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Substitution of winter chilling by spring forcing for flowering using sweet cherry as model crop

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ABSTRACT

Many horticultural crops such as apple, pear, plum, cherry, strawberry and Asparagus require a cold period in winter (chilling) with a subsequent warm period (forcing) for flowering. The objective of the present work was to investigate the effects of more forcing due to projected diminishing available chill as a result of climate change and elaborate the possibility of substitution of chilling by forcing, using cherry as the most affected crop. Therefore, 160 potted sweet cherry trees were exposed to different chilling in four consecutive winters at Klein Altendorf, near Bonn (50 °N), Germany. Three cherry cultivars with a wide range of chilling requirement (3-fold) were employed in eight scenarios per variety per year, ranging from −50% less/insufficient chill for warm temperature zone winters to +50% more or excess chill for cold winter fruit growing regions:

1. The *minimum chill* fulfilment of the cherry trees ranged from 400 CH (Chilling Hours) in low chill, 550 CH in medium chill and 750 CH in the high chill variety associated with *maximum forcing* of ca. 11.000 GDH (Growing Degree Hours) for low, ca. 12.000 GDH for medium and ca. 13.000 GDH for high chill varieties for sufficient flowering.
2. With *optimum* chill, the *optimum* forcing was ca. 8.000 GDH (> 12 °C), irrespective of variety, allowing upscaling of the results to possibly other varieties. Trees exposed to *excess chilling* (150%) required less forcing (ca. 4000 GDH) to reach full bloom. Hence, chilling can compensate for up to half of the required forcing, i.e. ca 4.000 GDH.
3. Ratios of forcing to chilling were computed for future comparisons, which ensure flowering in the orchard.
4. Slightly negative temperatures (−5 °C to 0 °C), which are presently exempt in the common chilling models but common in the fruit growing regions, contributed to chilling accumulation of the fruit trees.
5. A novel scheme was developed to visualise these regulatory mechanisms in tree physiology.

Overall, the results have shown that diminishing chilling as a result of climate change can be compensated for, in part up to 50%, by a larger amount of forcing to obtain natural flowering in the orchard.

1. Introduction

Many horticultural crops such as apple, pear, plum and cherry, as well as strawberries and perennial vegetables such as *Asparagus* require chill, i.e. a period of cool temperature during the winter season to induce buds to flower in spring (Lang et al., 1987). Winter temperatures differ from the colder Scandinavian climate to the Mediterranean climate, the latter associated with possibly insufficient winter chilling (cold period) followed by a longer period of forcing. Climatic conditions in temperate zones, where cherry is grown, as an intermediate situation are characterized by variable winter chilling followed by a forcing period (Couvillon and Erez, 1985); recent climate change may reduce available chilling in temperate zones (IPCC, 2013). In the past, the emphasis of studies was on chilling, whereas the subsequent forcing received relative little attention. Hence, it remains unclear, whether shorter or longer chilling periods in the winter can be compensated or substituted, and to which extent, by longer or shorter forcing periods, to ensure flowering and hence yields in the orchard.

Among fruit crops, sweet cherry (*Prunus avium* L.) requires the greatest chilling with up to 1500 Chilling Hours (CH) (Kaufmann and Blanke, 2017a), which is hence categorised as one of the most affected tree crop by environmental change and consequent temperature rises, particularly in warmer winters (Luedeling et al., 2011a) and was chosen here as model crop. In Southern France, mild winters with insufficient chilling led to an average of 32% yield loss in sweet cherry (Millan et al., 2009). The relative portions of forcing and chilling requirements

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are difficult to quantify due to uncertainty of a number of issues. Past chilling experiments with cut branches in moist paper in the dark at a constant temperature in a cold chamber (Mahmood et al., 2000a; Heide, 1993; Alburquerque et al., 2008; Ramos et al., 2018) allow relatively easy quantification of chill effects, but conclusions drawn from such artificial environments are difficult to apply to whole trees under natural weather and light viz. environmental conditions (photoperiod) (Mahmood et al., 2000b). To our knowledge, no study has been carried out with in-situ observations (over several years) on (potted viz. transportable) entire intact cherry trees of different varieties with a broad range of chilling requirement and exposed to 24 scenarios (different chilling and forcing conditions) each winter including natural winter temperature regimes and modified environmental conditions in an unheated greenhouse to simulate climate change.

The hypothesis of this work was that chilling and forcing can be substituted by each other to a certain extent and one can compensate for the other, irrespective of variety, a result, which can be used in upscaling and that negative temperatures contribute to chilling accumulation.

The objective of this project was to investigate the effect of diminishing available chill as a result of climate change on forcing accumulation. This study further aims to elaborate thresholds for minimum chilling fulfilment and its interaction with forcing accumulation. The work includes possible effects of slightly negative temperatures (0 °C to − 5 °C) and the effects of simulated climate change with a predicted 2 °C global temperature increase (IPCC, 2013) on chilling availability in the temperate climate zone (50 °N), the major pome and stone fruit growing belt in Europe using climate sensitive sweet cherry as model crop. To achieve these goals, 160 potted sweet cherry trees of three varieties with a wide range of chilling requirements were raised over two years to initiate uniform flower buds before applying 24 chilling scenarios (8 scenarios per variety) per year followed by forcing to determine the effect on flowering.

2. Materials and methods

2.1. Location and environmental conditions

Klein-Altendorf Research Centre is located near Bonn, Germany (50 °N) with an averaged 9.8 °C annual temperature and a mild Westerly wind climate buffered by the Rhine valley during the winter (Blanke and Kunz, 2009). Chilling accumulated in winters 2012/13, 2013/14, 2014/15 and 2015/16 either outside in the orchard or in an unheated greenhouse to simulate recent climate change at Campus Klein-Altendorf of the University of Bonn (Table 1).

2.2. Materials - sweet cherry trees

The 160 sweet cherry (*Prunus avium* L.) trees (colour supplement 1) were grafted on dwarfing GiSelA 5 rootstock and planted in 35 L pots on 24 March 2011 in order to initiate uniform flower buds over the 1.5 years before chilling treatments commenced in October 2012. The sweet cherry varieties were chosen to cover their widest possible range in chilling needs, a high chill variety '*Schneiders späte Knorpelkirsche*', '*Brooks*' as a medium chill and '*6000CZ*' as a low chill variety (Gratacós and Cortés, 2007; Luedeling et al., 2013; Kaufmann and Blanke, 2017b). The cv. '*Schneiders späte Knorpelkirsche*' is an old widespread variety and first archived in 1850 in Europe, while both cvs '*Brooks*' and '*6000CZ*' are from California, the latter especially bred for its low chilling environment.

Table 1
Average (based on hourly records) temperatures in the orchard and unheated greenhouse during the chilling period in the winter.

Date	Location	Winter temperature in °C*
Winter 2012/13	Orchard	3.4
	Unheated Greenhouse	4.7
Winter 2013/14	Orchard	6.0
	Unheated Greenhouse	7.0
Winter 2014/15	Orchard	4.7
	Unheated Greenhouse	6.8
Winter 2015/16	Orchard	6.7
	Unheated Greenhouse	8.2

* 22 October till 28 February.

2.3. Methods - experimental layout and scenario description

Eight groups of four trees were formed for each variety. To acquire chilling, trees of the first three groups of each variety were placed in an unheated greenhouse in the autumn, while those of the second three groups were left outside in a cherry orchard. For these two groups, viz. unheated greenhouse and orchard, a control group with four trees of each variety was set up under the two environments. Each group of four trees equals one climate scenario; a certain amount of natural accumulated chilling and forcing in a heated greenhouse.

Chilling was assessed using beginning of leaf fall as physiological plant parameter (Kaufmann and Blanke, 2017b) with intact potted trees subjected to one of eight climate scenarios (Table 2) under natural conditions in terms of diurnal temperature and photoperiod fluctuations; this is in contrast to previous reports with cut branches stored in a refrigerator at a constant temperature without light. Our scenarios included exposure to either about 50% less chilling of the estimated chilling optimum, or up to 50% additional chilling on top of the chilling optimum to cater for all possible weather extremes, possibly associated with environmental change and areas of increased chill projection.

After the targeted chill accumulation was reached, the potted trees were transported from the orchard or the unheated greenhouse to a heated greenhouse with the natural photoperiod and diurnal temperature fluctuation (heated to > 12 °C) to prevent any further chilling and subject the cherry trees to environmental conditions to start forcing and induce flowering. In the heated greenhouse, flower buds were counted on each tree and full bloom assessed, when 50% of flowers for a tree opened (BBCH 65; Meier et al., 1994 equivalent to F2; Fleckinger, 1955). Groups viz scenarios are labelled as follows. The first letter of the scenario abbreviation denotes the cherry variety (C= '*6000CZ*'; B='*Brooks*'; S='*Schneiders*'), the first number the year (2012/13 = 1… 2015/16 = 4), the second the letter location (orchard = O, unheated greenhouse = G) and last number the group in each year (Table 2).

2.4. Computation of the three chilling models based on our own hourly temperature records

Chilling Hours, Units and Portions were computed from our own on-site meteorological data obtained at 10 min intervals from temperature loggers (Datahog, Skye Ltd., Pontys, Wales, UK) placed at 2 m height between the trees. Chilling computation started at the beginning of leaf fall, the period identified when the tree prepares for dormancy (Hillmann et al., 2016; Kaufmann and Blanke, 2017b) (Table 2). Chilling was computed using the Utah model, the Dynamic model and the Growing Degree Hours with the program "R" ("R" version 2.15.3, Lucent Technologies, USA) and R-chill package (Luedeling et al., 2011b). In the computation, we used the oldest and most widespread Chilling Hours model, which adds the number of hours with temperatures of 0 to 7.2 °C (Weinberger, 1950). It was originally developed for peaches in Georgia (USA), but is now applied to many other types of fruit crops in other climates without adaption. Since the Chilling Hour model originated from warm winter regions without frost, we computed two versions of the Chilling Hour model, the original approach (Weinberger, 1950) and our own modified version for an environment with slightly negative temperatures (− 5 °C to 7.2 °C), typical for the temperate zone fruit growing belt along 50 °N. The third chilling model applied was the