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Modeling the influence of extreme climate variability on sugarcane yield gap in Reunion Island

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Abstract:

Among other challenges, the already increasing incidence and intensity of extreme climate events are a major threat to global crop production. Sugarcane represents the main source of sugar and important part of ethanol and material for electric energy productions in tropics and sub-tropics and grown in climatic areas subjected to extreme events.

Reunion Island presented extremely contrasting climates and is regularly subjected to tropical cyclones. In this study, we used the crop model MOSICAS, combined with spatial databases (sugarcane field boundaries, soil type, meteorological data and irrigation management practices) to predict the potential and water-limited cane yield over the entire island from 1998 to 2018. Therefore, we compared them to actual cane yield from sugar producers in five agro-climatic zones. The average total yield gap (YG_T , i.e. difference between potential cane yield and actual yield) over Reunion Island was 96 t ha^{-1} , of which 66% was due to water deficit. YG_T increased to 120 t ha^{-1} with increasing temperature, radiations and precipitations, highlighting the influence of others biotic and abiotic limiting factors.

Extreme climate indices were calculated for heavy rain, extreme winds, high temperature and drought at the agro-climatic zone scale and their influence on yield gap was assessed using a Principal Component Analysis (PCA). Yield gap was strongly correlated with the first axis of this PCA ($\rho=0.56$), highlighting how extreme precipitation induced increase in YG_T . Based on a clustering analysis on extreme precipitation and wind, 4 agro-climatic clusters were defined. Actual yield loss (difference between yield and the yield of the best year in the same zone) was in average 10 t ha^{-1} higher in the cluster with the highest precipitation and wind than the cluster with low extreme events, and sugarcane losses could reach 28 t ha^{-1} .

The objective of this study was to assess the impact of extreme climate variability on cane yield gap in Reunion Island. It highlights how sugarcane yield is constrained by both abiotic factors and extreme events occurrence in Reunion Island. The implication for sugarcane management under extreme events is discussed.

Keywords: extreme climate; Sugarcane; Yield gap; Crop model; Reunion

1. Introduction

The key role of crop models is to help understand and predict the effects and interactions between climate, soil and management on crop development and yield. Crop models can provide insights into the main emerging agricultural challenges such as food security, sustainability and how to cope with the possible negative effects of climate change (Spiertz, 2012). Among these challenge, extreme weather events are expected to increase worldwide and are expected to reduce crop production (Field et al., 2012; Porter et al., 2014). The already increasing incidence and intensity of extreme climate events are seen as the principle immediate threat to global crop production (Meehl et al., 2000; Rosenzweig et al., 2001; Olesen et al., 2007; Urban et al., 2012; Min et al., 2011; Lobell et al., 2008, 2013). Therefore, anticipating and calculating their effect on crop yields is important for topics ranging from food security to the economic viability of biomass products.

Among other crops, sugarcane represents a major source of sugar, ethanol and material for electric energy productions in tropics and sub-tropics. In the energy sector, the demand for ethanol and electricity is likely to increase, as it could replace fossil fuels and reduce greenhouse gas emissions (Goldemberg et al., 2014; Leal et al., 2013). Due to their agroclimatic zones, sugarcane plantations faced various extreme events such as extreme temperature (e.g. India, Mall et al., 2016), drought (e.g. Australie, Inman-Bamber et al., 2005), flood (e.g. Florida, Gilbert 2008) or storm (e.g. Beuzelin et al., 2009), which could be responsible for strong yield loss (e.g. 54-64% under 3-month flood, Gilbert et al., 2008) up to cane failure (e.g. under drought, Inman-Bamber et al, 2005).

Yield Gap (YG) analysis, based on the differences between different crop yield types, provides a basis for identifying the main factors affecting crop yield and providing valuable information to guide the interventions of growers, researchers, public agencies and stakeholders (van Ittersum et al., 2013). The following types of crop yields can be considered: the potential yield (Y_P), which is the yield of a given cultivar only determined by solar radiation, air temperature, photoperiod, CO_2 concentration, genotype and plant populations ; the water-limited yield (Y_W) which is the same than Y_P , but additionally influenced by water deficit resulting from the rainfall amount and distribution along the crop cycle, as well as soil water holding capacity and evapotranspiration; and finally the actual or average yield (Y_A) which is defined as the yield actually obtained by farmers, considering fertilizer limitations as well as soil fertility, pests and diseases damages. According to Dias and Senthelas (2018), the difference between Y_P and Y_W results in the YG caused by water deficit (YG_W), whereas the difference between Y_W and Y_A gives the YG caused by crop management and hazards (YG_M).

While the use of crop models as a tool to analyze temporal and spatial variation of yield gaps appears to be straightforward, relatively few examples of this type of application can be found in literature for sugarcane. Most of these studies aimed to better separate the effect of climate and management on sugarcane yield (Garside et al., 1997 ; Jones et al., 2015 ; Cheeroo-Nayamuth et al., 2011; Van den Berg and Singels, 2013) but, to our knowledge, none of them have tried to link extreme events and yield gap.

Reunion island is a particularly adapted agro-climatic zone to assess the impact of extreme weather events variability on sugarcane yield gap. Around 23 thousand ha are cultivated with sugarcane in Reunion Island, representing about 58% of total agricultural areas (DAAF, 2015). Planted area with sugarcane ranged from sea level m to >1000 m above sea level resulting in large differences in temperature, radiation or wind conditions. The Reunion Island also presents a very strong precipitation variability over the island, with very low (<30 mm y^{-1}) or high precipitation (>5000 mm y^{-1}) depending on location. Moreover, growers face cyclones regularly, as well as fluctuating dry periods during winter.

Considering that yield gap studies are of high importance for guiding strategic actions to improve crop yields, in particular for tropical islands with such diverse environmental conditions and extreme events, the objectives of this study were i) to assess the magnitude of sugarcane yield gaps due to water deficit and crop management in Reunion Island over the last 20 years and, ii) to assess the impact of climate variability and extreme events intensity on sugarcane yield gap.

2. Material & Method

2.1. Cane management data over Reunion Island

Reunion Island is commonly divided into 5 agro-climatic zones (Fig. 1). As presented in Fig. 1 and Fig. S1, two of them are rainfed in majority: Beaufonds (East part of the island) and Bois Rouge (North East) while the others are irrigated for around 50% of the area: Savanna (North West) and Le Gol (South West) and one is an intermediary zone with 20% of the area being irrigated: Grand Bois (South).

A detailed identification of 10,403 sugarcane fields was made over Reunion Island (Fig. 1d), which should represent nearly all the actual sugarcane fields in 2017. The identification was performed by combining a remote-sensing approach and the use of databases from several institutes (Centre Technique Interprofessionnel de la Canne et du Sucre, CTICS) or state agency (Direction de l'Alimentation, de l'Agriculture et de la Forêt.). At the end, all cane fields were associated with a planted area (m²), an irrigation management (drip or spray irrigation when irrigated) and planted cane varieties. The irrigation management was obtained from the CTICS database (2008, resumed in Fig S1). When not identified, the irrigation management was assumed to be a spray irrigation in Savanna, Le Gol and Grands Bois, and was assumed not to be irrigated in the east part of the island (Beaufonds and Bois Rouge, personal communication with the CTICS). The sugarcane varieties in each field were obtained from the DAAF database in 2017 (resumed in Fig. S1). Between 20 and 40% of sugarcane fields were not identified with a given variety due to a lack of information. When we did not know the variety, we assumed that the planted variety was the R570 in Savanna, Le Gol and Grand Bois, and the R579 in Beaufonds and Bois Rouge. We choose these two varieties when no data were available because there are the most planted variety in these agro-climatic zones (CTICS, personal communications).

2.1. Climate data

Based on the annual precipitation and altitude range maps (Fig. 1a,b), 33 climatic areas were defined over Reunion Island. These maps were obtained through the AWARE Atlas (<https://smartis.re/p/AWARE>) developed by the CIRAD institute in Reunion Island. In each climatic zone, the centroid was assessed and daily climatic data (precipitation - PPT, global radiation - R_G, potential evapotranspiration - ETP, minimum - T_{MIN} and maximum temperature - T_{MAX}) were obtained using the METEOR software (<https://smartis.re/METEOR>). The software interpolated the daily weather data at requested localization based on a station network from the CIRAD and Météo-France (Fig. S2). Daily weather data in each of the 33 climatic zones were interpolated from 1998 to 2018. Wind speed data used for the storm indice calculation (see section 2.5) were not interpolated but obtained in 5 meteorological stations (one per agro-climatic zone) at similar distance and altitude from the coast (except for the North-West zone where cane are grown in altitude, Fig. S2). A detailed soil water holding capacity map - SWC (Fig. 1c) was also obtained from the AWARE Atlas. Soil water holding capacity over Reunion Island range from 10 to 200 mm in cane areas.

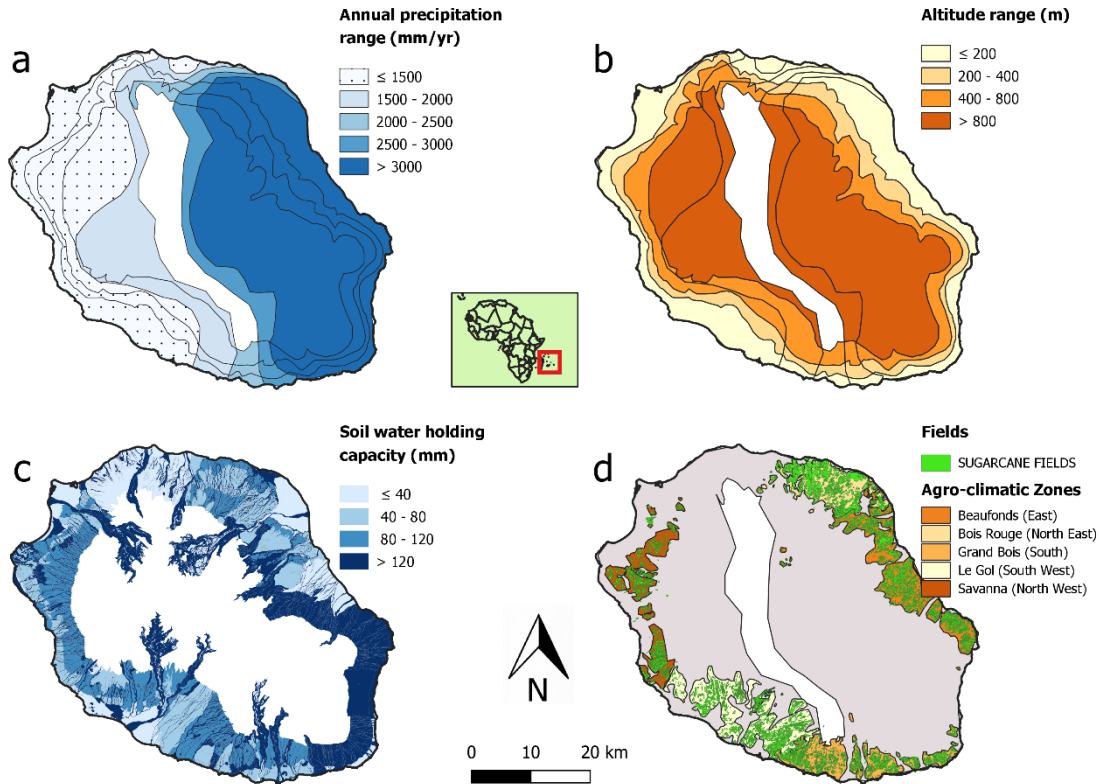


Fig 1. Soil, climate and cane field data over Reunion Island. Annual precipitation (a) and altitude range (b) were used to define climatic areas. Soil water holding capacity over Reunion Island (c) range from 10 to 200 mm in agricultural areas. Each cane fields over the island were identified and associated with an agro-climatic zone (d). Sources: a: Météo-France & Cirad ; b: IGN & SHOM ; c: Raunet 1988 ; d: ASP 2016 from IGN ; production: Cirad AIDA, 2019; EPSG:32740 - WGS84 / UTM 40Sud.

In the current study, PPT, T_{MEAN} (daily average temperature), ETP and R_G were averaged per year in each cane field. Then, the average annual climatic data and SWC in a given agro-climatic zone was calculated as the average field-scale data weighted by the field planted areas. Additionally, a climatic variable integrating the sum of annual precipitation and the quantity of irrigated water was defined (PPT_{IRR}).

2.2. MOSICAS model presentation

The MOSICAS model (Martiné and Todoroff, 2002) simulates the daily sugarcane growth at a field scale for given management scenarios. MOSICAS, a deterministic thermoradiative type model that accounts for water stress, consists of growth and carbon balance modules linked to a water balance module. The modeling of Leaf Area Index (LAI) is a ‘big leaf’ type, and is based on the balance between daily increase (growth) and daily decrease (senescence) in leaf surface area. This balance is mainly driven by temperature and is limited by radiation with respect to leaf mass and water stress. MOSICAS converts the daily intercepted photosynthetically active radiation (PAR) into daily gain in total dry mass. This conversion process is affected by temperature and water stress coefficients, as well as a maintenance respiration coefficient and the variety maximum radiation conversion efficiency. The partitioning of total dry mass gain to root and aboveground dry mass gain is regulated

by dynamic allometric fractions that depend on thermal time. Then, the partitioning of daily increase in aboveground dry mass to daily increase in millable stalk dry mass is regulated by dynamic allometric fractions that depend on the amount of aboveground biomass. The partitioning of daily increase in millable stalk mass to daily increase in structures is regulated by a dynamic allometric fraction that depends on the amount of existing millable stalk mass, temperature and water stress indexes. The remaining biomass not allocated to structures is stored as stalk sucrose. Above-ground and stalk water content is assumed constant (parameter) at the beginning of the growth and decreased with thermal time. The model code, executable and manual are open-source (General Public Licence) and available on Github repositories (<https://github.com/ChristinaMathias/MOSICAS>). The main model equations driving cane growth are described in supplementary information (S3).

2.3. MOSICAS calibration

Cane varieties were calibrated using the ECOFI open database (Christina et al., 2020b). The ECOFI database includes 58 trials in total (60 varieties) carried out by CIRAD and partners from 1988 to the present, in Reunion Island and a few other countries (e.g. Guadeloupe, South Africa). The link between the ECOFI database and the MOSICAS model was performed using R script to create model input (also available in <https://github.com/ChristinaMathias/MOSICAS>). The model was calibrated using various measurements (Fig. S4): LAI, fraction of intercepted radiation (faPAR), aboveground dry and fresh mass, stalk dry and fresh mass, as well as aboveground and stalk water content. Calibration of parameters followed an iterative hierarchical process where priorities of decreasing order were the leaf area dynamics and interception, radiation conversion into biomass, biomass partitioning and sensitivity to water stress (Supplementary Material S3 –Calibration Procedure and Results, Fig. S3). The R570, R579, R585 and R586 cane varieties were calibrated using 20, 3, 9 and 9 ratoon crop cycles, respectively. In total, 21 parameters were calibrated. The LAI base temperature of 3 other varieties (R581, R582 and R583) were obtained from literature as used in the web version of the model (<https://smartis.re/MOSIWEB>). As no experimental data were available to parameterized other planted variety in Reunion Island, we assumed that additional sugarcane varieties were identical to the R570 or R579, as it is historically the most planted varieties in the island. Details on parameter values for the different varieties are given in Table S1.

2.4. Sugarcane yield simulations & observations

Actual fresh sugarcane yield (Y_A) and the average date of half-campaign for cane harvest were obtained from sugarcane industries from 1998 to 2018 in the 5 agro-climatic zones presented previously. To match observations, sugarcane growth was simulated using the MOSICAS model in each field from 1998 to 2018. In each agro-climatic zone, all fields were assumed to have the same harvest date, defined as the date of half-campaign. Considering that the harvest campaign last around 6 months in Reunion Island, we considered that a sugarcane field was harvested at five different dates (half-campaign, ± 1 months and ± 2 months), and the average yield was used. As an approximation, all sugarcane fields over Reunion Island were assumed to be ratoon crop as no information on new planted cane were available on the whole period. When field were irrigated, irrigation management was assumed to be $12,000 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ (fixed dose of 25 mm week^{-1}), which represents common practices in Reunion, with an efficiency of 1 for drop irrigation and 0.9 for spray irrigation (i.e. means that 10% of irrigated water is lost outside the field). Five soil layers were defined in the MOSICAS model. Each layer had identical wilting point, field capacity and saturation, avoiding thus differences in terms of water drainage. To take into account the difference of soil water holding capacity (Fig. 1c), the soil depth was adjusted to match this value.

Two types of simulations were performed at field scale: sugarcane yield at the thermoradiative potential (Y_P , not taking into account water stress) and sugarcane yield taking into account water stress (Y_W). The MOSICAS model does not take into account fertilizer stress or other biotic stresses such as weed pressure. All components of cane growth were simulated but only the fresh stalk yield (equivalent to millable stalk) was used in this study and defined as “cane yield”. The average Y_P and Y_W in a given agro-climatic zone was calculated as the average field-scale Y_P and Y_W weighted by the field planted areas. Total Yield Gap (Y_{GT}) was defined as the difference between Y_P and the actual cane yield (Y_A), averaged at the agro-climatic zone scale. Water-limited yield gap (Y_{GW}) was defined as the difference between Y_P and Y_W . Finally, Y_G caused by crop management and hazards (Y_{GM}) was defined as the difference between Y_W and Y_A .

2.5. Extreme events index

Based on daily climatic data, Extreme Climatic Index (ECI) were defined at the agro-climatic scale: extreme precipitation (ECI_{PPT}), extreme temperature (ECI_{TMAX}), extreme drought (ECI_{DRY}) and extreme wind speed (ECI_{WIND}) index. For precipitation, ECI_{PPT} was defined at the field scale as the proportion of daily precipitation above a threshold (defining extreme precipitations) between two harvest dates. The precipitation threshold was assessed as the 97.5% quantile of measurements from 1998 to 2018 across space and was equal to 28.2 mm d^{-1} . Using the same method, ECI_{TMAX} was defined as the proportion of extreme daily event with T_{MAX} higher than 31.7°C . Considering ECI_{DRY} , in each field all drought events between two harvest dates were characterized by their duration in days. A threshold of 12 days for drought duration was defined using the 97.5% quantile across space and time. Finally, ECI_{DRY} was defined as the number of drought event higher than 12 days in each field between two harvest days. Average ECI_{PPT} , ECI_{TMAX} and ECI_{DRY} per agro-climatic zone were then calculated as the average field scale ECI weighted by the field area. Considering ECI_{WIND} , interpolated field scale wind speed was not available and only one station per zone was used. The ECI_{WIND} index was calculated using the daily maximum wind speed with the same method as previous ECI with a threshold of 16 m s^{-1} .

2.6. Statistical and data analyses

The whole dataset is accessible via Dataverse (Christina et al., 2020c). All statistical analyses were made using R 3.6 (R Development Core Team 2019). Weather data (Fig 2.) and ECI (Fig 4) were compared among agro-climatic zones using Tukey HSD test (multcomp R package). Differences were considered statistically significant if $p < 0.05$. To improve data visualisation (Fig. 2, 3 and 5), smooth regression were performed using local polynomial regression fitting with variability bands (loess.sd function from the msir R package with a constant smoothing parameter of 0.5). Principal components analyses (PCA) were used to visually illustrate separately the effects of climate variables (Fig. 3), on one hand, and extreme climate indices (Fig. 5), on the other hand. PCA was performed with FactoMineR and factoextra R packages. Correlation between the first two axes of the PCA and Y_{GT} and Y_{GM} were tested using a spearman correlation test (cor.test function). Finally, a hierarchical clustering analysis was performed on the ECI_{PPT} and ECI_{WIND} components to illustrate the effect of cyclones (HCPC function in FactoMineR package). Based on this analysis, 4 groups were isolated and the difference of Y_{GT} , Y_{GM} and actual yield loss (i.e. the difference between the maximum Y_A and the Y_A of each year in a given agro-climatic zone) among these groups were tested using a Dunn multiple test comparison, as the residual normality and homoscedasticity conditions were not satisfied (dunn.test R package). In this Dunn test case, differences were considered statistically significant if $p < 0.025$.

3. Results

3.1. Sugarcane yield and yield gap variability

Actual cane yield (Y_A) was similar among agro-climatic zones (74 t ha^{-1} in average) except for the North-West zone (57 t ha^{-1} in average, Fig 2a). This North-West zone was characterized by a low average daily temperature (20.4°C , Fig 2b) and low annual precipitation (614 mm y^{-1} , Fig 2c). The East and North-East zones were the warmest (22.3°C) and wettest areas (1801 mm y^{-1}). Nevertheless, actual sugarcane yield showed an annual variability. The coefficient of variation due to annual variability was similar among agro-climatic zones and varied from 8 % to 11 %. Moreover, for a given zone the difference of yield between the best year and the worst one varied between 20 t ha^{-1} (North West) and 31 t ha^{-1} (East).

In average, the simulated potential (Y_P) and water-limited (Y_W) yields at the agro-climatic zone scale were $170 (+/-19)$ and $106 (+/- 33) \text{ t ha}^{-1}$, leading to a total yield gap (Y_{GT} , i.e. difference between Y_P and Y_A) of 96 t ha^{-1} (Fig 2d). This yield gap resulted from a 64 t ha^{-1} water limited yield gap (Y_{GW} , difference between Y_P and Y_W) and from a 32 t ha^{-1} yield gap due to management and hazard (Y_{GM} , i.e. difference between Y_W and Y_A), in average. While Y_P showed little annual variation, with a coefficient of variation ranging from 2 to 3 % depending on the agro-climatic zone, Y_W presented a higher variability over years, ranging from 13 % (North East) to 26 % (North West). In comparison, Y_A had annual variations ranging from 8 to 11 %.

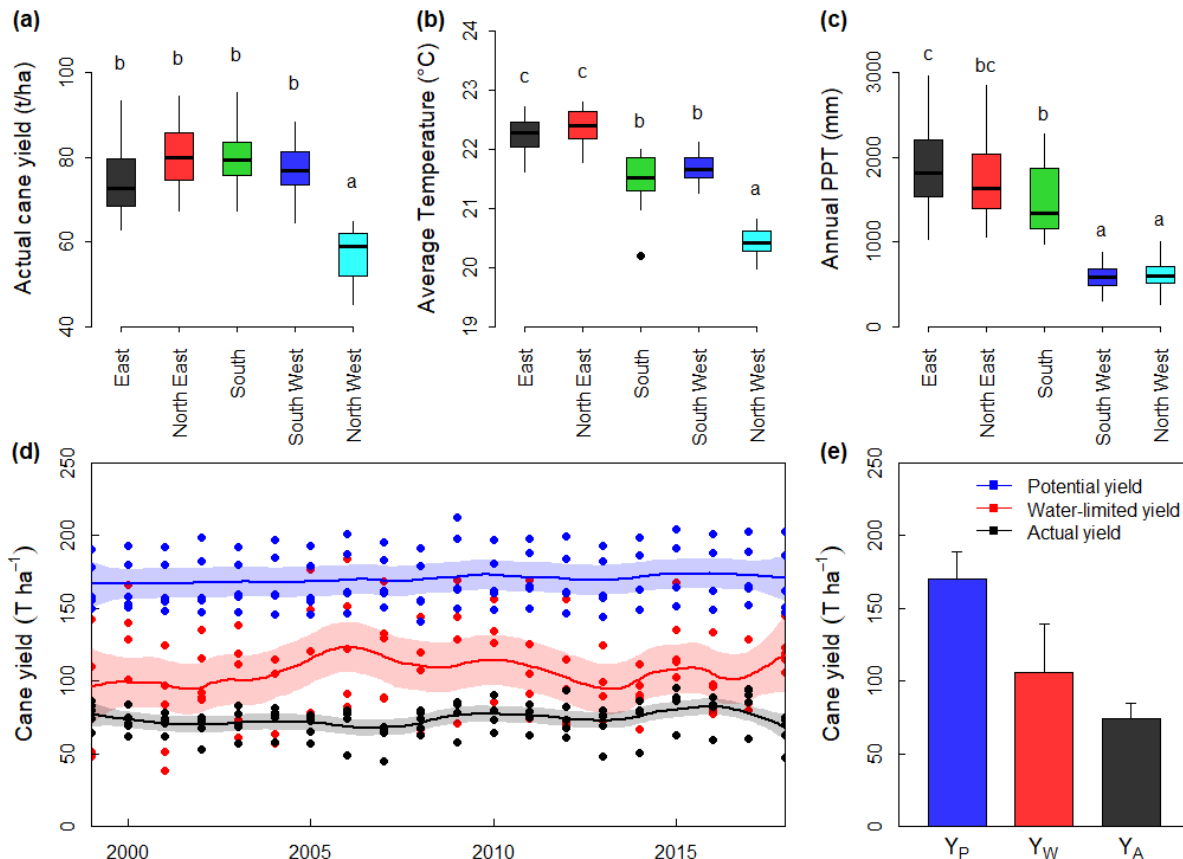


Fig 2. Average actual cane yield (a), daily temperature (b) and annual precipitation (PPT, c) over the 1998-2018 period depending on the agro-climatic zone define in Fig 1d. The annual evolution of cane yield (Y_A , black), simulated water-limited yield (Y_W , red) and potential yield (Y_P , blue) is presented in (d) and averaged in (e). A polynomial smooth regression over years was added (line) with standard deviation (transparent color).

3.2. Climate variability and yield gap

Based on a principal component analysis (PCA) we summarized 5 soil and climatic variables into 2 climatic indexes (CI1 and CI2, Fig 3a). The first component (CI1, 67.9% of the explained variance) was mainly determined via the average daily temperature (T_{MEAN}), global radiation (R_G), potential evapotranspiration (ETP) and soil water holding capacity (SWC). The annual water input (precipitation + irrigation, PPT_{IRR}) contributed to both IC1 and the second component (CI2, 18.1% of the explained variance).

Total yield gap (YG_T) was positively correlated with CI1 value ($\rho_{SPEAR} = 0.56$, $p < 10^{-6}$), with YG_T reaching around 120 t ha^{-1} in warm and high ETP environments (Fig 3b). In colder environments (i.e. low values of CI1), YG_T was relatively constant (around 90 t ha^{-1}). YG_T was also positively correlated ($\rho_{SPEAR} = 0.23$, $p=0.021$) with CI2, but it varied less from 90 t ha^{-1} in low precipitation environments to 110 t ha^{-1} in high precipitation ones (Fig 3c).

Following a similar pattern, management yield gap (YG_M) was positively correlated with CI1 ($\rho_{SPEAR} = 0.57$, $p < 10^{-6}$). YG_M increased from 0 to 80 t ha^{-1} , with increasing temperature and ETP. YG_M was also strongly correlated with CI2 ($\rho_{SPEAR} = 0.60$, $p < 10^{-6}$). In low precipitation environments, YG_M was null but reached 80 t ha^{-1} for the years and zones with the highest precipitations.

In warmer and higher ETP environment, YG_T increased mainly due the increase in YG_M while YG_W (difference between YG_T and YG_M) remained relatively constant. In higher precipitation environments, YG_T also increased due to increase in YG_M but YG_W decreased.

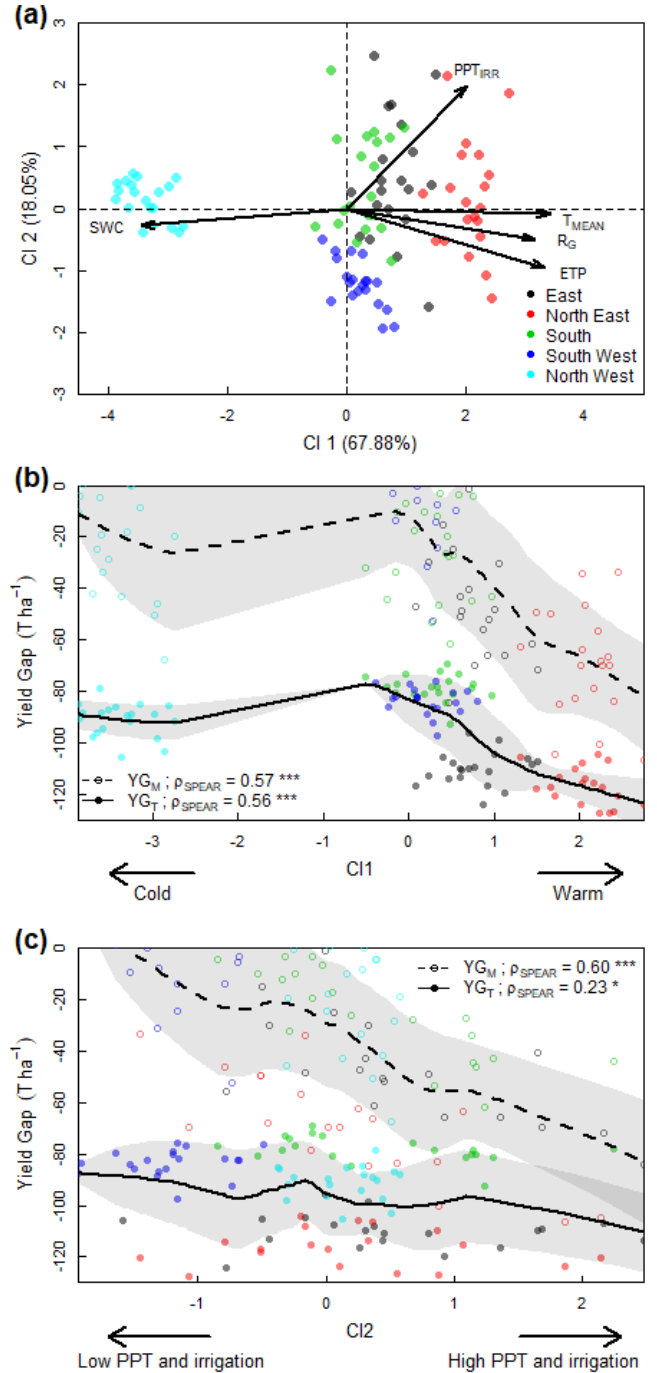


Fig 3. Principal component analysis (PCA) on average soil and climatic variables per agro-climatic zones (a): Average daily temperature (T_{MEAN}), global radiation (R_G), potential evapotranspiration (ETP), annual water input (precipitation + irrigation, PPT_{IRR}) and soil water holding capacity (SWC). The change in total (YG_T) and management (YG_M) yield gaps with the two first axis of the PCA (CI1 and CI2) are shown in b and c. The spearman correlation between the yield gaps and the PCA axis are indicated. A polynomial smooth regression was added (line) with standard deviation (transparent). Arrows were added to help the figure interpretation.

3.3. Extreme climate events and yield gap variability

Extreme events occurrence varied among agro-climatic zones (Fig 4). Extreme rainfall (ECI_{PPT}) occurred more in the East and South coasts of Reunion Island than in the West Coast (Fig 4a). The North-East and South coasts underwent frequent extreme wind speed events (ECI_{WIND}) than the rest of the island (Fig 4b). Extreme drought events (ECI_{DRY}) showed the opposite pattern than ECI_{PPT} , with the East Coast with the lowest values and the West Coast with the highest values (Fig 4c). Finally, considering, extreme daily temperature (ECI_{TMAX}), the East Coast was little impacted, contrary to the South and North West zones, and even more to the South-West agro-climatic zone (Fig 4d).

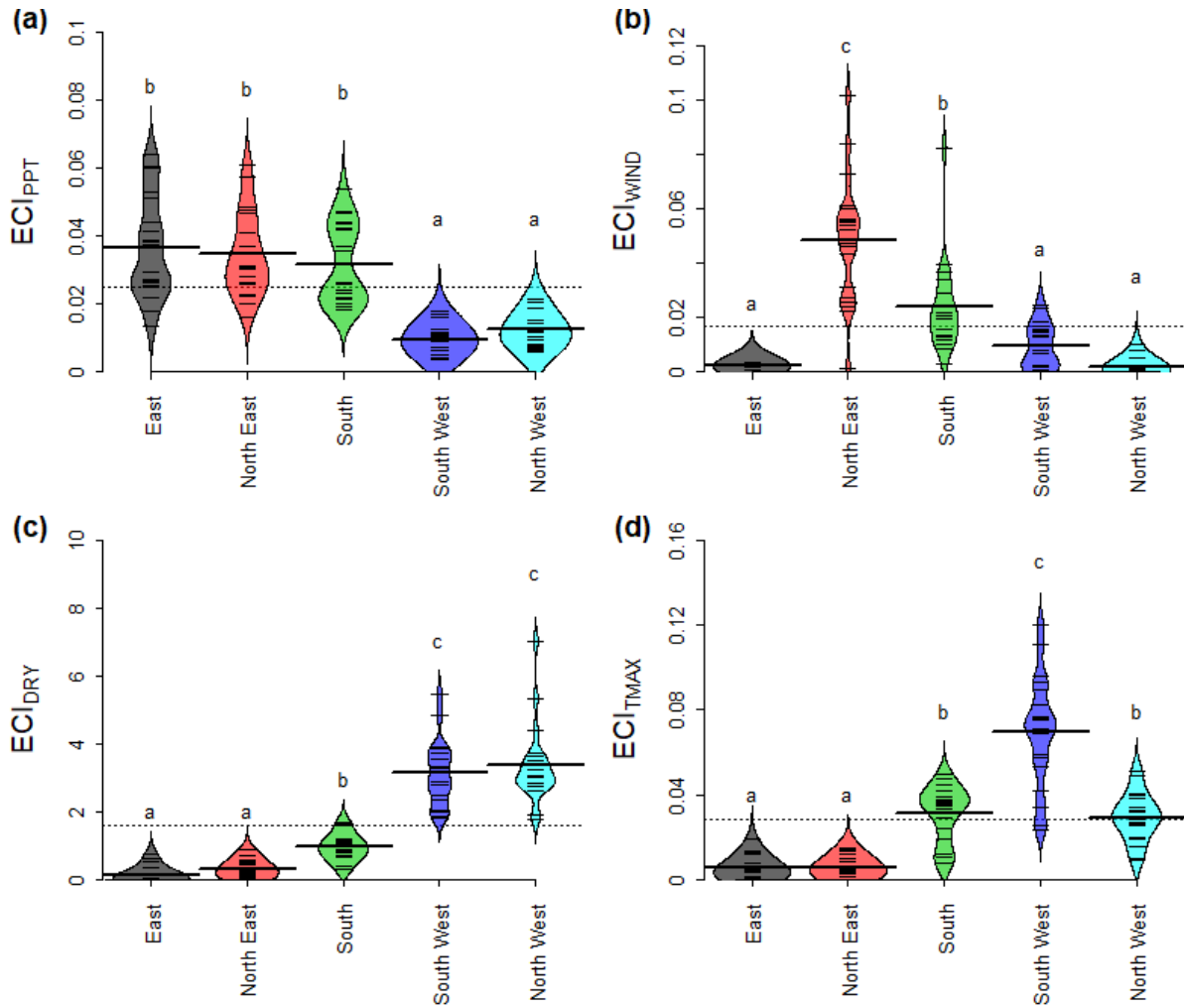


Fig. 4. Bean plot density of extreme events indices depending on the agro-climatic zones: extreme rain (ECI_{PPT} , a), wind speed (ECI_{WIND} , b), drought (ECI_{DRY} , c) and temperature (ECI_{TMAX} , d). A Tukey test was performed and significant differences ($p < 0.05$) among zones are indicated by different letters a, b, c.

Based on a PCA these for extreme event index were summarized into 2 extreme climatic indexes (ECI_1 and ECI_2 , Fig 5a). The first component (ECI_1 , 60.3% of the explained variance) was mainly determined via ECI_{PPT} , ECI_{DRY} and ECI_{TMAX} . The ECI_{WIND} contributed to both ECI_1 and the second component (ECI_2 , 20.2% of the explained variance).

Total yield gap (YGT) was negatively correlated with $ECI1$ value ($\rho_{\text{SPEAR}} = -0.56$, $p < 10^{-6}$), with YGT reaching around 120 t ha^{-1} in environments with extreme rainfall events (Fig 5b). In drier environments (i.e. high values of $ECI1$), YGT was relatively constant (86 t ha^{-1}). YGT was not monotony correlated with $ECI2$ but the lowest YGT values were found in environments with medium wind speed events (Fig 5c).

Following a similar pattern, management yield gap (YGM) was negatively correlated with $ECI1$ ($\rho_{\text{SPEAR}} = -0.80$, $p < 10^{-6}$). YGM increased from 0 to 100 t ha^{-1} , with increasing extreme rainfall events. Similarly, to YGT , YGM was not correlated with $ECI2$ but the lowest values were found to medium wind speed environments.

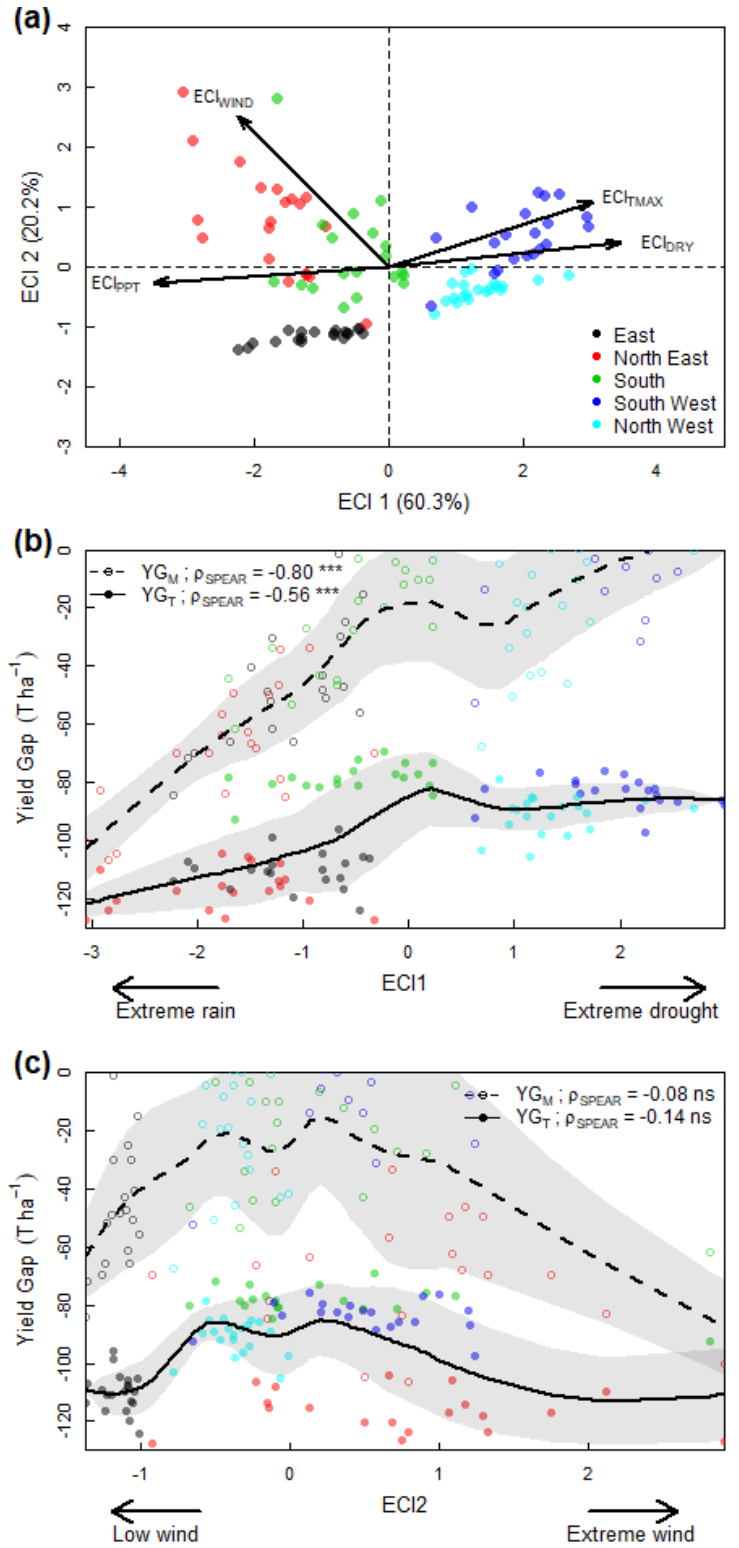


Fig 5. Principal component analysis (PCA) on extreme climatic index defined in section 2.5 (a): the extreme climatic indices were calculated based on high precipitation (ECI_{PPT}), high wind (ECI_{WIND}), maximum temperature (ECI_{TMAX}) and drought length (ECI_{DRY}). The change in total (YGT) and management (YGM) yield gaps with the two first axis of the PCA ($ECI2$) are shown in b and c. The spearman correlation between the yield gaps and the PCA axis are indicated. A polynomial smooth regression was added (line) with standard deviation (transparent). Arrows were added to help the figure interpretation.

3.4. Yield loss under extreme rainfall and wind speed

Based on a hierarchical clustering analysis on ECI_{PPT} and ECI_{WIND} variables, four clusters of year-zone units were defined (Fig 6a). The cluster 1 included environments with low ECI_{PPT} and ECI_{WIND} . The cluster 2 included environments with higher ECI_{WIND} values but with low ECI_{PPT} . The clusters 3 and 4 both included environments with high ECI_{PPT} , but only the cluster 4 also showed extreme high wind speed events. Management yield gap (YG_M), total yield gap (YG_T) and actual yield loss (i.e. difference between the actual yield of the best year of a given zone with the considered year) all increased from group 1 to 4 (Fig 6). In average, YG_T , YG_M and actual yield loss were equal to 92, 16 and 12 t ha⁻¹ in cluster 1 with low rainfall and wind extreme events. In environments with high rainfall and wind extreme events, YG_T increased by 11 and 22 %, YG_M by 265 and 393%, and actual yield loss increased by 58 and 85%, in clusters 3 and 4 respectively. In years with high precipitation and wind extreme events (clusters 3 and 4), the loss in actual cane yield was 19 t ha⁻¹ in average, compared to the year with highest yield, and could reach 28 t ha⁻¹.

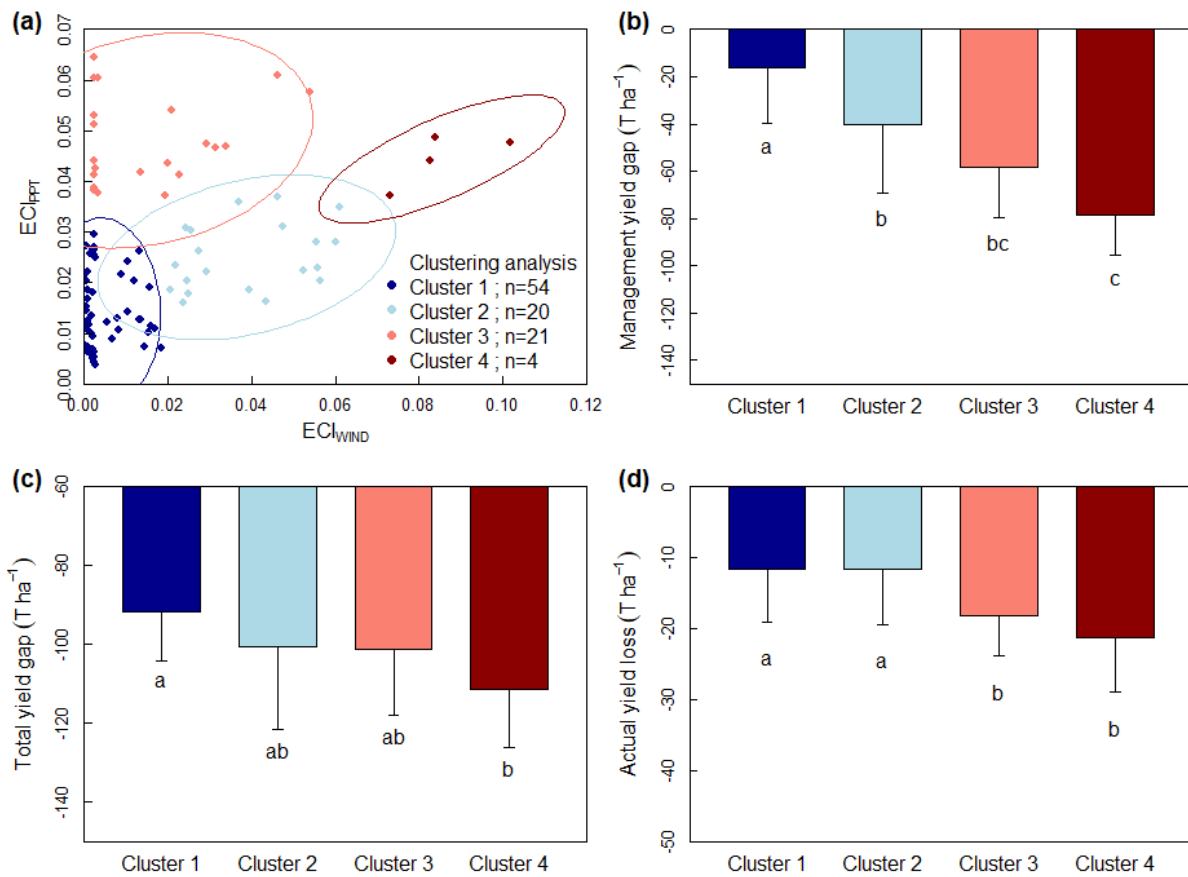


Fig. 6. Clustering analysis on extreme indices for precipitation (ECI_{PPT}) and wind speed (ECI_{WIND}) variables (a): four clusters were defined. Mean management yield gap, total yield gap and actual yield loss depending on these clusters are presented in b,c,d. The actual yield loss is defined as the difference between the Y_A of the best year and the Y_A of each year in a given agro-climatic zone. Different letters indicated significant difference using a dunn test analysis.

4. Discussion

4.1. Yield gap in Reunion Island

The assessed total yield gap (i.e., the difference between thermoradiative potential cane yield and actual cane yield) over Reunion Island in our study was 96 t ha^{-1} on average (ranging from 67 to 132.6 t ha^{-1} depending on the years and zones). In this study, all fields were assumed to be ratoon crop which could slightly increase the yield gap at the regional scale. Nevertheless, this yield gap was weaker than the yield gap assessed in other countries. As, an example, Dias and Sentelhas (2018) assessed an average yield gap of 134 t ha^{-1} over Brazil. Similarly, Zu et al. (2018) assessed a regional average yield gap in China of 156.3 t ha^{-1} , varying from 74.82 t ha^{-1} to 214.2 t ha^{-1} , depending on climate conditions and crop management practices.

Our results showed that the proportion of the yield gap due to water deficit and crop management was strongly variable. In average, water deficit account for 66% of the total yield gap in Reunion Island, which was similar with has been found in other climates (e.g. 73% in Brazil, Dias and Senthelos). As shown in this study, this proportion differed spatially and annually, with 88% in average in the dry west coast and 50% in the east wet coast (Fig S5). Part of this spatial variability could be explained by irrigation difference between east and west, but YG_w was only $\sim 25 \text{ t ha}^{-1}$ higher in rainfed fields than in irrigated ones in average whatever the precipitation (Fig S6). As a comparison, in the neighbour Mauritius Island, previous studies have shown more than 100 t ha^{-1} yield differences between irrigated and rainfed modeled water-limited yield (Cheeroo-Nayamuth et al. 2011). Another part of this variability could be explained by soil water holding capacity (SWC), in particular because irrigation appeared to be inefficient for SWC lower than 75 mm (Fig. S7). Nevertheless, while at the field scale SWC variability strongly influenced YG_w (Fig S7), average sugarcane field SWC per agro-climatic zone was only varying from 85 to 104 mm in our study. Consequently, the remaining factor explaining YG_w differences in the agro-climatic zones in Reunion Island could be caused by factors not taken into account in Mosicas model such as increasing biotic and abiotic pressure on yields link to climate (weed pressure, management practices...).

4.2. Increasing yield gap with source availability

Our study highlighted how yield gap increase with thermoradiative sources (T_{MEAN} , R_G , ETP) and water source (precipitation + irrigation, PPT_{IRR}) availability in Reunion Island. Such observation means that sugarcane growth cannot reach its full potential even with increasing radiation use potential. This observation suggested than other limiting factors for sugarcane growth occurred, such as fertilization, weed pressure or water losses.

In Reunion Island, limiting fertilization is not likely to be a main factor explaining increasing YG with source availability, because growers received fertilization advice based on subsidized soil analysis in Reunion Islands (Serdaf program, Versini et al., 2018). Nevertheless, this factor has to be considered as inadequate nutrition has been highlighted as a major impact explaining yield gap in other countries such as China (Zu et al., 2018) or South Africa (Van de Berg and Singels, 2013) with similar fertilization rates. Rather than fertilizers amount, a fertilizer use efficiency decreasing with higher rain (due to nitrate lixiviation, volatilization or surface erosion for example) could explain the increasing YG. As an example, Poultney et al. (2019) assessed the fertilizer use efficiency as only 22% during a rainy year in the North-East coast of Reunion.

Increased thermoradiative and water source availability is also likely to increase weeds pressure on sugarcane growth (Patterson et al., 1999; Ibrahim 1984), which is a main constraint in most tropical climate (Oerke 2006, 2004). Temperature and precipitation are the primary variables controlling the

distribution of vegetation (Woodward and Williams, 1987). Weeds share the same trophic level with crops and compete with crops for the resources. Additionally, growth of weeds of warm season is generally very responsive to small increases in temperature (Flint et al., 1984; Flint and Patterson, 1983; Patterson, 1993). Consequently, increase in weed pressure could be a factor explaining the increase in yield gap observed in Reunion Islands under elevated temperature and precipitation.

Finally, the water use efficiency under higher precipitation must be considered due to the irregular topography of agricultural basin, particularly in high altitude. The model could underestimate the water loss due to drainage or runoff in these steep reliefs. Nevertheless, we argue that this effect in high altitude on water-limited yield should be limited because the fields in highest altitudes already showed the highest proportion of precipitation loss into drainage in our simulation (Fig S8), probably due to the lower ETP and water consumption by canes in altitude. Consequently, we hypothesize that the increasing yield gap with increasing thermoradiative and water sources would mainly be due to decreasing fertilizer use efficiency and increasing weed pressure.

4.3. Managing sugarcane under extreme events

This study suggests that storms and cyclones are main factors affecting the yield gap and inducing yield loss in Reunion Island. Total yield gap increased by 20 t ha⁻¹ when high extreme precipitation and wind speed events occurred, corresponding to a similar increase in actual yield loss. Issues with storms is not limited to this part of the Indian Ocean, other productive countries such as Philippines with extreme winds (Stromberg et al., 2011) or USA with flood (Deren et al., 1991) are sensitive to these extreme events which can cause considerable economic damage. In Reunion island drought and warm event intensity is relatively low, inducing weak effect on yield gap in this study. Nevertheless, other countries have been shown to be much more sensible to extreme temperature (e.g. India, Mall et al., 2016) or drought (e.g. Australia, Inman-Bamber et al., 2005).

The effect of storms on yield is variable and it could directly influence crop physiology or impact crop yield through other biotic and abiotic pressure. As an example, Gilbert et al. 2008 showed that long-term flooding in Florida causes prolonged anoxia in the root zone leading to reductions of 10–78% in sugarcane leaf nutrient concentration, as well as leaf area index (LAI) decrease. Additionally, Beuzelin et al. (2009) highlighted how the increase in pest severity after a storm in Louisiana was a crucial factor explaining low yield values. Extreme winds can also directly impact crop losses through stalk growth termination (Moore et al., 1984).

Whatever the cause (cane physiology or breakage), opening the canopy can have drastic consequences when multiple storms can occur, such as in Reunion Island. In particular, these conditions promote soil erosion and weed development. The pouring of the canes allows light to reach the ground which favours the emergence of weeds and the recovery of plants kept under cover, such as vines (climbing weed or vine weed). These infested areas are therefore difficult to weed because they are not easily spotted and are inaccessible due to the mass of vegetation.

Considering that climate change is likely to increase extreme events occurrence (Cai et al., 2015), there is need to adapt cultural practice to reduce sugarcane sensitivity to storm. A first possibility already highlighted in 1940s by Hebert and Arcenaux (1940) is the use of wind-resistant clones. In their study in Louisiana, field survey showed large difference of broken cane (varying from 0.5 to 21% of total cane) depending of cultivars. Secondly, management practices should be promoted to limit soil erosion and weed pressure after storms. For example, the use of cover crops to limit erosions (Perret et al., 1996, Normand 1998) or improve weed control (Christina et al., pre-print) has been investigated in Reunion island and other sugarcane countries, but it could only be used at the

beginning of the sugarcane crop cycle (three months before canopy closure). Another possibility is to promote the conservation of straw mulch in the field. In a review, conservation of straw has been shown to considerably reduce soil erosions and weed pressure, particularly when the amount of straw is superior to 8 t ha⁻¹ (Carvalho et al., 2017). Finally, one could expect a potential increase in fertilizer leaching and runoff after storms. Not surprisingly, nitrogen loss through runoff or leaching showed high variations depending on location, climate and fertiliser rate (Thornburn et al., 2011) and tend to increase with higher rainfall (Reading et al., 2019). In comparison, the relation between extreme rainfall events and fertilizer loss remained poorly investigated, probably because farmers naturally avoid fertilizing during periods of climatic risk.

Increasing extreme weather events worldwide are an immediate threat to global crop production (Meehl et al., 2000; Rosenzweig et al., 2001; Olesen et al., 2007; Urban et al., 2012; Min et al., 2011; Lobell et al., 2008, 2013). Promoting crop management to make agrosystems more resilient to climatic hazards is a topical issue in the tropics.

5. Conclusion

In average, average total yield gap over Reunion Island was predicted as 96 t ha⁻¹, of which 66% was due to water deficit. This yield gap increased up to 120 t ha⁻¹ with increasing thermoradiative and water source availability, highlighting the influence of others biotic and abiotic limiting factors. The use of extreme climate indices allows us to assess the impact of tropical cyclones and storm on yield gap and yield loss. In average, yield loss was around 19 t ha⁻¹ in the zone and years with the highest precipitation and wind speed events, but this loss could reach 28 t ha⁻¹. Considering the considerable economic damage implied by yield loss under extreme events, there is a need to adapt cultural practice to frequent storms in tropical areas, particularly in the context of climate change.

Acknowledgements

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Supplementary Material S1 – Cane management data in Reunion Island

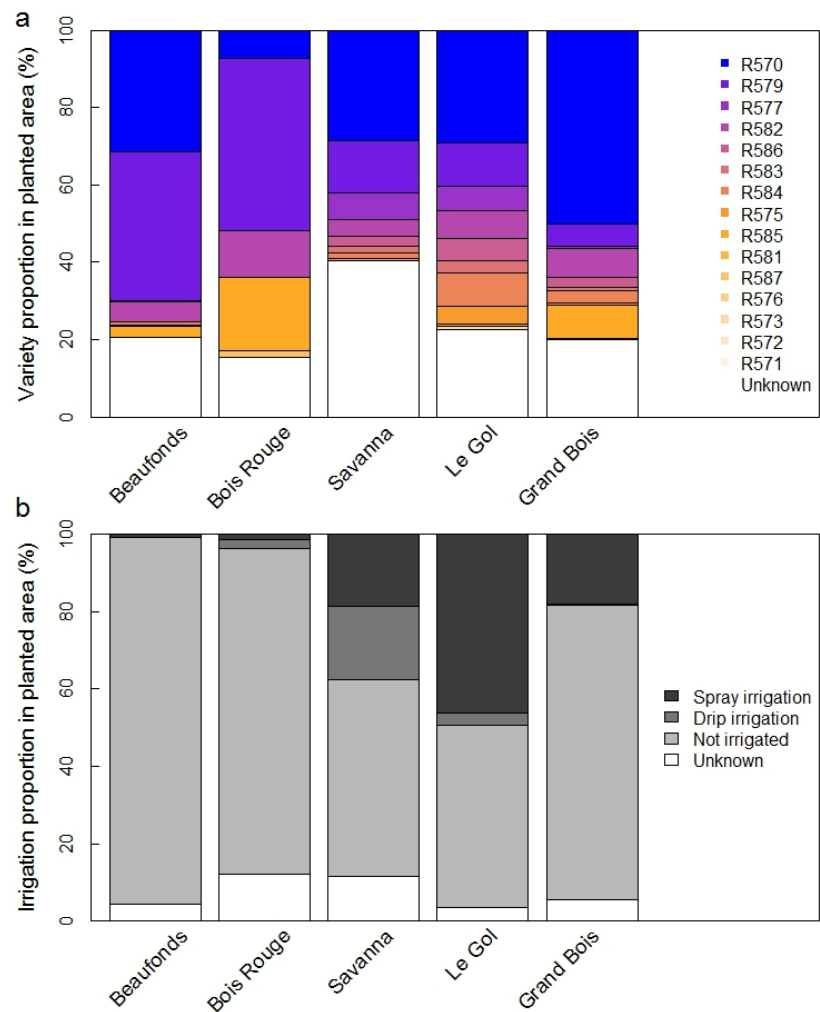


Fig. S1. Planted variety (a) and irrigation management (b) proportions in the 5 agro-climatic zones in Reunion Island.

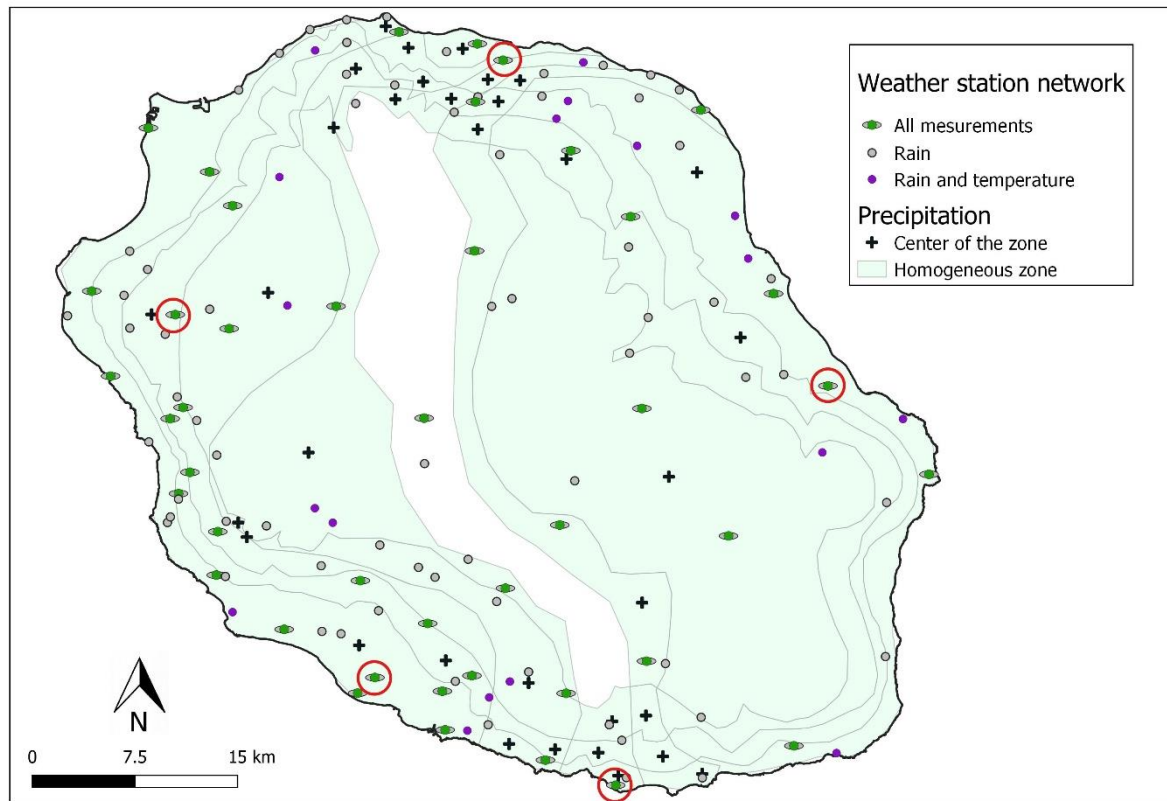


Fig S2. Location of the weather station network used to interpolate daily weather data. The stations with a red circle were used to calculate the extreme wind speed index. The black cross represent the center of each climatic zone, where weather data were interpolated.

Supplementary Material S2 – Calibration Procedures and results

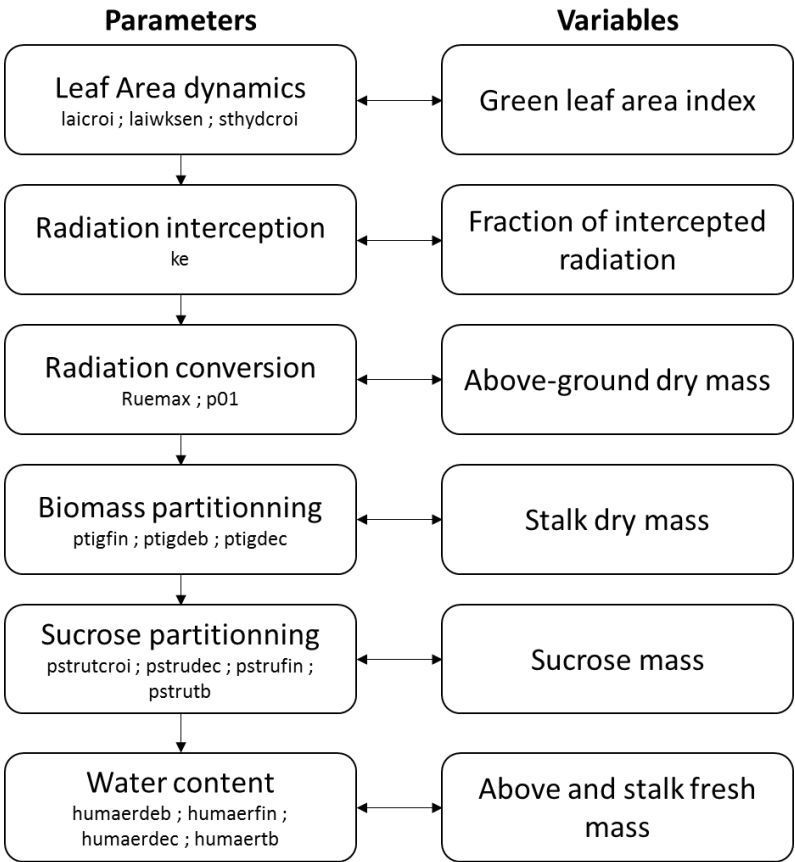


Figure S3. Schematic of calibration procedure. The boxes show the order of decreasing priority in the calibration procedure and the observed variables used of parameter estimation.

Table S1. Parameter values and description used in the MOSICAS model

Parameter	description	Cane variety				Source
		R570	R579	R585	R586	
<i>humaerdeb</i>	Initial above ground biomass water content (%)	85.51	85.51	87.17	84.41	Calibrated
<i>humaerdec</i>	Rate of decrease in above ground biomass water content	0.0058	0.0058	0.0054	0.0044	Calibrated
<i>humaerfin</i>	begining in decrease of above ground biomass water content	914.39	914.39	823.97	1024.19	Calibrated
<i>humaertb</i>	Base temperature for above ground biomass water content	13.70	13.70	11.88	11.43	Calibrated
<i>humstemdeb</i>	Initial stem water content (%)	88	88	88	88	fixed
<i>humstemdec</i>	Rate of decrease in stalk water content	0.0704	0.0704	0.0704	0.0704	fixed
<i>ke</i>	extinction coefficient	0.482	0.482	0.482	0.482	Calibrated
<i>laicroi</i>	growth rate of lai	0.0040	0.0042	0.0042	0.0042	Calibrated
<i>laimax</i>	Maximum LAI	7	7	7	7	fixed
<i>laith</i>	base temperature for lai calculation	12	11.2	12	12	Calibrated
<i>laiwksen</i>	sensitivity of lai to water stress	0.0100	0.0110	0.0110	0.0110	Calibrated
<i>p01</i>	coefficient for maintenance effect on conversion.	1.0665	0.0968	1.1998	0.5001	Calibrated
<i>p04</i>	coefficient for diffused radiation effect on conversion.	0	0	0	0	fixed
<i>pstrudec</i>	Extinction coefficient of daily fraction of millable stalk dry mas allocated to structures	1.2162	7.9221	3.8088	1.3913	Calibrated
<i>pstrufin</i>	Final daily fraction of stalk dry mass allocated to structures	0.6914	0.5842	0.5135	0.6209	Calibrated
<i>pstrutb</i>	Temperature threshold from which fraction of stalks dry mass allocated to structures is decreasing.	25.37	18.39	22.52	23.67	Calibrated
<i>pstrutcroi</i>	Temperature effect on daily fraction of millable stalks dry mas allocated to structures	0.0081	0.0181	0.0062	0.0104	Calibrated
<i>ptigdeb</i>	Beginning of millable stalk dry mass appearance	499.68	579.01	199.42	292.23	Calibrated
<i>ptigdec</i>	Extinction coefficient of daily fraction of aboveground dry mass allocated to millable stalk	1.8846	2.0213	1.2420	1.6556	Calibrated
<i>ptigfin</i>	Final daily fraction of aboveground dry mass allocated to millable stalk	0.9606	0.8906	1.1930	0.7953	Calibrated
<i>ruemax</i>	conversion coefficient of intercepted photosynthetic radiation into total dry mass	2.6154	3.2381	3.1907	3.1049	Calibrated
<i>ruetopt</i>	Optimum temperature for conversion.	30.4	30.4	30.4	30.4	Calibrated
<i>ruetk</i>	Effect of temperature on conversion.	0.00037	0.00037	0.00037	0.00037	Calibrated
<i>sthydbio</i>	Sensitivity to water stress index (swdf1) for mass accumulation.	0.6	0.6	0.6	0.6	Calibrated
<i>sthydcroi</i>	Sensitivity to water stress index (swdf2) for growth. Plant parameter	0.500	0.514	0.514	0.514	Calibrated
<i>pracfin</i>	Proportion of dry mass allocated to roots in ratoon	0.1	0.1	0.1	0.1	fixed

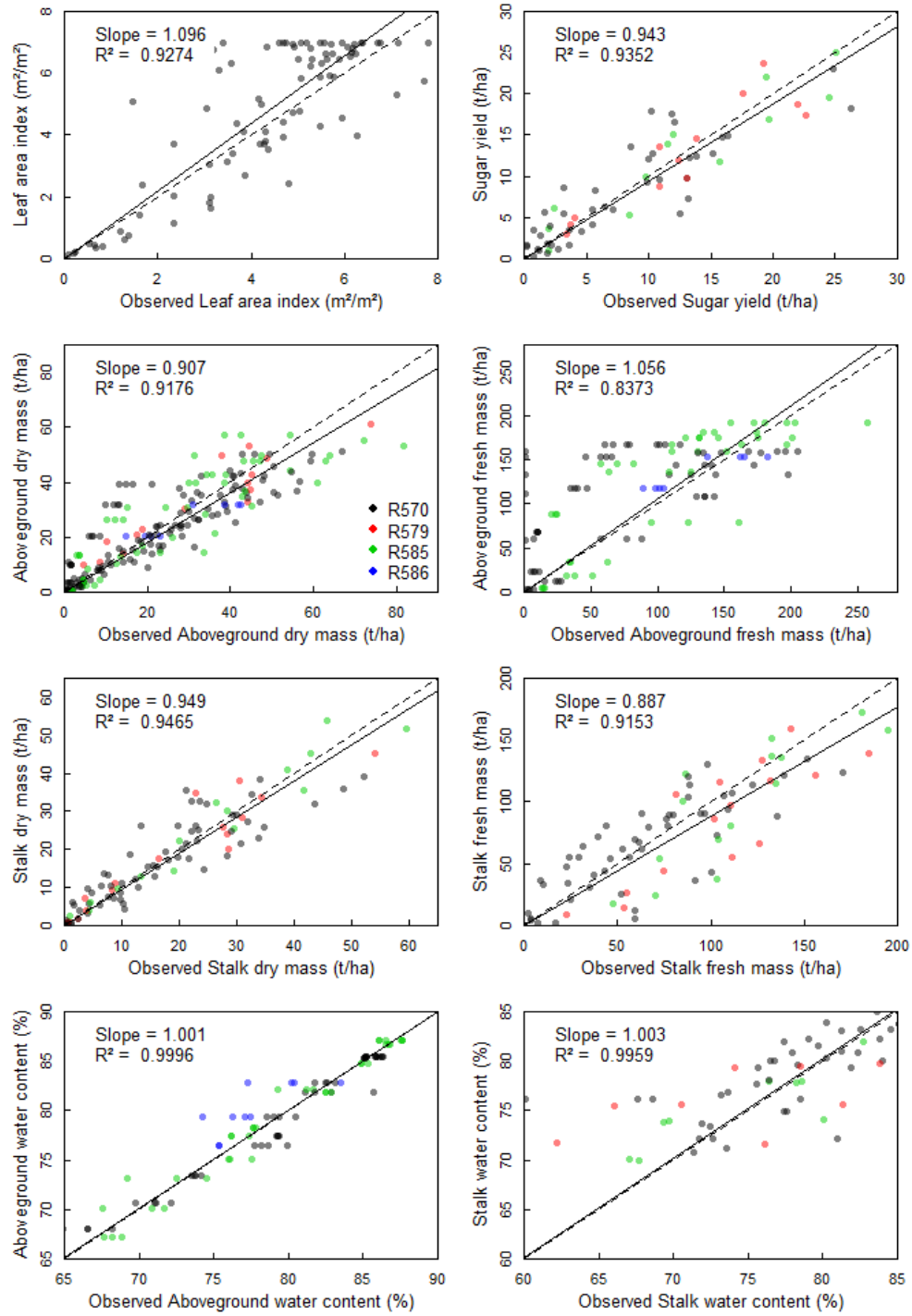


Fig. S4. MOSICAS calibration of 4 cane varieties using the ECOFI database. The model was calibrated using leaf area index, sugar yield, aboveground dry and fresh mass, stalk dry and fresh mass and aboveground and stalk water content.

Supplementary Material S3 – Description of cane growth main equations in MOSICAS model

- LAI calculation

In the daily time step mosicas model, the leaf area index (LAI_d) for a given day d is a variable that grows as a function of temperature, water stress and intra-specific competition. The daily growth in lai ($glai$) is computed as follow:

$$glai = laicroi_p * LAI_{d-1} * \left(1 - \frac{LAI_{d-1}}{laimax_p}\right) * T_{LAI} * swdf_{LAI}$$

Where $laicroi_p$ is a plant parameter, LAI_{d-1} , the LAI of the previous day, $laimax_p$ the maximum leaf area and is a plant parameter, $swdf_{LAI}$ the soil water deficit factor for LAI_d . T_{LAI} is the accumulated thermal energy during the day and is defined as:

$$T_{LAI} = \frac{Tmax_d - Tmin_d}{2} - laitb_p$$

Where $Tmax_d$ and $Tmin_d$ are the maximum and minimum daily temperature, and $laitb_p$ is a plant parameter and represents the base temperature for growth in LAI_d .

The leaf mortality due to water stress ($slai$) is calculated as follows:

$$slai = laiwksen_p * (1 - swdf_{LAI}) * LAI_{i-1}$$

Where $laiwksen_p$ is a plant parameter and represents a sensitivity to water stress.

Finally, LAI_d is calculated as:

$$LAI_d = LAI_{d-1} + glai + slai$$

- Intercepted radiation

The daily photosynthetic active radiation intercepted by the canopy ($pari$) is calculated based on the bear-lamber law:

$$pari = 0.5 * R_g * (1 - e^{-ke_p * LAI_d}) * \left(1 - p04_p * \left(\frac{R_g}{R_e} - 0.75\right)\right)$$

Where R_g is the daily global incident radiation and ke_p , a plant parameter defining the extinction coefficient, $p04_p$, a plant parameter that takes into account the diffuse radiation effect and R_e , the global extraterrestrial radiation.

- Radiation conversion into dry mass

The total dry mass (dmt_d) at a given day d is calculated as the sum of the total dry mass of the previous day and the daily growth in dry mass ($gdmt$). The daily $gdmt$ is calculated as:

$$gdmt = ruemax_p * pari * swdf_{rue} * k_{age} * k_T$$

And:

$$dmt_d = dmt_{d-1} + gdmt$$

Where $ruemax_p$ is the maximum radiation use efficiency, $swdf_{rue}$, the soil water deficit factor for radiation use, and k_{age} and k_T some parameter defining the effect of maintenance respiration and temperature, respectively.

The effect of temperature on radiation conversion is defined as:

$$k_T = 1 - ruetk_p * \sqrt{|T_{diu} - rueopt_p|}$$

Where $rueopt_p$ and $ruetk_p$ are plant parameters that define the optimal temperature for radiation use efficiency and a parameter used in the response of this efficiency to temperature, respectively. T_{diu} defines the average temperature during daylight:

$$T_{diu} = 0.25 T_{min} + 0.75 T_{max}$$

The effect of maintenance respiration is calculating based on the total dry mass (dmt_d)

$$k_{age} = 1 - \left(dmt_d * \frac{p01_p}{10^4} \right)^3$$

Where $p01_p$ is a plant parameter to take into account maintenance respiration

- Dry mass partitioning

The daily total dry mass accumulated (gdm_t) is firstly allocated to aerial part vs roots. In case of plant crop, the dry mass allocated to roots (k_{rac}) decreases with thermal time:

$$k_{rac} = pracdeb_p - pracdec_p * sdd$$

And

$$k_{rac} = \min(k_{rac}, pracfin_p)$$

Where $pracdeb_p$, $pracdec_p$ and $pracfin_p$ are plant parameters (Table S1), and sdd is the sum of degree days since planting (base temperature = 0°C).

In case of ratoon crop, the dry mass allocated to roots is assumed constant and equal to $pracfin_p$.

Consequently, the aerial dry mass ($dmaer_d$) and daily dry mass allocated to aerial parts are equal to:

$$dmaer_d = dmaer_{d-1} + gdmaer$$

And

$$gdmaer = gdm_t * (1 - k_{rac})$$

The aboveground dry mass is partitioned into millable stalk dry mass ($dmstm_d$), as follows:

$$dmstm_d = dmstm_{d-1} + gdmstm$$

$$gdmstm = gdmaer * pstemfin_p * \left(1 - e^{-\frac{pstemdec_p}{1000}(dmaer_d - pstemdeb_p)} \right)$$

Where $pstemfin_p$, $pstemdec_p$ and $pstemdeb_p$ are plant parameters (Table S1).

The model also simulated the sucrose accumulation into the stalk as well as aboveground water content but these processes were not used into this study.

- Cane yield: fresh cane mass

Finally, the fresh stalk mass ($fmstm$) and the stalk humidity are calculated as follows:

$$fmstm = \frac{dmstm}{100 - humstm}$$

$$humstm = humstemdeb_p - humstemdec_p * das$$

Where das is the number of day since stalk appearance, and $humstemdeb_p$ and $humstemdec_p$ are plant parameters (Table S1).

The stalk appearance is defined as the day when the aboveground dry mass reached a value higher than $pstemdeb_p$.

- Water stress index

Simulation of the soil water balance relies on a CERES type water module, including soil evaporation, soil drainage, plant evaporation and rainfall infiltration. The detailed of these equations can be found in the source code of MOSICAS (<https://github.com/ChristinaMathias/MOSICAS>). Two soil water deficit factors are calculated for LAI_d growth ($swdf_{LAI}$) and radiation conversion into dry mass ($swdf_{DM}$):

$$swdf_{LAI} = \left(\frac{swd}{0.94 - 0.25 * \frac{psilb}{tmp}} \right)^{sthydbio_p}$$

$$swdf_{DM} = \left(\frac{swd}{1.25 \left(0.94 - 0.25 * \frac{psilb}{tmp} \right)} \right)^{sthydcroi_p}$$

Where $psilb$ is a pression parameter defined as 8 according to Brisson 1992 and Slabber 1982, tmp the maximum transpiration of the day according to actual canopy, $sthydbio_p$ and $sthydcroi_p$ are plant parameters defining the sensitivity to water stress.

swd is the soil water deficit and calculated as follows:

$$swd = \frac{SWC}{FC - WP}$$

Where SWC is the actual soil water content, FC the field capacity and WP the welting point.

And tmp the maximum transpiration of the day is calculated as follows:

$$tmp = ETP * Kmax_p * \sqrt{\min(1, \frac{LAI_d}{3})}$$

Where ETP is the daily potential evapotranspiration (mm) and $Kmax_p$ the maximum crop coefficient (plant parameter).

Supplementary Material S4 – Complementary results

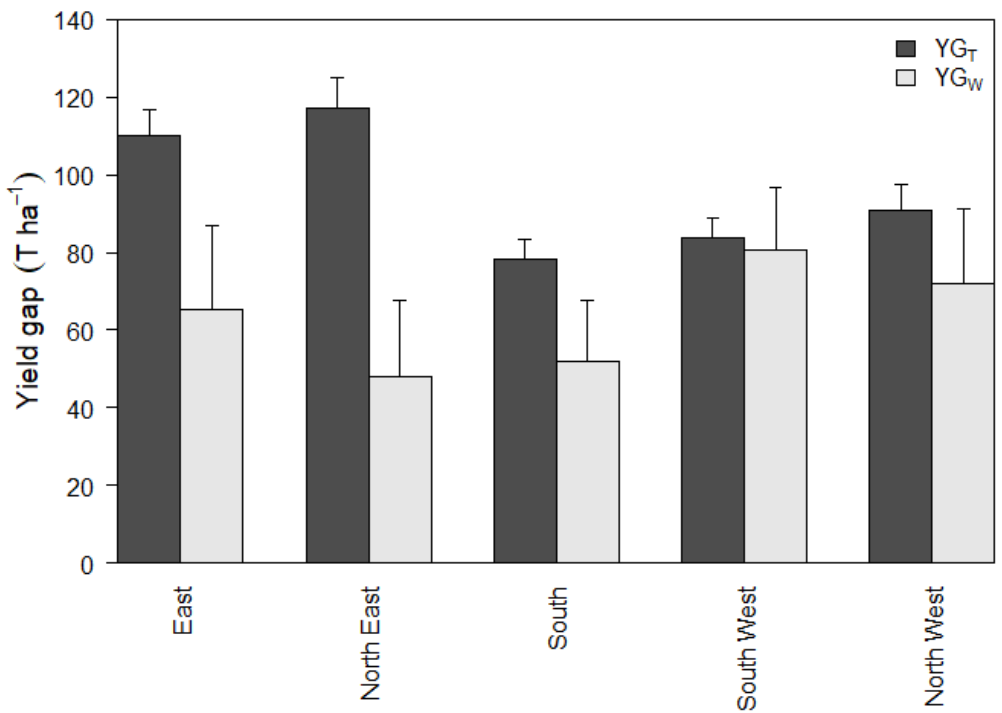


Fig S5. Average total yield gap (YG_T) and yield gap due to water-deficit (YG_W) per agro-climatic zone in Reunion Island from 1998 to 2018.

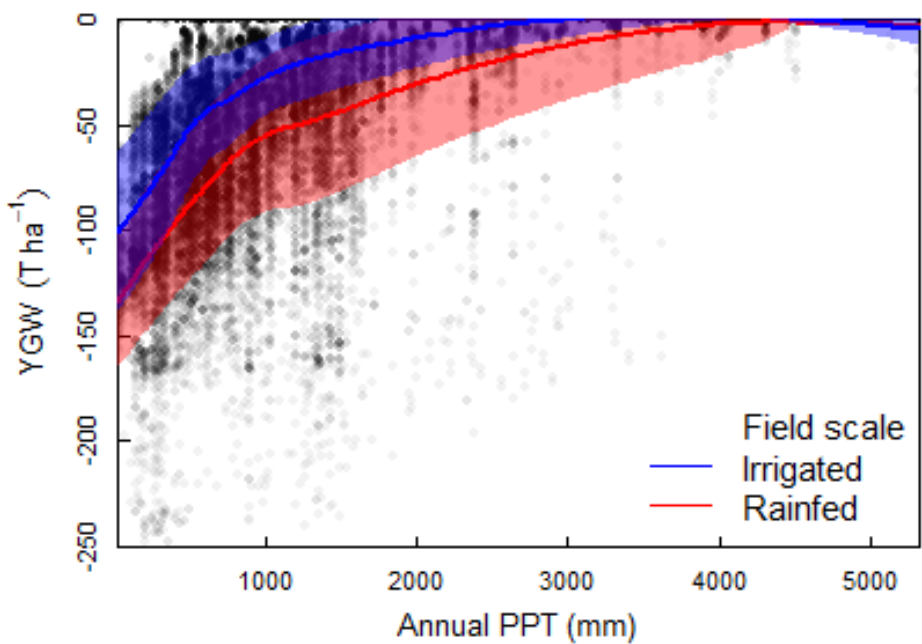


Fig S6. Field scale yield gap due to water deficit (YG_W) in irrigated and rainfed fields depending on annual precipitation (PPT).

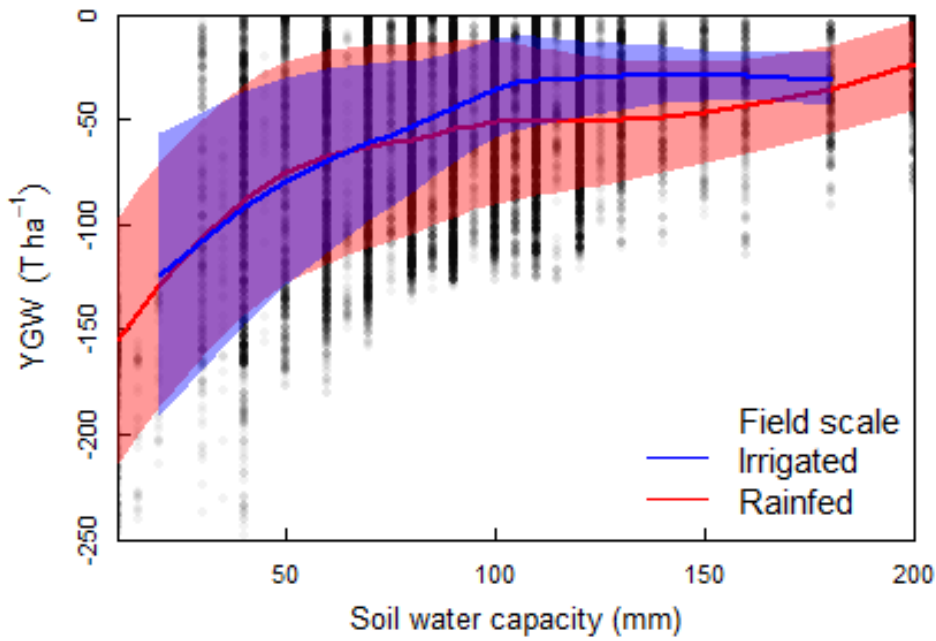


Fig S7. Field scale yield gap due to water deficit (YG_W) in irrigated and rainfed fields depending on soil water holding capacity.

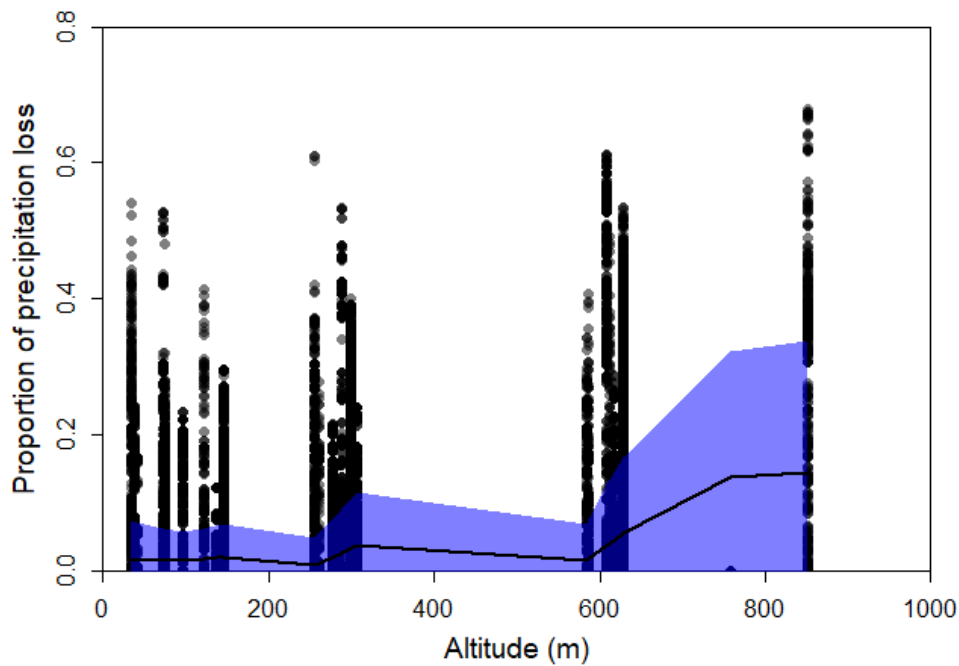


Fig S8. Change in proportion of precipitation loss (drainage / precipitation) at the field scale depending on altitude (black point). A polynomial smooth regression over altitude was added (line) with standard deviation (transparent blue).