Literature Review Materials

We want to narrate the paper in a way that

“Traditionally we are using LAT and MAT to see clines, but what that really means is the percentage overlap of climate -> we expect percentage overlap to be a better predictor??

Go through papers and paste usable materials in here

Wording that i can use

For introduction & discussion

For methodology

# Introduction

## (Aitken & Bemmels, 2015) Time to get moving: assisted gene flow of forest trees

**Geographic variation in trees has been investigated since the mid-18th century. Similar patterns of clinal variation have been observed along latitudinal and elevational gradients in common garden experiments for many temperate and boreal species.**

**Scientists have studied relationships between tree populations and environmental characteristics of their provenances in common garden experiments for over 250 years, long before Clausen et al. (**[**1940**](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0014)**,** [**1948**](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0015)**) conducted their much-cited reciprocal transplant experiments in California with the herbaceous perennial Achillea millefolium and other species.**

**In summary, by the end of the 1800s it was fairly widely recognized in Europe that (i) temperate and boreal tree species vary geographically in a manner corresponding to their provenance climate of origin, (ii) trees need to be planted in common gardens to observe this variation, (iii) most variation is continuous along environmental gradients rather than discrete or ecotypic, (iv) variation is more often physiological (e.g. in growth rate or phenology) than morphological and involves tradeoffs between growth rate and cold tolerance in many cases, and (v) seed for reforestation should in most cases be procured locally to ensure adequate growth and hardiness. More recent studies improved on experimental design, multiple sites or environments, phenotyping methods, and sources of climate data for provenance trials, and produced a more nuanced understanding of the genetic influence of provenance, the environmental effects of experimental environments and their interactions. New population genomic analyses are generating a better understanding of the genetic architecture of climate-related traits and confirming geographic patterns of local adaptation.**

**To what extent are patterns of local adaptation along climatic gradients similar among species within a given geographic region?** If clines in phenotypic traits are similar, can average patterns of sympatric variation guide AGF or identify critical climatic variables as a first approximation for untested species? **We reanalysed data from the literature on provenance trials in temperate tree species from western North America to address these questions. This is an ideal region of focus because of the many provenance trials conducted on native tree species that are important for forestry, and because its high topographic complexity means that turnover in climate occurs rapidly and heterogeneously over short geographic spaces. Clines along climate gradients are thus especially likely to reflect local adaptation to climate, rather than non-adaptive phenomena resulting from population demographic history.**

**Here, we review the history of genecological research in forest trees, emphasizing the relationships between populations and climate. We then highlight advances in genecology and other relevant fields in recent decades; summarize key findings from population genetics and genomics relevant to local adaptation; present data on the concordance of genetic clines among tree species in western North America; and discuss the implications for managing tree populations in a rapidly warming world.**

## (Alberto et al., 2013) Potential for evolutionary responses to climate change - evidence from tree populations

Evolutionary responses are required for tree populations to be able to track climate change. Results of 250 years of common garden experiments show that most forest trees have evolved local adaptation, as evidenced by the adaptive differentiation of populations in quantitative traits, reflecting environmental conditions of population origins. On the basis of the patterns of quantitative variation for 19 adaptation-related traits studied in 59 tree species (mostly temperate and boreal species from the Northern hemisphere), we found that genetic differentiation between populations and clinal variation along environmental gradients were very common (respectively, 90% and 78% of cases). Thus, responding to climate change will likely require that the quantitative traits of populations again match their environments. We examine what kind of information is needed for evaluating the potential to respond, and what information is already available. We review the genetic models related to selection responses, and what is known currently about the genetic basis of the traits. We address special problems to be found at the range margins, and highlight the need for more modeling to understand specific issues at southern and northern margins. We need new common garden experiments for less known species. For extensively studied species, new experiments are needed outside the current ranges. Improving genomic information will allow better prediction of responses. Competitive and other interactions within species and interactions between species deserve more consideration. Despite the long generation times, the strong background in quantitative genetics and growing genomic resources make forest trees useful species for climate change research. The greatest adaptive response is expected when populations are large, have high genetic variability, selection is strong, and there is ecological opportunity for establishment of better adapted genotypes.

It is also now understood that the rate of adaptation required by climate change varies among geographic regions (Loarie et al., [2009](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0121)). Modeling work on the potential of populations and species to respond genetically to recent climate change is advancing (see Hoffmann & Sgrò, [2011](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0075); Franks & Hoffmann, [2012](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0052); Shaw & Etterson, [2012](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0182) for recent reviews). The immediate responses via phenotypic plasticity have also been considered in the context of climate change (Nicotra et al., [2010](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0145)).

**Trees exhibit a high degree of phenotypic plasticity with respect to climatic variation. Phenological shifts of bud flush in response to recent increases in temperatures have been widely documented** (Menzel & Fabian, [1999](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0130); Menzel et al., [2006](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0131); Parmesan, [2006](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0152)).

**Multiple-site provenance trials can be used to examine the plastic responses of populations in new environment**s. This can be quantified with response functions for individual populations, which describe the change in a trait as a function of transfer distance or change in environmental factors (Rehfeldt et al., [1999](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0164), [2002](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0166)). Provenance trials have been planted in sites that vary with respect to many environmental variables, such as temperature or water availability (Morgenstern, [1978](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0134); Kramer, [1995](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0103); Shutyaev & Giertych, [1997](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0183); Rehfeldt et al., [1999](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0164), [2002](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0166); Worrell et al., [2000](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0206); Reich & Oleksyn, [2008](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0167); Vitasse et al., [2010](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0199)).

**The plastic response of different traits (e.g., phenology in trees) to variation in climate is, however, often much more complex than in heuristic models of adaptation (s**ee e.g., Valladares et al., [2007](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0194); Caffarra et al., [2011](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0026); Hänninen & Tanino, [2011](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0068)).

## (Gill et al., 2015) Changes in autumn senescence in northern hemisphere deciduous trees: a meta-analysis of autumn phenology studies

Air temperatures around the globe are increasing (Jones et al., 2012), which has measurable effects on a variety of plant processes. Specifically, the effects of climate change on the phenology of vegetation have received increased attention over the past several decades as any factor that alters the timing of early growing season leaf-out and senescence has the potential to affect a variety of ecosystem properties. For example, the timing of leaf-out and senescence of deciduous plants has been shown to affect plant competition (Fridley, 2012), plant growth (Myneni et al., 1997) and ecosystem carbon uptake (Barichivich et al., 2012). Changes in phenology also affect surface albedo through differences in reflectance between closed and bare canopies (Richardson et al., 2013). While leaf-out has been shown to advance over the past century as a result of increasing air temperatures (Linderholm, 2006; Polgar and Primack, 2011), the relationship between temperature and leaf senescence remains less well understood (García-Plazaola et al., 2003; Richardson et al., 2013). Leaf senescence completes the growing season for deciduous trees and therefore factors that delay leaf-off can lengthen the period of plant photosynthesis and increase rates of gross primary productivity (Richardson et al., 2010). Thus, an extension of the growing season can contribute to reduced atmospheric CO2 concentrations due to enhanced carbon sequestration in terrestrial plants (Penuelas et al., 2009; Richardson et al., 2013). However, the increase in carbon uptake may be partially offset by increased rates of ecosystem respiration (Piao et al., 2008).

The lack of consistent relationships between air temperature and timing of leaf senescence suggests that autumn senescence may be influenced by a variety of factors that obscure its relationship with temperature.

## Range-wide parallel climate-associated genomic clines in Atlantic salmon

**Clinal variation across replicated environmental gradients can reveal evidence of local adaptation, providing insight into the demographic and evolutionary processes that shape intraspecific diversity.** Using 1773 genome-wide single nucleotide polymorphisms we evaluated latitudinal variation in allele frequency for 134 populations of North American and European Atlantic salmon (*Salmo salar*). We detected 84 (4.74%) and 195 (11%) loci showing clinal patterns in North America and Europe, respectively, with 12 clinal loci in common between continents. Clinal single nucleotide polymorphisms were evenly distributed across the salmon genome and logistic regression revealed significant associations with latitude and seasonal temperatures, particularly average spring temperature in both continents. Loci displaying parallel clines were associated with several metabolic and immune functions, suggesting a potential basis for climate-associated adaptive differentiation. **These climate-based clines collectively suggest evidence of large-scale environmental associated differences on either side of the North Atlantic.** Our results support patterns of parallel evolution on both sides of the North Atlantic, with evidence of both similar and divergent underlying genetic architecture**. The identification of climate-associated genomic clines illuminates the role of selection and demographic processes on intraspecific diversity in this species and provides a context in which to evaluate the impacts of climate change.**

## (Acevedo et al., 2006) Efecto de la procedencia geográfica y de la fertilización en la fenología del brote terminal en plántulas de pseudotsuga sp.

In most of the cases, a significant association was not found between the phenological traits and the data of origin of the populations (p>0.05). **The only exception was the date of budburst, which showed a relatively strong negative correlation (r=−0.78) with the altitude of the site of origin; that is, populations from higher elevation tended to initiate the growth of the terminal shoot sooner** (Table 3).

Background & Context

Problem Statement

Project Goals

Hypothesis

# Methods and Materials

## (Gill et al., 2015) Changes in autumn senescence in northern hemisphere deciduous trees: a meta-analysis of autumn phenology studies

A meta-analysis was conducted of published studies from the peer-reviewed literature that reported autumn senescence dates for deciduous trees in the northern hemisphere, encompassing 64 publications with observations ranging from 1931 to 2010.

We assembled a database of peer-reviewed

“We assembled a database of peer-reviewed publications using the Web of Science search engine. We used all combinations of the following search terms as ‘topics’: ‘autumn’ or ‘fall’; ‘phenology’ or ‘senescence’; ‘tree’ or ‘plant’ or ‘forest’; and ‘leaf’. We limited the search to English-language, peer-reviewed journal articles published before 25 February 2013. The search resulted in 760 publications, but we limited our subsequent analysis to all publications that report either (1) the date of tree leaf senescence in a given year (for one year or a series of years) or (2) a rate of change in tree leaf senescence dates over time or temperature for a reported measurement period. We limited the data set to publications that report estimates of autumn leaf senescence for ecosystems with one annual senescence period. To optimize data resolution, we included only those publications in which researchers monitored phenology more frequently than 14 day intervals throughout the senescence period. We included measurements from both young and mature trees and, in the cases of experimental studies, used data from reference treatments only. Within publications, we considered unique sites and plant species to represent independent data. We extracted data from tables and text when available and used DataThief (version 1.6; Tummers, 2006) to extract values presented in the figures.”

Might need a table and a figure like this too

Studies were distributed throughout North and South America, Europe and Asia, with data concentrated in the eastern USA, Europe and Japan (Fig. 1). The distribution of studies was heavily skewed toward the northern hemisphere, with only two studies located in the southern hemisphere. Due to lack of sufficient replication in the southern hemisphere, **we focus our analysis on senescence trends in the northern hemisphere alone. We identified 64 publications and 1121 independent measurements that met our criteria.**

Table

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## (Aitken & Bemmels, 2015) Time to get moving: assisted gene flow of forest trees

We focused on adaptive clines in three traits expected to impact fitness of natural populations that are commonly phenotyped: height growth potential, timing of spring shoot phenological events associated with growth initiation (‘spring events’), and timing of fall phenological events associated with growth cessation (‘fall events’). We identified clines along gradients in mean annual temperature (MAT), selected as a broad proxy for overall climate, and mean summer precipitation (MSP), intended to reflect growing season drought stress. Due to few studies on trees species from very dry climates, and less consistent adaptive clines identified along the gradient in MSP, we focus primarily on results for MAT and caution that our results may not be applicable to species and regions where climates are becoming much drier and drought-related mortality is a major concern (Allen et al. [2010](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0005)).

We searched the literature for data sets from provenance trials in which height or timing of spring or fall shoot events was reported. Our search was restricted to temperate tree species native to western Canada and the United States, west of and including the Rocky Mountains. Species native to this region but found primarily in boreal forests, deserts, grasslands or Mediterranean climates were excluded. We initially searched using Web of Science (Thompson Reuters, New York, NY) for articles on provenance trials and common gardens individually for each tree species native to British Columbia (Klinka et al. [2000](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0052)). We then expanded this search to include all conifers and common angiosperm trees (Little [1971](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0068)) that met our broader geographic and ecological criteria, by scanning titles of search results for species plus the word ‘provenance’ in the University of Michigan Library (using Summon®, ProQuest, Ann Arbor, MI, USA). We retained data sets in which multiple populations were grown in a common environment, including greenhouse environments and field sites within and beyond the species’ native range. **All data sets for ‘spring events’ recorded the timing of bud flush, whereas we pooled timing of bud set, growth cessation and leaf abscission into a single category of ‘fall events’ because of an insufficient number of studies assessing bud set**. All three fall events are steps towards the initiation of dormancy prior to development of cold hardiness, and the timing of these events reflects local adaptation to maximize the length of the growing season while avoiding fall frost injury (Howe et al. [2004](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0045); Rohde and Bhalerao [2007](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0086); Cooke et al. [2012](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0016)). In natural populations of Populus, the timings of these events are highly correlated (Rohde et al. [2011](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0087), McKown et al. [2013](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0076)). **Although genetic mechanisms underlying these traits are complex (Cooke et al.** [**2012**](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0016)**), pooling fall events is justified given the shared pressures from natural selection that underlie observed patterns in all three traits.**

**If multiple observations of spring or fall events were available, only those from the year with the greatest variance in timing of these events were included.**

Timing of spring and fall events must have been measured in units of calendar days, not using a quantitative scale on a single day.

Provenance MAT was estimated for each population using ClimateWNA (Wang et al. [2012](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0104)) with provenance latitude, longitude and elevation provided in original publications. Simple linear regressions of population mean values of phenotypic traits versus provenance MAT were performed for each species (Fig. [4](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-fig-0004)A). To facilitate comparisons among species, regression slopes for height growth potential were rescaled to units of percent change per degree Celsius increase in provenance MAT (%·°C−1), with 100% assigned to the expected height growth potential at the midpoint of provenance MAT. Regression slopes for timing of spring and fall events were retained in days per degree Celsius increase in provenance MAT (d·°C−1), but a value of zero was assigned to the expected date of spring and fall events at the midpoint of the provenance MAT values. Similar analyses were conducted for population MSP (Tables S1–S3). Although variation in phenotypic traits along climatic gradients may be nonlinear and better modelled by a quadratic function, visual inspection confirmed that most relationships were approximately linear (Figures S2–S9), and linear models were applied to all species to facilitate interspecific comparisons.

A total of 23 data sets (for 18 species) were available for height growth potential, 11 data sets (eight species) for spring events and six data sets (five species) for fall events (Fig. [4](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-fig-0004)B, Tables S1–S3). Datasets containing population means from all studies are archived in Dryad (Aitken and Bemmels [2015](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0511)). In addition to documenting adaptive clines, we determined how representative the provenance trial data sets are of climatic conditions found across each species’ geographic range. To assess this, we compared the range of MAT and mean July precipitation (MJP) among provenances to the realized niche of each species along gradients in the same climate variables.

## (Alberto et al., 2013) Potential for evolutionary responses to climate change - evidence from tree populations

Next, we examine the patterns of quantitative genetic

variation in tree species in general and in these European conifers in

particular to evaluate the effects of selection for local adaptation. We reviewed

the literature of provenance trials and found a total of

112 studies on 19 relevant traits related mostly to phenology, growth, cold or

drought tolerance or other ecophysiological traits, among which were 36 studies

# Discussion

Did we say stronger in europe than NA or smth?? Need to check my scratch papers

It appears that the higher the latitude (farther north), the earlier the spring event, AND the earlier the fall event

Higher in elevation (garden), then later fall doys -> ALT NG ABIAMA Worrall 1983

[**https://academic.oup.com/aob/article/116/6/875/161733**](https://academic.oup.com/aob/article/116/6/875/161733)

**Changes in autumn senescence in northern hemisphere deciduous trees: a meta-analysis of autumn phenology studies**

Among the meteorological measurements examined, October temperatures were the strongest predictors of date of senescence, followed by cooling degree-days, latitude, photoperiod and, lastly, total monthly precipitation**, although the strength of the relationships differed between high- and low-latitude sites.** **Autumn leaf senescence has been significantly more delayed at low (25° to 49°N) than high (50° to 70°N) latitudes across the northern hemisphere**, with senescence across high-latitude sites more sensitive to the effects of photoperiod and low-latitude sites more sensitive to the effects of temperature. **Delays in leaf senescence over time were stronger in North America compared with Europe and Asia.**

## (Aitken & Bemmels, 2015) Time to get moving: assisted gene flow of forest trees

Statistically significant regressions of timing of spring events versus provenance MAT were found in six of 11 data sets (four of eight species; Table S2). The signs of slopes varied and were mostly shallow, ranging from −5.1 to 4.6 d·°C−1, with a mean R2 of 0.46 (range: 0.26 to 0.82; significant regressions only). In three species, spring events occurred earliest in populations from colder provenances, while in one species, the opposite trend was observed. In contrast, regressions of timing of fall events versus provenance MAT were statistically significant and consistent in direction in all six data sets (five species), with fall events occurring earliest in populations from colder provenances (Table S3). Population mean date of fall events increased by an average of 6.3 d·°C−1 (range: 0.89 to 11.4 d·°C−1; t-test for significant difference from zero: P = 0.0149), with a mean R2 of 0.63 (range: 0.25 to 0.90). Alberto et al. ([2013](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0004)) also concluded elevational and latitudinal clines in bud set were more consistent among species than clines in bud flush in a larger number of temperate and boreal tree species from multiple continents.

Weak or inconsistent clines in spring events, in contrast to strong, consistent clines in fall events, may reflect more complex patterns of local adaptation in spring. While fall events are usually triggered by critical photoperiod, or in some cases by completion of predetermined growth, spring bud flush is initiated after attaining both sufficient chilling and an adequate heat sum (Fig. [2](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-fig-0002)). The average timing of bud flush for a population may depend on particular local climatic patterns that allow for adequate chilling and heat sum accumulation at the transition from winter to spring. Chilling and heat sum requirements, and the timing of bud flush in a given environment, can vary among sympatric species; for example, opposite directions of adaptive clines in bud flush have been reported along a shared elevational gradient in Fagus sylvatica compared to Fraxinus excelsior and Quercus petraea (Vitasse et al. [2010](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0100)).

Complex and species-specific adaptive variation in bud flush timing would render the impacts of climate change and AGF much less straightforward for spring than for fall events or height growth potential.

The potential for phenotypic plasticity in bud flush timing as a response to climate change is high, and this phenotypic plasticity is not always adaptive (Duputié et al. [2015](https://onlinelibrary.wiley.com/doi/full/10.1111/eva.12293?msclkid=39d853a4baca11ec835f5304db159207#eva12293-bib-0022)).

shared adaptive clines in height growth potential and fall events support the conclusions that local adaptation is common in widespread temperate trees, and that patterns of adaptation along climatic gradients are often very similar among species.

## (Alberto et al., 2013) Potential for evolutionary responses to climate change - evidence from tree populations

The results of the summary in Table [3](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-tbl-0003) show that the two phenological traits differ in their patterns. For bud flush, both altitudinal and latitudinal clines showed similar shallow slopes, but the direction of adaptation varied greatly among species (Table [3](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-tbl-0003)a). For example, high altitude populations from the same transect flushed late in Q. petraea (Fig. [4](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-fig-0004)a), whereas in F. sylvatica they flushed early (Vitasse et al., [2009](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0198)). This could reflect different compromises in the adaptive tradeoff between maximizing the growing season length and exposing new leaves to late frosts. Bud flush is triggered by the accumulation of cold (or chilling) sums followed by heat (or forcing) sums above a threshold temperature sum. These genetically determined critical temperature sums and thresholds may vary among species, and to a lesser extent among populations of the same species (Hänninen & Tanino, [2011](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0068)). Bud flush in late successional species is also more influenced by photoperiod than in early successional species (Körner & Basler, [2010](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0101); Basler & Körner, [2012](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0016)). Bud set showed steeper slopes for both gradients and in all species more northern or higher altitude populations had earlier bud set (Table [3](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-tbl-0003)b). These data suggest that differential selection on bud set is systematically stronger than on bud flush. Bud flush may display higher phenotypic plasticity as temperatures increase. In contrast, bud set is largely governed by photoperiods, and modulated by temperatures and drought, which results in a more predictable environmental signal from year to year and location to location (Böhlenius et al., [2006](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0020)). In a warming climate, spring phenology can likely respond and advance without much genetic change, as has already been seen in many species (Gienapp et al., [2008](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0053)), provided that the chilling requirement has been met. However, if chilling temperature requirements have not been met, in some cases bud flush may even be delayed (Hänninen & Tanino, [2011](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0068)), as already seen recently in Tibet (Yu et al., [2010](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0213)). In the fall, a change in bud set date is more likely to require a genetic change in photoperiodic responses. Some studies suggest that the heritability of bud flush is higher than for bud set (Howe et al., [2003](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0079)), but estimates of the additive genetic component are rarely available in the literature. The latitudinal slopes were also much steeper than the altitudinal ones (Table [3](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-tbl-0003)b). Sundblad & Andersson ([1995](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12181#gcb12181-bib-0191)) have suggested that along the altitudinal gradients there may be more gene flow so populations do not become as differentiated. **The simple calibration factors we used also may not capture all aspects of the environme**nt.

## (Gill et al., 2015) Changes in autumn senescence in northern hemisphere deciduous trees: a meta-analysis of autumn phenology studies

Among the meteorological measurements examined, October temperatures were the strongest predictors of date of senescence, followed by cooling degree-days, latitude, photoperiod and, lastly, total monthly precipitation, although the strength of the relationships differed between high- and low-latitude sites. Autumn leaf senescence has been significantly more delayed at low (25° to 49°N) than high (50° to 70°N) latitudes across the northern hemisphere, with senescence across high-latitude sites more sensitive to the effects of photoperiod and low-latitude sites more sensitive to the effects of temperature. **Delays in leaf senescence over time were stronger in North America compared with Europe and Asia.**

The results indicate that leaf senescence has been delayed over time and in response to temperature, although low-latitude sites show significantly stronger delays in senescence over time than high-latitude sites. While temperature alone may be a reasonable predictor of the date of leaf senescence when examining a broad suite of sites, it is important to consider that temperature-induced changes in senescence at high-latitude sites are likely to be constrained by the influence of photoperiod. Ecosystem-level differences in the mechanisms that control the timing of leaf senescence may affect both plant community interactions and ecosystem carbon storage as global temperatures increase over the next century.