# Supplements for: Changes and trends in budburst and leaf flush across Europe and North America

## A meta-analysis of local adaptation in spring phenology studies

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2023

## 1 Additional Methods

We had to exclude several studies that reported spring events on a quantitative scale. This was because (1) such studies usually only assessed where on the scale the spring event of a tree fell onto on the same days across different years (e.g. Robson et al., 2013; Vander et al., 2015; Santini et al., 2014; Schueler & Liesebach, 2004), and (2) scales are not always consistent across different studies (Chmura & Rozkowski 2002; Dhont et al., 2010; Wang et al., 2022). Such factors made it impossible to convert the quantitative scale to DOY.

We additionally excluded several studies because we could not pinpoint their location, or because they focused on non-native species or elevational trends. We excluded studies that did not provide the exact latitude and longitude of the common garden (Bongarten, 1978) or the provenances (Hall et al., 2007; Soolanayakanahally et al., 2013), or they did not link the latitude and longitude of each provenance to the DOY of spring events (Deans & Harvey, 1996). We also left out studies in which woody plants from North American provenances were planted in common gardens in Europe (Cannell et al., 1987; Lavadinovic et al., 2013) because we wanted to test continental variations. Finally, as we are focused on latitudinal trends we excluded studies that examined only provenance altitude (Vitasse et al., 2009; Vitasse et al., 2010; Li et al., 1997; Alberto et al., 2011; Acevedo-Rodríguez et al., 2006).

Table 1: This table includes all publications that met search criteria for this meta-analysis. Some studies had more than one gardens and two studies shared the same garden (D)

| **No.** | **Publication** | **Continent** | **Garden ID** | **Species** | **Species Type** | **Spring Event Definition** | **Fall Event** | **Fall Event Definition** |
|---|---|---|---|---|---|---|---|---|
| 1 | Hamann et al., 1998 | North America | A | *Alnus rubra* | Angiosperm | Bud burst | Yes | Leaf abscission |
| 2 | Rehfeldt, 1994 | North America | B | *Picea engelmannii* | Gymnosperm | Bud burst | Yes | Leaf cessation |
| 3 | Bower Aitken, 2008 | North America | C | *Pinus albicaulis* | Gymnosperm | Leaf flush | No | n.a. |
| 4 | McKown et al., 2013 | North America | D | *Populus trichocarpa* | Angiosperm | Bud burst Leaf flush | Yes | Bud set |
| 5 | Mimura Aitken 2007 | North America | D | *Picea sitchensis* | Gymnosperm | Bud burst | Yes | Bud set |
| 6 | Kuser, 1980 | North America | E | *Tsuga heterophylla* | Gymnosperm | Bud burst | Yes | Bud set |
| 7 | Farmer, 1993 | North America | F | *Populus balsamifera* | Angiosperm | Bud burst | No | n.a. |
| 8 | Hannerz et al., 1999 | North America | G | *Tsuga heterophylla* | Gymnosperm | Bud burst | No | n.a. |
| 9 | White et al., 1979 | North America | H | *Pseudotsuga menziesii* | Gymnosperm | Bud burst | No | n.a. |
| 10 | Guo et al., 2021 | North America | I | *Picea mariana* | Gymnosperm | Bud burst | No | n.a. |
| 11 | Dixit et al., 2020 | North America | J | *Pinus ponderosa* | Gymnosperm | Bud burst | No | n.a. |
| 12 | Hawkins Dhar 2012 | North America | K/L/M | *Betula papyrifera* | Angiosperm | Bud burst | No | n.a. |
| 13 | Rosique-Esplugas, 2021 | Europe | Q* | *Fraxinus excelsior* | Angiosperm | Leaf flush | Yes | Leaf senescence |
| 14 | Petkova et al., 2017 | Europe | R* | *Fagus sylvatica* | Angiosperm | Bud burst | Yes | Leaf senescence |
| 15 | Sogaard et al., 2008 | Europe | S* | *Picea abies* | Gymnosperm | Bud burst | No | n.a. |
| 16 | Gömöry Paule 2011 | Europe | T* | *Fagus sylvatica* | Angiosperm | Bud burst | No | n.a. |
| 17 | Alberto et al., 2011 | Europe | U*/V* | *Quercus petraea* | Angiosperm | Bud burst | No | n.a. |

Table 2: Model summary of the relationship between spring event day of year (DOY)and provenance latitude (lat_prov), fitted by different species within a garden (species_garden). European gardens and species are denoted by an asterisk(*).

| **Parameter** | **mean** | **sd** | **10%** | **50%** | **90%** |
|---|---|---|---|---|---|
| (Intercept) | 112.6 | 5.4 | 105.8 | 112.6 | 119.4 |
| b[lat_prov species_garden:*Alnus_rubra_A]* | -0.7 | 0.3 | -1.1 | -0.7 | -0.4 |
| b[lat_prov species_garden:*Betula_papyrifera_K]* | 1.1 | 0.4 | 0.5 | 1.1 | 1.6 |
| b[lat_prov species_garden:*Betula_papyrifera_L]* | 0.9 | 0.4 | 0.4 | 0.9 | 1.4 |
| b[lat_prov species_garden:*Betula_papyrifera_M]* | 0.8 | 0.4 | 0.3 | 0.8 | 1.3 |
| b[lat_prov species_garden:*Fagus_sylvatica_R*]* | 0.2 | 0.3 | -0.2 | 0.2 | 0.7 |
| b[lat_prov species_garden:*Fagus_sylvatica_T*]* | 0.2 | 0.2 | -0.1 | 0.2 | 0.4 |
| b[lat_prov species_garden:*Fraxinus_excelsior_Q*]* | 0.9 | 0.3 | 0.4 | 0.9 | 1.3 |
| b[lat_prov species_garden:*Picea_abies_S*]* | -0.4 | 0.5 | -1 | -0.3 | 0.2 |
| b[lat_prov species_garden:*Picea_engelmannii_B]* | 0 | 0.2 | -0.3 | 0 | 0.2 |
| b[lat_prov species_garden:*Picea_mariana_I]* | -0.3 | 0.5 | -0.9 | -0.3 | 0.2 |
| b[lat_prov species_garden:*Picea_sitchensis_D]* | -0.1 | 0.2 | -0.4 | -0.1 | 0.1 |
| b[lat_prov species_garden:*Pinus_albicaulis_C]* | -1.2 | 0.3 | -1.6 | -1.2 | -0.7 |
| b[lat_prov species_garden:*Pinus_ponderosa_J]* | -0.5 | 0.7 | -1.4 | -0.5 | 0.4 |
| b[lat_prov species_garden:*Populus_balsamifera_F]* | 0.2 | 0.4 | -0.3 | 0.2 | 0.8 |
| b[lat_prov species_garden:*Populus_trichocarpa_D]* | 0.7 | 0.2 | 0.5 | 0.7 | 1 |
| b[lat_prov species_garden:*Pseudotsuga_menziesii_H]* | 0.6 | 0.3 | 0.2 | 0.6 | 1 |
| b[lat_prov species_garden:*Quercus_petraea_U*]* | -0.1 | 0.7 | -1 | -0.1 | 0.8 |
| b[lat_prov species_garden:*Quercus_petraea_V*]* | -0.1 | 0.7 | -1 | -0.1 | 0.7 |
| b[lat_prov species_garden:*Tsuga_heterophylla_E]* | -0.8 | 0.3 | -1.2 | -0.8 | -0.4 |
| b[lat_prov species_garden:*Tsuga_heterophylla_G]* | 0.6 | 0.5 | 0 | 0.6 | 1.3 |
| sigma | 5.1 | 0.1 | 4.9 | 5.1 | 5.3 |
| Sigma[species_garden:(Intercept),(Intercept)] | 1604.9 | 600.8 | 957.6 | 1491.2 | 2411.2 |
| Sigma[species_garden:lat_prov,(Intercept)] | -23 | 10.3 | -36.6 | -21.2 | -11.7 |
| Sigma[species_garden:lat_prov,lat_prov] | 0.5 | 0.2 | 0.3 | 0.5 | 0.8 |

Table 3: Model summary of the relationship between spring event day of year (DOY)and provenance MAT (MAT_prov), fitted by different species within a garden (species_garden). European gardens and species are denoted by an asterisk(*).

| **Parameter** | **mean** | **sd** | **10%** | **50%** | **90%** |
|---|---|---|---|---|---|
| (Intercept) | 115.1 | 5.1 | 108.7 | 115 | 121.7 |
| b[MAT_prov species_garden:*Alnus_rubra_A]* | 0.9 | 0.5 | 0.2 | 0.9 | 1.5 |
| b[MAT_prov species_garden:*Betula_papyrifera_K]* | -3.4 | 0.7 | -4.4 | -3.4 | -2.5 |
| b[MAT_prov species_garden:*Betula_papyrifera_L]* | -2.1 | 0.7 | -3 | -2.1 | -1.2 |
| b[MAT_prov species_garden:*Betula_papyrifera_M]* | -1.4 | 0.7 | -2.3 | -1.4 | -0.5 |
| b[MAT_prov species_garden:*Fagus_sylvatica_R*]* | -0.5 | 0.7 | -1.4 | -0.5 | 0.4 |
| b[MAT_prov species_garden:*Fagus_sylvatica_T*]* | 1 | 0.3 | 0.6 | 1 | 1.5 |
| b[MAT_prov species_garden:*Fraxinus_excelsior_Q*]* | -1.2 | 0.6 | -1.9 | -1.2 | -0.4 |
| b[MAT_prov species_garden:*Picea_abies_S*]* | 1.1 | 0.9 | 0 | 1.1 | 2.2 |
| b[MAT_prov species_garden:*Picea_engelmannii_B]* | 0.1 | 0.3 | -0.4 | 0.1 | 0.5 |
| b[MAT_prov species_garden:*Picea_mariana_I]* | 0.6 | 0.6 | -0.2 | 0.6 | 1.3 |
| b[MAT_prov species_garden:*Picea_sitchensis_D]* | 0.3 | 0.4 | -0.2 | 0.3 | 0.8 |
| b[MAT_prov species_garden:*Pinus_albicaulis_C]* | 2.3 | 0.7 | 1.4 | 2.3 | 3.2 |
| b[MAT_prov species_garden:*Pinus_ponderosa_J]* | -0.1 | 0.5 | -0.7 | -0.1 | 0.5 |
| b[MAT_prov species_garden:*Populus_balsamifera_F]* | -0.3 | 0.6 | -1 | -0.3 | 0.4 |
| b[MAT_prov species_garden:*Populus_trichocarpa_D]* | -0.6 | 0.2 | -0.9 | -0.6 | -0.3 |
| b[MAT_prov species_garden:*Pseudotsuga_menziesii_H]* | -0.4 | 0.3 | -0.8 | -0.4 | 0 |
| b[MAT_prov species_garden:*Quercus_petraea_U*]* | -0.5 | 0.4 | -1 | -0.5 | -0.1 |
| b[MAT_prov species_garden:*Quercus_petraea_V*]* | -0.8 | 0.4 | -1.3 | -0.8 | -0.4 |
| b[MAT_prov species_garden:*Tsuga_heterophylla_E]* | 3.9 | 0.7 | 3.1 | 3.9 | 4.8 |
| b[MAT_prov species_garden:*Tsuga_heterophylla_G]* | -0.8 | 1.3 | -2.5 | -0.8 | 0.8 |
| sigma | 4.9 | 0.1 | 4.8 | 4.9 | 5.1 |
| Sigma[species_garden:(Intercept),(Intercept)] | 537.4 | 170.4 | 349.2 | 508.8 | 760.8 |
| Sigma[species_garden:MAT_prov,(Intercept)] | -9.7 | 10 | -22.2 | -8.7 | 1.6 |
| Sigma[species_garden:MAT_prov,MAT_prov] | 3.4 | 1.5 | 1.9 | 3.2 | 5.3 |

Table 4: Model summary of the relationship between fall event day of year (DOY)and provenance latitude (lat_prov), fitted by different species within a garden (species_garden). European gardens and species are denoted by an asterisk(*).

| Parameter | mean | sd | 10% | 50% | 90% |
|---|---|---|---|---|---|
| (Intercept) | 325.5 | 35 | 287.1 | 318.9 | 373.9 |
| b[lat_prov species_garden:*Alnus_rubra_A]* | -2.3 | 0.5 | -3 | -2.3 | -1.6 |
| b[lat_prov species_garden:*Fagus_sylvatica_R*]* | 0.2 | 0.6 | -0.5 | 0.3 | 1 |
| b[lat_prov species_garden:*Fraxinus_excelsior_Q*]* | -1.2 | 0.6 | -1.9 | -1.2 | -0.5 |
| b[lat_prov species_garden:*Picea_engelmannii_B]* | -0.1 | 0.3 | -0.5 | -0.1 | 0.3 |
| b[lat_prov species_garden:*Picea_sitchensis_D]* | -5.5 | 0.3 | -5.9 | -5.5 | -5.2 |
| b[lat_prov species_garden:*Populus_trichocarpa_D]* | -9.5 | 0.3 | -9.9 | -9.5 | -9.1 |
| b[lat_prov species_garden:*Tsuga_heterophylla_E]* | -3.8 | 0.4 | -4.3 | -3.8 | -3.3 |
| sigma | 8.2 | 0.3 | 7.8 | 8.2 | 8.6 |
| Sigma[species_garden:(Intercept),(Intercept)] | 13147.6 | 4738.9 | 7953.6 | 12418.3 | 19373.1 |
| Sigma[species_garden:lat_prov,(Intercept)] | -326.3 | 126.5 | -481.1 | -309.2 | -191.2 |
| Sigma[species_garden:lat_prov,lat_prov] | 12.2 | 8.4 | 6.5 | 10.2 | 19.2 |

Table 5: Model summary of the relationship between fall event day of year (DOY)and provenance MAT (MAT_prov), fitted by different species within a garden (species_garden). European gardens and species are denoted by an asterisk(*).

| Parameter | mean | sd | 10% | 50% | 90% |
|---|---|---|---|---|---|
| (Intercept) | 270.3 | 23.1 | 238.7 | 273.6 | 296.9 |
| b[MAT_prov species_garden:*Alnus_rubra_A]* | 2.8 | 1.1 | 1.4 | 2.8 | 4.3 |
| b[MAT_prov species_garden:*Fagus_sylvatica_R*]* | -0.2 | 1.6 | -2.2 | -0.2 | 1.9 |
| b[MAT_prov species_garden:*Fraxinus_excelsior_Q*]* | 1.6 | 1.3 | -0.1 | 1.6 | 3.4 |
| b[MAT_prov species_garden:*Picea_engelmannii_B]* | 0.3 | 0.8 | -0.7 | 0.2 | 1.2 |
| b[MAT_prov species_garden:*Picea_sitchensis_D]* | 11.2 | 0.9 | 10.1 | 11.1 | 12.3 |
| b[MAT_prov species_garden:*Populus_trichocarpa_D]* | 10.5 | 0.5 | 9.9 | 10.5 | 11.2 |
| b[MAT_prov species_garden:*Tsuga_heterophylla_E]* | 7.3 | 0.9 | 6.2 | 7.3 | 8.5 |
| sigma | 10.7 | 0.4 | 10.2 | 10.7 | 11.3 |
| Sigma[species_garden:(Intercept),(Intercept)] | 4746.1 | 2270.5 | 2455.2 | 4247.7 | 7676.8 |
| Sigma[species_garden:MAT_prov,(Intercept)] | -328 | 177.8 | -545.8 | -301.2 | -150.8 |
| Sigma[species_garden:MAT_prov,MAT_prov] | 40.8 | 28.3 | 19.4 | 33.4 | 68.8 |

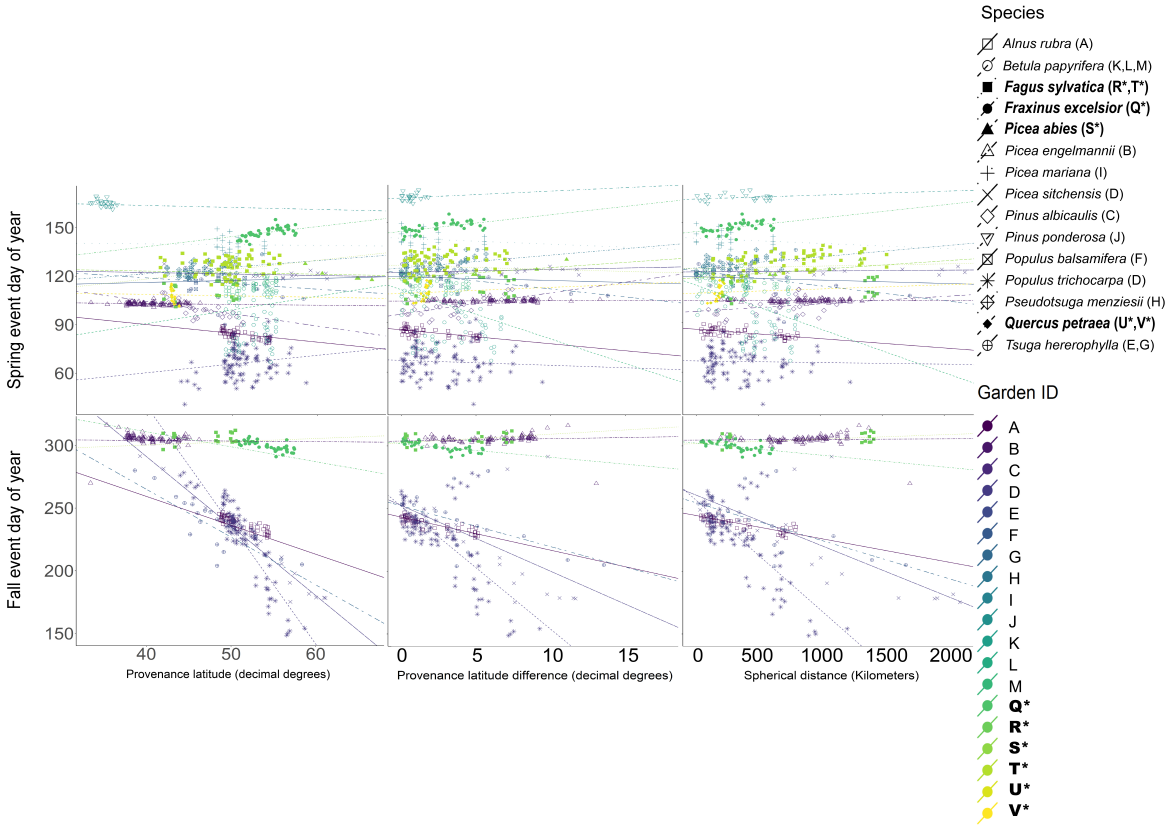


Figure 1: Results were similar across different distance metrics: provenance latitude, difference between provenance and garden latitude, and spherical distance between provenance and garden.

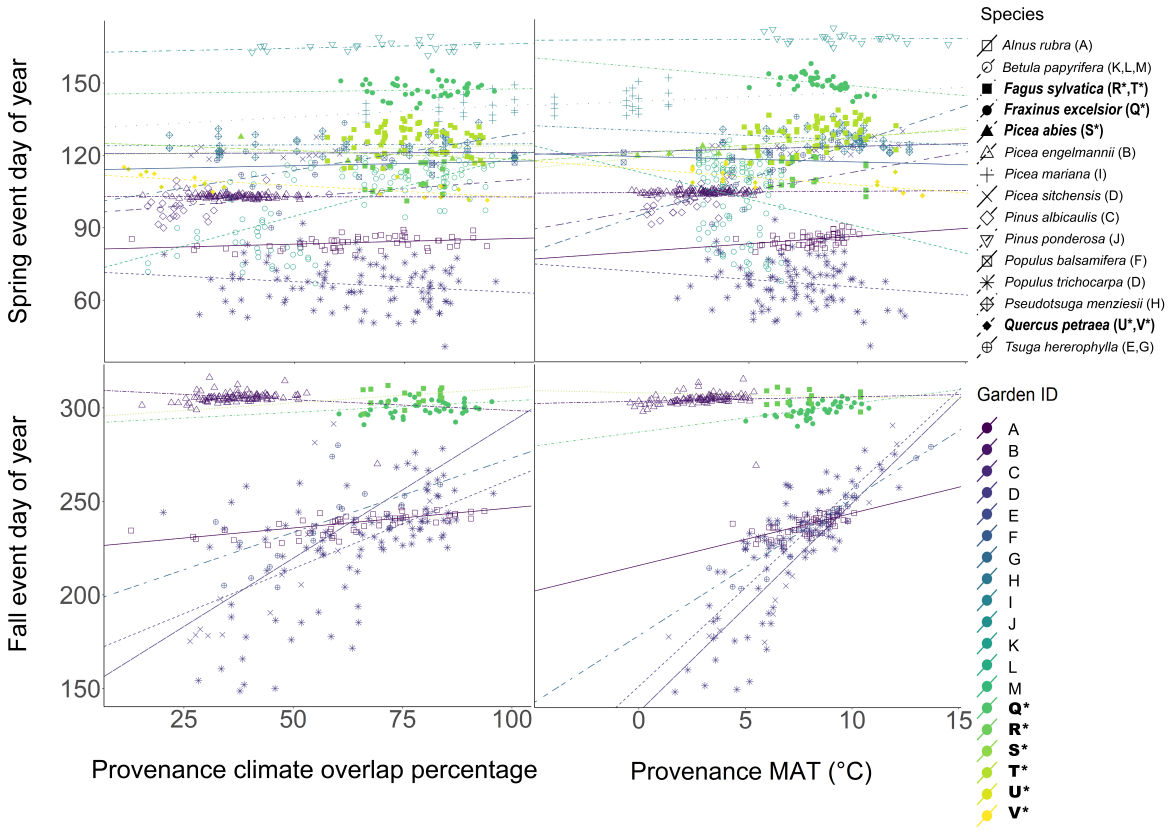


Figure 2: Results from using climate overlap were not qualitatively different than using MAT.

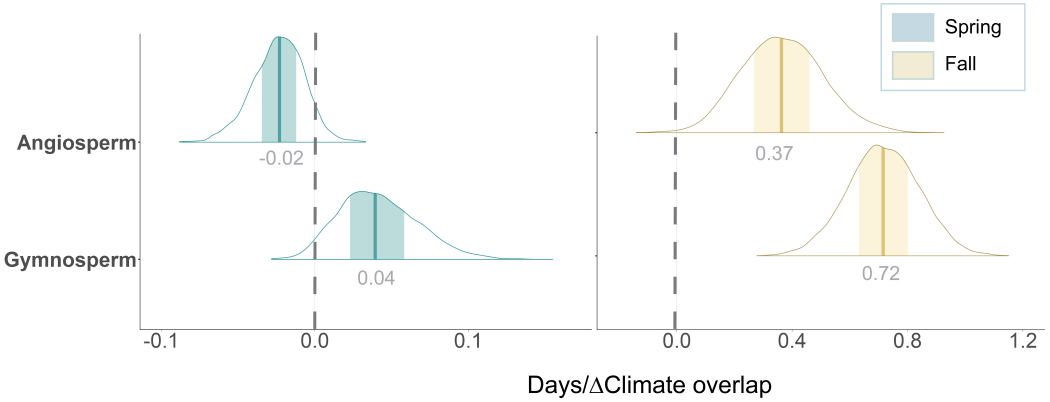


Figure 3: We observed very weak effects of climate overlap on spring events (0.01 [0.02 - 0.03] days per one per cent increase in climate overlap), nearly identical across angiosperms (0.02 [0.00 - 0.05]) and gymnosperms (0.04 [0.00 - 0.09]). Fall events advanced as climate overlap declined, but slightly more strongly for gymnosperms (advancing 0.72 [0.51 - 0.92] days per one per cent decline in climate overlap).

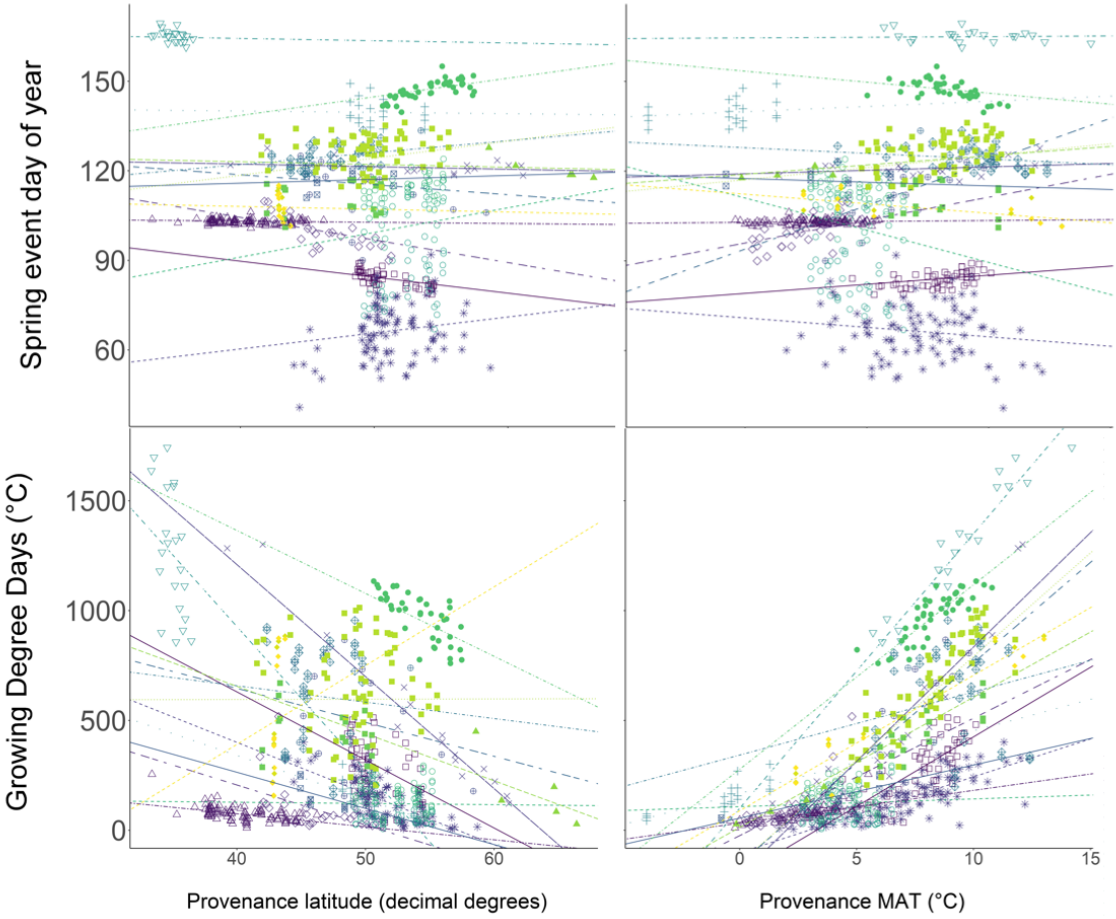


Figure 4: Growing Degree Days (GDD)on each day of spring event in relation to provenance latitude and MAT, coded by symbol for species and color for garden with linear fits from hierarchical Bayesian models.

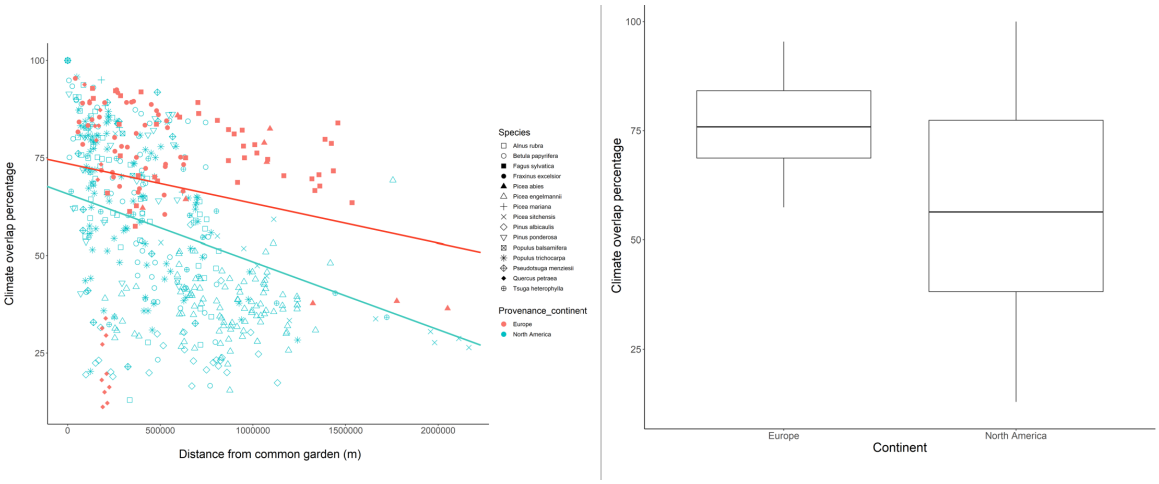


Figure 5: The closer a garden is to a provenance, the more overlap in temperature. Higher extend of climate overlap in European studies.

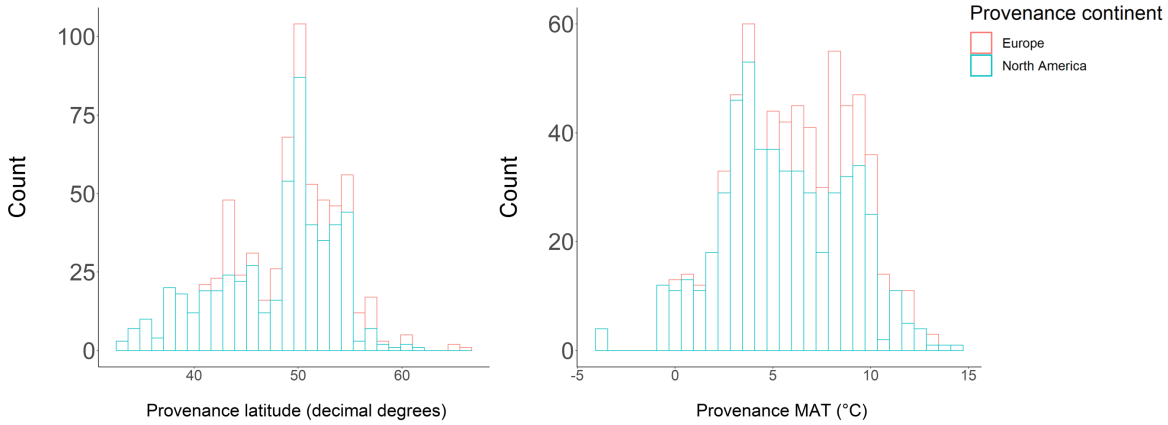


Figure 6: Placeholder.

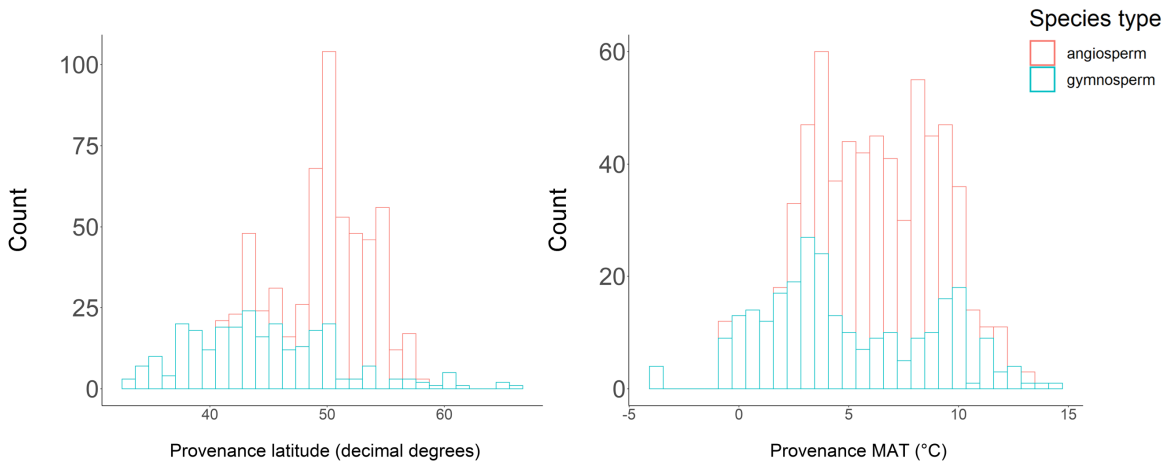


Figure 7: Placeholder