Historical phenological responses in apple tree to contrasting warming contexts may clarify future crucial responses in Europe

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World region *Location*	Latitude / Longitude	Altitude (m)	Climatic zone *Climate type*	Temperature data period	Phenological data Period	Cultivar	Stage (BBCH)	Collaborative institute
Western Europe			Temperate					
Bonn, Germany	50°37'N/6°59'E	160	*Continental*	1959-2013	1958-2013	Golden D.	61,65	INRES
Gembloux, Belgium	50°34'N/4°41'E	138	*Continental*	1964-2013	1984-2013	Golden D.	61	CRA-W
Angers, France	47°28'N/0°38'W	38	*Oceanic*	1963-2013	1963-2013	Golden D.	61	INRA France
Conthey, Switzerland	46°13'N/7°18'E	504	*Continental*	1970-2013	1970-2013	Golden D.	65	Agroscope
					1975-2013	Gala	65	
Trento, Italy	46°4'N/11°7'E	419	*Continental*	1983-2013	1983-2013	Golden D.	61,65	CRA-FRF
Forli, Italy	44°13'N/12°2'E	34	*Mediterranean*	1970-2013	1970-2013	Golden D.	61,65	CRA-FRF
Nîmes, France	43°44'N/4°30'E	52	*Mediterranean*	1966-2013	1974-2013	Golden D.	61,65	Ctifl
					1979-2013	Gala	61,65	
					1980-2013	Fuji	61,65	
Northern Africa			Mild					
Ain Taoujdate, Morocco	33°56'N/5°13'W	499	*Mediterranean*	1973-2013	1984-2013	Golden D.	61,65	INRA Morocco
Southern Brazil			Mild					
Caçador, Santa Catarina	26°47'S/51°1'W	960	*Subtropical*	1961-2013	1984-2013	Golden D.	61,65	EPAGRI
					1982-2013	Gala	61,65	
					1982-2013	Fuji	61,65	
Sao Joaquim, Santa Catarina	28°29'S/49°93'W	1353	*Subtropical*	1955-2013	1972-2013	Golden D.	61,65	EPAGRI
					1972-2013	Gala	61,65	
					1976-2003	Fuji	61,65	

Table 1 – Flowering and temperate data collected in climate-contrasting regions for three apple cultivars.

BBCH61 BBCH65 G.D. Gala Fuji

CONTEXT

Floral phenology responses to warming in temperate fruit trees have rarely been compared in contrasting warming contexts. This is an appropriate framework in deciduous woody plants for highlighting varying flowering responses to diverse warming contexts, which would potentially combine chill accumulation declines (warming impact on bud dormancy) and heat accumulation increases (warming impact on bud growth) (Schwartz and Hanes 2010).

Future flowering and dormancy responses to continuous warming would be crucial to ensure regular fruit bearing in apple in the warmest European cropping regions (Legave et al. 2013).

OBJECTIVE and METHODS

This study aims to provide a comprehensive overview of historical flowering responses recorded in apple in contrasting warming contexts. To examine this issue, a dataset was constituted from flowering dates collected for two main BBCH stages and several cultivars in both temperate regions of western Europe suitable for apple cropping and in unsuitable mild regions of northern Morocco and southern Brazil, where insufficient fruit bearing is mainly due to inadequate flowering phenology and intensity (Table 1 and Fig. 1). Additionally, the dynamics of bud dormancy and growth until the blooming phase were compared in southern France (CEHM near Nîmes), northern Morocco (Ain Taoujdate) and southern Brazil (Palmas near Caçador). Multiple change-point models, including piecewise constant and linear models, were applied to series of flowering date, flowering duration and temperature, aiming to statistically analyse both flowering responses and temperature changes (Legave et al. 2015). Two forcing tests (one-bud cuttings and Tabuenca's test) were used to analyse the dormancy and growth dynamics (Malagi et al. 2015).

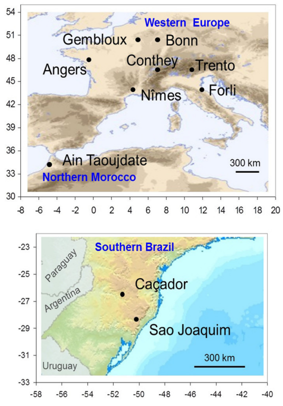


Figure 1 – Geographical distribution of locations in both Hemispheres

RESULTS and DISCUSSION

1. Differentiated responses of flowering date and blooming duration

A new overview in space and time of flowering date changes was provided in apple tree highlighting not only flowering date advances, as in previous studies (Guédon and Legave 2008), but also stationary flowering date series (Fig. 2). At global scale, differentiated flowering time patterns resulted from interactions between regional differences in the thermal determinisms of flowering date and in the impacts of warming context. This may explain flowering date advances in most of European regions (change-point instant at the end of the 1980s, Fig.3) and in Morocco (later instant in 1994) vs. stationary flowering date series in the Brazilian regions. A notable exception in Europe was found in the French Mediterranean region (Nimes) where the flowering date series became stationary from 1974 to 2013 due to both marked winter and spring warming (Fig. 2). Conversely, the durations of the blooming phase were significantly far longer in mild regions compared to temperate regions, whereas the duration series were stationary whatever the region.

Figure 3 – Change-point distribution for two-segment constant models (BBCH61series)

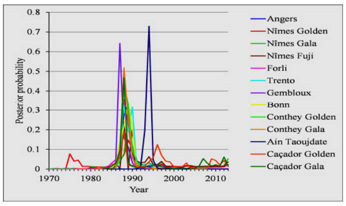
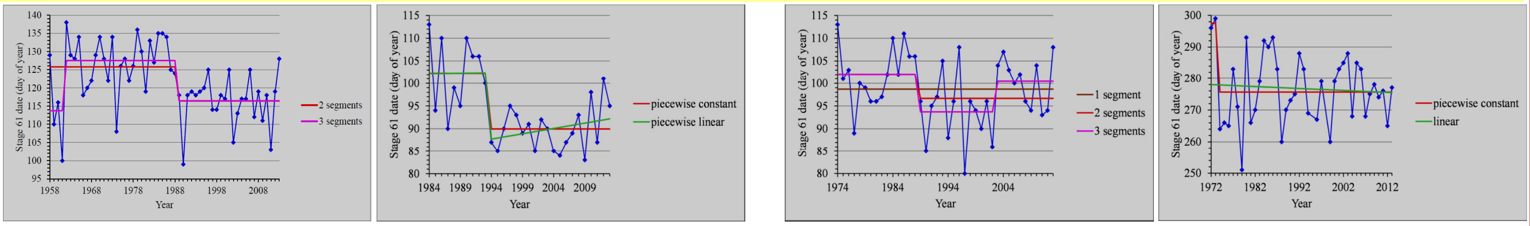


Figure 2 – Segmentation of BBCH61 stage date series using optimal piecewise constant and linear models in the case of Golden Delicious (Legave et al. 2015):

Flowering advance in Bonn (1962-2013) linked to « spring » warming — Flowering advance in Ain Taoujdate (1984-2013) linked to « spring » warming — Flowering stationarity in Nîmes (1974-2013) linked to « winter » warming and « spring » warming — Flowering stationarity in Sao Joaquim (1974-2013) no significant warming



2. Differentiated dynamics of bud dormancy and growth

In the temperate conditions of southern France, the successive phases of para- endo- and eco-dormancy were clearly identified for the vegetative buds. Conversely, superficial endo-dormancy was recorded in southern Brazil (Fig. 4).

This was related to relatively low "winter" temperatures in France (min. temperature clearly below 10°C from Nov. to Feb.) vs. high "winter" temperatures from May to August in Brazil, as no mean temperature below 12°C up to mid-July in some years. In addition, the eco-dormancy durations of flower buds were clearly longer in France than in Brazil (Table 2). This was also related to relatively low "spring" mean temperatures in France (10,5°C) vs. high "spring" mean temperatures in Brazil (15,5°C). Such contrasting dynamics of both bud dormancy and growth between France and Brazil might explained adequate flowering at the blooming phase in France (Fig. 5) vs. inadequate flowering in Brazil (Fig. 6) (Malagi et al. 2015).

Figure 4 – Dormancy dynamics of vegetative buds (cutting test).

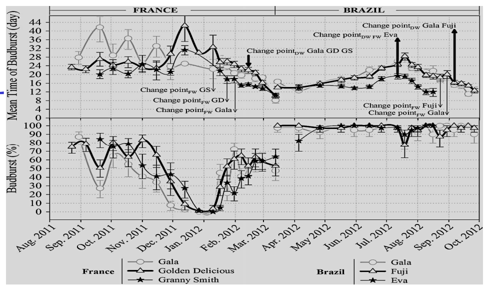


Figure 5 – Intense flowering and short blooming duration in southern France.

Cropping region	southern France			southern Brazil	
Cultivar	GD	Gala	GS	Gala	Fuji
2011-2012	47	46	46	14	14
2012-2013	71	69	69	26	26

Table 2 – Duration (days) of flower bud growth from en-dodormancy release (Tabuenca's test) to BBCH61 stage.

Figure 6 – Weak flowering and extended blooming duration in southern Brazil.

WHICH FUTURE CRUCIAL IMPACTS ON FLORAL PHENOLOGY AND CONSEQUENCES ?

European Mediterranean regions of apple cropping might be gradually affected in near future by excessive delays of dormancy release linked to declines in "winter" chill accumulation. This would be especially crucial in the French Mediterranean region (Nîmes) where stationarities of flowering stage dates were found over forty years. In fact, this apparent stationary was the result of both marked chill declines and heat increases (Legave et al., 2013). At tree and orchard scales, this could cause future phenological disorders similar to those observed in mild regions. Continuous warming from autumn to spring in the French Mediterranean region (as in 2015-2016) could excessively increase bud competitions, firstly during the fulfilment of chilling requirements in endo-dormancy and later during the fulfilment of heat requirements in eco-dormancy, finally leading to poor flowering intensity and excessive durations of the blooming phase (Fig. 6).

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