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Win-win: Improved irrigation management saves water and increases yield for Robusta coffee farms in Vietnam

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ABSTRACT

Robusta coffee is critically important for the economy and farmers of Vietnam, but also requires substantial irrigation leading to dwindling water resources. Developing clear recommendations for improved irrigation water management, while maintaining or increasing yield is therefore a key knowledge need for the coffee industry. We analyse 10-cropping-year data (2008/2009–2017/2018) of 558 farms across four major coffee-producing provinces in Vietnam's Central Highlands using CROPWAT and hierarchical Bayesian modelling to (1) identify irrigation requirements under different climatic conditions, and (2) investigate the potential for improved irrigation management strategies. In average rainfall years the majority of farmers in Dak Nong and Lam Dong supplied an equivalent of 455–909 L tree^{-1} (assuming 1100 plants ha^{-1}) with corresponding average yields ranging from 2149 to 3177 kg ha^{-1}. In Dak Lak and Gia Lai the predominant range was equivalent to 1364–1818 L tree^{-1} (corresponding average yields: 2190 to 3203 kg ha^{-1}). In dry years more water was supplied through irrigation at various levels depending on the province: varying between 1364–1818 L tree^{-1} in Dak Lak and Gia Lai, and 909–1364 L tree^{-1} in Dak Nong and Lam Dong. Our study also shows that irrigation water can be reduced by 273–536 L tree^{-1} (300–590 m^3 ha^{-1}) annually from the current levels in average rainfall years while still achieving average yield levels greater than 3000 kg ha^{-1}. In dry years reductions of 27–218 L tree^{-1} (30–240 m^3 ha^{-1}) are possible. With adequate management of the key crop practices affecting coffee yields, substantial water savings at the provincial scale could be achieved. Thus, our findings could serve as a basis for province-specific irrigation water management in Robusta coffee farms that will not only reduce overall water use, but also potentially maintain satisfactory yield levels.

1. Introduction

Low and unreliable rainfall conditions, especially during critical growth stages, can make coffee production challenging in leading coffee-producing countries and impact negatively on the entire global coffee sector. To cope with such adverse patterns and assist with better plant growth conditions and satisfactory yield levels over years, coffee farmers rely on irrigation (D'haeze et al., 2005a; Assis et al., 2014; Amarasinghe et al., 2015; Perdoná and Soratto, 2015; Sakai et al., 2015; Boreux et al., 2016; Liu et al., 2016). Irrigation amounts in coffee vary depending on the annual rainfall distribution, the severity of the dry season, and soil type and depth (Carr, 2001).

In Robusta coffee (*Coffea canephora* Pierre ex A. Froehner) production systems in Vietnam, the second largest coffee-producing country globally (GSOV, 2017; ICO, 2019), the need for irrigation during the dry season (January-April) and its role in controlling the timing of flowering is of great importance for achieving high yield (Carr, 2001; Amarasinghe et al., 2015).

Coffee production in Vietnam is dominated by Robusta coffee, which accounts for 95 % of the national production (GSOV, 2017). The irrigation application as advised by the Vietnam Ministry of Agriculture and Rural Development (MARD) is 400 L tree^{-1} per round in three rounds a year, that is 1200 L tree^{-1} year^{-1}, assuming 1100 plants per hectare (MARD, 2016; UTZ, 2016). However, irrigation data from previous studies indicated an average amount often twice the recommended application amount in provinces like Dak Lak (D'haeze, 1999; Luong and Tauer, 2006; D'haeze, 2008). The major source of irrigation water in coffee-producing provinces in the Central Highlands region is groundwater (Cheesman and Bennett, 2005; D'haeze et al., 2005b). Excessive groundwater exploitation, associated with variable rainfall patterns (Hoegh-Guldberg et al., 2020), causes groundwater tables to decline and, if not properly addressed, threatens the

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natural refilling of aquifers, as well as the livelihoods of populations relying on the coffee industry (Minderhoud et al., 2017; Lee et al., 2018).

While characterizing Robusta coffee farms under irrigation in Dak Lak, D'haeze (1999) denoted that irrigation amounts usually exceeded the crop water requirement, endangering water resources across this province. Subsequent studies confirmed such conclusions (D'haeze et al., 2003, 2005b; Amarasinghe et al., 2015; Nguyen and Sarker, 2018). They also outlined strategies for improved irrigation water use and sustainable production in Robusta coffee farms. These include the reduction of irrigation supply during average climatic conditions and capacity building of farmers to better understand on-farm water and input management (D'haeze et al., 2005b; Amarasinghe et al., 2015). These studies were, however, limited to either one district or one province. As such, they might not provide sufficient insights for developing region-specific best irrigation management practices across the Vietnamese coffee-producing provinces, where different environmental conditions are found. Efficient irrigation management practices while ensuring satisfactory coffee bean yield are therefore key to sustainable coffee production in Vietnam.

Using data of 558 Robusta coffee farms over 10 cropping seasons (2008/2009–2017/2018), the main objective of this study is to provide further insights into existing irrigation management strategies in Robusta coffee farms in Vietnam. Specifically, we aimed to (1) characterize irrigation management patterns and quantify crop water requirements throughout the season in four major Vietnamese Robusta coffee-producing provinces; (2) quantify the potential coffee yield gain to additional irrigation during the critical coffee growth period (blossoming through to fruit set) using a hierarchical Bayesian modelling approach; and (3) identify the potential for improved province-specific irrigation management strategies. The findings of this study could serve as a basis for capacity building on best irrigation management practices in Robusta coffee farms in Vietnam and other regions with similar coffee growing conditions.

2. Materials and methods

2.1. Study area

The study area was located in four coffee-producing provinces in the Central Highlands: Dak Lak, Dak Nong, Lam Dong and Gia Lai (Fig. 1). These provinces account for approximately 90 % of Vietnam's average annual export of coffee (GSOV, 2017; Ho et al., 2017; Kouadio et al., 2018). Robusta coffee is typically grown as an un-shaded and clean-weeded monocrop in the Central Highland provinces. Two main soils dominate the Central Highlands region: reddish-yellow Acrisols and reddish-brown Ferrosols, with coffee mostly cultivated on Ferrosols (Tien et al., 2015; Tiemann et al., 2018). The Central Highlands is dominated by a humid tropical climate. The January-April (JA) period corresponds to the dry season, followed by a rainy season from May to October. Maximum temperatures were normally above 24 °C throughout the year, and the average monthly solar radiation ranged from 428 to 698 MJ m^{-2}. Annual rainfalls varied on average between 1800 and 3000 mm in these regions, with more than two-thirds falling during the monsoon season between May and October.

2.2. Farm data

Data were collected within the Sustainable Management Services (SMS) program implemented by ECOM Agroindustrial Corporation since 2005 in Vietnam, with more than 5000 coffee farmers enrolled within the program (as of 2018). Coffee farm activities are regularly monitored throughout every crop season, with three to four farm surveys each year and farm data collected using designed questionnaires. Data were managed through the SMS database within ECOM, in addition to records, which are kept by individual farmers.

For this study, representative sampling was used to compile data from the SMS database over the 2008–2017 period. The selection was based on differences in farm size, proportion of coffee areas, climate, and water resources. 558 farmers were selected across 18 districts in the study provinces: 180, 120, 93 and 165 farmers in Dak Lak (6 districts), Dak Nong (4 districts), Gia Lai (3 districts), and Lam Dong (5 districts), respectively. Data of the 2008–2017 period were collected during the last quarterly farms survey in 2017 (5580 observations in total). All farm data were cross-checked with those of the SMS database to verify their consistency.

Basin and sprinkler irrigation are the two traditional irrigation methods in Vietnam. The sampling was carried out in such a way that it represented both irrigation methods. The source of irrigation water is mainly from the dug open wells at farms and/or nearby lakes, depending on the province. Plants are irrigated during the dry season (January-April) which coincides with the critical crop stages of blossoming and fruit set. Farmers were trained to monitor the water discharge time by the pump so that they can control the irrigation volumes and keep records. The data collected consisted of farm characteristics (altitude, farm area, age of trees, plant density, and area harvested), coffee yield, amount and frequency of irrigation, and type and proportion of fertilizers applied. All the data were anonymised before any analysis performed in this study.

2.3. Calculations of coffee water and irrigation requirements

The CROPWAT program (version 8) (FAO, 2018) was used to determine the potential crop water requirement (CWR) in Robusta coffee farms for each of the study provinces over 2008–2017. All the calculation procedures were based on Allen et al. (1998) and Steduto et al. (2012). The input data were daily climate data (maximum and minimum temperatures, relative humidity, rainfall, sunshine hours, and wind speed), soil data (available water capacity, field capacity, wilting point, and infiltration rate), coffee crop data (phenological stage duration, depletion coefficient, root depth, crop coefficient, yield response factor, and crop height), and observed irrigation data. Soil and crop data used in the calculations are presented in Table 1. Soil data were sourced from Vietnam Soils and Fertilizers Research Institute (http://www.sfri.org.vn). Coffee crop data were retrieved from Allen et al. (1998) and Steduto et al. (2012). Climate data at the district scale from 2008 to 2017 were retrieved from National Aeronautics and Space Administration (NASA)'s Tropical Rainfall Measuring Mission website (https://pmm.nasa.gov/trmm) for rainfall, and Prediction Of Worlwide Energy Resources website (https://power.larc.nasa.gov/) for the remaining climate variables (maximum and minimum temperatures, relative humidity, sunshine hours, and wind speed). The use of satellite-based weather data was justified by the lack of all variables required in CROPWAT at the district scale across the study provinces (only observed rainfall data were available for the majority of districts). Climate data at the district scale were used to take into account the spatial variability of data such as rainfall.

CWR, which corresponds to the amount of water that needs to be supplied to the crop, was calculated as $\mathrm{CWR} = \mathrm{ET}_0 \times \mathrm{K}_c$, where ET_0 refers to the reference crop evapotranspiration, and K_c is the crop coefficient. ET_0 was calculated using the FAO Penman-Monteith equation (Allen et al., 1998). CWR was computed under standard conditions, i.e. disease-free, non-limiting nutrient, and soil water conditions, and, as such, corresponds to the potential CWR. CWR and effective rainfall were calculated over January-April (JA) (to reflect the sensitive crop stages, as well as irrigation periods) and January-December periods. The irrigation water requirement during the JA period was then calculated as the difference between CWR and effective rainfall, and was

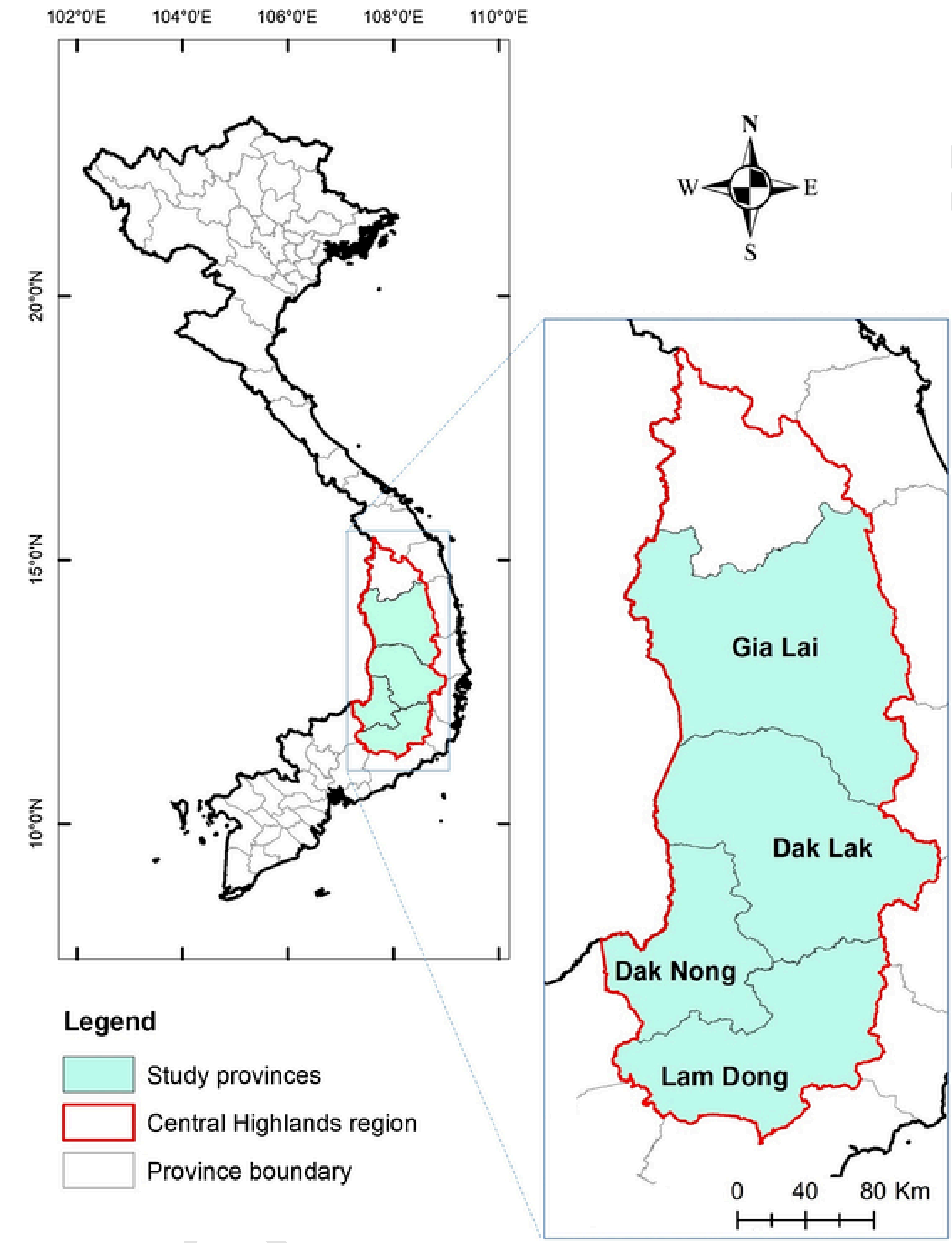

Fig. 1. Location of the study coffee-producing provinces in Vietnam. (Source: https://gadm.org/).

compared against the applied irrigation amounts for each Robusta coffee farm across the selected provinces. We assumed a seepage loss of 20 %, that is 80 % irrigation efficiency (Amarasinghe et al., 2015).

2.4. Empirical relationships between coffee yield and irrigation

Coffee yields were modelled using hierarchical Bayesian modelling, which included random effects to account for potential spatial and temporal correlations. The full model for response variable y (i.e. coffee yield) at site i at time j was as follows:

$$y_{ij} \sim N(\mu_{ij}, \sigma^2) \quad (1)$$

$$\text{With } \mu_{ij} = \alpha + \sum_{j=1}^{p} \beta_j x_{ij} + \varepsilon_{\text{year}[j]} + \varepsilon_{\text{site}[i]} + \varepsilon_i \quad (2)$$

where α is the intercept; β are the p linear effect parameters and x_{ij} are the (ith level of the jth covariate) p covariates. Error (ε) terms are random spatial effects for year and site, with each being modelled as identically and independently distributed random variables. ε_i are the residuals (i.e. the unstructured random effects).

The predictor variables or covariates were year (to detrend yields), JA effective rainfall, effective irrigation (effective irrigation is 80 % of the supplied irrigation, assuming 20 % as seepage loss) and fertilizer. Urea and NPK were the dominant chemical fertilizers applied in all four Robusta coffee-producing provinces during the study period (Byrareddy et al., 2020). Predictors were standardized ($x-\mu_x/\sigma_x$) so effect sizes could be compared (Gelman and Hill, 2007). Effective rainfall and effective irrigation were fit with a second-degree polynomial. Two-way interactions between predictors were included as well. All models were fit using the integrated nested Laplacian approxima-

Table 1
Soil and crop parameters used for the calculations in CROPWAT. Red loamy soils are found predominantly in Dak Lak, Dak Nong and Gia Lai; Grey loamy soils are found predominantly in Lam Dong. Soil data were sourced from the Vietnam Soils and Fertilizers Research Institute (SFRI) (http://www.sfri.org.vn). Crop parameters were retrieved from Allen et al. (1998); Steduto et al. (2012) and and Amarasinghe et al. (2015).

Soil parameter	Soil type			
	Red Loamy soil	Grey Loamy soil		
Total available soil moisture (mm m $^{-1}$)	180	160		
Initial available soil moisture (mm m $^{-1}$)	144	128		
Maximum rain infiltration rate (mm d $^{-1}$)	30	40		
Initial soil moisture depletion (%)	20	20		
Maximum rooting depth (m)	9	9		
Crop parameter	Crop stage			
	Initial	Development	Mid-season	Late season
Kc (-)	0.93	0.95	0.95	0.93
Stage (d)	85	85	85	110
Rooting depth (m)	1.5	1.5	1.5	1.5
Critical depletion fraction (-)	0.5	0.5	0.5	0.5
Yield response factor (-)	1	1	1	1
Crop height (m)	3	3	3	3

tion from the INLA package (Rue et al., 2009; Lindgren and Rue, 2015).

Using the model outputs, the potential yield gain corresponding to the amount of irrigation that needs to be applied in order to achieve the maximum possible yield was investigated for each province. We further assessed the potential for improved irrigation management strategies for each province. Based on the ranges of reported Robusta coffee yields, irrigation amounts, and calculated CWR, two scenarios for coffee yields - average and locally feasible (hereafter referred to as recommended yield) - were analysed for different categories of irrigation amounts and induced water stresses. All data and statistical analyses were performed using R (R Core Team, 2018).

3. Results

3.1. Climate patterns and irrigation practices across the study provinces during 2008–2017

Overall, the total annual rainfall varied between 900 and 2600 mm in all study provinces during 2008–2017, with lower amounts recorded in 2014 (Fig. 2a). Increasing annual rainfall was recorded between 2008–2010 and 2014–2017 in the majority of the provinces; the exception was Lam Dong where the annual rainfall decreased between 2008 and 2009. Dak Lak and Gia Lai received less rainfall on average than Dak Nong and Lam Dong. Dak Nong and Gia Lai experienced more dry years during the 2008–2017 period (7 out of 10 years) than Lam Dong or Dak Lak (Table 2). In Dak Lak, years were particularly dry during 2015–2017. In Lam Dong, rainfall patterns were predominantly normal over the study period. Focusing on the critical Robusta coffee growth period of January-April, less than 600 mm rainfall were recorded generally in all provinces, with even lower amounts (< 200 mm) at Gia

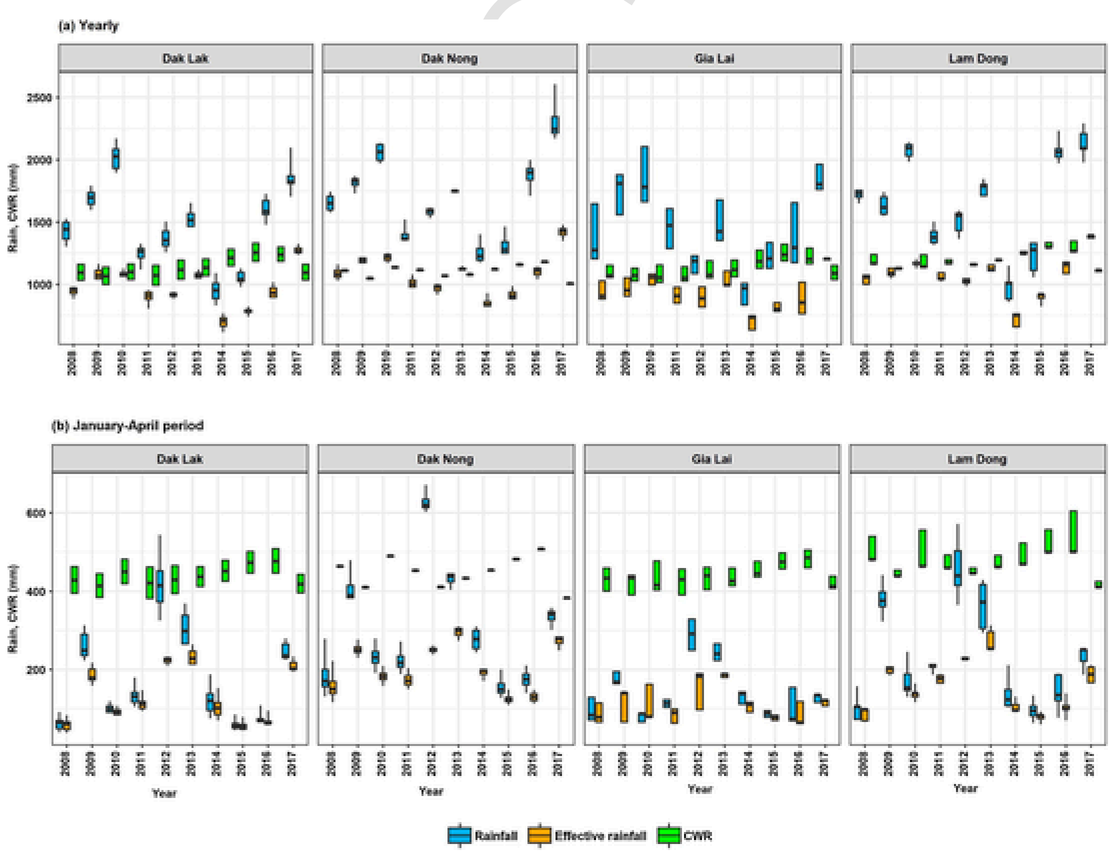

Fig. 2. Boxplots of the yearly (**a**) and January to April (**b**) rainfall, effective rainfall and crop water requirement (CWR) during 2008–2017 for each of the study provinces. Upper and lower border of the boxes represent the 3rd and 1st quartile, respectively. The line within the box represents the median value. Bars extend to the minimum and maximum values. CWR and effective rainfall estimates were calculated using CROPWAT. Note the low variations of CWR values for Dak Nong (both periods) and Lam Dong (yearly).

Table 2
Rainfall patterns across the districts in the selected Robusta coffee-producing provinces during 2008–2017. Rainfall records from 1985 to 2014 were used. For the January-December period, dry (D) -(below-average-rainfall condition), normal (N) -(average-rainfall condition) and wet (W) -(above-average-rainfall condition) years correspond to years belonging to percentiles 0–30, 30–70, and 70–100, respectively. Likewise, for the January-April period, below-average (BA), average (A) and above-average (AA) years correspond to years belonging to percentiles 0–30, 30–70, and 70–100, respectively.

		January-December										January-April									
Province	District	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Dak Lak	Buon Ma Thuot	D	N	N	D	D	D	D	D	D	N	BA	AA	BA	BA	AA	AA	BA	BA	BA	A
	Cu Mugar	D	N	N	D	D	D	D	D	D	N	BA	AA	BA	BA	AA	AA	BA	BA	BA	A
	Krong Ana	D	N	N	D	D	D	D	D	D	N	BA	A	BA	BA	AA	AA	BA	BA	BA	A
	Krong Buk	D	N	N	D	D	D	D	D	N	N	BA	AA	BA	BA	AA	AA	BA	BA	BA	AA
	Krong Nang	D	D	W	D	D	D	D	D	D	N	BA	AA	BA	BA	AA	AA	BA	BA	BA	AA
	Krong Pak	D	N	N	D	D	D	D	D	N	N	BA	AA	BA	A	AA	AA	BA	BA	BA	A
Dak Nong	Dak GLong	D	D	N	D	D	D	D	D	N	N	BA	A	BA	BA	AA	AA	BA	BA	BA	A
	Dak Mil	D	N	N	D	D	D	D	D	D	N	BA	AA	BA	BA	AA	AA	A	BA	BA	A
	Dak RLap	D	D	N	D	D	D	D	D	N	W	BA	AA	BA	BA	AA	AA	A	BA	BA	A
	Dak Song	D	N	N	D	D	D	D	D	N	N	BA	A	BA	BA	AA	AA	A	BA	BA	A
Gia Lai	Chu Prong	D	D	N	D	D	D	D	D	D	N	BA	AA	BA	A	AA	AA	A	BA	BA	A
	Dak Doa	D	N	N	D	D	D	D	D	D	N	BA	A	BA	BA	AA	AA	A	BA	A	A
	Ia Grai	D	N	D	D	D	D	D	D	D	N	BA	AA	BA	A	AA	AA	A	BA	BA	A
Lam Dong	Bao Lam	D	D	N	D	D	D	D	D	N	N	BA	AA	A	BA	AA	AA	BA	BA	BA	A
	Bao Loc	D	D	N	D	D	D	D	D	W	W	BA	AA	BA	A	AA	AA	BA	BA	BA	A
	Di Linh	D	D	W	D	D	N	D	D	W	W	BA	AA	BA	A	AA	AA	BA	BA	BA	A
	Duc Trong	D	D	W	D	D	N	D	D	N	N	BA	AA	BA	A	AA	AA	BA	BA	BA	A
	Lam Ha	D	D	N	D	D	N	D	D	N	N	BA	AA	BA	BA	AA	AA	BA	BA	BA	A

Source: NASA's Tropical Rainfall Measuring Mission and Prediction Of Worlwide Energy Resources website (https://pmm.nasa.gov/trmm).

Lai in 9 out of 10 years (Fig. 2b). For this province JA average rainfall during 2008–2017 was only 144 mm, compared to Dak Nong which received around 270 mm on average during the same period if the 2012 exceptional JA rainfall (Fig. 2b) is discarded in the calculations.

Irrigation was applied one to four times per year during 2008–2017 across the Robusta coffee-producing provinces (Table 3; Table S1). The volumes differed significantly between provinces depending on the year ($p < 0.05$; Table S1). Plant densities in the surveyed farms were on average 1100 trees ha^{-1}. Dak Lak and Gia Lai were the provinces with higher irrigation amounts (on average 1345 and 1445 L $tree^{-1}$ $year^{-1}$ (148 and 159 mm $year^{-1}$), respectively), compared to Dak Nong and Lam Dong (on average 973 and 918 L $tree^{-1}$ $year^{-1}$ (107 and 101 mm $year^{-1}$), respectively) (Table 3). In the majority of years the amounts applied in Dak Lak and Gia Lai were statistically similar ($p > 0.05$). Likewise, the amounts applied in Dak Nong and Lam Dong did not differ statistically (Table S1). The irrigation amounts reported also varied depending on rainfall patterns during January-April. For instance in 2012 or 2017, irrigation was predominantly applied in January-February (2012) or February (2017) in all provinces, with amounts ranging between (327 and 382 L $tree^{-1}$) 36 and 42 mm $year^{-1}$. Only in Gia Lai did some farmers irrigated from January to March (Table S1).

3.2. Comparisons between irrigation requirements and water input (rainfall and irrigation)

CWRs were greater than effective rainfall during the JA period in all the study provinces, and varied on average between 380 and 570 mm (5%–51% of CWR satisfied; Fig. 2b). Given coffee plants require a period of induced water stress (Carr, 2001), the irrigation amount and frequency need to be managed accordingly by farmers. The percentages

Table 3
Mean irrigation amounts (Irrig. app.), irrigation water requirement (IWR) and crop water satisfaction (WS) during the January-April period for selected Robusta coffee-producing provinces in Vietnam during 2008–2017. IWR was calculated as the difference between crop water requirement (CWR; calculated using CROPWAT (See section 2.3)) and effective rainfall. WS was the ratio between water input (effective rainfall + irrigation supplied) and potential crop water requirement. Numbers in parentheses are the standard deviations.

	Variables	Units	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Dak Lak	IWR	mm	369 (44)	229 (46)	358 (32)	307 (55)	205 (39)	204 (42)	347 (48)	416 (32)	408 (39)	210 (31)
(N = 180)	Irrig. round	(n)	4	3	4	4	2	4	4	4	3	1
	Irrig. app.	mm	189 (10)	144 (7)	189 (10)	189 (10)	85 (4)	185 (10)	174 (10)	172 (8)	114 (9)	36 (3)
	WS	%	50	73	55	64	69	88	54	41	34	57
Dak Nong	IWR	mm	304 (39)	158 (18)	307 (18)	278 (20)	159 (9)	137 (14)	261 (12)	356 (15)	377 (13)	110 (15)
(N = 120)	Irrig. round	(n)	3	3	2	3	2	3	3	3	2	1
	Irrig. app.	mm	136 (22)	126 (11)	77 (9)	137 (21)	77 (7)	134 (21)	123 (21)	127 (21)	86 (19)	39 (5)
	WS	%	58	86	50	63	76	93	64	47	39	79
Gia Lai	IWR	mm	342 (43)	304 (48)	357 (28)	328 (31)	246 (27)	246 (22)	345 (28)	398 (15)	399 (44)	302 (12)
(N = 93)	Irrig. round	(n)	4	3	4	4	3	4	4	4	3	2
	Irrig. app.	mm	191 (10)	145 (7)	191 (10)	191 (10)	131 (6)	186 (10)	176 (10)	173 (7)	113 (9)	93 (6)
	WS	%	56	56	53	59	68	78	55	45	36	46
Lam Dong	IWR	mm	419 (22)	246 (5)	365 (47)	296 (26)	223 (9)	204 (36)	387 (36)	445 (27)	443 (58)	230 (25)
(N = 165)	Irrig. round	(n)	3	3	2	3	2	3	3	3	2	1
	Irrig. app.	mm	124 (18)	124 (18)	83 (12)	125 (17)	80 (8)	122 (15)	118 (13)	98 (25)	76 (9)	36 (3)
	WS	%	37	67	41	59	65	78	41	30	30	49

of crop water satisfaction during 2008–2017, expressed as the ratio between water input (sum of JA effective rainfall and irrigation) and CWR, varied between 34–88 %, 39–93 %, 36–78 %, and 30–78 %, for Dak Lak, Dak Nong, Gia Lai, and Lam Dong, respectively, depending on the year (Table 3).

From the engagement with farmers during the survey, irrigation plans (e.g., when to start and how much and how often to irrigate) were typically made based on rainfall during November-December of the previous year, as well as JA rainfall patterns. Analysing the data according to rainfall patterns during January-April show that farmers in Gia Lai generally supplied a similar amount of irrigation in above-average and average seasons (Table 4). In the remaining provinces (Dak Lak, Dak Nong and Lam Dong) the mean irrigation amounts applied during above-average JA periods were relatively higher than those in average JA periods. However, such variations have to be interpreted cautiously, particularly in Dak Lak and Lam Dong where the number of surveyed districts experiencing average rainfall conditions during January-April represented less than the third of the total cases during 2008–2017 (Table 2). The relatively high irrigation amounts recorded during above-average JA rainfall conditions in provinces like Dak Lak or Gia Lai is because in those years rainfall was received towards the end of April. Above-average JA rainfall conditions were recorded across all provinces in 2012 and 2013 (Table 4), with irrigation limited only to January-February in 2012 (irrigation was also applied in March at Gia Lai) (Table S1). However in 2013 the total amount of irrigation applied was among the highest during the study period, regardless of the province; suggesting that farmers were rather adopting a no-risk behaviour even though rainfall patterns seem favourable (Table S1). High irrigation amounts did not result necessarily in higher Robusta coffee yields (Table 4). For example in Dak Nong, Robusta coffee yields were similar in both average or above-average years, although more irrigation was supplied in above-average years.

3.3. Relationships between irrigation and Robusta coffee yields

Since the yield is the result of all processes occurring during the growth cycle and given fertilizer application was not limited to January to April, the year classification based on total annual rainfall (Table 2) was used in the modelling approach. Year-to-year coffee yield variability is provided in Fig. S1. The relationships between coffee yield and each of the predictors varied according to the rainfall patterns (Fig. 3). Effective irrigation and JA effective rainfall strongly influenced coffee yield in Dak Lak in dry years (Fig. 3b). Likewise, in Gia Lai irrigation influenced Robusta coffee yields positively in dry years, though marginally compared to Dak Lak. In normal years in Dak Lak, JA effective rainfall influence on yield was low; but irrigation tended to negatively impact on yields (Fig. 3a). Such adverse impact of irrigation on yield in normal years was also found in Dak Nong and Gia Lai. In Dak Nong, in normal years, or in Lam Dong, in dry years many predictors influenced robusta coffee yield in a similar way (Fig. 3).

Within the limits of rainfall conditions observed during the study period, we analysed the variations of Robusta coffee yield according to the interaction between effective irrigation and JA effective rainfall. In normal years, a combination of higher effective rainfall and irrigation often had no effect on coffee yields and / or was detrimental (Fig. 4a). This is because the water stress induced from effective rainfalls in those years were beneficial to yields. In Dak Lak and Dak Nong, the highest coffee yields were found at effective rainfall levels ≥ 200 mm (Dak Lak) or ≥ 300 mm (Dak Nong) and effective irrigation ≤ 40 mm (≤ 364 L tree^{-1}). In these provinces, the lowest yields were found predominantly under a combination of high effective rainfall and high effective irrigation. In Gia Lai effective rainfall ranging from ~125 to 175 mm (~1136–1591 L tree^{-1}) coupled with an effective irrigation ≤ 75 mm (≤ 682 L tree^{-1}) resulted in the highest coffee yields (Fig. 4a). An, exception to these patterns was observed for Lam Dong where highest coffee yields seemed to result from combined high effective rainfall and effective irrigation in normal years (Fig. 4a). In dry years there was an increase in coffee yields for increased irrigation in Dak Lak and Gia Lai (Fig. 4b). In Lam Dong low yields were associated with higher effective irrigation (> 90 mm (> 818 L tree^{-1})); higher yields, however, were recorded for effective irrigation levels < 90 mm (< 818 L tree^{-1}) (Fig. 4b).

The analysis of potential yield gain to additional irrigation (Fig. 5) shows that, overall, the potential yield gain was up to 180 and 410 kg ha^{-1} in normal and dry years, respectively. In normal years yield gains in Lam Dong were up to 180 kg ha^{-1} for additional irrigation up to 60 mm (545 L tree^{-1}) (Fig. 5a). The gain was marginal (< 40 kg ha^{-1}) in Dak Lak for additional irrigation up to 40 mm (364 L tree^{-1}), but no yield gain afterwards. Additional irrigation did not result in coffee yield gain in Dak Nong or Gia Lai. In dry years (Fig. 5b), there was a strong yield gain for additional irrigation in provinces such as Dak Lak and Gia Lai, which typically received less rainfall. Indeed, the gain in Gia Lai was up to 405 kg ha^{-1} for additional irrigation ranging from 20 to 80 mm (182–727 L tree^{-1}). In Dak Nong, such gain was marginal (up to 50 kg ha^{-1}), whereas there was no gain in Lam Dong (Fig. 5b).

3.4. Potential for improved irrigation management strategies

Based on the ranges of Robusta coffee yields across the selected provinces, we investigated the variation of irrigation supply (< 50 mm (< 455 L tree^{-1}), 50–100 mm (455–909 L tree^{-1}), 100–150 mm (909–1364 L tree^{-1}) and 150–200 mm (1364–1818 L tree^{-1})) at different levels of Robusta coffee yields for each of the provinces. In Dak Nong and Lam Dong the majority of coffee farmers supplied 455–909 L tree^{-1} in normal years, with corresponding average yields ranging from 2149 to 3177 kg ha^{-1} (Table 5). In dry years, the predominant range of irrigation supply was 909–1364 L tree^{-1}. In both provinces higher coffee yields (> 3000 kg ha^{-1}) were also reported for irrigation supply < 455 L tree^{-1} in normal years, or between 455–909 L tree^{-1} in dry years; suggesting a potential for reducing irrigation supply while achieving better yield levels. Similar conclusions can be drawn for Dak Lak and Gia Lai in normal years. In Dak Lak farmers applying higher amounts (1364–1818 L tree^{-1}) could reduce the supply to (909–1364 L tree^{-1}) or even < 455 L tree^{-1}, and still achieve the same level of yield. Likewise, in Gia Lai, there were cases where yields > 3000 kg ha^{-1} were achieved with (455–909 L tree^{-1}) irrigation (Table 5). In dry years the pattern in these two provinces was slightly different in terms of irrigation amounts and corresponding yields > 3000 kg ha^{-1}. Although the predominant irrigation supply in both provinces was

Table 4
Mean irrigation amounts and Robusta coffee yields according to January-April rainfall patterns for each of the study provinces in Vietnam during 2008–2017. For a given category, the means were calculated with all years belonging to that category. Refer to Table 2 for year classification. Numbers in parentheses are the standard deviations.

Year classification	Below-average rainfall		Average rainfall		Above-average rainfall	
	Irrigation (mm)	Yield (kg ha^{-1})	Irrigation (mm)	Yield (kg ha^{-1})	Irrigation (mm)	Yield (kg ha^{-1})
Dak Lak	171 (29)	2380 (47)	80 (64)	2540 (447)	127 (51)	2499 (503)
Dak Nong	113 (32)	2465 (435)	87 (46)	2556 (522)	110 (31)	2530 (486)
Gia Lai	174 (29)	2462 (451)	144 (41)	2744 (434)	155 (26)	2639 (564)
Lam Dong	103 (25)	2790 (498)	80 (43)	3056 (390)	109 (25)	2800 (499)

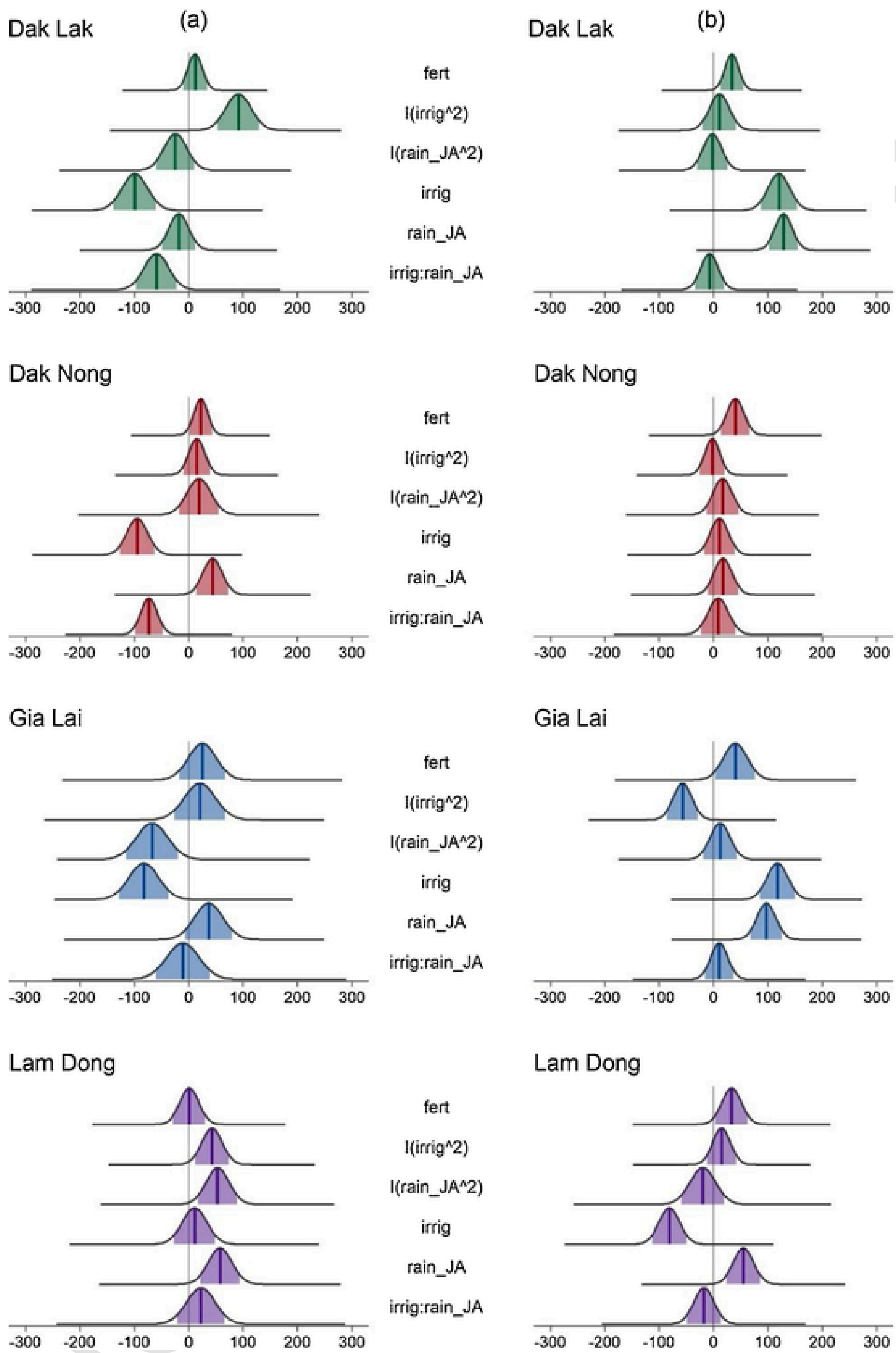

Fig. 3. Standardised parameter estimates of model predictors. The model for each of study provinces was determined using data for normal (**a**) and dry (**b**) years separately (see Table 2 for year classification). *fert, irrig* and *rain_JA* refer to fertilizers (urea + NPK), effective irrigation supplied (80 % of the reported supply) and effective rainfall during January-April, respectively; *I(irrig^2)* and *I(rain_JA^2)* correspond to the square value of *irrig* and *rain_JA*, respectively; and *irrig:rain_JA* is the interaction between *irrig* and *rain_JA*.

1364–1818 L tree^{-1}, only in Dak Lak irrigation water of 455–909 L tree^{-1} can be applied and result in such high yields. In Gia Lai, during dry years high irrigation was often associated with higher yields and so the potential of irrigation reductions during dry conditions may be limited (Table 5).

With the aim of finding out which satisfactory and recommended yield levels can be achieved while reducing irrigation supplies, we further evaluated the effect of induced water stress on coffee yields based on the calculated CWR (Fig. 6). For recommended coffee yield set to 3000 kg ha^{-1}, there could be generally a reduction of 30–59 mm (273–536 L tree^{-1}) of irrigation supply from current levels applied (80–159 mm (727–1445 L tree^{-1})) to reach the average yields in normal years. In Dak Lak a farmer with a current yield level of 2540 kg ha^{-1} and irrigation supply of 80 mm (727 L tree^{-1}) can reduce this supply to 50 mm (455 L tree^{-1}) (through an increase of induced water stress) and reach 3000 kg ha^{-1}. The highest potential reduction of irri-

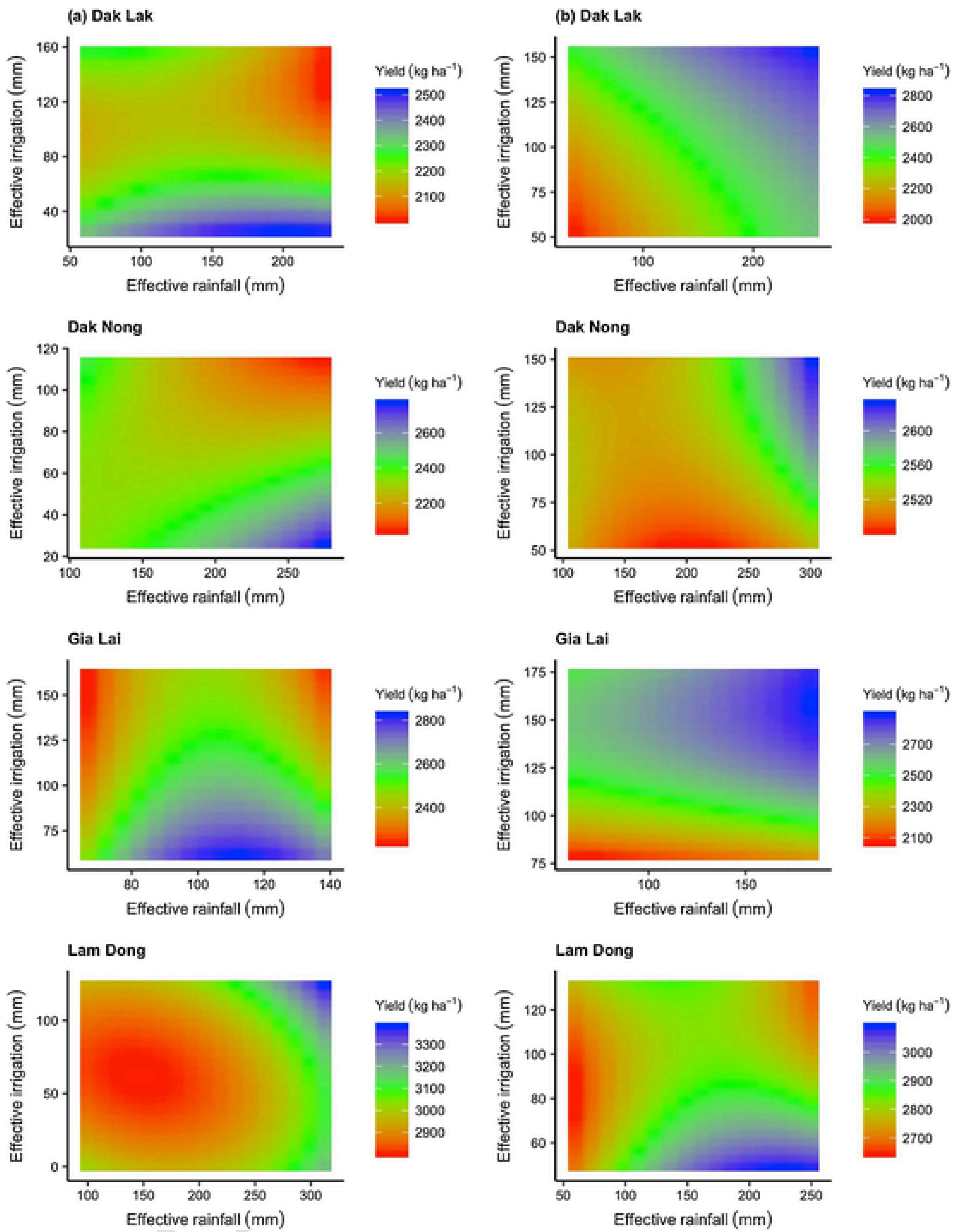

Fig. 4. Variation of Robusta coffee yield according to the effective rainfall during January-April and effective irrigation for each of the study provinces during normal (**a**) and dry (**b**) years (See Table 2 for year classification). The effective irrigation was assumed as 80 % of the irrigation supplied. (Note different ranges on x and y axes.).

gation was found for Gia Lai during normal years, resulting in 9% increase in yield from average to recommended yield levels (Fig. 6).

In dry years reducing irrigation supply from 3 to 24 mm (27–218 L tree^{-1}) can occur while still achieving yield levels of around 3000 kg ha^{-1}, although this does vary between provinces. Gains in yield from current average levels to locally recommended levels while reducing irrigation supply varied depending on the province: 5%–18% in normal years and 7%–26% in dry years, with lower and higher percentages found in Lam Dong and Dak Lak, respectively, in both year categories (Fig. 6).

4. Discussion

We analysed the potential for improved irrigation management practices in four major Robusta coffee producing provinces in Vietnam. The surveyed coffee farmers applied variable irrigation amounts depending on the province, with similarities of practices found in provinces presenting similar rainfall patterns (Dak Lak and Gia Lai on one side, and Dak Nong and Lam Dong on the other). Compared to the official amount recommended (132 mm year^{-1} (1200 L tree^{-1}); MARD (2016)), irrigation supplies were generally greater than this threshold

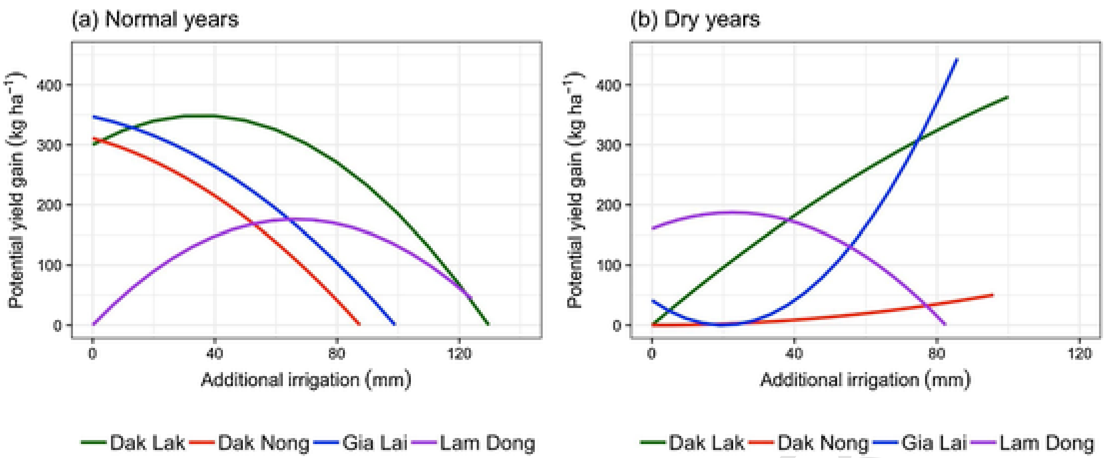

Fig. 5. Potential Robusta coffee yield gain versus additional irrigation as observed during 2008–2017 for each of the study provinces in normal (**a**) and dry (**b**) years (see Table 2 for year classification).

in surveyed farms across Dak Lak and Gia Lai; lesser or similar irrigations amounts than the threshold were applied in the remaining provinces Dak Nong and Lam Dong (Table 3). The relatively low annual rainfall received in Dak Lak and Gia Lai can justify the relatively high irrigation water supplies in these provinces. Other reasons could be the biased assumption persisting in the mindset of some farmers that the more irrigation you supply the higher your coffee yields, and the slow adoption of new official recommendations. The previous official recommendation for irrigation amount was 650 L tree^{-1} round^{-1} in three rounds yearly, that is 215 mm year^{-1} (Cheesman et al., 2007). In line with D'haeze et al. (2003) or Amarasinghe et al. (2015) who highlighted over-irrigation practices in Dak Lak, our results indicate that such practices have not changed over years.

Irrigation during January-April impacted positively Robusta coffee yields in dry years; but an excessive water supply resulted in adverse effects in normal years, which is in line with the conclusions of D'haeze (2008) and Amarasinghe et al. (2015). The first irrigation is supplied for inducing and synchronous flowering in case rainfall is delayed, and maximize the potential yield. The exception found in Lam Dong in normal years (highest coffee yields associated with combined high effective rainfall and effective irrigation; Fig. 4a) could be explained by the adoption of the grafting technique in that province over the last five years. Through grafting the number of productive branches are increased. With such increase in productive branches, high coffee yields would be achieved with high irrigation supplies under good rainfall conditions. Our study also shows that there is a potential of reducing irrigation supply to 273–536 L tree^{-1} (30–59 mm) annually from the current levels in normal years and achieve yield levels of > 3000 kg ha^{-1} (Fig. 6). In dry years that reduction could be 27 - 218 L tree^{-1} (3–24 mm). Assuming a density of 1100 plants ha^{-1}, such savings in normal years are equivalent to 300–590 m^3 ha^{-1} (30–240 m^3 ha^{-1} in dry years) depending on the provinces. These amounts can also vary according to the irrigation method since in our study the sampling was carried out in order to represent equally basin and sprinkler irrigation methods. Nonetheless, with the study provinces having coffee areas ranging from 80,000 ha (Gia Lai) to 202,000 ha (Dak Lak) (GSOV, 2017), the irrigation water savings could be noticeable at the provincial scale. The adoption of smart watering technology for irrigation could also help in water savings, along with labour and energy for coffee farmers. It is important to stress that reaching the locally recommended yield levels cannot not be possible without managing properly the other crop practices affecting Robusta coffee yields (e.g., fertilization, pruning, etc.). Hence, the need to build or reinforce the capacity of farmers about those aspects too.

Given the dependency of Robusta coffee production on irrigation supplies in dry seasons in Vietnam, climate variability can notably influence both seasonal irrigation planning and day-to-day irrigation scheduling. Robusta coffee farmers in the study provinces typically made their irrigation schedules based on rainfall during November-December of the previous year, as well as January-April rainfall patterns. Although the study period spanned 10 years, and above-average January-April rainfall patterns were found during two to three years across the selected provinces (Table 2), the change in irrigation supplies between 2012 and 2013 (years both ranked as above-average January-April period on records) highlight the potential of using seasonal climate forecasts (SCF) to aid in irrigation planning. The beneficial use of SCF in decision-making on farms have been demonstrated for cereals, cotton and sugar (see for examples Meinke and Stone (2005)). Integrating local SCF to coffee production modelling would potentially help increase the preparedness of Robusta coffee farmers in terms of irrigation activities.

5. Conclusion

The climate variability and over-use of water for irrigating Robusta coffee in Vietnam poses several threats including the reduction of coffee yield and product quality, reduction of ground and surface water resources, with the corollary of limiting water supply for household consumption and for the production of hydropower. It could also affect other agricultural water users, such as irrigated rice farming. Ensuring better irrigation management strategies should become an integral part of farm management system in Robusta coffee, so that positive environmental and socio-economic benefits can be established throughout the coffee supply chain for consistent and sustainable production. As such, the findings of our study are a good start and could help guide further investigations for improved province-specific irrigation water management in Robusta coffee farms in Vietnam. Increasing farmers' awareness about environmental issues related to excessive irrigation in coffee farms and reinforcing/building their capacity on best irrigation practices are therefore important for water conservation and sustainable coffee production in the study provinces.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Table 5
Variation in Robusta coffee yields under different levels of irrigation supply for each of the study provinces in Vietnam.

	Irrigation application levels (mm)							
	Summaries of dry years				Summaries of normal years			
	< 50	50–100	100–150	150–200	< 50	50–100	100–150	150–200
Dak Lak								
A. Sample distribution (no)								
> 3000		22	5	207	31		4	2
2500–3000		73	40	339	112		30	27
2100–2500		73	103	248	35		95	87
≤ 2000		13	26	81	2		79	36
B. Average yield (kg ha $^{-1}$)								
> 3000		3239	3000	3166	3101		3000	3000
2500–3000		2649	2564	2652	2662		2593	2586
2100–2500		2242	2187	2224	2275		2149	2186
≤ 2000		1752	1723	1697	1730		1649	1679
Dak Nong								
A. Sample distribution (no)								
> 3000		18	130	25	45	7	2	
2500–3000		64	223	44	40	53	13	
2100–2500		46	147	31	5	134	22	
≤ 2000		9	63	10		22	17	
B. Average yield (kg ha $^{-1}$)								
> 3000		3237	3135	3204	3123	3151	3145	
2500–3000		2637	2651	2654	2667	2623	2673	
2100–2500		2172	2193	2189	2226	2187	2142	
≤ 2000		1681	1659	1639		1751	1614	
Gia Lai								
A. Sample distribution (no)								
> 3000			37	164		55	6	2
2500–3000		2	87	181		33	11	14
2100–2500			82	107		3	22	34
≤ 2000			18	24			25	12
B. Average yield (kg ha $^{-1}$)								
> 3000			3116	3203		3214	3073	3165
2500–3000		2605	2635	2671		2752	2601	2541
2100–2500			2193	2190		2320	2069	2168
≤ 2000			1692	1770			1716	1770
Lam Dong								
A. Sample distribution (no)								
> 3000		218	254	4	75	76	69	4
2500–3000		93	190		18	59	23	
2100–2500		46	215	8	1	48	1	
≤ 2000		5	26			9		
B. Average yield (kg ha $^{-1}$)								
> 3000		3255	3258	3365	3253	3177	3272	3633
2500–3000		2727	2719		2754	2695	2738	
2100–2500		2216	2248	2229	2400	2149	2400	
≤ 2000		1640	1585			1744		

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106350.

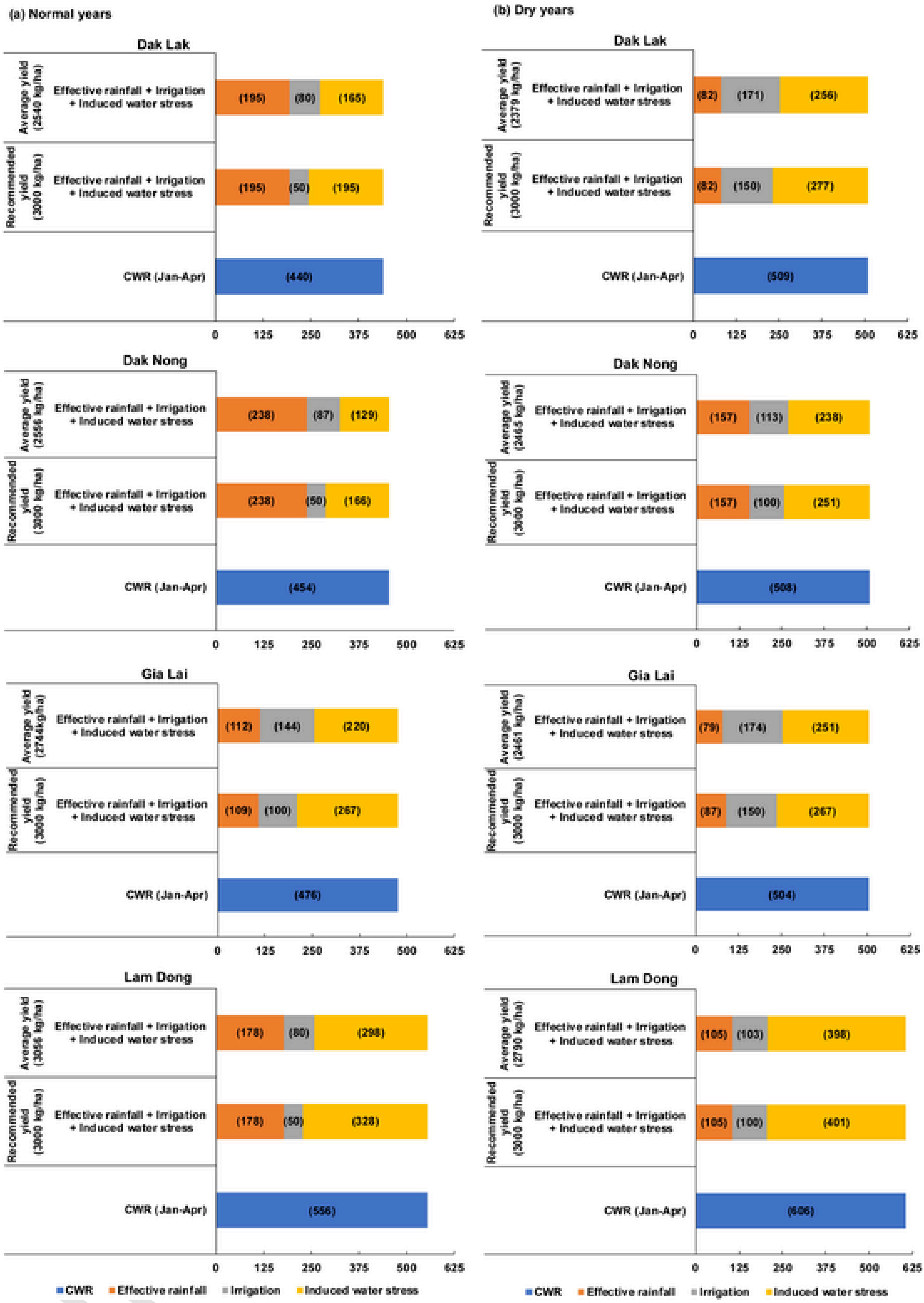

Fig. 6. Variations of effective rainfall, irrigation and induced water stress under different Robusta coffee yield scenarios in Dak Lak, Dak Nong, Gia Lai and Lam Dong for normal (**a**) and dry (**b**) years (see Table 2 for year classification). *CWR* correspond to the potential crop water requirement during January-April. CWR and Effective rainfall estimates were calculated using CROPWAT.

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