The use of ecoclimatic indicators as a strategy to take into account the effects of repeated heat waves in oilseed rape performance predictions

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AGROCLIMATIC CONTEXT

Global warming projections

Global warming leads to both an increase in climate time-scale averages, and an increased probability of occurrence of extreme events, such as heat waves (Fig. 1). Heat waves are expected to become **more frequent, to last longer and to increase in intensity** during the reproductive phase of economically important crops, such as oilseed rape (Magno et al., 2021).

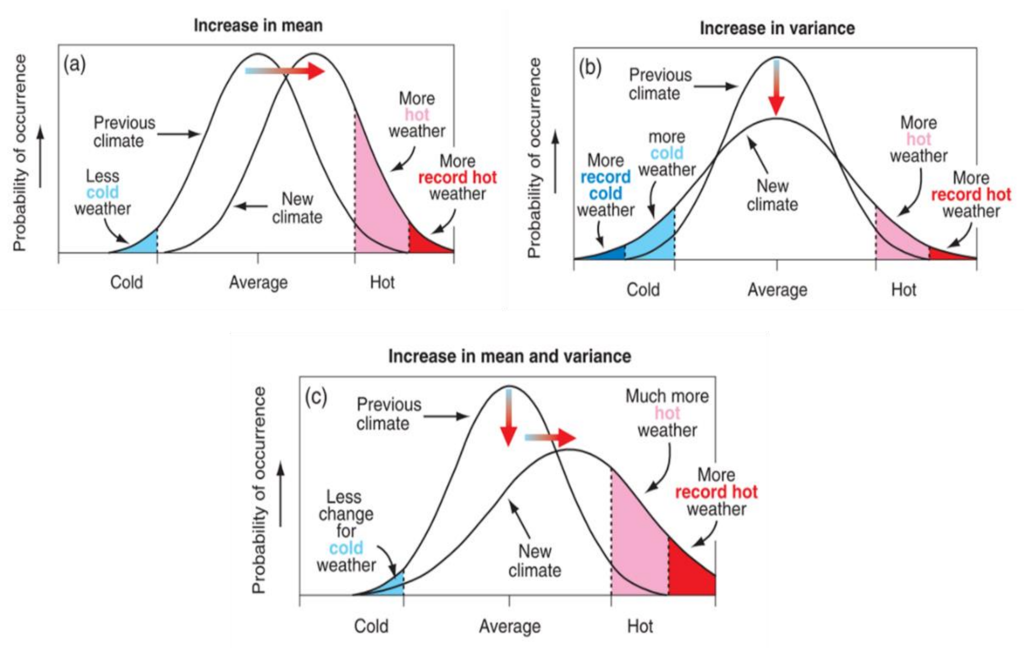


Fig. 1 : Illustrative diagram of extreme temperatures tendencies (Griggs and Noguer, 2002).

Stress memory concept

Recent studies pointed out the **beneficial stress memory effects** that can be induced when plants are exposed to abiotic stresses several times during their crop cycle. The effects of a previous exposure to similar stresses are potentially beneficial since the plants are more prepared/primed to recover when the stress recurs (Fig. 2).

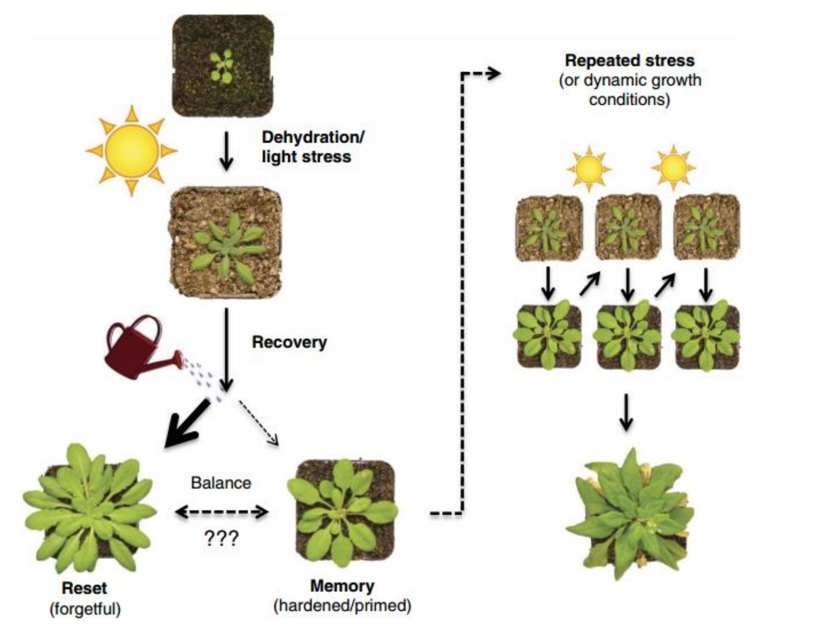


Fig. 2 : Beneficial stress memory effect illustrated for water stress (Crisp et al., 2016).

OBJECTIVES

The effects of several successive stressing events do not equal the sum of the effects of each individual event, thus leading to unexpected crop responses to repeated stresses

$$Effet1 + Effet2 + \cdots + Effet\,k \neq \sum_{k=0}^{n} Effet\,k$$

How to address stress memory in predictive crop modelling approaches, with the aim of better estimating the effects of repeated stresses on crop yield and quality of harvested products?

STEP 1: Define agroclimatic indicators based on the specific physiological stages of development of each crop species (i.e. ecoclimatic indicators, Caubel et al., 2015)

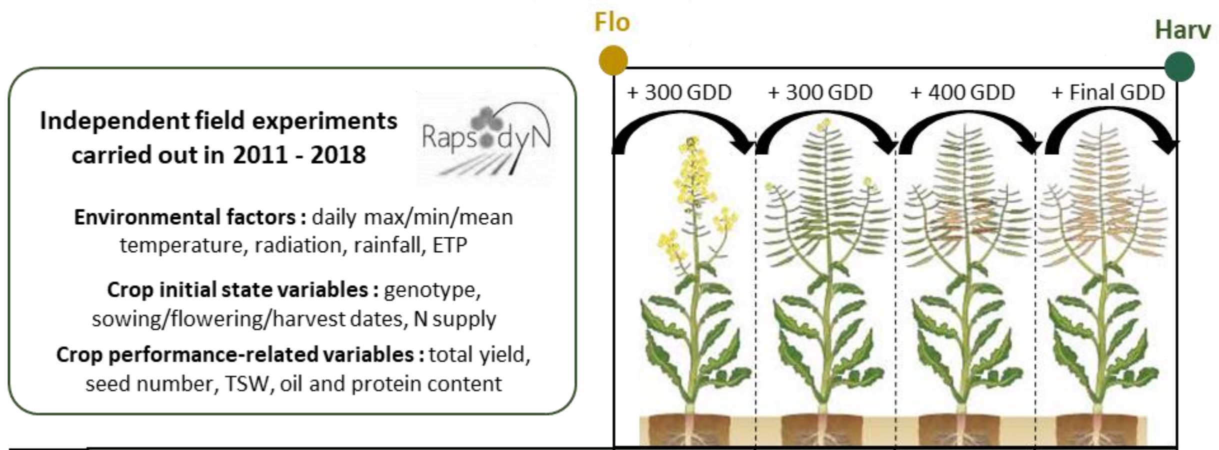
STEP 2: Test several combinations of ecoclimatic indicators to find the best fit predictive models of the final crop performance-related variables

STEP 1

Ecoclimatic indicators

The ecoclimatic indicators were defined based on large datasets in winter oilseed rape acquired from PIA Rapsodyn. The original datasets were composed of **weather data and crop performance-related variables** (i.e. yield, oil and protein contents) measured in 26 combinations of location x year in France (Corlouer et al., 2019).

The definition of the ecoclimatic indicators required two major steps: (i) **the plant cycle was divided into four intervals** after flowering, according to the physiological stages of development in oilseed rape (i.e. P300, P600, P1000, Pharv); and (ii) the **number of warm days** (i.e. with daily maximum temperature above 25°C and 30°C) was scored during the cycle and in each interval, thus resulting in 10 ecoclimatic indicators (Fig. 3).



Key periods	Physiological stages in the oilseed rape growth cycle	P300 Seed number fixation	P600 Allocation to pods growth	P1000 Allocation to seeds growth	Pharv Seed maturation
Ecoclimatic indicators	Number of days with Tmax > 25°C (in intervals)	P300_25	P600_25	P1000_25	Pharv_25
	Number of days with Tmax > 30°C (in intervals)	P300_30	P600_30	P1000_30	Pharv_30
	Number of days with Tmax > 25°C (in total)	Ptot_25			
	Number of days with Tmax > 30°C (in total)	Ptot_30			

Fig. 3 : Simplified scheme of oilseed rape growth stages after flowering, displaying the physiological intervals based on key periods (in green). Ten ecoclimatic indicators were defined (in gray) : eight of them based on the physiological intervals and the two others considered the whole period from flowering until harvest.

STEP 2

Best fit models

Statistical models were developed to look for predictive correlations between the ecoclimatic indicators and the crop performance-related variables (Fig. 3).

For this purpose, (i) several models that differed from the **combination of ecoclimatic indicators** were tested; and (ii) the **best fit predictive models** of each crop performance-related variables (Table 1) were selected based on the Akaike Information Criterion (AIC), as performed in Akmouche et al. (2019).

Table 1 : Summary of the r-squared and p-value of the three fit models used to predict each of the 5 final performance-related variables. P300_30 and P600_30 were not taken into account in the composition of the models because their value was zero. Levels of significance were p < 0.05*, p < 0.01** and p < 0.001***

Variables	Model 1		Model 2		Model 3	
	r-squared	p-value	r-squared	p-value	r-squared	p-value
Seed yield	0.092	0.000 ***	0.134	0.000 ***	0.545	0.000 ***
Seed number	0.071	0.014 *	0.423	0.000 ***	0.652	0.000 ***
Thousand Seed Weight	0.244	0.000 ***	0.562	0.000 ***	0.658	0.000 ***
Seed lipid concentration	0.221	0.000 ***	0.458	0.000 ***	0.582	0.000 ***
Seed protein concentration	0.116	0.000 ***	0.380	0.000 ***	0.511	0.000 ***

The tested models were the following ones:

Model 1: Final variable = Ptot_25 + Ptot_30

Model 2: Final variable = P300_25 + P600_25 + P1000_25 + P1000_30 + Pharv_25 + Pharv_30

Model 3: Final variable = Model 2 + interactions between early (i.e. P300 and P600) and late (i.e. P1000 and Pharv) indicators

Model 1, which considers the sum of stressful events over the whole period, was the least predictive model for all plant variables. The predictive power was doubled when considering ecoclimatic indicators (i.e. Model 2), and even better with Model 3 which took into account their interactions.

IMPACTS ON SEED QUALITY

Early indicators had more negative effects in oil content ✖ **Late indicators had more negative effects in protein content**

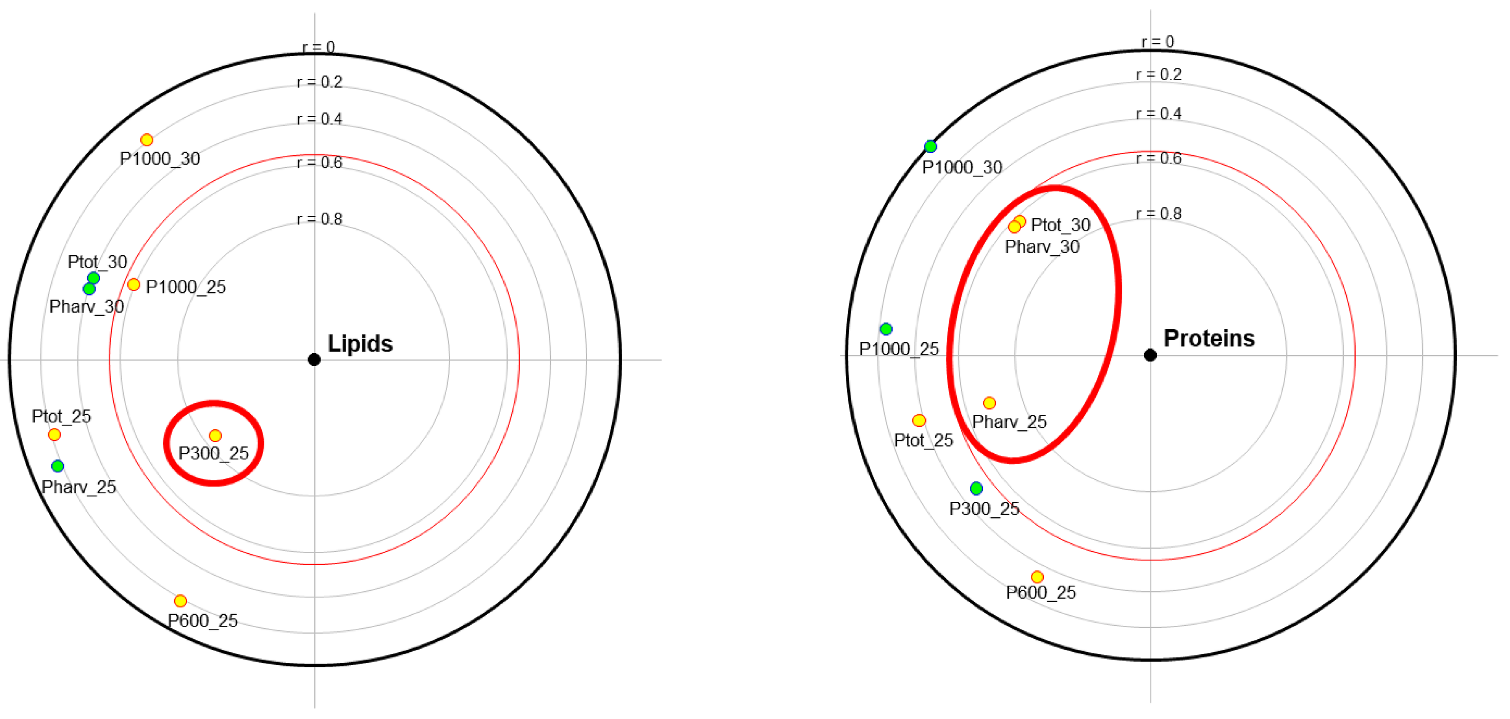


Fig. 4 : Focused Principal Component Analysis (FPCA, Falissard, 1999) for oil and protein contents with the 10 pre-defined ecoclimatic indicators.

CONCLUSIONS

- Oilseed rape final performances were tightly related to the **timing, frequency and intensity** of high temperature events after flowering
- The outcome of several successive stressful events **is not equal to the sum** of each individual effect
- The interactions of ecoclimatic indicators highlighted how an **early stress can modulate the effect of a latter one**, that is namely memory effect. The model with interactions was much more predictive of the final crop performances than a single cumulative indicator
- Consider stress memory in predictive crop models can help to **better estimate the effects of repeated stresses** on crop yield and quality

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