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Research paper

Increase in the risk of exposure of forest and fruit trees to spring frosts at higher elevations in Switzerland over the last four decades

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ABSTRACT

Winters and early springs are predicted to become warmer in temperate climates under continued global warming, which in turn is expected to promote earlier plant development. By contrast, there is no consensus about the changes in the occurrence and severity of late spring frosts. If the frequency and severity of late spring frosts remain unchanged in the future or change less than spring phenology of plants does, vulnerable plant organs (dehardened buds, young leaves, flowers or young fruits) may be more exposed to frost damage. Here we analyzed long-term temperature data from the period 1975–2016 in 50 locations in Switzerland and used different phenological models calibrated with long-term series of the flowering and leaf-out timing of two fruit trees (apple and cherry) and two forest trees (Norway spruce and European beech) to test whether the risk of frost damage has increased during this period. Overall, despite the substantial increase in temperature during the study period, the risk of frost damage was not reduced because spring phenology has advanced at a faster rate than the date of the last spring frost. In contrast, we found that the risk of frost exposure and subsequent potential damage has increased for all four species at the vast majority of stations located at elevations higher than 800 m while remaining unchanged at lower elevations. The different trends between lower and higher elevations are due to the date of the last spring frost moving less at higher altitudes than at lower altitudes, combined with stronger phenological shifts at higher elevations. This latter trend likely results from a stronger warming during late compared to earlier spring and from the increasing role of other limiting factors at lower elevations (chilling and photoperiod). Our results suggest that frost risk needs to be considered carefully when promoting the introduction of new varieties of fruit trees or exotic forest tree species adapted to warmer and drier climates or when considering new plantations at higher elevations.

1. Introduction

In temperate climates, the greatest risk of frost injury to herbaceous and woody plant species occurs during the period of vegetation onset in spring, and this risk appears to be a strong driver of evolution (Inouye, 2000; Vitasse et al., 2014b). In early spring, prior to bud break, buds of forest species in temperate climatic zones are in a phase of eco-dormancy and their resistance to frost decreases progressively as temperature rises (dehardening period) reaching a minimum as new leaves emerge (Lenz et al., 2013b; Sakai and Larcher, 1987; Vitasse et al., 2014b). The timing of vegetation onset is therefore decisive in minimizing the risk of frost injury (Lenz et al., 2016). This is why late spring frost events are climatic extremes with high ecological and evolutionary importance, likely controlling the latitudinal and elevational limits of temperate trees (Kollas et al., 2014; Körner et al., 2016).

Destruction of foliage, flowers and unripe fruits due to late spring frost is a considerable loss for trees since it negatively affects nutrient storage, growth, reproduction, leaf development, and ultimately survival in subsequent years (Vanoni et al., 2016). In addition, late spring frosts may cause important economic losses, in particular when they affect the flower or fruit tissue in orchards and vineyards, which can dramatically reduce fruit production (Rodrigo, 2000). In forest trees, frost injury can affect the production of biomass (Dittmar et al., 2006), which is a loss for the timber industry, and may eventually weaken trees, resulting in them becoming more vulnerable to pathogens (Wargo, 1996). Temperate trees have thus adapted their spring phenology to begin their development in spring in connection to the mean-long term probability of late spring frost events (Lenz et al., 2016).

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Fig. 1. Frost damage observed on European beech on June 22, 2016 induced by a late spring frost event on April 28, 2016 in the Swiss Jura Mountains at 1100 m a.s.l. (© photo: left M.R., right Y.V. June 22, 2016).

Nevertheless, wild trees seldom experience serious frost injury to developing leaves and flowers within their natural distribution ranges (e.g. Fig. 1). In orchards, breeding objectives are prioritized to increase fruit production so that the current and future cultivated varieties may not be well synchronized with the long-term probability of late spring frosts. A challenging issue for fruit growers today is to assess whether promoting new varieties adapted to warmer and drier climates during summer time (generally having earlier spring phenology), could be more profitable in future decades. This would occur if the latest potentially damaging frost in spring would advance (i.e. occur earlier in the year) to a greater extent than the advance of spring phenology. Similarly, in forestry, the challenge is to determine which species or local provenances are most suitable to grow under future warmer conditions in future decades. In contrast to crop plants, which can be irrigated, forest trees must be able to cope with severe droughts, the frequency and intensity of which are expected to increase in future decades in Switzerland (Scherler et al., 2016). Thus, forest managers are currently turning towards the scientific community to get insights on which climatic extremes, with which frequency, will affect trees, and whether exotic species more able to withstand such climatic extremes should be considered for plantations (Lindner et al., 2010). In such discussions, the focus has often been placed on the ability of the future trees to withstand extreme drought whereas the relationship between spring phenology and potential frosts has largely been ignored.

Widespread frost damage to natural vegetation and crops has recently been reported. For instance the frost event that occurred in the eastern United States in early April 2007 caused extensive damage to crops and wild vegetation across large areas (Augspurger, 2009; Gu et al., 2008). Three years later, in spring 2010, another important frost event affected forests in the northeastern United States, with a strong negative impact on productivity (Hufkens et al., 2012). In Europe, significant frost damage to cultivated and forest trees was reported in 1995 in France (Ningre and Colin, 2007), in 2011, 2016 and 2017 in Switzerland (Fig. 1), and in south Germany and northeastern France (Kreyling et al., 2012a). In the majority of these examples, frost damage occurred after an unusually warm period that triggered precocious spring phenology. However, it is still unclear whether the risk of natural and cultivated trees encountering frost damage has recently changed, because both spring phenology and minimum temperatures need to be analyzed simultaneously over a long period, which is limited by the amount of available data. Only a few studies have addressed whether plants have been at higher or lower risk from spring frosts in recent decades (Augspurger, 2013; Bennie et al., 2010; Hänninen, 1991; Rigby and Porporato, 2008; Scheifinger et al., 2003). While it is very likely that overall frost frequency has been reduced and will continue to decline in the future (IPCC, 2013), this does not necessarily mean that the risk of frost damage to natural and cultivated trees is decreasing. Temperate forest trees are most vulnerable to frost when the leaves are emerging from buds in spring (Vitasse et al., 2014b), and this period of vulnerability has advanced substantially in response to warmer temperatures. For instance, using ground observations of forest trees from over 3′800 locations in Western Europe, Fu et al. (2014) showed that the leaf-out date of temperate trees has advanced by about 13 days during the period 1982–2011.

The phenological shift of spring onset in response to climate change has considerable implications for crop management, especially in agriculture and forestry, human health (transport of allergens and disease vectors), as well as in numerous supporting and regulating ecosystem services such as nutrient cycle and carbon storage (Polgar and Primack, 2011; Richardson et al., 2013). In addition, foresters, farmers and fruit growers may adapt to warmer and drier climate during summer by using earlier new varieties, provenances or alternative species, potentially resulting in greater exposure to frost damage.

Since the mid-1980s, there has been an unresolved debate over whether the risk of frost damage on temperate plants will increase in future decades under continued climate change. For instance, Hänninen (1991) predicted an increased risk of frost damage under an expected warmer climate in Finland. Augspurger (2013) drew the same conclusion when focusing on 20 woody species in Illinois (USA), while no change or even a decreased risk was expected in the future decades in other studies in the Netherlands and Italy (Eccel et al., 2009b; Kramer, 1994a). Overall, late spring frosts were predicted to generally occur earlier but the stochasticity of such events is such that plants might be at higher risk of encountering frost damage, especially in more continental areas (Kreyling et al., 2012b). These contradictory predictions are likely due to the lack of sites where long time series of phenological observations have been recorded along with temperature. In addition, when both datasets are available, frost damage is too rare to investigate whether its frequency has changed in recent decades. A robust alternative is to quantify the safety margin against frost by comparing the timing of the last spring frost event with the observed or predicted date of flowering or leaf-out dates (Lenz et al., 2016; Lenz et al., 2013b) and testing whether this safety margin has changed over the last decades (Scheifinger et al., 2003). There are three alternative hypotheses associated with climate change and frost damage: (i) the risk of frost damage remains unchanged because both phenology and the frost-free period advance to the same extent (Fig. 2, hypothesis a); (ii), the risk of frost damage decreases because phenology advances less than the frost-

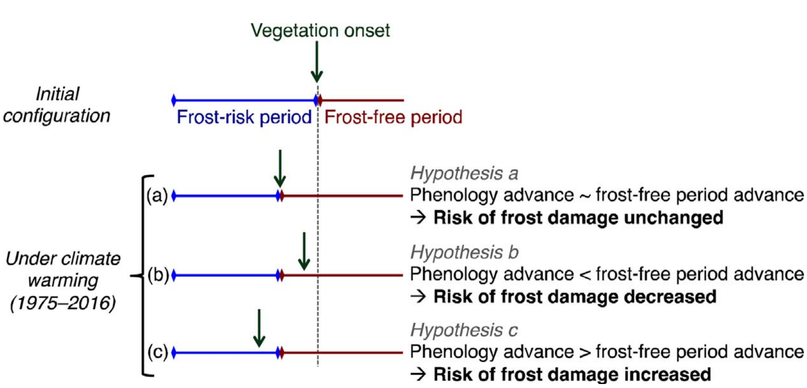

Fig. 2. Theoretical hypotheses on how the risk of spring frost damage to trees could change under climate warming.
Hypothesis a, the risk of frost damage remains unchanged because both phenology and the frost-free period advance to the same extent.
Hypothesis b, the risk of frost damage decreases because phenology advances less than the frost-free period.
Hypothesis c, the risk of frost damage increases because phenology advances more than the frost-free period.