



Tree Physiology 35, 112–123
doi:10.1093/treephys/tpu106



Research paper

Differentiation of persistent anatomical defensive structures is costly and determined by nutrient availability and genetic growth-defence constraints

Xoaquín Moreira^{1,4}, Rafael Zas², Alejandro Solla³ and Luis Sampedro²

¹Institute of Biology, Laboratory of Evolutive Entomology, University of Neuchâtel, Rue Emile-Argand 11, 2000 Neuchâtel, Switzerland; ²Misión Biológica de Galicia (MBG-CSIC), Apdo 28, 36080 Pontevedra, Galicia, Spain; ³Ingeniería Forestal y del Medio Natural, Universidad de Extremadura, Avenida Virgen del Puerto 2, 10600 Plasencia, Spain; ⁴Corresponding author (xmoreira1@gmail.com)

Received July 1, 2014; accepted November 10, 2014; published online January 15, 2015; handling Editor Michael Ryan

Conifers exhibit a number of chemical and anatomical mechanisms to defend against pests and pathogens. Theory predicts an increased investment in plant defences under limited nutrient availability, but while this has been demonstrated for chemical defences, it has rarely been shown for anatomical defensive structures. In a long-lived woody plant, we tested the hypothesis that limited nutrient availability may promote an improved differentiation of persistent anatomical defences. We also hypothesized that the costs of differentiation of those long-term anatomical structures may be determined by genetic constraints on early growth potential. Using *Pinus pinaster* Ait. juveniles, we performed a greenhouse study with 15 half-sib families subjected to experimental manipulation of phosphorus (P) availability and herbivory-related induced responses. When plants were ~30 cm high, half of the plant material was treated with methyl jasmonate to induce defences, and 2 weeks later plants were harvested and the abundance of resin canals in the cortex and xylem was assessed. Density of constitutive resin canals in the cortex and the total canal system was ~1.5-fold higher in plants under limited P availability than in fully fertilized plants. Availability of P did not significantly influence the inducibility of resin canal traits. We found negative genetic correlations between plant growth and the density of constitutive canals in the xylem and total canal system, but only under conditions of limited nutrition. These results demonstrate for the first time that differentiation of constitutive anatomical-based defences is affected by P limitation. Moreover, results also evidence the existence of genetic constraints between plant growth and constitutive defensive investment, where lineages with the highest growth potential showed the lowest investment in constitutive resin canals.

Keywords: growth-defence trade-offs, growth-differentiation balance hypothesis, maritime pine, *Pinus pinaster*, resource allocation, resource availability hypothesis, traumatic resin ducts.

Introduction

Conifers, the largest and longest-lived plants on the planet, have evolved potent and effective defensive mechanisms against a vast number of herbivores and pathogens (Schulman 1954). Conifer defences are largely based on the combination of high concentrations of a diverse array of carbon-based compounds

(i.e., chemical defences) and physical structures (i.e., defences of an anatomical nature), which reduce the impact of their enemies (Franceschi et al. 2005, Mumm and Hilker 2006). These defences can also be classified as constitutive (always present in the plant) or inducible (produced in reaction to biotic challenges), the latter presumably having evolved in response

to differences in the strength and variability of challenging factors (Karban 2011). Induced defences are expected to be more cost-efficient than constitutive defences, as the former are only produced when required in response to environmental cues. Constitutive defences, on the other hand, are supposedly favoured where there is a high risk of herbivory.

It is well known that the production of constitutive chemical defences varies principally in response to diverse abiotic factors such as soil nutrient availability (Orians et al. 2003, Cipollini and Heil 2010, Heil 2010). It is also widely accepted that plants invest relatively more energy in constitutive defences when living in resource-poor conditions than in resource-rich conditions. Based on comparisons of defensive phenotypes across species, the resource availability hypothesis (RAH) predicts that plants adapted to resource-poor and stressful habitats will be slow growing and consequently invest significantly in constitutive defences, because their high tissue value means that losses due to herbivory are more costly (Coley et al. 1985, Endara and Coley 2011). Similarly, based on the physiological trade-off between growth and chemical defences, and on conflicts between biosynthetic pathways, the growth-differentiation balance hypothesis (GDBH) predicts that under resource-impooverished conditions growth is limited more than photosynthesis, and the consequent excess of carbon is diverted to the production of defences (Herms and Mattson 1992). The environment is also thought to modulate the expression of induced defences (reviewed by Cipollini and Heil 2010), but empirical evidence for this is still limited and sometimes inconsistent, especially in long-lived plant species. For instance, induced investment in chemical defences was found to be greater under nutrient-limiting conditions in young pine trees (Sampedro et al. 2011), while an increase in resin flow in response to mechanical damage was found to be constrained by drought stress in mature pine trees (Lombardero et al. 2000).

Trade-offs between the allocation of resources to constitutive defences versus other plant functions such as growth have been reported in greenhouse and field studies for several herbaceous (reviewed by Koricheva 2002) and woody plants (Zas et al. 2005, Donaldson et al. 2006, Osier and Lindroth 2006, Sampedro et al. 2011). In contrast, and probably due to the difficulty of assessment, much less is known about the existence of genetic-based trade-offs (i.e., negative genetic correlations) associated with the expression of induced defences (Cipollini et al. 2003, Cipollini and Heil 2010), especially in trees (but see Sampedro et al. 2011). Such negative correlations between growth potential and the expression of constitutive or induced defences reflect the costs of defences in terms of fitness, and are evidence of the heritable, genetic trade-offs between life functions, and are therefore of evolutionary relevance (Agrawal et al. 2010, Sampedro 2014). Genetic trade-offs between growth and defence (either constitutive or induced) might be also strongly modulated by environmental conditions. Several authors have

observed that these trade-offs only emerge under limiting soil nutrient availability, and are weak or absent when conditions are more favourable for growth (e.g., Osier and Lindroth 2006, Donaldson and Lindroth 2007, Sampedro et al. 2011).

Increased production of chemical defences in secretory cells and tissues in response to biotic stress is commonly accompanied by the differentiation of physical barriers and anatomical structures of defence. In particular, pine trees produce numerous constitutive and inducible resin canals in their cortex and xylem tissues, forming a network of storage ducts surrounded by secretory parenchyma (Franceschi et al. 2005). This network supplies a copious resin flow in the wounding sites, which acts as the first barrier against herbivores and pathogens (Krokene et al. 2003, Franceschi et al. 2005, Mumm and Hilker 2006, Solla et al. 2006). Differentiation of such anatomical defensive structures in pine trees is persistent and irreversible, and it depletes large amounts of carbohydrate reserves (e.g., Bonello et al. 2006). The formation of canals involves slow and expensive processes such as cell division and differentiation, as opposed to chemical defences that usually involve rapid plastic changes in the metabolism of secretory cells (Bonello et al. 2006). Therefore, the effects of the environment on the allocation of resources for anatomical defensive changes, and the associated costs in terms of vegetative fitness, might be expected to be greater than those previously observed for chemical defensive changes. However, while the influence of nutrient availability on the defensive phenotype and on their costs has been well documented for chemical defences (Koricheva 2002, Donaldson et al. 2006, Osier and Lindroth 2006, Sampedro et al. 2011), it has been rarely reported for anatomical defensive traits.

The aim of this study was to investigate the effects of limited nutrient availability on the differentiation between constitutive and induced anatomical defensive structures (namely the resin canal system), using pine trees as a long-lived woody plant model. We investigated the genetic trade-offs between growth and resin canal formation that are symptomatic of the vegetative costs associated with defence. We also examined genetic variation in constitutive and induced anatomical defences, and in the response of these defences to phosphorus (P) availability. We performed a greenhouse experiment with *Pinus pinaster* Ait. (Pinaceae) half-sib families where P availability and herbivore-induced responses were experimentally manipulated. Herbivore-induced responses were mimicked by applying methyl jasmonate (MJ), a plant hormone involved in the signalling of defensive responses against chewing herbivores and necrotrophic pathogens (Thaler et al. 2012). We focused on soil P availability because P is the most limiting nutrient for growth of young *P. pinaster* trees in our study area (Martíns et al. 2009) and because P was previously reported to drive herbivore damage and resistance in young *P. pinaster* plantations (Zas et al. 2006, Moreira et al. 2008). We hypothesized

that (i) pine juveniles growing under P-limited conditions would show higher constitutive and induced differentiation of resin canals compared with pines growing under complete fertilization, (ii) there would be genetic variation between families in constitutive and induced resin canal traits and in their response to P availability, (iii) the differentiation of resin canals would trade-off with growth and (iv) the vegetative costs associated with producing anatomical defences, expressed as negative family correlations between resin canal and plant growth traits, could be context dependent, and they would be more relevant under limited P availability than under complete fertilization.

Materials and methods

Natural history

Pinus pinaster is a conifer species of great economic and ecological relevance in southern Europe and the Mediterranean basin. The distribution range of this species extends from Portugal and northern Spain to south-western France, Italy and Morocco (Richardson 1998). It generally occurs at low to moderate elevations, mostly from sea level to 600 m (Richardson 1998).

As with other conifer species, *P. pinaster* has a well-defined defensive arsenal against a broad range of ecologically important herbivores and pathogens (Moreira et al. 2008, Sampedro et al. 2011). This defensive arsenal is mostly based on the constitutive and induced production of resin and phenolic compounds (Sampedro et al. 2011). Both types of secondary compounds are present in large concentrations in all tissues along the plant, imposing ecologically relevant physiological costs (Mumm and Hilker 2006, Sampedro et al. 2011, Moreira et al. 2014, Villari et al. 2014).

Conifer resin is a viscous liquid composed of terpenoids, of which ~50% are diterpenes (C_{20}) and diterpene acids (called resin acids) that make the resin thick and sticky (Phillips and Croteau 1999, Franceschi et al. 2005, Bohlmann 2008). The remaining 50% is a variable mixture of volatile terpenes (monoterpenes, C_{10} ; and sesquiterpenes, C_{15}) that serve as a solvent for the transport of non-volatile diterpenes (Phillips and Croteau 1999, Franceschi et al. 2005, Bohlmann 2008). The conifer resin is constitutively synthesized and accumulated in specialized secretory structures, such as resin canals (ducts), resin blisters and resin cavities (Phillips and Croteau 1999, Trapp and Croteau 2001). Constitutive axial resin canals appear in both the xylem and the cortex following a scattered distribution. Herbivore wounding and fungal infection in pine trees elicit local and systemic damage signalling in which jasmonic acid derivatives are known to be crucial (Martin et al. 2002, Miller et al. 2005, Krokene et al. 2008). In response to damage, pine trees can develop traumatic resin canals in the secondary xylem, which are usually found in tangential series of one or two rows within an annual ring of xylem (Krokene et al. 2003, Franceschi et al. 2005). The defensive function of the resin canal system is

well documented, and more dense resin canals have been associated with improved field resistance to insect pests and pathogens (Kane and Kolb 2010, Moreira et al. 2012a, Ferrenberg et al. 2014).

Experimental design

A controlled greenhouse experiment with pine genetic entries, soil P fertilization and induction of defences as the main factors was carried out. The experiment followed a randomized split-split design replicated in four blocks, with soil P fertilization (two levels: complete and P-limited) as the whole factor, treatment of defence induction (two levels: control [i.e., constitutive] and MJ-induced plants) as the split factor, and 15 genetic entries (open-pollinated half-sib families of known mother trees) as the split-split factor. In total, there were 240 plants corresponding to 4 blocks \times 2 soil P treatments \times 2 induction treatments \times 15 genetic entries.

Plant material, culture and greenhouse conditions

Pinus pinaster families were randomly selected from a broader collection of mother trees belonging to the Atlantic coast population of Galicia (NW Spain). A description of climate, soil characteristics, genetic variation in resistance and other characteristics of the study area and pine population can be consulted in Sampedro et al. (2011). The 15 open-pollinated pine families studied here were a random subset of the 34 families included in Sampedro et al. (2011), a companion paper that focused on chemical defences in stems and needles of the same trees. In February 2006, pre-weighed pine seeds were individually sown in 2-l pots filled with a mixture of perlite and peat (1 : 1 v : v) and covered with a 1–2-cm layer of sterilized sand. To avoid pathogens, seeds were preventively treated before sowing with a fungicide (Fernide®, Syngenta Agro, Madrid, Spain). All plants were grown in a research grade glasshouse (Forestry Research Centre of Lourizán, Xunta de Galicia, Pontevedra, Spain), with controlled temperature (10 °C minimum temperature at night; 25 °C maximum temperature during daytime) and light (minimum 12 h per day). Fungicide was also applied to the substrate every 2 months.

Treatments of fertilization and induction of defensive responses

One month after sowing, the fertilization treatments (complete and P-limited fertilizer) were applied every 2 days by subirrigation. The complete fertilizer was a balanced solution containing 100 : 20 : 70 : 7 : 9 mg l⁻¹ of N : P : K : Ca : Mg, respectively, and the necessary amounts of micronutrients and trace elements. This solution was a modification of that used by local nurseries for optimum seedling growth of this pine species. The P-limited fertilizer solution contained the recommended levels of N, K, Ca and Mg as described above, but the availability of P was reduced 10-fold to 2 mg l⁻¹. Fertilizer solutions

were prepared every 2 weeks, and the pH was adjusted to 6.5 in both treatments.

On 2 August 2006, when average height of P-limited and complete fertilized plants were 21.9 ± 0.7 and 44.3 ± 1.3 cm, respectively, 120 plants (i.e., half of the total number) were individually treated with a solution of 22 mM MJ (Sigma-Aldrich, St Louis, MO, USA) suspended in deionized water with ethanol 2.5% (v : v). The remaining 120 plants were treated with the carrier solution (2.5% ethanol) and acted as control. Treatments were sprayed evenly over the foliage with a handheld sprayer, each plant receiving 2.6 ± 0.2 or 3.7 ± 0.3 ml of solution (P-deficient and complete fertilization plants, respectively). To avoid cross-contamination, treatments were applied in separate greenhouse chambers and plants remained in those separate spaces for 24 h to dry.

Sampling, measurements and histological analyses

At 2 weeks after application of the induction treatment, plant height was measured and all pine juveniles were harvested, transported to the lab in ice coolers and immediately sampled for histological analyses and total biomass determination. A 5-cm-long subsample of the apical portion of the stem from each plant was immediately placed in a glass vial and fixed in formalin–acetic acid–ethyl alcohol for ~48 h according to [Moreira et al. \(2008\)](#) and then transferred to 70% ethyl alcohol for storage until sectioning and staining. Cross-sections (90 μ m thick) were made using a sliding microtome. Sections were stained with 0.1% aqueous Safranin and Fast Green according to standard procedures ([Ruzin 1999](#), [Moreira et al. 2008](#)). Photographs were taken with a Nikon Digital Sight DS-U1, mounted on a Nikon SMZ-U binocular microscope at $\times 20$ magnification. Image analysis was performed on a quarter of cross-section as in [Moreira et al. \(2012a\)](#) using the Phloemalyzer v.2.12 image analysis software developed at the Pacific Forestry Centre (British Columbia Forest Service, Victoria, BC, Canada).

The resin canal system of the cortex and xylem, as well as the total canal system (i.e., sum of cortex and xylem), was characterized in terms of (i) resin canal density (the number of axial resin canals per unit area) and (ii) relative conductive area (%), obtained by dividing the total transectional area occupied by resin canals by the total area of the tissue assessed, and then multiplying by 100 ([Moreira et al. 2008](#)).

Statistical analyses

Preliminary analyses of the effects of induction treatment (control vs MJ application) on growth and resin canal traits were carried out with a proper mixed model to solve split-split designs ([Littell et al. 2006](#)) using the PROC MIXED procedure of SAS System (version 9.2, SAS Institute, Cary, NC, USA). These models included the fixed effects of P availability, defence induction treatment (T) and their interaction, and the random effects of the Family (F) and its interaction with the

main effects, as well as the random effects of the blocks (B), and the B \times P and B \times P \times T interactions.

Analyses of constitutive resin canal traits (control untreated plants) and of their inducibility after MJ application (see below) were also carried out independently with a mixed model using the PROC MIXED procedure of SAS ([Littell et al. 2006](#)). The main effect of soil P availability was considered as a fixed factor. The block (B) and B \times P interaction were considered random factors in order to analyse the main factor P with the appropriate error term. Family and P \times F interaction were also considered as random factors, and the associated variance components were estimated by restricted maximum likelihood. The statistical significance of the variance components for each random factor was assessed using likelihood ratio tests, where the difference is two times the log-likelihood of the models including and excluding that random factors are distributed as one-tailed χ^2 , with one degree of freedom ([Littell et al. 2006](#)). Normality was achieved by log-transforming the raw data.

Because resin canal traits in induced plants are a result of the sum of pre-existing constitutive levels plus the induced response, variability in the induced mode would not properly represent the variation in inducibility, i.e., in the ability to increase defences after induction. Thus, in order to test for the effect of P availability and genetic variation on inducibility per se, we analysed our data using a bootstrap approximation, where inducibility of each induced plant was estimated as the difference between the value of the resin canal trait for a given plant and that of the other four plants of the same family and P treatment in the control treatment ([Moreira et al. 2013](#)). This resulted in four estimates of inducibility for each induced plant, which were considered as repeated measures on the same subject. For the statistical analysis of this inducibility trait a repeated measures mixed model, with F, F \times P treatment and F \times B as random factors, was used ([Moreira et al. 2013](#)).

In the case of the analyses of growth traits (height and biomass), we used a similar repeated measures approach, analysing the effect of the three main factors (P, F and P \times F) on the loss of growth caused by induction treatment (i.e., on the differences in height and biomass between MJ-induced and control plants). Effects of P availability and genetic variation on growth (i.e., height and biomass) in a larger collection of pine families ($N = 34$) were reported elsewhere ([Sampedro et al. 2011](#), [Moreira et al. 2012b](#)). Here we report the results of the same analyses for the specific material included in the present study, i.e., the 15 *P. pinaster* families.

In order to evaluate the trade-offs between constitutive and induced defences and growth potential, we studied the genetic correlations (family correlations) between pairs of traits. Family correlation between traits is a measure of the degree to which two traits are covariant as a result of pleiotropy or linkage disequilibrium (sensu [Agrawal et al. 2010](#)), and negative family correlations evidence a genetic-based trade-off between alternative

functions that could be relevant for evolutionary dynamics. Family correlations between pine growth and anatomical defences were estimated separately for the constitutive (control) and MJ-treated (inducibility) treatments across soil P treatments. These correlations were estimated using the best linear unbiased prediction (BLUP) values for each family in each P treatment, as obtained with the mixed models described above for the analyses of the constitutive resin canals and their inducibility.

In order to estimate the relative impact of chemical and anatomical defences on growth reduction, we performed multiple regression analyses for those treatments and variables showing significant genetic variation between the 15 families and significant negative genetic correlations with growth in this study. We also included in the analysis the chemical defensive traits reported by [Sampedro et al. \(2011\)](#) for the families in this study fulfilling the same requirements. Thus, we included in the model the concentration of a non-volatile resin in the stems and total polyphenolics in the needles ([Sampedro et al. 2011](#)), density of resin canals in the xylem and total density of resin canals as predictors of pine growth.

Results

Effect of exogenous application of MJ on growth and resin canal traits

Exogenous application of MJ significantly reduced plant height and biomass, which were 19 and 18% lower in MJ-treated plants than in control plants (Table S1 and Figure S1 available as Supplementary Data at [Tree Physiology Online](#)). Exogenous application of MJ significantly increased the density of resin canals in the cortex (18%), xylem (27%) and the total section

(25%), and increased the relative conductive area of canals in the cortex (82%), xylem (66%) and the total section (70%) compared with control plants (Table S2 and Figure S2 available as Supplementary Data at [Tree Physiology Online](#)).

Genetic and environmental effects on pine growth under constitutive and MJ-induced conditions

Nutrient limitation strongly affected pine growth under constitutive conditions (Table S3a and Figure S3 available as Supplementary Data at [Tree Physiology Online](#)), but did not alter the reduction in growth caused by MJ induction treatment (Table S3b and Figure S4 available as Supplementary Data at [Tree Physiology Online](#)). Specifically, under constitutive conditions, total height and biomass of plants grown under P-limited treatment were 39 and 58% lower, respectively, than those under the complete fertilizer (Figure S3 available as Supplementary Data at [Tree Physiology Online](#)). Pine families differed significantly in height under constitutive conditions and also differed in the reduction in growth caused by MJ (Table S3 available as Supplementary Data at [Tree Physiology Online](#)). Variation among pine families in biomass was also significant, but only under constitutive conditions (Table S3 available as Supplementary Data at [Tree Physiology Online](#)). We did not detect significant family variation in plasticity of growth (height and biomass) in response to soil P availability in the families included in this study (non-significant $F \times P$ interaction; Table S3 available as Supplementary Data at [Tree Physiology Online](#)).

Genetic and environmental effects on constitutive resin canals

Availability of P significantly influenced constitutive resin canal traits (Table 1a, Figure 1a). Density of cortex resin canals and

Table 1. Effects of P availability, pine family and their interaction on constitutive resin canal traits and on their inducibility. Summary of mixed models analysing the effect of P-limitation on several traits describing the resin canal system of 15 *P. pinaster* open-pollinated families in (a) constitutive mode and (b) herbivore-induced responses associated with jasmonate signalling (inducibility). Phosphorus availability is a fixed effect, and the F -values and corresponding df are shown. The family effect (F) and $P \times F$ interaction are random effects, and the corresponding likelihood ratio significance tests (χ^2) are shown. Significant P -values ($P \leq 0.05$) are shown in bold.

	P availability (P)		Family (F)		F \times P	
	$F_{1,3}$	P	χ^2	P	χ^2	P
(a) Constitutive						
Cortex resin canal density	25.11	0.015	–	–	–	–
Cortex resin canal relative conductive area	5.26	0.105	–	–	–	–
Xylem resin canal density	0.50	0.532	–	–	3.9	0.024
Xylem resin canal relative conductive area	6.55	0.083	0.7	0.201	0.6	0.219
Total resin canal density	23.88	0.016	–	–	1.0	0.159
Total resin canal relative conductive area	0.00	0.985	1.9	0.084	0.1	0.376
(b) Inducibility						
Cortex resin canal density	4.46	0.125	–	–	0.4	0.263
Cortex resin canal relative conductive area	1.68	0.285	13.9	<0.001	13.0	<0.001
Xylem resin canal density	1.87	0.265	3.8	0.026	16.8	<0.001
Xylem resin canal relative conductive area	1.33	0.333	1.0	0.159	18.3	<0.001
Total resin canal density	6.87	0.079	2.2	0.069	8.0	0.002
Total resin canal relative conductive area	3.54	0.156	5.8	0.008	20.1	<0.001

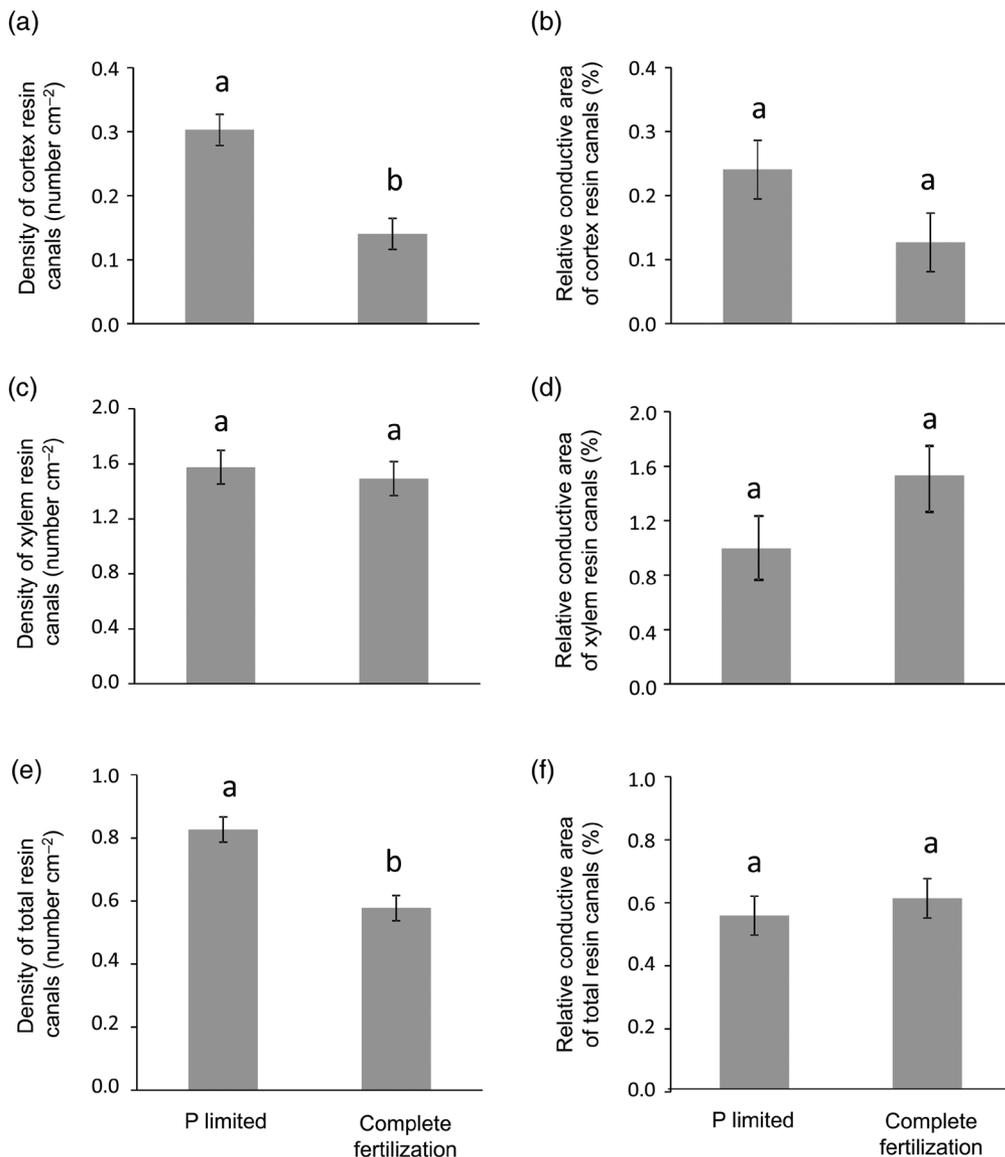


Figure 1. Effect of P availability on constitutive resin canal. Resin canal density and relative conductive area of constitutive resin canals in the cortex (a and b), xylem (c and d) and the whole stem section (e and f) of *P. pinaster* juveniles belonging to 15 open-pollinated families growing in a nutrient-rich (complete fertilization) and in P-limited media. Bars are least square means (\pm s.e. ($N=60$)). Results of the mixed model are presented in Table 1a. Different letters indicate significant differences (at $P < 0.05$) between fertilization treatments.

total number of constitutive resin canals was 2.1-fold and 1.4-fold greater, respectively, in plants grown under the P-limited treatment than in control plants (Figure 1a and e). Constitutive resin canal traits did not significantly differ between families (Table 1a). However, families differed in the phenotypic plasticity of the constitutive density of xylem resin canals in response to P availability as evidenced by a significant $F \times P$ interaction (Table 1a; genetic variation in phenotypic plasticity).

Genetic and environmental effects on the inducibility of resin canals

Although the inducibility of resin canals appeared to be consistently lower under complete nutrition than under P-limited conditions in both the xylem and the cortex (Figure 2), the

differences were not statistically significant in either case (Table 1b). Inducibility of cortex and total relative conductive area and inducibility of xylem resin canal density significantly differed between families (Table 1b). Moreover, significant genetic variation in response to P availability was observed, in terms of the phenotypic plasticity of the induced density and relative conductive area of xylem and total resin canals, and also in the relative conductive area of cortex resin canals (significant $F \times P$ interactions; Table 1b).

Genetic correlations between resin canal and plant growth traits

We found a negative family correlation between the density of constitutive resin canals and plant growth, significant for

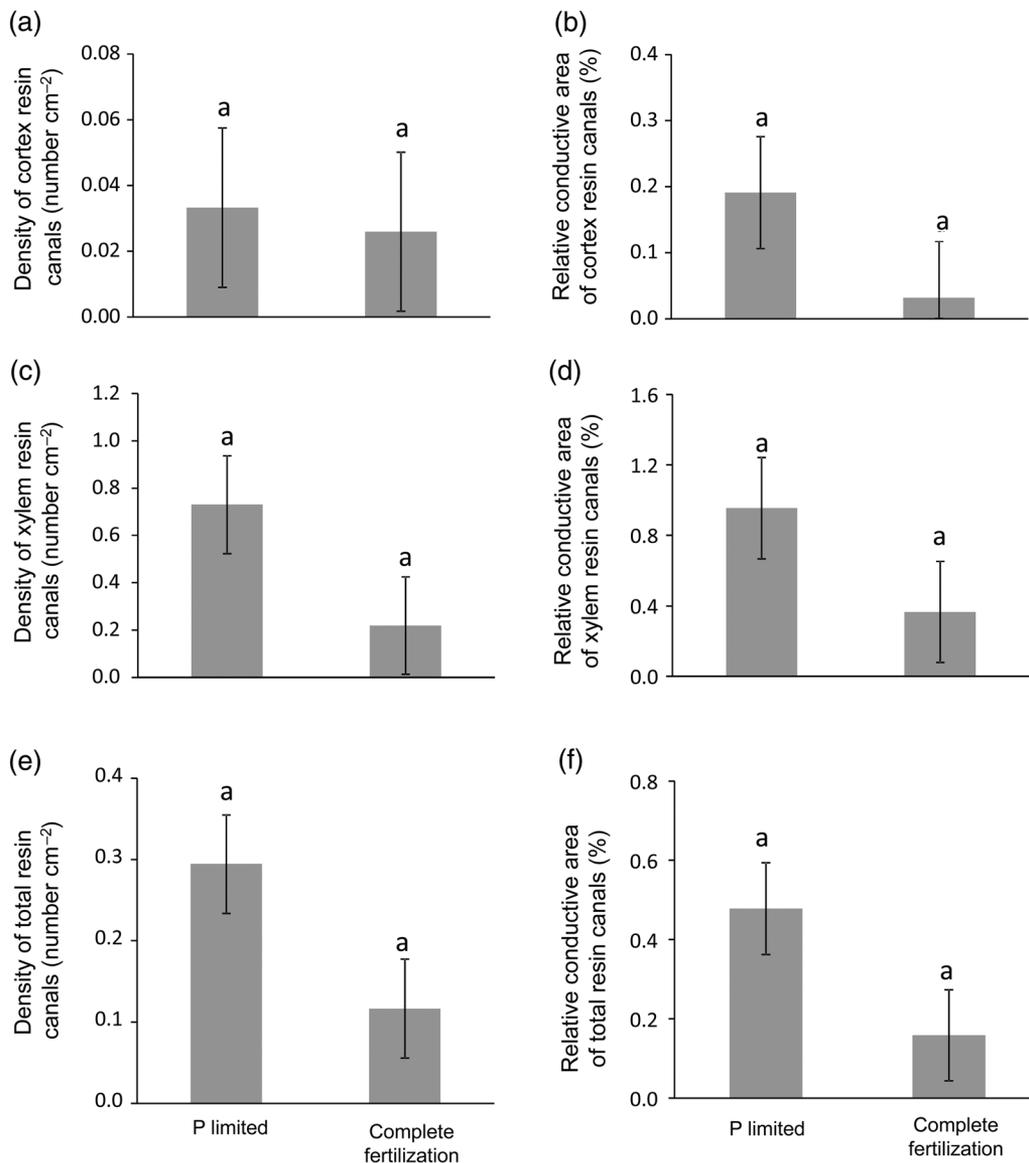


Figure 2. Effect of P availability on the inducibility of resin canal traits. Inducibility of resin canal density and relative conductive area in response to herbivore-damage signalling in the cortex (a and b), xylem (c and d) and the whole stem section (e and f) of *P. pinaster* juveniles belonging to 15 open-pollinated families growing in a nutrient-rich (complete fertilization) and in P-limited media. Bars are lsmeans \pm s.e. ($N = 60$). Results of the mixed model are presented in Table 1b. Herbivore-induced responses were elicited by exogenous application of MJ.

canals in the xylem and for total resin canals, but only under P-limiting conditions (Table 2); this suggests that such growth-defence trade-offs are context dependent. Family correlations between plant growth and other constitutive resin canal traits were mostly negative, but not significant (Table 2). On the other hand, no significant relationship at the family level between induced resin canal traits and the loss of plant growth associated with the MJ induction was observed, in either P-limited or complete fertilization treatments (Table 3).

As both anatomical defensive traits (Table 2) and chemical defences (Sampedro et al. 2011) showed significant trade-offs with growth rates, we used a multiple regression approach for identifying which defensive trait had the greatest effect

on growth (see Table S4 available as Supplementary Data at *Tree Physiology* Online). Despite both resin canals and the concentration of a non-volatile resin being significantly related to pine growth at the family level when analysed separately, density of resin ducts was the only trait that was significant when included in a multiple regression model, explaining the largest part of the variation in family growth (Table S4 available as Supplementary Data at *Tree Physiology* Online).

Discussion

The results showed that nutrient availability strongly influenced the early resource allocation to constitutive anatomical defences

Table 2. Genetic-based trade-offs between early growth and constitutive resin canal traits. Pearson's r coefficients (and significance levels) from family correlations between several traits of the constitutive resin canal system and plant growth in young *P. pinaster* grown under P-limiting and complete fertilization conditions. Negative significant family correlation evidences a heritable inverse genetic co-variation between growth and defence. Observed trade-offs were context dependent, as they were not evident under complete fertilization. Correlations were estimated using the best linear unbiased prediction (BLUP) values for each family and P treatment. Significant coefficients ($P < 0.05$) are in bold. $N = 15$ open-pollinated families.

	P-limited		Complete fertilization	
	Height	Biomass	Height	Biomass
Cortex resin canal density	– ¹	–	–	–
Cortex resin canal relative conductive area	–	–	–	–
Xylem resin canal density	–0.631 (0.021)	0.409 (0.164)	0.303 (0.272)	0.017 (0.951)
Xylem resin canal relative conductive area	–0.207 (0.459)	–0.007 (0.980)	0.007 (0.981)	–0.217 (0.438)
Total resin canal density	–0.769 (0.001)	0.289 (0.296)	0.282 (0.309)	0.129 (0.647)
Total resin canal relative conductive area	–0.170 (0.545)	–0.326 (0.236)	–0.172 (0.540)	–0.320 (0.245)

¹Because of null estimations of F and P × F variances the corresponding BLUP values are equal to zero.

Table 3. Family-based Pearson's r coefficients (and significance levels) between early growth and inducibility of resin canal traits. Pearson's r coefficients (and significance levels) from family correlations between several traits describing the inducibility of resin canal system and the reduction in plant growth due to the induction treatment in young *P. pinaster* grown under P-limiting and complete fertilization conditions. These correlations were estimated using the BLUP values for each family and P treatment. $N = 15$ open-pollinated families. Herbivore-induced responses were elicited by exogenous application of MJ.

	P-limited		Complete fertilization	
	Height	Biomass	Height	Biomass
Cortex resin canal density	–0.244 (0.381)	0.065 (0.819)	0.209 (0.454)	–0.165 (0.556)
Cortex resin canal relative conductive area	–0.162 (0.564)	0.409 (0.146)	–0.300 (0.277)	0.438 (0.103)
Xylem resin canal density	0.388 (0.153)	–0.281 (0.311)	0.459 (0.085)	0.260 (0.348)
Xylem resin canal relative conductive area	0.388 (0.152)	–0.021 (0.942)	–0.066 (0.816)	0.410 (0.129)
Total resin canal density	0.307 (0.265)	–0.332 (0.227)	0.358 (0.190)	–0.000 (0.999)
Total resin canal relative conductive area	0.239 (0.392)	0.299 (0.279)	–0.306 (0.267)	0.264 (0.341)

in *P. pinaster*, whereas it had no effect on their inducibility. In particular, the density of constitutive resin canals in the cortex and in the whole stem section was higher under P-limiting conditions than under complete fertilization. Nutrient availability also influenced the extent of vegetative costs associated with plant defensive investment. Our results showed genetic-based trade-offs between the formation of constitutive resin canals and plant growth, which only emerged under P-limited conditions. Finally, we found genetic variation in the inducibility of some resin canal traits, and in the response of most inducible resin canal traits to P availability (i.e., significant F × P availability interaction).

Effects of soil P availability on constitutive resin canals

Plasticity of the constitutive resin canals observed in the cortex in response to nutrient availability was also recorded in several other field and greenhouse studies of conifers (e.g., van Akker et al. 2004, Moreira et al. 2008). In an extensive field study performed in NW Spain, unfertilized 2-year-old seedlings of *P. pinaster* showed up to 30% more resin canal density in the cortex than the fertilized seedlings, whereas soil fertilization had no effect on the resin canal system in the xylem (Moreira et al. 2008). In another field experiment performed in BC (Canada),

van Akker et al. (2004) reported that fertilization significantly reduced constitutive resin canal density of 12-year-old *Picea glauca* × *P. engelmannii* hybrids. Results also agree with previous work reporting increased accumulation of chemical defences under impoverished nutrient conditions. Particularly, in a greenhouse experiment using the same plant material as in the current study, Sampedro et al. (2011) observed that pine seedlings growing under P-limited conditions had higher concentrations of constitutive stem resin, needle total phenolics and needle condensed tannins than plants growing under complete fertilization. Overall, these results support the predictions of ecological theories (e.g., GDBH, RAH) about the effects of limited resource availability on the allocation to constitutive defences of plants (Stamp 2003). These theories predict that due to physiological trade-offs between plant growth and secondary metabolism investment, and due to the high value of tissues when growth is slow, plants growing under limited resource conditions should be highly protected by constitutive defences. Our results regarding greater constitutive resin canals under nutrient deprivation may provide a mechanistic explanation for understanding the results of several field studies reporting negative effects of stand fertilization on conifer

tree resistance to phloem feeders (e.g., van Akker et al. 2004, Zas et al. 2005, 2006).

Effects of soil P availability on the inducibility of resin canal traits

Induction of resin canals after MJ application has been previously reported in several conifer species, as MJ application is known to be a useful chemical treatment mimicking herbivore-induced responses. In particular, extensive formation of traumatic resin ducts in the xylem in response to MJ has been reported for *Picea abies* (Franceschi et al. 2002, Martin et al. 2002, Krokene et al. 2003, 2008) and *Picea sitchensis* (Miller et al. 2005), but no previous studies have analysed the effect of MJ on the canal system of pine species. Nonetheless, pine trees are known to respond to herbivore feeding by producing traumatic resin ducts in the xylem (Moreira et al. 2008). On the other hand, the increase in resin canal density in the cortex after MJ application was probably due to a decrease in the cortex area rather than an increase in the number of resin canals. Resin canals in the cortex are known to be altered by biotic challenges in other conifer species (Kuroda 1998), but again no previous information is available for pine species.

In contrast to constitutive resin canals, our results show that inducibility of resin canal differentiation was not dependent on nutrient availability. Accordingly, using the same experimental plants, Sampedro et al. (2011) found that inducibility of a non-volatile resin in juvenile pine trees was similar in both P treatments. In the same study, however, Sampedro et al. (2011) found that inducibility of total polyphenolics was significantly greater under P-limited conditions. Contrastingly, other studies with annual plants have reported the opposite pattern, with increased inducibility of chemical defences under improved growing conditions. For example, Dietrich et al. (2004) reported that *Arabidopsis thaliana* showed significant induced production of total soluble proteins only when cultivated under high nitrogen conditions. We think that due to their different life-history determinants, different modes of defences (quantitative vs qualitative, respectively) and the different nature of their chemical defences (e.g., carbon- vs nitrogen-based), the influence of nutrient availability on induced defences of long-lived pine trees and herbaceous plants is probably not comparable.

Effects of soil P availability on the costs associated with constitutive and induced resin canals

Our results show that the costs associated with constitutive resin canal formation were contingent upon the availability of P in the soil. Most notably, a genetic-based trade-off between the density of constitutive resin canals in the xylem (and in the total section) and plant growth occurred only under limited availability of P. Fitness costs associated with the production of constitutive chemical defences under resource-limited

environments have been commonly observed in a diverse array of long-lived tree species (e.g., Lindroth et al. 2001, Donaldson et al. 2006, Osier and Lindroth 2006, Donaldson and Lindroth 2007, Sampedro et al. 2011), but to the best of our knowledge this is the first study showing early fitness costs associated with constitutive anatomical defences in a tree species. Specifically for *P. pinaster*, in a previous study with the same experimental plants, we found that growth rates were lower in pine families showing the highest concentrations of constitutive non-volatile terpenes, again only under P-limited conditions (Sampedro et al. 2011). Using a multiple regression approach we found that production of resin canals provoked higher reductions in growth than chemical defences (see Table S4 available as Supplementary Data at *Tree Physiology* Online). This result was expected, as the production of resin canals in conifer trees is a more energy-costly process (based on cell division and differentiation) than the production of chemical defences (based on local changes in cell metabolism) (Bonello et al. 2006).

No vegetative costs were associated with the inducibility of resin canals in either P-limited or complete fertilization. This finding does not agree with our previous work reporting a negative family correlation between induced chemical defences and plant growth under P-limited conditions (Sampedro et al. 2011). One possible explanation for this is that the production of resin canals in conifer trees is a slower process than the production of chemical defences (Bonello et al. 2006); if more than 2 weeks had elapsed between the induction treatment and the assessment of growth, vegetative costs may well have been detected. Other previous studies using conifer (Villari et al. 2014) and herbaceous (e.g., van Dam and Baldwin 1998) plants reported either no growth costs associated with induced defences or fitness costs arose only under rich-resource conditions (e.g., van Dam and Baldwin 2001, Cipollini 2010). Further research is needed to derive general patterns about fitness costs associated with the inducibility of defences and to determine (i) which defensive compounds are more or less canalized, (ii) the magnitude of allocation costs they generate and (iii) under what environmental conditions fitness costs are magnified.

Genetic variation in constitutive and induced anatomical defences and in their response to P availability

We found genetic variation in the inducibility of changes in the relative conductive area of cortex and total resin canals, and also in the inducibility of increases in xylem resin canal density, but not in constitutive resin canals. These results agree with our previous observations in young pine trees, where we found genetic variation in the inducibility of diterpenes in the stem and total phenolics in the needles (Sampedro et al. 2011, Moreira et al. 2013). Similarly, Agrawal et al. (2002) also found genetic variation in the induction of chemical and mechanical defences in wild radish. Genetic variation in the inducibility of plant

defences indicates that defensive strategies have the potential to evolve further in response to continued herbivore pressure.

We also found genetic variation in the response of most inducible resin canal traits (density and relative conductive area of xylem and total resin canals and relative conductive area of cortex resin canals) to P availability (i.e., significant F × P availability interaction). Although genetic variation in the response of constitutive defences to environmental conditions has been commonly observed in tree species (e.g., Donaldson et al. 2006, Osier and Lindroth 2006, Donaldson and Lindroth 2007), little is known in the case of inducible defences. Further studies should be undertaken to fill this gap in our knowledge, as genetic variation in the response of inducible defences allows the continued evolution of phenotypic plasticity, i.e., the ability of an individual or genotype to express different phenotypes across varying environmental conditions.

Implications for forest management

Recent studies have provided evidence that resin canals are reliable proxies of pine tree resistance against pests and pathogens. For example, Kane and Kolb (2010) observed that ponderosa pine trees that survived drought-associated bark beetle attacks in forests of northern Arizona had larger and denser resin canal ducts in the xylem than those that died. Similarly, Ferrenberg et al. (2014) found that pine trees resistant to bark beetles had significantly more resin ducts in the xylem than susceptible trees. Resin duct characteristics could, thus, offer a metric for assessing tree resistance and predicting the spatial/temporal spread of pests such as bark beetles during epidemic events (e.g., Gaylord et al. 2013). From an applied point of view, elicitation of inducible resin canals by MJ application to seedlings in the nursery could be an attractive measure to protect forest plantations from early biotic challenges. In this sense, Zas et al. (2014) recently found that exogenous MJ application to young pine trees in the nursery markedly increased the concentration of non-volatile resins in the stems and drastically reduced the subsequent attack of a phloem-feeder weevil (*Hylobius abietis*). As resin canals are known to be major proxies of pine tree resistance to pests and pathogens, understanding defensive allocation to resin canals, their genetic variation and environmental modulation could be considered in managing forest tree resistance and ultimately in forest management practices.

Conclusions

As previously reported for chemical defences (Sampedro et al. 2011), this work reveals that nutrient availability (particularly that of P, a major growth-limiting nutrient for the studied population) is a major driver in the differentiation of anatomical defences in young *P. pinaster*. Availability of P in the soil had significant effects on resource allocation to constitutive resin canals, the induction of canal formation and the emergence of related

vegetative costs. As insects are a major cause of early mortality in *P. pinaster*, our findings are of great relevance for understanding the strategies used by this light-demanding pioneer tree against herbivory during its early life stages.

Supplementary data

Supplementary data for this article are available at *Tree Physiology Online*.

Acknowledgments

The authors thank Patricia Martins for her superb technical assistance in the experimental set-up, Elena Cubera, Santiago Martínez, Oscar Fontán and Sara Varela for their help in plant sampling and assessments, Chema Mendaña and his collaborators for their assistance with the greenhouse, Dr René Alfaro (Pacific Forestry Centre, Victoria, BC, Canada) for providing the image analysis software, César Cendán for his help with histological analyses and David Brown for language editing. Comments and suggestions by Luis Abdala-Roberts (University of California-Irvine) and two anonymous reviewers helped to improve the manuscript.

Conflict of interest

None declared.

Funding

This research was supported by grants RTA07-100 and AGL2012-40151.

References

- Agrawal AA, Conner JK, Johnson MT, Wallsgrove R (2002) Ecological genetics of induced plant defense against herbivores: additive genetic variation and costs of phenotypic plasticity. *Evolution* 56:2206–2213.
- Agrawal AA, Conner JK, Rasmann S (2010) Tradeoffs and adaptive negative correlations in evolutionary ecology. In: Bell M, Eanes W, Futuyma D, Levinton J (eds) *Evolution after Darwin: the first 150 years*. Sinauer Associates, Sunderland, MA, pp 243–268.
- Bohmann J (2008) Insect-induced terpenoid defenses in spruce. In: Schaller A (ed) *Induced plant resistance to herbivory*. Springer, Dordrecht, The Netherlands, pp 173–187.
- Bonello P, Gordon TR, Herms DA, Wood DL, Erbilgin N (2006) Nature and ecological implications of pathogen-induced systemic resistance in conifers: a novel hypothesis. *Physiol Mol Plant Pathol* 68:95–104.
- Cipollini D (2010) Constitutive expression of methyl jasmonate-inducible responses delays reproduction and constrains fitness responses to nutrients in *Arabidopsis thaliana*. *Evol Ecol* 24:59–68.
- Cipollini D, Heil M (2010) Costs and benefits of induced resistance to herbivores and pathogens in plants. *CAB Rev Perspect Agric Vet Sci Nutr Nat Res* 5:1–25.

- Cipollini DF, Purrington CB, Bergelson J (2003) Costs of induced responses. *Basic Appl Ecol* 4:79–89.
- Coley PD, Bryant JP, Chapin FS (1985) Resource availability and plant antiherbivore defense. *Science* 230:895–899.
- Dietrich R, Ploss K, Heil M (2004) Constitutive and induced resistance to pathogens in *Arabidopsis thaliana* depends on nitrogen supply. *Plant Cell Environ* 27:896–906.
- Donaldson JR, Lindroth RL (2007) Genetics, environment, and their interaction determine efficacy of chemical defense in trembling aspen. *Ecology* 88:729–739.
- Donaldson JR, Kruger EL, Lindroth RL (2006) Competition- and resource-mediated tradeoffs between growth and defensive chemistry in trembling aspen (*Populus tremuloides*). *New Phytol* 169:561–570.
- Endara MJ, Coley PD (2011) The resource availability hypothesis revisited: a meta-analysis. *Funct Ecol* 25:389–398.
- Ferrenberg S, Kane JM, Mitton JB (2014) Resin duct characteristics associated with tree resistance to bark beetles across lodgepole and limber pines. *Oecologia* 174:1283–1292.
- Franceschi V, Kreckling T, Christiansen E (2002) Application of methyl jasmonate on *Picea abies* (Pinaceae) stems induces defense-related responses in phloem and xylem. *Am J Bot* 89:578–586.
- Franceschi V, Krokene P, Kreckling T (2005) Anatomical and chemical defenses of conifer bark against bark beetles and other pests. *New Phytol* 167:353–376.
- Gaylord ML, Kolb TE, Pockman WT, Plaut JA, Yezpez EA, Macalady AK, Pangle RE, McDowell NG (2013) Drought predisposes piñon-juniper woodlands to insect attacks and mortality. *New Phytol* 198:567–578.
- Heil M (2010) Plastic defence expression in plants. *Evol Ecol* 24:555–569.
- Hermes DA, Mattson WJ (1992) The dilemma of plants: to grow or defend. *Q Rev Biol* 67:283–335.
- Kane JM, Kolb TE (2010) Importance of resin ducts in reducing ponderosa pine mortality from bark beetle attack. *Oecologia* 164:601–609.
- Karban R (2011) The ecology and evolution of induced resistance against herbivores. *Funct Ecol* 25:339–347.
- Koricheva J (2002) Meta-analysis of sources of variation in fitness costs of plant antiherbivore defenses. *Ecology* 83:176–190.
- Krokene P, Solheim H, Kreckling T, Christiansen E (2003) Inducible anatomical defense responses in Norway spruce stems and their possible role in induced resistance. *Tree Physiol* 23:191–197.
- Krokene P, Nagy NE, Solheim H (2008) Methyl jasmonate and oxalic acid treatment of Norway spruce: anatomically based defense responses and increased resistance against fungal infection. *Tree Physiol* 28:29–35.
- Kuroda K (1998) Seasonal variation in traumatic resin canal formation in *Chamaecyparis obtusa* phloem. *IAWA J* 19:181–189.
- Lindroth RL, Roth S, Nordheim EV (2001) Genotypic variation in response of quaking aspen (*Populus tremuloides*) to atmospheric CO₂ enrichment. *Oecologia* 126:371–379.
- Littell RC, Milliken GA, Stroup WW, Wolfinger R, Schabenberger O (2006) SAS system for mixed models, 2nd edn. SAS Press Series, Cary, NC.
- Lombardero MJ, Ayres MP, Lorio PL, Ruel JJ (2000) Environmental effects on constitutive and inducible resin defences of *Pinus taeda*. *Ecol Lett* 3:329–339.
- Martin D, Tholl D, Gershenzon J, Bohlmann J (2002) Methyl jasmonate induces traumatic resin ducts, terpenoid resin biosynthesis, and terpenoid accumulation in developing xylem of Norway spruce stems. *Plant Physiol* 129:1003–1018.
- Martins P, Sampedro L, Moreira X, Zas R (2009) Nutritional status and genetic control of phenotypic plasticity to nutrient availability in *Pinus pinaster*. A multisite field study in NW Spain. *For Ecol Manag* 258:1429–1436.
- Miller B, Madilao LL, Ralph S, Bohlmann J (2005) Insect-induced conifer defense. White pine weevil and methyl jasmonate induce traumatic resinosis, de novo formed volatile emissions, and accumulation of terpenoid synthase and putative octadecanoid pathway transcripts in Sitka spruce. *Plant Physiol* 137:369–382.
- Moreira X, Sampedro L, Zas R, Solla A (2008) Alterations of the resin canal system of *Pinus pinaster* seedlings after fertilization of a healthy and of a *Hylobius abietis* attacked stand. *Trees* 22:771–777.
- Moreira X, Alfaro RI, King JN (2012a) Constitutive defenses and damage in Sitka spruce progeny obtained from crosses between white pine weevil resistant and susceptible parents. *Forestry* 85:87–97.
- Moreira X, Zas R, Sampedro L (2012b) Genetic variation and phenotypic plasticity of nutrient re-allocation and increased fine root production as putative tolerance mechanisms inducible by methyl-jasmonate in pine trees. *J Ecol* 100:810–820.
- Moreira X, Zas R, Sampedro L (2013) Additive genetic variation in resistance traits of an exotic pine species: little evidence for constraints on evolution of resistance against native herbivores. *Heredity* 110:449–456.
- Moreira X, Mooney KA, Rasmann S, Petry WK, Carrillo-Gavilán A, Zas R, Sampedro L (2014) Trade-offs between constitutive and induced defences drive geographical and climatic clines in pine chemical defences. *Ecol Lett* 17:537–546.
- Mumm R, Hilker M (2006) Direct and indirect chemical defence of pine against folivorous insects. *Trends Plant Sci* 11:351–358.
- Orians CM, Lowery S, Fritz RS, Roche BM (2003) The effects of plant genetic variation and soil nutrients on secondary chemistry and growth in a shrubby willow, *Salix sericea*: patterns and constraints on the evolution of resistance traits. *Biochem Syst Ecol* 31:233–247.
- Osier TL, Lindroth RL (2006) Genotype and environment determine allocation to and costs of resistance in quaking aspen. *Oecologia* 148:293–303.
- Phillips MA, Croteau RB (1999) Resin-based defenses in conifers. *Trends Plant Sci* 4:184–190.
- Richardson DM (1998) Ecology and biogeography of *Pinus*. Cambridge University Press, Cambridge.
- Ruzin SE (1999) Plant microtechnique and microscopy. Oxford University Press, New York.
- Sampedro L (2014) Physiological trade-offs in the complexity of pine tree defensive chemistry. *Tree Physiol* 34:915–918.
- Sampedro L, Moreira X, Zas R (2011) Costs of constitutive and herbivore-induced chemical defenses in pine trees emerge only under low resources availability. *J Ecol* 99:818–827.
- Schulman E (1954) Longevity under adversity in conifers. *Science* 119:396–399.
- Solla A, Sánchez-Miranda A, Camarero JJ (2006) Radial-growth and wood anatomical changes in *Abies alba* infected by *Melampsorella caryophyllacearum*: a dendroecological assessment of fungal damage. *Ann For Sci* 63:293–300.
- Stamp N (2003) Out of the quagmire of plant defense hypotheses. *Q Rev Biol* 78:23–55.
- Thaler JS, Humphrey PT, Whiteman NK (2012) Evolution of jasmonate and salicylate signal crosstalk. *Trends Plant Sci* 17:260–270.
- Trapp S, Croteau R (2001) Defensive resin biosynthesis in conifers. *Annu Rev Plant Physiol Plant Mol Biol* 52:689–724.
- van Akker L, Alfaro RI, Brockley R (2004) Effects of fertilization on resin canal defences and incidence of *Pissodes strobi* attack in interior spruce. *Can J For Res* 34:855–862.
- van Dam NM, Baldwin IT (1998) Costs of jasmonate-induced responses in plants competing for limited resources. *Ecol Lett* 1:30–33.
- van Dam NM, Baldwin IT (2001) Competition mediates costs of jasmonate-induced defences, nitrogen acquisition and transgenerational plasticity in *Nicotiana attenuata*. *Funct Ecol* 15:406–415.

- Villari C, Faccoli M, Battisti A, Bonello P, Marini L (2014) Testing phenotypic trade-offs in the chemical defence strategy of Scots pine under growth-limiting field conditions. *Tree Physiol* 34: 919–930.
- Zas R, Sampedro L, Prada E, Fernandez-Lopez J (2005) Genetic variation of *Pinus pinaster* Ait. seedlings in susceptibility to the pine weevil *Hylobius abietis* L. *Ann For Sci* 62:681–688.
- Zas R, Sampedro L, Prada E, Lombardero MJ, Fernández-López J (2006) Fertilization increases *Hylobius abietis* L. damage in *Pinus pinaster* Ait. seedlings. *For Ecol Manag* 222:137–144.
- Zas R, Björklund N, Nordlander G, Cendán C, Hellqvist C, Sampedro L (2014) Exploiting jasmonate-induced responses for field protection of conifer seedlings against a major forest pest, *Hylobius abietis*. *For Ecol Manag* 313:212–223.