temperature in the day, and the temperature every next day :

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where is the temperature added every day .

* + 1. **Radiation Use Efficiency (RUE).** It represents a conversion measure of intercepted radiation to crop biomass (Lake et al., 2021) . RUE is a critical factor that quantifies the conversion efficiency of absorbed radiation into biomass for a given crop (Lake et al., 2021). It comprises the crop's ability to use solar energy for growth, thus representing an essential component in determining crop productivity. This study established a constant RUE value according to the process reported by Cock & Connor (2021), defined as follows:

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Where the Biomass Dry is the weight or mass of organic matter , and Intercepted Photosynthetically Active Radiation (IPAR) is the real proportion used by the crop in biomass generation ; according to López-López et al. (2016) IPAR represents a proportion of about 38% of PAR in cocoa crops.

* + 1. It is the impact of the carbon-dioxide in biomass growth. The following expression allows to determine the – RUE relationship:

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where “represents the crop-specific sensitivity of to elevated ” (Zhao et al., 2019) and is the atmospheric concentration .

* + 1. . It represents the impact of temperature on cocoa crop biomass growth. The following equation allows obtaining the temperature impact:

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where is the daily temperature , is the required temperature for crop growth and phenology development and is the optimal temperature for crop growth .

* + 1. . It is the impact of heat stress in crop growth. It is obtained through the following expression:

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where, is the daily maximum temperature , represents the threshold related to the start of the biomass reduction due to heat stress , and is the temperature when there is no crop biomass growth .

* + 1. . It represents the biomass sensitivity to drought stress through the following expression:

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where represents the sensitivity of RUE to drought stress (ARID index), and the ARID index can be obtained through the following equation:

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where the index changes regarding the minimum value between the evapotranspiration ( - ) and the Plant Available Water . But is a conditional parameter that relies on environmental conditions and soil properties. is mainly conditioned by the water depletion and the Total Available Water . represents the amount of water that the cocoa crop can extract from the root zone calculated through the following equation:

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where, is the water content at field capacity , the water content at wilting point , and the rooting depth . Regarding , is calculated through:

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where, represents the water depleted in the root zone during the day in .

1. **Cocoa crop yield response factor**

Once calculated the cocoa yield under normal and water stress conditions using the SIMPLE crop model, the Steduto et al. (2012) formula allows obtaining the yield reduction regarding the effect of crop evapotranspiration reduction in stress conditions using the Penman-Monteith (Allen et al., 2006) procedure. The Steduto formula relates:

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where is the actual crop yield or crop yield under water stress conditions , is the maximum crop yield , represents the actual evapotranspiration [], the total maximum crop evapotranspiration [], and is a dimensionless parameter that represents the crop yield response factor and relates the amount of yield reduction regarding the evapotranspiration reduction in water stress conditions. Since yield and evapotranspiration parameters relies on daily calculations the yield response factor follows the same behavior. Nevertheless, this study determines the factor according to only crop production stages (i.e., every days approximately).

1. **Harvest Index**

It represents the crop harvested portion by the total crop production biomass. The following formula allows determining the crop harvest index:

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**Yield estimation parameters**

Table C1: Yield parameters summary

Yield parameters summary

| Component | Input Parameters | Unit | Independent Parameter | Source |
| --- | --- | --- | --- | --- |
| Harvest index | Average pod weight |  |  | Estimated based on (Cerón Salazar et al., 2020) |
| Number of pods per plant |  |  | (Cerón Salazar et al., 2020) |
| Cocoa beans weight per plant |  |  | (Cerón Salazar et al., 2020) |
| Radiation | - |  | - | (NASA, 2021) |
| Function Solar | Maximum solar radiation interception - | - | - | (Romero Vergel et al., 2022) |
| Cumulative temperature - |  | - | (Romero Vergel et al., 2022) |
| Harvest temperature - |  | - | (Romero Vergel et al., 2022) |
| Cumulative temperature - |  | - | (Romero Vergel et al., 2022) |
| Radiation Use Efficiency (RUE) | Biomass dry |  | - | Estimated based on (Cerón Salazar et al., 2020) |
| Photosynthetically Active Radiation (PAR) |  | - | (NASA, 2021) |
| Intercepted Photosynthetically Active Radiation (IPAR) |  | - | López-López et al. (2016) |
| Function | Carbon-dioxide - |  | - | (Dlugokencky et al., n.d.) |
| RUE sensitivity index to - | - | - | (Romero Vergel et al., 2022) |
| Function Temperature | Daily temperature - |  | - | (NASA, 2021) |
| Required temperature for growth - |  | - | (Romero Vergel et al., 2022) |
| Optimal temperature for growth - |  | - | (Romero Vergel et al., 2022) |
| Function Heat | Daily maximum temperature - |  | - | (NASA, 2021) |
| Heat stress threshold - |  | - | (Romero Vergel et al., 2022) |
| No growth temperature threshold - |  | - | (Romero Vergel et al., 2022) |
| Function Water | sensitivity to drought stress - | - | - | Estimated (seek objective) |
| Water stress index - | - | Evapotranspiration - () | Estimated |
| Plant Available Water – PAW (mm) | Estimated |
| Soil type | (León-Moreno et al., 2019) and (Soil Science Division Staff, 2017) |
| The water content at field capacity - () | (Saxton & Rawls, 2006) |
| The water content at wilting point - () | (Saxton & Rawls, 2006) |
| Maximum rooting depth () | (Allen et al., 2006) |