**Pra-GE-ATLAS: empowering *Pinus radiata* stress and breeding research through a multi-omics database**

Víctor Roces1,2, María Jesús Cañal1, Juan Luis Mateo3, Luis Valledor1\*

1 Plant Physiology, Department of Organisms and Systems Biology, Faculty of Biology and Biotechnology Institute of Asturias, University of Oviedo, Asturias, Spain

2 Department of Molecular Biology, Max Planck Institute for Biology Tübingen, Tübingen, Germany

3 Department of Computer Science, University of Oviedo, Asturias, Spain

\* Correspondence: [valledorluis@uniovi.es](mailto:valledorluis@uniovi.es)

**Running title**: Pra-GE-ATLAS: *Pinus radiata* multiomics database.

# Abstract

In recent decades, research on model organisms have significantly increased our understanding of core biological processes in plant science. However, this focus has created a substantial knowledge bottleneck due to the limited phylogenetic and ecological spectrum covered. Gymnosperms, especially conifers, represent a molecular and ecological diversity hotspot among seed plants. Despite their importance, research on these species is notably underrepresented, primarily due to a slower pace of investigation resulting from a lack of community-based resources and databases. To fill this gap, we developed P(inus)ra(diata)-G(ene)E(xpression)-ATLAS, which consists of several tools and two main modules: transcriptomics and proteomics, presented in this work for the forestry commercial and stress-sensitive species *Pinus radiata*. We summarised and centralised all the available information to provide a comprehensive view of the gene expression landscape. To illustrate how applications of the database lead to new biological insights, we integrated multiple regulatory layers across tissues and stressors. While stress favors the retention of small introns, harmonised alternative splicing analyses reveal that genes with conifers’ iconic large introns tend to be under constitutive regulation. Furthermore, the degree of convergence between stressors differed between regulatory layers, with proteomic responses remaining highly distinctive even through intergenerational memory tolerance. Overall, Pra-GE-ATLAS aims to narrow the distance between angiosperms and gymnosperms resources, deepening our understanding of how characteristic pine features have evolved. Pra-GE-ATLAS is available at <https://rocesv.github.io/Pra-GE-ATLAS>.

**Keywords**: database, atlas, gymnosperms, systems biology, splicing.

# Introduction

Model organisms have played a crucial role in deepening our understanding of core biological processes, shaping research topics in plant sciences. However, there is a strong bias in the taxa studied, with angiosperms, particularly Magnoliopsida, representing 93 % of the records (Shiu and Lehti-Shiu, 2023). This creates a huge knowledge bottleneck, mainly due to the narrow phylogenetic and ecological spectrum covered. Gymnosperms and angiosperms are the two major groups of extant seed plants, exhibiting extreme differences in life spans, species diversity and reproductive biology. Moreover, gymnosperms are an ancient clade that represents four of the five main lineages of seed plants and dominate boreal and temperate forests. Despite this, gymnosperms remain largely underrepresented in plant research, specially in molecular biology (Leebens-Mack et al., 2019; Niu et al., 2022). Therefore, the establishment of model organisms in gymnosperms becomes crucial, as minimal efforts could be translated into maximal plant community benefits, leveraging the evolutionary and ecological properties of this clade.

Among gymnosperms, conifers represent the most diverse group, comprising approximately 615 species that contribute to 39 % of the world's forests. *Pinus*, with 113 species, is the largest clade and one of the most important genus of trees (Jin et al., 2021), serving as a relevant model for exploring molecular divergence in seed plants. However, pinesmolecular evolutionary features pose a double-edge sword. While they provide valuable ecophysiological insights, their slow growth, long-lived nature, giant genomes and high repetitive elements content are far from those attributes proper of model species (De La Torre et al., 2020). Although recent incredible genomics efforts (Niu et al., 2022), the current post-genomic era has laid the groundwork for the emergence of other “-omics” and has challenged traditional views on how genes encode phenotypes, moving beyond a genic-centered perspective. Taking advantage of this data explosion, systems biology has gained relevance for its holistic approach to modeling complex biological processes (Argelaguet et al., 2020). Multi-omics profiling is becoming quite common, promising insights into the characterisation of unexplored species lacking reference genomes. In addition, recent RNA sequencing (RNA-seq) studies indicate that transcriptomes are often underestimated, even in model organisms (S. Zhang et al., 2020). Large-scale functional genomics data, such as transcriptomics and proteomics, can provide direct evidence for a high-resolution gene expression landscape. Nonetheless, the generation of curated databases and resources derived from cumulative research outputs becomes crucial to address the focus gap in this genus and facilitate future investigations.

To tackle these challenges, we constructed P(inus)ra(diata)-G(ene)E(xpression)-ATLAS, the most extensive pine multi-omics database to date, designating the forestry commercial and stress-sensitive species *Pinus radiata* as reference. We generated new datasets and centralised all the available transcriptomics and proteomics information in a single hub, encompassing various dimensions. To showcase how the results derived from the generated resources could be used to gain biological insights, we conducted in-depth characterisation and integrated multiple regulatory layers across tissues and stressors. Constitutive regulation of long introns was observed, while stress favoured the retention of smaller introns. Additionally, the agreement between stress responses varied between regulatory layers, with proteomics revealing highly unique responses maintained through intergenerational effects, potentially mediated by the translation of specialised members of gene families. We believe that Pra-GE-ATLAS will be a valuable database, not only supporting conifers research but also contributing to the assessment of the conservation of molecular plant discoveries across a broad range of dissimilar taxa.

# Results

## Construction and overview of Pra-GE-ATLAS

To gain a comprehensive understanding of *P. radiata* expression landscape, we obtained, uniformly processed and integrated multi-omics data, encompassing transcriptomics and proteomics, sourced from research articles and public repositories (**Figure 1, Figure S1**). The consolidated datasets, totaling 990 Gb and 1.89 billion high-quality reads from 141 RNA-seq transcriptomic samples, and 160 Gb and 202 RAW files from 155 MS-based proteomics samples, were analysed and summarised in the P(inus)ra(diata)-G(ene)E(xpression)-ATLAS database.

We generated a high quality reference transcriptome for *P. radiata*. The Benchmarking Universal Single Copy Ortholog (BUSCO) detected high completeness (>96 %) when compared against Embryophyta (**Table S1**). This quality metric, comparable to other *de novo* high quality gymnosperms transcriptomes (Visser et al., 2023), alongside an average of 80 % reads mapping back, indicate a high-quality reference appropriate for downstream analyses. The final assembly served as database for the identification and quantification of proteins. A total of 7697 proteins met all the criteria for further characterisation (see **Methods**), significantly suparssing the number reported by previous proteomics studies in this organism (Pascual et al., 2016; Pascual et al., 2017; Escandón et al., 2017; Lamelas et al., 2020; Amaral et al., 2021; García-Campa et al., 2022; Lamelas et al., 2022), and reinforcing the need for high-quality species-specific databases in proteomic approaches (Romero-Rodríguez et al., 2014).

In summary, Pra-GE-ATLAS database was constructed based on two modules, transcriptomics and proteomics, containing the largest amount of *P. radiata* – related data up to date. It provides access to various common online tools, enabling the extrapolation of findings from other species to our reference and establishing a foundation for in-depth research on this pine species.

## Transcriptomics module: Core genes transcriptionally regulated and associated regulatory features

We characterised transcriptional module grouping changes in alternative splicing (AS) and gene expression (GE) into three core sets (see **Methods**): constitutively-alternative spliced/expressed (Pan), stress-specific (Stress), and tissue-specific (Tissue) events/genes.

Global differences between GE and AS regulation were observed based on the number of shared genes/events between core sets (**Figure 2A**). PanGE, TissueGE, and their overlap constituted the biggest intersections, while most stress genes were shared with other sets. Conversely, each AS set specific events formed the largest intersections and the most substantial overlap occurred between StressAS and TissueAS. These findings suggested that GE could be the primary transcriptional mechanism, while AS seem to be more finely tuned in its regulatory role. Further inspection of AS sets trends was performed, checking the proportions between different AS types (**Figure 2B**). Consistent with previous studies (Martín et al., 2021), IR and AltAD were the most prevalent type of genome-wide AS. Nevertheless, the only prevalent type particularly enriched compared to Genome background was AltAD in AS-NR and PanAS. Thus, emphasising potential differences in functional impact and/or regulatory features associated with AS sets and types. Examining gene-level intersections (**Figure 2C**), the only set demonstrating a greater number of genes regulated by AS than GE, and with a lower overlap with the latter, was Stress.

To assess the functional relevance of AS, we researched their predicted impact on the canonical ORF (**Figure 2D**). Notably, for IR and AltAD events, we observed a significant enrichment in cases predicted to disrupt ORF for PanAS. Additionally, StressAS and TissueAS sets were predicted to significantly alter not-CDS regions, such as untranslated regions. Altogether, AS regulation appeared to be more linked to expression regulation and protein remodelling rather than functional variation in protein sequence.

To investigate genomic features related to AS regulation and type, exon and intron features were computed for each AS set (see **Methods**, **Figure 2E**). Genomic features showed a low degree of convergence across sets, with the unique exception of AltAD events significantly preferring smaller transcripts. IR PanAS events were enriched in transcripts with more and longer introns, higher upstream splice site GC content, and smaller flanking exons. Conversely, IR StressAS and TissueAS were preferentially presented in transcripts with less and smaller introns, and lower upstream GC content. In the case of ES, PanAS depicted the main hallmarks of exon definition, such as smaller target exons with longer upstream introns. Additionally, ES PanAS and TissueAS events presented lower transcript lengths, and lower and higher GC content in the target and downstream exon, respectively. Curiously, ES and AltAD exons across stresses and tissues were mainly located in the first exons. Overall, the different patterns emerged suggest that genomic features could be crucial for explaining specific regulation in splicing patterns in *Pinus*.

To provide a biological interpretation, functional enrichment analyses were conducted (**Figure 2F**). The functional terms covered by AS core sets exhibited a limited spectrum of pathways. PanAS and StressAS were the sets that shared most of the functional terms, emphasising RNA processing as an autoregulatory process. Remarkably, TissueAS showed enrichment only in redox homeostasis, representing the most divergent functional profile among sets. In contrast, GE sets included a broad range of functions, including terms essential for all types of regulation, such as phytohormones action. Briefly, the terms validated expected biological insights, such as photosynthesis enriched in PanGE and TissueGE, and secondary metabolism and redox homeostasis enriched in TissueGE and StressGE. In this case, PanGE stood out as the set with the most divergent profile.

Given the potential primary role of GE, we conducted a WGCNA (**Figure 2F**). In total, 20 co-expressed modules were identified and correlated with design factors. The largest modules tended to be related to tissues. This was illustrated by M03, which showed a positive correlation with bud and vascular tissues, and M04/M06 highlighting needle identity with some signals related to *P. pluvialis*/*F. circinatum*, respectively. However, stress-specific modules were also elucidated. Examples include M07, M09 and M10 representing *F.* *circinatum* stress. Using the previously introduced modules, both bud-vascular M03 and *F. circinatum* M10 revealed functional terms inherent to those design factors that were not represented in TissueGE and StressGE, such as DNA damage response, chromatin organisation and cell division.

## Proteomics module: The landscape of protein information

The proteomic data generated in this study enabled us to inspect tissue signatures (**Figure 3A-C**). Enrichments of differential proteins revealed pathways involved in the functioning of each tissue, such as photosynthesis in needles, and RNA processing in buds (**Figure 3A**). Furthermore, attending to the size of the intersection between differential proteins, a decreasing trend was detected following the order needle>bud>root. These discoveries suggested that these tissues had different degrees of identity. Tissue hallmarks were complemented by volcano analyses (**Figure 3B**). The most relevant proteins remained consistent across comparisons and expanded previous mentioned pathways for roots and buds. Root tissue was mainly linked to energy metabolism (e.g ATP SYNTHASE SUBUNIT B). While functions in buds highlighted their role as a differentiating tissue with regulatory capabilities, the strongest markers were related to defense responses (e.g TERPENE SYNTHASE). Lastly, an evolutionary evaluation of protein abundance constraints was performed using Proteome Age Index (PAI) (**Figure 3C**). Although no differences were exhibited in root and bud, needles presented smaller PAI values, indicating a greater abundance of proteins with older evolutionary origins.

The stress diversity compiled in the proteomics module (**Figure 3D,E**) allowed the identification of shared functions across environmental clues, underscoring protein homeostasis and biosynthesis (**Figure 3D**). The largest intersections, which consisted of stress-stress rather than stress-control comparisons, revealed a low degree of convergence across stress proteins. Despite some common pathways being regulated for most stresses, the primary protein effectors appeared to diverge across conditions. Most relevant proteins in volcano analyses (**Figure 3E**) pointed to potential master features that were not significantly/consistently enriched at the pathway level, such as chromatin organisation (e.g HISTONE H2A) and RNA processing (e.g SM-LIKE PROTEIN LSM).

A total of 12 modules were detected by WGCNA, clustering proteins abundance across all conditions (**Figure 3F**). The largest module, M01, was related to tissues. M01 unveiled previously exposed functions and new ones such as vesicle trafficking and multiprocess/external-stimuli response (**Figure 3G**). The high resolution of protein modules revealed unknown stress dynamics. Heat stress presented modules related to each subcellular location and M09 correlating responses across nucleus and chloroplast. Nevertheless, UV stress was more specific, differing between chloroplast response and chloroplast response negatively correlated with nucleus, illustrated by M03 and M05. Despite both modules represented UV chloroplast response, their different relationship with the nucleus was also supported by the implication of distinct pathways such as protein translocation.

## Application 1: Exploring unique and shared sources of transcriptional variation across multiple tissues and stressors

To exemplify applications of the generated resources, we investigated into the coordination of GE and AS in defining tissues using multi-omics factor analysis (MOFA) (**Figure 4**). Overall, MOFA inferred eight latent factors (LFs), with GE contributing to the majority of the total variance (**Figure 4A**). We examined the variance explained by the LFs and identified LF1 and LF3 as the most biologically relevant to discriminate between tissues (**Figure 4B**). Briefly, LF1 variance, mainly constituted by GE but also including remarkable AS variation, differed between needles and the rest of the tissues, while the GE-dominant LF3 variance mostly described the differences between buds/needles and vascular-related tissues.

These interpretations were supported by the top absolute loadings in each factor (**Figure 4C**). LF1 needle identity was reflected by photosynthetic required genes such as *RIBULOSE-PHOSPHATE 3-EPIMERASE* (*RPE)*.LF3 bud/needle identity was illustrated by cuticle related genes such as *CUTIN SYNTHASE2 (CUS2)*.Interestingly, LF1 specific enriched functions differed between regulatory layers and included cellular respiration and external stimuli response at the GE level, and redox homeostasis and secondary metabolism within AS layer (**Figure 4D**). LF3 specific enriched terms pointed to key divergent functions between xylem/phloem and needle/bud such as lipid metabolism and plant reproduction. From an evolutionary perspective, it seems that tissue identities described in LF1 had older origins than the distinctions covered by LF3 (**Figure 4D**). This was illustrated by enrichments in genes with younger origins (Phylostratum (PS), lower and higher PS denote older and younger origins) at the GE level in LF3 and very young gene family founder events (Phylostratum Family (PSF)) at the AS level. Additionally, these findings were further confirmed by Transcriptome Age Index (TAI) profiles which detected increasing TAI values across tissues, from older to younger origins, following the order needle>bud>xylem>phloem (**Figure S2A**).

Finally, to demonstrate that applications derived from Pra-GE-ATLAS could be translated into new biological insights, we evaluated splicing of potential isoform markers across tested tissues with different ages in an exploratory fashion (**Figure 4E**). Three genes were chosen based on differential contributions: *SIGNAL RECOGNITION PARTICLE 43 KDA, CHLOROPLASTIC (CAO), SUGAR TRANSPORTER ERD6 (ERD6),* and *COMPONENT OF CIRCADIAN EVENING COMPLEX CLOCK ELF4 (ELF4-like)*. All genespreferentially expressed the smallest isoforms in adult needles. While the largest *CAO* and medium-sized *ERD6* isoforms were common for buds and juvenile needles, most of the medium-sized *CAO* isoforms were juvenile-specific and large *ERD6* isoform was juvenile needle-specific. Lastly, while the *ELF4-like* budisoformdiversity did not reflect a clear pattern, large *ELF4-like* isoforms appeared to be juvenile-specific.

Next, we employed MOFA multigrouped framework to evaluate the degree of convergence in *P. radiata* transcriptional responses to multiple stressors (**Figure 4F-H**). Due to a stress-related higher prevalence of particular types, such as IR (Laloum et al., 2018), we decided to split AS by type. A total of eight LFs were detected, with most of them being uniquely related to GE, the layer contributing to the majority of variance (**Figure 4F**). We identified the top three LFs as biologically relevant (**Figure 4G**). LF1 exhibited significant GE activity across all biotic stimuli, primarily associated with high stress damage. This was illustrated by high positive scores in most susceptible genotypes and stress samples under severe *D. septosporum*/*F. circinatum* and *P. pluvialis*, respectively. LF2 showed remarkable GE activity across *D. septosporum*, *F. circinatum* and heat, linked to control-stress differences. LF3 captured *F. circinatum*–specific susceptible-resistant genotype and stress-control variation for samples without genotype information. Furthermore, LF3 detected changes across all molecular layers, with higher variance explained by AS than GE.

The provided definitions were affirmed by the top loadings and functions for each LF (**Figure 4H,I**). For enrichment analyses, IR was selected as the AS representative (**Figure 4I**). LF1 shared biotic stress damage, represented by fungal-specific factors such as *ENDOCHITINASE 2 (CHTB2)* (**Figure 4H**)*,* and specifically enriched in redox homeostasis at both transcriptional levels (**Figure 4I**). Due to the control samples tissue composition, some of the genes illustrated by LF2 were shared with tissue LF3 bud/needle (**Figure 4C**). However, new genes exclusively linked to LF2 cross-stress control-associated variation were also suggested, such as *TRANSCRIPTION FACOR BHLH62 (BHLH62)*. LF3 stress/susceptible-genotype vs control-damaged/resistant-genotype pointed to different members of *CYSTEINE-RICH RECEPTOR-LIKE PROTEIN KINASE (CRK)* stress-responsive family (Y. Zhang et al., 2023). Evolutionary-related analyses revealed that LF2 was significantly enriched in younger phylostrata than LF1 at the GE level (**Figure 4I**). This notion was further inspected by TAI profiles (**Figure S2B**), which detected significantly younger transcriptomes in earlier stress phases for heat and *D. septosporum*.

Given that GE dominant role in transcriptional variation could mask AS differential contributions between tissues and stressors, we compared the relative PSI variation of stress versus tissues in our reference, *P. radiata*, and in *A. thaliana*, *D. melanogaster* and *H. sapiens* data produced by Martín et al. (2021) (see **Methods**, **Figure S2C**). Strikingly, we observed a contribution skewed towards stress and tissues in plant and metazoan species, respectively.

## Application 2: Uncovering proteomic cross-talk among stresses, subcellular locations, and intergenerational memory

Using MOFA, we identified shared and unique sources of proteomic variation across stressors (**Figure 5A-D**), subcellular locations (**Figure 5E-H**), and intergenerational memory (**Figure 5I-L**).

In the cross-stress total proteomes framework, four LFs were identified, all considered biologically meaningful (**Figure 5A**). These LFs disentangled stress-specific variance, with heat-specific LF1 discriminating between the earliest stress timepoint, and heat-specific LF2, *F. circinatum*-specific LF3, and UV-specific LF4 showing control/recovery-stress differences (**Figure 5B**). These results were supported by top absolute loadings (**Figure 5C**). Examples include several proteome remodelling features for LF1 and LF4, photosynthetic proteins and chaperones reflecting high temperatures main targets for LF2, and defense mechanisms illustrated by OXALATE OXIDASE 1 (OXO1) for LF3. The model captured common functions such as protein biosynthesis-homeostasis, chromatin organisation and photosynthesis (**Figure 5D**). Despite non meaningful constrained abundance patterns detected by PAI profiles (**Figure S2D**), enrichments revealed shared evolutionary origin signatures among abiotic stressors, with LF4 UV-related features being relatively younger at the gene level (**Figure 5D**).

Next, we integrated abiotic stressors total, nucleus and chloroplast proteomes and 11 LFs were identified. We selected LF2, LF6, LF7 and LF9 for further biological description (**Figure 5E**). LF2 explained the most variance and was associated with stress-independent subcellular location, highlighting functions such as protein modification and chloroplast-localised features through RHO-N DOMAIN-CONTAINING PROTEIN 1, CHLOROPLASTIC (RHON1) (**Figure 5F-H**). UV-specific LF6 characterised chloroplast response, while heat-specific LF7 and LF9 involved nucleus- and chloroplast-specific stressess, respectively. Stress- and localisation-specific LFs expanded previous pathways considering subcellular information. UV-specific LF6 unveiled chloroplast protein synthesis through ATP-DEPENDENT CLP PROTEASE ADAPTER PROTEIN CLPS1, CHLOROPLASTIC (CLPS1). Heat-specific LF7 and LF9 reflected nucleus coordination and chloroplast response with HEAT SHOCK FACTOR-DNA BINDING (HSF-DNA BIND) domains, and a wide set of small heat shock proteins, respectively. Stress-specific LFs responses still shared above mentioned terms and new ones, for instance RNA processing. PAI profiles did not detect constrained abundance patterns, but trends were appreciated when considering PAI profiles and enrichments together (**Figure 5H**, **Figure S2E**). The biggest differences between PAI values were observed between subcellular locations instead of stress timepoints. Additionally, the subcellular location with the younger profile also diverged between stressors, being the nucleus for heat and the chloroplast for UV. The latter was further emphasized with younger gene origins and family founder events enriched in UV-specific LF6 compared to heat-specific LF9.

Lastly, we interrogated whether shared cross-stress intergenerational memory variation could be detected at the protein level. To answer this, we integrated abiotic stressors chloroplast-enriched proteomes from two populations with similar genetic-backgrounds but different local-environment histories (**Figure S2F**) (García-Campa et al., 2022; Lamelas et al., 2022). Among six LFs, LF2, LF3, LF5 and LF6 were retained for subsequent analyses (**Figure 5I**). LF2 explained shared variance across populations but was only associated with UV (**Figure 5I,J**). Furthermore, LF2 displayed population-specific differences, as population E (PopE) could discriminate between all intensities, while samples under more severe conditions were merged for population T (PopT). While heat-specific LF3 also explained shared variance for both populations, LF3 did not detect population differential contributions because both populations mainly discriminated between control and severe heat intensities. Following the same pattern, LF5 and LF6 were UV- and heat-specific, respectively, discriminating the earlier timepoints in both cases. However, UV-specific LF5 reflected population differences mainly linked to earlier stress samples in PopE. Top absolute loadings (**Figure 5K**) and functional enrichments (**Figure 5L**) validated the results, illustrating protein homeostasis term shared among all LFs, and LF3 features being equivalent to previous abiotic stressors LF9 (**Figure 5G**). Since differential contributions to populations could reveal clues into intergenerational memory, we further inspected UV-specific LFs loadings. Interestingly, loadings highlighted a protein that could interact with RNA POLYMERASE SIGMA FACTOR (SIGA), essential for photosystem stoichiometry, and lignin biosynthesis reflected by CYNNAMYL ALCOHOL DEHYDROGENASE 3 (CAD3) (Bateman et al., 2021). Meaningful constrained patterns were not detected by PAI profiles (**Figure S2G**); however, UV-specific LFs enrichments uncovered slightly younger originated gene families in LF2 compared to LF5.

# Discussion

In this study, we constructed Pra-GE-ATLAS, the most extensive pine multi-omics database to date (**Figure 1**). Despite pine species constituting a clear hotspot of plant molecular diversity, their research remains largely underrepresented (De La Torre et al., 2020; Shiu and Lehti-Shiu, 2023). To fill this gap, Pra-GE-ATLAS offers data resources and tools aimed not only to assist *P. radiata* research but also to determine the extent of plant biology discoveries considering more dissimilar taxa.

Our research presents the most exhaustive AS analysis conducted in a pine species so far. Despite the divergent genomic architecture of conifers, characterised by long introns (Niu et al., 2022), IR is the most prevalent AS type, consistent with prior studies (Laloum et al., 2018) (**Figure 2B**). Notably, non-IR events, such as AltAD, underrated in plant science, are identified as widespread and overrepresented in more sets than IR, indicating potentially greater functional relevance (**fig 2B, D**). Overall, AS sequence variation appears to play a more significant role in regulating gene expression and protein abundance than introducing functional sequence changes. In line with earlier research indicating that pine genes with longer introns are constitutively expressed (Niu et al., 2022), the specific genic structure of conifers seems related to their AS regulation. Long introns surrounded by small exons and small exons surrounded by long introns are preferentially retained and skipped, respectively, in constitutively alternatively spliced transcripts (**Figure 2E**). Conversely, stress-induced IR appears to affect small introns at the beginning of the transcript. These observations highlight the innovative molecular strategies adopted by conifers to keep transcription efficacy. Finally, leveraging the phylogenetic position of pines, we extend the previously reported favoured regulation of AS under stress in *A. thaliana* (Martín et al., 2021) as a potential general feature in seed plants, contrasting with animal AS controlled in a tissue-specific manner (**Figure S2C**).

To illustrate applications of the generated resources, we integrated multiple regulatory layers across tissues and stressors. Tissue emerged as the primary driver of variation in the data. Our analyses revealed distinctive patterns according to tissues’ evolutionary origin, following the order from more to less conserved: needle>bud/root>xylem/phloem (**Figure 3C and Figure 4D; Figure S2A**). This trend aligns with the notion of needle identity being more constrained, supporting expected tissue-function acquisition during plant evolution (first photosynthesis), land colonisation (roots, tissue-transitions), and radiation of vascular plants (xylem/phloem) (Clark et al., 2023). Next, we examined tissue AS patterns, given the limited exploration of this aspect in plants. While GE predominantly dictated tissue variation and could differentiate between heterogeneous tissues on its own, splicing is required to distinguish between more dynamic definitions (**Figure 4A, B**). Additionally, we evaluated the splicing patterns of selected potential isoform markers across tissues with different ages. Interestingly, our observations extended beyond tissue-specific patterns to include age-specific trends, such as adult tissues preferentially expressing fewer and lower isoforms (**Figure 4E**). This highlights differences in the regulation of tissue-related functions, such as photosynthesis, *CAO*, solute transport, *ERD6*, and environmental perception, *ELF4-like*, through AS. Our findings underscore how the resources provided by Pra-GE-ATLAS can be utilised to generate novel biological insights.

Stress biology is a crucial aspect of plant science; however, the convergence among stress mechanisms remains poorly characterised. The transcriptional integration revealed shared variation across stressors (**Figure 4F,G**), while the proteomic integration depicted highly unique responses (**Figure 5**). A thorough examination of total proteomes revealed evolutionary signatures shared among abiotic stressors, including similar gene family founder events. The only shared proteomic variation across abiotic stressors described stress-independent subcellular locations, with stress-linked variation remaining highly distinctive. Despite the absence of recent whole-genome duplications in pines, large-scale dispersed duplications are prevalent, and expanded gene families are associated with stress responses (Niu et al., 2022). Considering the distinct stress compositions between both modules, our discoveries suggest that the higher transcriptional convergence may be explained because transcription, as one of the closest regulatory levels to the genome, lacks direct functional effects, and its variation is associated with response, duplication-derived redundancy and stochastic stress reprogramming. In contrast, proteins, being functional components, are modulated only in specialised members of gene families due to the expensive energy investment in translation. Shared variance across stressors was exclusively linked to GE, as AS only explained variance associated with resistant/susceptible genotypes under *F. circinatum* (**Figure 4F-H**). This underscores the relevance of AS in detecting stress-related changes at smaller scales, such as genotypes, suggesting the *CRK* family, known for anti-fungal activity, as novel targets for *F. circinatum* tolerance (Amaral et al., 2022; Y. Zhang et al., 2023). Considering a broader evolutionary context, our data supported the hypothesis that earlier/mild timepoints/intensities could be related with the regulation of younger genes (**Figure 4F and Figure 5J; Figure S2B**). However, these effects are partially masked by stronger constraints detected in tissues and subcellular locations.

*P. radiata*, due to its long-lived nature, provides an ideal example to explore intergenerational memory. To disentangle memory, we integrated two independently published matched assays describing chloroplast-enriched proteomes under heat and UV in two populations with similar genetic-backgrounds but different local-environmental histories (García-Campa et al., 2022; Lamelas et al., 2022) (**Figure 5I-L**). Thus, variation with differential contribution among populations could be defined as intergenerational memory consequences. We found memory evidence only under UV, associated with a higher sensitivity of PopE. Two potential non exclusive hypothesis could be highlighted. On one hand, chloroplasts could be more responsive to UV than heat stress, illustrated by younger PAI profiles and a greater variation explained by LF6 than LF9 (**Figure 5E-F; Figure S2E, G**). Therefore, depending on the organelle, certain stress modifications may be more proned to be remembered. On the other hand, given the specificity of proteomic responses, it is probable that UV range across locations was more divergent and/or plants were more sensitive to those changes (**Figure S2F**). The elevation range, which is related with UV exposure, have been described as a selective pressure on pine evolution, shifting their distribution and species diversity (Jin et al., 2021). Hence, our results suggest that the intergenerational features detected among populations may be originated from a greater susceptibility to elevation range rather than a cross-stress memory.

While we expect Pra-GE-ATLAS to be useful, we acknowledge certain limitations. As pines are considered non-model species, datasets covered a wide temporal range. Therefore, newly reported datasets, taking advantage of recent technological improvements, increased analytical resolution of MS, and both long-read sequencing and enhanced sequencers performance, will significantly improve the resources presented, owing to higher throughputs. The results promoted the potential application of Pra-GE-ATLAS to test new hypothesis in both intra-species, breeding targets, and inter-species, evolutionary stress studies, contexts. Here, we focused on transcriptomics and proteomics, which are closely linked to gene expression. Given the increasing availability of -omics data, the utility of Pra-GE-ATLAS will continue to grow, providing long-term support with annual updates. Our next steps involve the establishment of variation and metabolomic modules, and, once the genome of *P. radiata* is released, compute high-quality gene models. In summary, Pra-GE-ATLAS aims to narrow the distance between angiosperms and gymnosperms resources and designates the commercial and stress-sensitive species *P. radiata* as a reference for understanding the intriguing evolutionary features of pines.

# Materials and Methods

An overview of the bioinformatic workflow used in this study is shown in **Figure S1**.

## Plant materials

To generate the tissue proteomic dataset, we sampled seedlings (one-year-old) and adult trees, both maintained under routine management at the Plant Physiology Laboratory of the University of Oviedo. The following tissues were collected: roots (growing tips in seedlings), juvenile needles (single-needle fascicles, with a growth period of 1 cm in length, from seedlings), adult needles (mature multiple-needle fascicles, > 12 cm, from trees), and stem apical floral buds (less lignified and mature, from trees). For the tissue splicing evaluation, we additionally collected vegetative buds: juvenile buds (with leaf primordia differentiated into photosynthetically active primary needles around the shoot apical meristem in seedlings) and adult buds (with leaf primordia differentiating into scale leaves, and photosynthetic activity shifting to long needles in more distal positions, in trees). In all cases, three biological replicates for each tissue were constituted by pooling samples from two different plants.

## Protein extraction, digestion, fractionation and MS acquisition

Protein extraction was performed following phenol-sodium dodecyl sulfate (SDS) protocol according to Valledor et al. (2014). Initial amount varied from 75 to 250 mg of fresh weight depending on the processed tissue. As protein samples were dissolved with the detergent SDS, sixty µg of proteins were in gel fractionated and digested as described by Valledor and Weckwerth (2014). Peptides were cleaned, extracted and desalted as previously described (Valledor and Weckwerth, 2014). Peptides were analysed in a HPLC-MS/MS Orbitrap Fusion spectrometer (ThermoFisher Scientific), employing a 60-min gradient starting with 0.1 % formic acid and with 80 % acetonitrile as the mobile phase.

## RT-PCR analysis

Total RNA was extracted following Valledor et al. (2014). RNA concentration was determined by a Navi UV/Vis Nano Spectrophotometer and its integrity was checked by agarose gel electrophoresis. Next, cDNA was obtained by RevertAid kit (ThermoFisher Scientific) using random hexamers as primers following manufacturer's instructions. RT-PCR was performed with BesTaq polymerase (**Table S2**). Primers for each AS event were designed to amplify multiple splice variants in a single reaction.

## Data collection

We collected all transcriptomic data from *P. radiata* (term: “Pinus radiata”) available from the NCBI Short Read Archive with associated published reference to ensure high quality data (**Table S1**,last: February 2022). The transcriptomic data collection covered five tissues (bud, xylem, phloem, needle and megagametophyte), one abiotic stress (heat, with three time points), and three biotic stresses (*Fusarium circinatum*, *Dothistroma septosporum* and *Phytophthora pluvialis*, with five, three and two time points, respectively).

We collected all proteomic data from *P. radiata* (term: “Pinus radiata”) available based on PRIDE and PubMed search. Publication was required to ensure high quality data (**Table S3**, last: October 2023). The proteomic data collection covered three tissues generated in this study (root, needle and bud), one biotic stress (*F. circinatum*, with two time points), and two abiotic stresses (heat and ultraviolet (UV)) over three different subcellular locations (total proteins, nucleus and chloroplast). The heat and UV abiotic stress experiments included three and five time points, respectively, for total proteomes; six and three time points for nucleus proteomes; and four time points in both cases for chloroplast proteomes.

## Transcriptomics data processing

Trimmomatic v0.39 (Bolger et al., 2014), SortMeRNA (Kopylova et al., 2012) and Rcorrector were applied to remove adapters and low-quality reads, filter rRNA and correct sequencing errors, respectively. *Fusarium circinatum* reads were discarded mapping to FSP34 genome using bowtie2 (Langmead and Salzberg, 2012). Each condition was assembled independently and reads were normalised for those conditions exceeding 200 million reads using Trinity v2.15.1 (Grabherr et al., 2011). Cleaned reads were assembled using Trinity v2.15.1 and rnaSPADES v3.14 (Bushmanova et al., 2019). Lastly, assemblies were concatenated through EvidentialGene tr2aacds v2017.12.21 pipeline to reduce redundancy and select for the optimal assembled transcripts. The consensus assembly, based on EvidentialGene primary transcripts, was evaluated using BUSCO v5.2.2 (Simão et al., 2015), Trinity v2.15.1 Ex90N50, and backmapping (**Table S1**).

For subsequent procedures, a final assembly was created concatenating EvidentialGene primary transcripts with alternate transcripts. This was achieved after applying cd-hit -c 0.905 (Fu et al., 2012) within the alternate set. The final assembly was functionally annotated by EggNOG-mapper v2 (Cantalapiedra et al., 2021), Mercator4 v6 (Schwacke et al., 2019), Interproscan v5.44.79 (Jones et al., 2014) and dammit v1.

Salmon v1.5.2 (Patro et al., 2017) was employed to quantify expression levels against *Pinus taeda* v2.0.1 (the closest species with an available genome), obtained from TreeGenes (Falk et al., 2018; Jin et al., 2021). *De novo* splicing events were identified, classified, and quantified using KisSplice v2.6.2 (-k 51 -C 0.05) (Sacomoto et al., 2012), Kiss2refgenome v2.0.8, and kissDE v1.4.0, respectively. For AS events mapped to different genes due to at least one member of a gene family being alternatively spliced in a highly similar region, all annotations were retained. sva v3.48.0 (Leek et al., 2012) was employed to remove raw counts unwanted variation derived from study/sequencing-type. GenEra v1.4 (Barrera-Redondo et al., 2023) was then applied to identify gene families, their founder events, and determine the ages of *P. taeda* genes. NR database was completed adding gymnosperms data (*Abies alba, Ginkgo biloba, Gnetum montanum, Picea abies, Pinus lambertiana, Pseudotsuga menziesii* and *Sequoiadendron giganteum;* TreeGenes).

## Definitions of core AS and GE sets

Gene expression (GE) and alternative splicing (AS) trends were grouped into three core sets. To define the three core sets, we followed a similar approach as described by Martín et al., (2021):

Pan core set referred to genes/events that are expressed/alternatively spliced across most sample types. For PanAS set, we required sufficient read coverage in at least 20 % of the total samples. AS read coverage was defined based on kissDE default. We then defined the PanAS events as those with a Percent-Splice-In (PSI) between 0.1 and 0.9 (alternatively spliced) in > 70 % of samples with sufficient read coverage. For PanGE set only genes with an expression level of at least 20 normalised counts in at least 70 % of samples were considered.

Tissue core set referred to genes/events that are up/down regulated across tissues. Megagametophyte was excluded and phloem-xylem samples were grouped as vascular tissue due to the low number of samples. TissueAS required events with sufficient read coverage in at least two replicates for all tissue types, and the absolute difference in PSI between the target tissue and the average of the other tissues must be of at least 0.25. Then, genes with a median expression level of at least 5 normalised counts in at least one tissue type and a fold change of at least 3 in the same direction with related to all other tissues types were kept as TissueGE. DESeq2 v1.40.1 (Love et al., 2014) was applied to compute fold change.

To identify stress-regulated AS and GE, each stress experiment was compared against its respective matched control. Since the majority of the stress transcriptomic and proteomic experiments involved sampling similar phases, we uniformly renamed the different time points based on stress duration/intensity. AS events needed to have sufficient read coverage in at least two stress and control replicates for each of the five stress experiments studied. Then, only events with an absolute PSI difference of at least 0.15 in the same direction between stress and control conditions for at least two out of five stress experiments were retained as StressAS. Regarding StressGE, the same criteria was required considering at least 5 normalised counts and a fold-change of at least 2 as coverage and magnitude thresholds, respectively. Thus, ensuring that features are expressed/spliced and avoiding ambiguous regulation across stresses in opposite directions.

We established control groups for set comparison: background (Genome) and non-regulated (NR). Genome comprised events and genes that met the same coverage criteria and filters as those used to define each core set, but without any PSI-/fold change-related requirements. AS-NR group was determined on basis of each AS core set. For TissueAS, AS-NR events were those alternatively spliced and with an absolute PSI difference <0.05 for each tissue versus the rest. For StressAS, AS-NR events were those alternatively spliced in at least one sample and with an absolute PSI difference <0.05 in at least one stress experiment. Finally, to obtain a common AS-NR, we retained events that were part of both AS-NR sets. The intersections between genes and events were assessed using nVennR v0.2.3 (Pérez-Silva et al., 2018).

## Predicted protein impact and genomic regulatory feature analysis

Splicing variation effect were determined using custom scripts employing the following approach: (i) Kiss2refgenome v2.0.8 coordinates and GTF annotations were used to determine if the variation occurred inside/outside of coding-sequence (CDS), (ii) CDS-affecting isoforms were examined to detect if variation led to the introduction of premature termination codons (PTCs), (iii) CDS-affecting isoforms without PTCs underwent further evaluation to check if the variation disrupted the open reading frame (ORF) frameshift.

To compare exon and intron features associated with different AS core sets, Matt v1.3.1 (Gohr and Irimia, 2019) was employed. Briefly, Matt *cmpr\_introns*, for intron retention (IR) events, and *cmpr\_exons*, for exon skipping (ES) and alternative acceptor/donor site (altAD, both 5’ and 3’), commands were employed to extract and compare multiple intron and exon genomic features associated with AS regulation. Statistical significance was addressed by comparing each set to Genome.

## Proteomics data processing

Proteome Discoverer 2.2 (Thermo Fisher Scientific, USA) along with the Sequest-HT and MS-Amanda algorithms, were employed for peptide processing, and protein identification-quantification, establishing at least one high-confidence unique peptide umbral for protein identification and one peptide (unique/razor) per protein for label-free quantification. The final assembly underwent six-frame translation, and peptides exceeding 50 amino acids were retained and used as database.

Each proteome underwent preprocesing using pRocessomics v.0.1.13 (github.com/Valledor/pRocessomics). In summary, missing values and additional replicates for the *Fusarium circinatum*, heat stress total, and UV nucleus proteomes, were imputed using random forest method, with a threshold of 34 %. Variables present in less than 50 % of samples were dropped out. Abundance values were normalised by sample-centric approach and multiplied by the average intensity of all samples. Protein abundances were transformed with a log10(+1.1) for subsequent analyses. limma v3.56.2 (Ritchie et al., 2015) was employed to remove abundance unwanted variation. GenEra v1.4 was employed, as mentioned above, using *P. radiata* proteins as query.

## Proteins differential analyses

Statistical analyses of protein-level differential abundance were carried out using limma v3.56.2 employing FDR < 0.05 as threshold. For volcano, proteins were required to exhibit a log2(fold change)>1.5 to be considered biologically relevant. The intersections between differential proteins were assessed using UpSetR v1.4.0 (Conway et al., 2017).

## Co-expression network analyses

Weighted Gene Co-expression Analysis (WGCNA) was conducted using WGCNA v1.72-1 (Langfelder and Horvath, 2008) to identify highly co-expressed genes (sva batch-removed DESeq2 VST) and proteins (limma batch-removed log10(+1.1)). A signed-hybrid type of adjacency matrix was constructed, with β = 7/9 for proteins/genes, using biweight midcorrelation. Hierarchical clustering was performed, and co-expression modules were identified using dynamic tree cut height of 0.3 and a minimum module size of 30. Modules were named based on their size. Module eigengenes were employed to compute correlations between modules and design factors (traits). Only correlations with an adjusted-P<0.05 were considered. Module membership was computed based on the correlation between genes and module eigengenes for each module.

## Enrichment analyses

Enrichment analyses using Mercator4 terms were conducted using fgsea v1.26.0. Briefly, for the transcriptomics module, we applied an overrepresentation analysis (adjusted-P < 0.1). Meanwhile, for the proteins, gene set enrichment analyses (adjusted-P < 0.1) were performed using limma-derived statistics and modules membership.

## Evolutionary transcriptomics and proteomics

To investigate the potential existence of evolutionary constraints, we employed myTAI v0.9.3 (Drost et al., 2018). For evolutionary transcriptomics analyses, *P. taeda* gene ages and VST expression data were employed. For evolutionary proteomics analyses, *P. radiata* protein ages and log10(+1.1) abundance data were used. In both cases, the Transcriptome/Proteome Age Index (TAI/PAI) approach was followed for gene/protein age evaluation. The significance of evolutionary constraint was assessed using the FlatLineTest.

## Relative contribution of tissues and stress conditions to global PSI variation

For the comparisons of the relative contribution to the total PSI variation of tissue versus stress, we adopted a similar approach as described by Martín et al. (2021). We incorporated data from Martín et al. (2021) for *Arabidopsis thaliana, Drosophila melanogaster* and *Homo sapiens.* Due to the limited number of abiotic stress transcriptomic experiments in *P. radiata* and to find general stress trends, we chose to merge abiotic and biotic experiments. We required that AS events must have read coverage in all tissue types and three stress experiments, with a global PSI variation exceeding 10.

## Inference of hidden factors from multiple stresses and tissues sources

The Inference of sources of variation was carried out using MOFA2 (docker latest image: 2e858d684c5f) (Argelaguet et al., 2020). To characterise transcriptional variation in tissues, an ungrouped framework was executed, considering expression (VST) and splicing (PSI) as two distinct regulatory layers. Only the top 10,000 features with the highest variance (HVF) were considered. For the assessment of transcriptional variation between stresses, a grouped framework was employed, splitting AS by type and considering the top 10,000 and 5,000 HVFs for expression and splicing-related layers, respectively. To evaluate proteomic (log10(+1.1)) variation between stresses, three different grouped frameworks were computed, removing low variance features in each model. In all cases, model training was performed with maxiter = 100,000 and convergence\_mode = “slow”. Each biologically relevant latent factor underwent enrichment analysis (adjusted-P < 0.1).

## Database resource

We developed P(inus)ra(diata)-G(ene)E(xpression)-ATLAS database, a comprehensive multi-omics hub aimed to provide public access to the information generated in this work. Pra-GE-ATLAS features multiple tools: 1) Search section with interactive tables and heatmaps for quick retrieval of protein-, transcript-, splicing event-information. 2) Diamond BLASTP sequence alignment (Buchfink et al., 2021). 3) Fast computation of *P. radiata* orthologs and the mode and strength of selection (dN/dS ratio) based on our consensus assembly, using orthologr (Drost et al., 2015). 4) Functional enrichments. 5) Exploration of global co-expression modules and regulatory networks of target genes, leveraging data from the PPGR database (Yang et al., 2024). 6) Prediction of transcription factors and regulators, based on PlantRegMap and TAPscan v4 assignment rules (Tian et al., 2020; Petroll et al., 2024), along with motif analysis. Pra-GE-ATLAS is available at <https://rocesv.github.io/Pra-GE-ATLAS>.

# Data availability

All the data generated in this study are available at Pra-GE-ATLAS database <https://rocesv.github.io/Pra-GE-ATLAS> and<https://doi.org/10.5281/zenodo.10494507>. The code used in this work is available at <https://github.com/RocesV/Pra-GE-ATLAS_manuscript>. The mass spectrometry data have been deposited to the ProteomeXchange Consortium via the PRIDE (Perez-Riverol et al., 2022) partner repository with the dataset identifier PXD047869 (Reviewer account details: Username: reviewer\_pxd047869@ebi.ac.uk; Password: wL7XdldN).

# Acknowledgements

VR was supported by a fellowship from Spanish Minitry of Universities (FPU18/02953). We are grateful to Picasso, the supercomputing cluster of the University of Málaga, for kindly providing computational resources.

# Conflict of interest

The authors declare there is no conflict of interest.

# Author contributions

VR and LV conceived the study. VR and JLM designed the research. LV performed proteomic experiments. VR and LV collected the data. VR performed computational analyses, built the database and figures, analysed-interpreted the data and wrote the manuscript draft under supervision of LV, JLM and MJC. All authors revised, read, and approved the final manuscript.

# References

Amaral, J., Lamelas, L., Valledor, L., Castillejo, MA., Alves, A., and Pinto, G. (2021). Comparative proteomics of Pinus-Fusarium circinatum interactions reveal metabolic clues to biotic stress resistance. *Physiologia Plantarum*, *173(4), 2142-2154*.

Amaral, J., Valledor, L., Alves, A., Martín-García, J., and Pinto, G. (2022). Studying tree response to biotic stress using a multi-disciplinary approach: The pine pitch canker case study. In *Frontiers in Plant Science* (Vol. 13). Frontiers Media S.A.

Argelaguet, R., Arnol, D., Bredikhin, D., Deloro, Y., Velten, B., Marioni, J. C., and Stegle, O. (2020). MOFA+: A statistical framework for comprehensive integration of multi-modal single-cell data. *Genome Biology*, *21*(1).

Barrera-Redondo, J., Lotharukpong, J. S., Drost, H. G., and Coelho, S. M. (2023). Uncovering gene-family founder events during major evolutionary transitions in animals, plants and fungi using GenEra. *Genome Biology*, *24*(1).

Bateman, A., Martin, M. J., Orchard, S., Magrane, M., Agivetova, R., Ahmad, S., Alpi, E., Bowler-Barnett, E. H., Britto, R., Bursteinas, B., Bye-A-Jee, H., Coetzee, R., Cukura, A., Silva, A. da, Denny, P., Dogan, T., Ebenezer, T. G., Fan, J., Castro, L. G., … Zhang, J. (2021). UniProt: The universal protein knowledgebase in 2021. *Nucleic Acids Research*, *49*(D1), D480–D489.

Bolger, A. M., Lohse, M., and Usadel, B. (2014). Trimmomatic: A flexible trimmer for Illumina sequence data. *Bioinformatics*, *30*(15), 2114–2120.

Buchfink, B., Reuter, K., and Drost, H. G. (2021). Sensitive protein alignments at tree-of-life scale using DIAMOND. *Nature Methods*, *18*(4), 366–368.

Bushmanova, E., Antipov, D., Lapidus, A., and Prjibelski, A. D. (2019). RnaSPAdes: A de novo transcriptome assembler and its application to RNA-Seq data. *GigaScience*, *8*(9).

Cantalapiedra, C. P., Hern̗andez-Plaza, A., Letunic, I., Bork, P., and Huerta-Cepas, J. (2021). eggNOG-mapper v2: Functional Annotation, Orthology Assignments, and Domain Prediction at the Metagenomic Scale. *Molecular Biology and Evolution*, *38*(12), 5825–5829.

Clark, J. W., Hetherington, A. J., Morris, J. L., Pressel, S., Duckett, J. G., Puttick, M. N., Schneider, H., Kenrick, P., Wellman, C. H., and Donoghue, P. C. J. (2023). Evolution of phenotypic disparity in the plant kingdom. *Nature Plants*, *9*(10), 1618–1626.

Conway, J. R., Lex, A., and Gehlenborg, N. (2017). UpSetR: An R package for the visualization of intersecting sets and their properties. *Bioinformatics*, *33*(18), 2938–2940.

de La Torre, A. R., Piot, A., Liu, B., Wilhite, B., Weiss, M., and Porth, I. (2020). Functional and morphological evolution in gymnosperms: A portrait of implicated gene families. In *Evolutionary Applications* (Vol. 13, Issue 1, pp. 210–227). Wiley-Blackwell.

Drost, H. G., Gabel, A., Grosse, I., and Quint, M. (2015). Evidence for active maintenance of phylotranscriptomic hourglass patterns in animal and plant embryogenesis. *Molecular Biology and Evolution*, *32*(5), 1221–1231.

Drost, H. G., Gabel, A., Liu, J., Quint, M., and Grosse, I. (2018). MyTAI: Evolutionary transcriptomics with R. *Bioinformatics*, *34*(9), 1589–1590.

Escandón, M., Valledor, L., Pascual, J., Pinto, G., Cañal, M. J., and Meijón, M. (2017). System-wide analysis of short-term response to high temperature in Pinus radiata. *Journal of Experimental Botany*, *68*(13), 3629–3641.

Falk, T., Herndon, N., Grau, E., Buehler, S., Richter, P., Zaman, S., Baker, E. M., Ramnath, R., Ficklin, S., Staton, M., Feltus, F. A., Jung, S., Main, D., and Wegrzyn, J. L. (2018). Growing and cultivating the forest genomics database, TreeGenes. *Database*, *2018*(2018).

Fu, L., Niu, B., Zhu, Z., Wu, S., and Li, W. (2012). CD-HIT: Accelerated for clustering the next-generation sequencing data. *Bioinformatics*, *28*(23), 3150–3152.

García-Campa, L., Guerrero, S., Lamelas, L., Meijón, M., Hasbún, R., Cañal, M. J., and Valledor, L. (2022). Chloroplast proteomics reveals transgenerational cross-stress priming in Pinus radiata. *Environmental and Experimental Botany*, *202*.

Gohr, A., and Irimia, M. (2019). Matt: Unix tools for alternative splicing analysis. *Bioinformatics*, *35*(1), 130–132.

Grabherr, M. G., Haas, B. J., Yassour, M., Levin, J. Z., Thompson, D. A., Amit, I., Adiconis, X., Fan, L., Raychowdhury, R., Zeng, Q., Chen, Z., Mauceli, E., Hacohen, N., Gnirke, A., Rhind, N., di Palma, F., Birren, B. W., Nusbaum, C., Lindblad-Toh, K., … Regev, A. (2011). Full-length transcriptome assembly from RNA-Seq data without a reference genome. *Nature Biotechnology*, *29*(7), 644–652.

Jin, W.-T., Gernandt, D. S., Wehenkel, C., Xia, X.-M., Wei, X.-X., and Wang, X.-Q. (2021). Phylogenomic and ecological analyses reveal the spatiotemporal evolution of global pines. *PNAS*, *118*, 2022302118.

Jones, P., Binns, D., Chang, H. Y., Fraser, M., Li, W., McAnulla, C., McWilliam, H., Maslen, J., Mitchell, A., Nuka, G., Pesseat, S., Quinn, A. F., Sangrador-Vegas, A., Scheremetjew, M., Yong, S. Y., Lopez, R., and Hunter, S. (2014). InterProScan 5: Genome-scale protein function classification. *Bioinformatics*, *30*(9), 1236–1240.

Kopylova, E., Noé, L., and Touzet, H. (2012). SortMeRNA: Fast and accurate filtering of ribosomal RNAs in metatranscriptomic data. *Bioinformatics*, *28*(24), 3211–3217.

Laloum, T., Martín, G., and Duque, P. (2018). Alternative Splicing Control of Abiotic Stress Responses. In *Trends in Plant Science* (Vol. 23, Issue 2, pp. 140–150).

Lamelas, L., Valledor, L., Escandón, M., Pinto, G., Cañal, M. J., and Meijón, M. (2020). Integrative analysis of the nuclear proteome in Pinus radiata reveals thermopriming coupled to epigenetic regulation. *Journal of Experimental Botany*, *71*(6), 2040–2057.

Lamelas, L., Valledor, L., López-Hidalgo, C., Cañal, M. J., and Meijón, M. (2022). Nucleus and chloroplast: A necessary understanding to overcome heat stress in Pinus radiata. *Plant Cell and Environment*, *45*(2), 446–458.

Langfelder, P., and Horvath, S. (2008). WGCNA: An R package for weighted correlation network analysis. *BMC Bioinformatics*, *9*.

Langmead, B., and Salzberg, S. L. (2012). Fast gapped-read alignment with Bowtie 2. *Nature Methods*, *9*(4), 357–359.

Leebens-Mack, J. H., Barker, M. S., Carpenter, E. J., Deyholos, M. K., Gitzendanner, M. A., Graham, S. W., Grosse, I., Li, Z., Melkonian, M., Mirarab, S., Porsch, M., Quint, M., Rensing, S. A., Soltis, D. E., Soltis, P. S., Stevenson, D. W., Ullrich, K. K., Wickett, N. J., DeGironimo, L., … Wong, G. K. S. (2019). One thousand plant transcriptomes and the phylogenomics of green plants. *Nature*, *574*(7780), 679–685.

Leek, J. T., Johnson, W. E., Parker, H. S., Jaffe, A. E., and Storey, J. D. (2012). The SVA package for removing batch effects and other unwanted variation in high-throughput experiments. *Bioinformatics*, *28*(6), 882–883.

Love, M. I., Huber, W., and Anders, S. (2014). Moderated estimation of fold change and dispersion for RNA-seq data with DESeq2. *Genome Biology*, *15*(12).

Martín, G., Márquez, Y., Mantica, F., Duque, P., and Irimia, M. (2021). Alternative splicing landscapes in Arabidopsis thaliana across tissues and stress conditions highlight major functional differences with animals. *Genome Biology*, *22*(1).

Niu, S., Li, J., Bo, W., Yang, W., Zuccolo, A., Giacomello, S., Chen, X., Han, F., Yang, J., Song, Y., Nie, Y., Zhou, B., Wang, P., Zuo, Q., Zhang, H., Ma, J., Wang, J., Wang, L., Zhu, Q., … Wu, H. X. (2022). The Chinese pine genome and methylome unveil key features of conifer evolution. *Cell*, *185*(1), 204-217.e14.

Pascual, J., Alegre, S., Nagler, M., Escandón, M., Annacondia, M. L., Weckwerth, W., Valledor, L., and Cañal, M. J. (2016). The variations in the nuclear proteome reveal new transcription factors and mechanisms involved in UV stress response in Pinus radiata. *Journal of Proteomics*, *143*, 390–400.

Pascual, J., Canal, M. J., Escandon, M., Meijon, M., Weckwerth, W., and Valledor, L. (2017). Integrated physiological, proteomic, and metabolomic analysis of ultra violet (UV) stress responses and adaptation mechanisms in pinus radiata. *Molecular and Cellular Proteomics*, *16*(3), 485–501.

Patro, R., Duggal, G., Love, M. I., Irizarry, R. A., and Kingsford, C. (2017). Salmon provides fast and bias-aware quantification of transcript expression. *Nature Methods*, *14*(4), 417–419.

Perez-Riverol, Y., Bai, J., Bandla, C., García-Seisdedos, D., Hewapathirana, S., Kamatchinathan, S., Kundu, D. J., Prakash, A., Frericks-Zipper, A., Eisenacher, M., Walzer, M., Wang, S., Brazma, A., and Vizcaíno, J. A. (2022). The PRIDE database resources in 2022: A hub for mass spectrometry-based proteomics evidences. *Nucleic Acids Research*, *50*(D1), D543–D552.

Pérez-Silva, J. G., Araujo-Voces, M., and Quesada, V. (2018). NVenn: Generalized, quasi-proportional Venn and Euler diagrams. *Bioinformatics*, *34*(13), 2322–2324.

Ritchie, M. E., Phipson, B., Wu, D., Hu, Y., Law, C. W., Shi, W., and Smyth, G. K. (2015). Limma powers differential expression analyses for RNA-sequencing and microarray studies. *Nucleic Acids Research*, *43*(7), e47.

Romero-Rodríguez, M. C., Pascual, J., Valledor, L., and Jorrín-Novo, J. (2014). Improving the quality of protein identification in non-model species. Characterization of Quercus ilex seed and Pinus radiata needle proteomes by using SEQUEST and custom databases. *Journal of Proteomics, 105*, 85–91.

Romy, P., Varshney, D., Hiltemann, S., Finke, H., Schreiber, M., de Vries, J. and Rensing, S.A. (2025). Enhanced sensitivity of TAPscan v4 enables comprehensive analysis of streptophyte transcription factor evolution. *The Plant Journal, 121*, e17184.

Sacomoto, G. A. T., Kielbassa, J., Chikhi, R., Uricaru, R., Antoniou, P., Sagot, M. F., Peterlongo, P., and Lacroix, V. (2012). Kissplice: De-novo calling alternative splicing events from RNA-seq data. *BMC Bioinformatics*, *13*.

Schwacke, R., Ponce-Soto, G. Y., Krause, K., Bolger, A. M., Arsova, B., Hallab, A., Gruden, K., Stitt, M., Bolger, M. E., and Usadel, B. (2019). MapMan4: A Refined Protein Classification and Annotation Framework Applicable to Multi-Omics Data Analysis. *Molecular Plant*, *12*(6), 879–892.

Shiu, S.-H., and Lehti-Shiu, M. D. (2023). Evolution of research topics and paradigms in plant sciences. *BioRxiv*.

Simão, F. A., Waterhouse, R. M., Ioannidis, P., Kriventseva, E. v., and Zdobnov, E. M. (2015). BUSCO: Assessing genome assembly and annotation completeness with single-copy orthologs. *Bioinformatics*, *31*(19), 3210–3212.

Tian, F., Yang, D.C., Meng, Y.Q., Jin, J. and Gao, G. (2020) PlantRegMap: charting functional regulatory maps in plants. *Nucleic Acids Research, 48*, D1104-D1113.

Valledor, L. and Weckwerth, W. (2014). An improved detergent-compatible gel-fractionation LC-LTQ-orbitrap-MS workflow for plant and microbial proteomics. *Methods in Molecular Biology*, 1072, 347–358.

Valledor, L., Escandón, M., Meijón, M., Nukarinen, E., Cañal, M. J., and Weckwerth, W. (2014). A universal protocol for the combined isolation of metabolites, DNA, long RNAs, small RNAs, and proteins from plants and microorganisms. *Plant Journal*, *79*(1), 173–180.

Visser, E. A., Kampmann, T. P., Wegrzyn, J. L., and Naidoo, S. (2023). Multispecies comparison of host responses to Fusarium circinatum challenge in tropical pines show consistency in resistance mechanisms. *Plant Cell and Environment*, *46*(5), 1705–1725.

Yang, S., Zong, W., Shi, L., Li, R., Ma, Z., Ma, S., Si, J., Wu, Z., Zhai, J., Ma, Y., Fan, Z., Chen, S., Huang, H., Zhang, D., Bao, Y., Li, R. and Xie, J. (2024) PPGR: a comprehensive perennial plant genomes and regulation database. *Nucleic Acids Research, 52*, D1588-DD1596.

Zhang, S., Li, R., Zhang, L., Chen, S., Xie, M., Yang, L., Xia, Y., Foyer, C. H., Zhao, Z., and Lam, H. M. (2020). New insights into Arabidopsis transcriptome complexity revealed by direct sequencing of native RNAs. *Nucleic Acids Research*, *48*(14), 7700–7711.

Zhang, Y., Tian, H., Chen, D., Zhang, H., Sun, M., Chen, S., Qin, Z., Ding, Z., and Dai, S. (2023). Cysteine-rich receptor-like protein kinases: emerging regulators of plant stress responses. In *Trends in Plant Science* (Vol. 28, Issue 7, pp. 776–794).

# Figure legends

**Figure 1.** **Overview of Pra-GE-ATLAS.** Pra-GE-ATLAS is a refined multi-omics platform compiling the largest transcriptomics and proteomics collections to date for *P. radiata*. Pra-GE-ATLAS provides user-friendly search functionalities and tools to explore and analyse processed tissue- and stress-related changes, as well as to extrapolate data from other species to this reference. Pra-GE-ATLAS DB is available at: <https://rocesv.github.io/Pra-GE-ATLAS/>.

**Figure 2. Transcriptional module global description. A)** Venn diagrams showing all intersections between gene expression (GE, upper) and alternative splicing (AS, lower) core sets (see **Methods**). Pan = genes/events that are expressed/alternatively spliced in the vast majority of samples; Stress = genes/events that are up/down regulated in stress experiments; Tissue = genes/events that are up/down regulated across tissues. **B)** Proportion of each type of AS event in each AS core set (see **Methods**). NR = non-regulated; Genome = background set constituted by events that passed the same coverage criteria and filters; IR = intron retention; ES = exon skipping; AltAD = alternative splice acceptor/donor sites; AS-Unknown = events that passed coverage criteria and filters without classification. Significant enrichment compared to genome background are marked with “\*”. **C)** Venn diagrams showing intersections between gene expression (GE, left) and alternative splicing (AS, right) genes for each core set. **D)** Percentage of intron retention (first), exon skipping (second) and alternative splice donor and acceptor sites (Alternative A/D, third) events belonging to the different AS core sets located out/in CDS regions. Among the latter category (in CDS regions), the percentage of events with potential effects in protein levels are indicated. Gen. = genome background; Not-CDS = outside CDS regions; PTC = sequence variation inside CDS regions introduce premature termination codons; Disrupt = sequence variation inside CDS regions force out of frame reading; Change = sequence variation inside CDS change CDS region sequence. Significant enrichment compared to genome background are marked with “\*”. **E)** Schematic representation of genomic regulatory features associated with each AS core sets for introns (first) and exons (second and third). Only features with statistical significant differences for each AS core set were represented. Arrows summarise which features show significant differences respect to Genome background and the direction of these differences (higher-red or lower-blue). “X” indicates no statistically significant difference. Intron features (first) include (from top to bottom and left to right): length of the upstream (UP) exon, target intron, polypyrimidine tract (PT) and downstream (DO) exon; GC content of the upstream 5’ splice region; number of introns; distance between branch point (BP) and 3’ splice site (ss); score of the polypyrimidine tract; rank and/or position of the target intron. Exon features for exon skipping (second) include (from top to bottom and left to right): length of the upstream exon, upstream intron, upstream polypyrimidine tract, target exon, downstream intron, downstream exon and transcript; GC content of the target exon, 5’ splice region and downstream exon; score of the upstream branch point, polypyrimidine tract, 5’ splice region and downstream branch point; rank and/or position of the target exon. Exon features for alternative acceptor donor site (third) include (from top to bottom and left to right): length of the downstream exon and transcript; GC content of the upstream 5’ splice region, target exon and downstream exon; score of the upstream and downstream branch points; rank and/or position of the target exon. **F)** Heatmaps depicting significant overrepresented Mercator functional categories (p-value adjusted < 0.1; -log10(p-adjusted)) and network modules-trait correlations (p-value adjusted < 0.05; pearson). Biosynthe = biosynthesis; hom = homeostasis; CHO = carbohydrate; met = metabolism; reg = regulation; org = organisation; PS = photosynthesis; resp = response; cellular resp = cellular respiration; transloc = translocation; mod = modification; dmg = damage.

**Figure 3. Protein module global description. A)** From left to right: heatmaps showing Mercator functional categories normalised enrichment scores (NES, first), significance (p-value adjusted < 0.1, second) and matrix layout (third) for all intersections of differential proteins between tissues. Letters in significance heatmap highlight for which tissue the functional term is significantly enriched. B = Bud; N = Needle. **B)** Summary of volcano analyses (see **Methods**) indicating top marker proteins for each differential contrast between tissues. **C)** Proteomic Age Index (PAI) corresponding high values to younger protein genes. Flat line test p-value < 0.05 highlight a significant evolutionary pattern. **D)** From left to right: heatmaps showing Mercator functional categories normalised enrichment scores (NES, first), significance (p-value adjusted < 0.1, second) and matrix layout (third) for all intersections of differential proteins between stress experiments. Letters in significance heatmap highlight for which condition the functional term is significantly enriched. H = Heat; U = UV; C = Control; R = Recovery. **E)** Summary of volcano analyses (see **Methods**) indicating top marker proteins for each differential contrast between stress conditions. **F)** Heatmap depicting significant network modules-trait correlations (p-value adjusted < 0.05; Pearson). T1-T4 correspond to low-very high stress intensities. FU = *Fusarium*. **G)** From left to right: heatmaps showing Mercator functional categories normalised enrichment scores (NES, first) and significance (p-value adjusted < 0.1, second) for all network modules. “\*” in significance heatmap highlights for which particular module the functional term is significant. Met = metabolism; hom = homeostasis; resp = response; cellular resp = cellular respiration; mod = modification; reg = regulation; org = organisation; PS = photosynthesis; act = action; dmg = damage.

**Figure 4. Identification of the main transcriptional sources of variation in tissues and stresses. A)** Percentage of explained variance (%) by each latent factor (LF) and regulatory layer (gene expression, GE; alternative splicing, AS) for ungrouped tissues framework. **B)** Scatter plot of latent factor 1 (x-axis) and latent factor 3 (y-axis) illustrating the variation described. Samples are coloured according to tissues. **C)** Table showing top absolute loading genes for latent factors 1 and 3. **D)** Heatmaps depicting significant (FDR < 0.1, -log10(FDR)) enriched Mercator functional terms (green), genes ages (purple) and family founder events ages (blue) for each regulatory layer. PS/F = gene/family-founder phylostratum. Lower phylostratum values correspond to genes with older origins. **E)** Experimental validation of tissues/age-induced AS events by RT-PCR. The primers used allow the amplification of multiple splice variants (see **Methods**). **F)** Percentage of explained variance (%) by each latent factor (LF) and regulatory layer (gene expression, GE; intron retention, IR; exon skipping, ES; alternative acceptor donor site, Alt; alternative splicing without classification, AS) for grouped stress framework. **G)** Scatter plots of latent factors 1, 2 and 3 illustrating the variation described. Colours denote stress treatments. Different figures denote genotypes. DO = *Dothistroma*; FU = *Fusarium*; HS = heat; PH = *Phytophthora*; dmg = damage. T1-T4 correspond to low-very high stress intensities. **H)** Table showing top absolute loading genes for latent factors 1, 2 and 3. **I)** Heatmaps depicting significant (FDR < 0.1, -log10(FDR)) enriched Mercator functional terms (green), genes ages (purple) and family founder events ages (blue) for gene expression and intron retention regulatory layers. PS1 = cellular organisms; PS2 = Eukaryota; PS3 = Viridiplantae; PS4 = Streptophyta; PS5 = Streptophytina; PS6 = Embryophyta; PS7 = Tracheophyta; PS8 = Euphyllophyta; PS9 = Spermatophyta; PS10 = Acrogymnospermae; PS11 = Pinidae; PS12 = Pinaceae; met = metabolism; CHO = carbohydrate; org = organisation; resp = response; reg = regulation; hom = homeostasis; mod = modification; transloc = translocation; PS = photosynthesis; biosynthe = biosynthesis.

**Figure 5. Characterisation of shared and unique sources of stress variation at protein level.** Due to the high complexity of proteomics data four LFs were selected to perform in-depth characterisation. **A)** Percentage of explained variance (%) by each latent factor (LF) for grouped all stresses total proteomes framework. FU = *Fusarium*; HS = heat. **B)** Scatter plots of latent factors 1, 2, 3 and 4 illustrating the variation described. Colours denote stress treatments. R = Recovery. T1-T4 correspond to low-very high stress intensities. **C)** Table showing top absolute loading proteins for latent factors 1, 2, 3 and 4. **D)** Heatmaps depicting significant (FDR < 0.1, -log10(FDR)) enriched Mercator functional terms (green), genes ages (purple) and family founder events ages (blue). PS/F = gene/family-founder phylostratum. Lower phylostratum values correspond to genes with older origins. **E)** Percentage of explained variance (%) by each latent factor (LF) for grouped abiotic stresses all proteomes framework. **F)** Scatter plots of latent factors 2, 6, 7 and 9 illustrating the variation described. Colours denote stress intensity. Figures denote subcellular location. Chloro = chloroplast. **G)** Table showing top absolute loading proteins for latent factors 2, 6, 7 and 9. **H)** Heatmaps depicting significant (FDR < 0.1, -log10(FDR)) enriched Mercator functional terms (green), genes ages (purple) and family founder events ages (blue). **I)** Percentage of explained variance (%) by each latent factor (LF) for grouped abiotic stresses chloroplast proteomes framework. LF1 was excluded as it primarily captured variation not linked to the biological factors under study. PopE = population E (non-stressed); PopT = population T (stressed) (see **Figure S2F**). **J)** Scatter plots of latent factors 2, 3, 5 and 6 illustrating the variation described. Colours denote stress intensity. Figures denote stress type. E = population E; T = population T. **K)** Table showing top absolute loading proteins for latent factors 2, 3, 5 and 6. **L)** Heatmaps depicting significant (FDR < 0.1, -log10(FDR)) enriched Mercator functional terms (green), genes ages (purple) and family founder events ages (blue). PS1 = cellular organisms; PS2 = Eukaryota; PS3 = Viridiplantae; PS4 = Streptophyta; PS5 = Streptophytina; PS6 = Embryophyta; PS7 = Tracheophyta; PS8 = Euphyllophyta; PS9 = Spermatophyta; PS10 = Acrogymnospermae; PS11 = Pinidae; PS12 = Pinaceae; met = metabolism; CHO = carbohydrate; org = organisation; resp = response; reg = regulation; hom = homeostasis; mod = modification; transloc = translocation; PS = photosynthesis; biosynthe = biosynthesis.

# Supplemental Information

**Figure S1.** **Overview of the methods workflow.**

**Figure S2. Evolutionary transcriptomics and proteomics patterns, tissues vs stress contribution to global PSI variation in different species and populations experimental design. A)** Transcriptomic Age Index (TAI) of tissues corresponding high values to younger genes. Flat line test p-value < 0.05 highlights a significant evolutionary pattern. **B)** Transcriptomic Age Index (TAI) corresponding high values to younger genes. HS = heat; DO = *Dothistroma*; PH = *Phytophthora*; FU = *Fusarium*. Individual stress experiments with significant evolutionary patterns are highlighted with “\*”. **C)** Comparison of the relative contribution to the total PSI variation of the tissue samples vs stress experiments in each species. The total PSI variation for each AS event is calculated as the sum of two relative contributions: (i) the PSI range across tissues, (ii) the maximum difference between PSI among stress experiments (see **Methods**). Colours represent the number of AS events found on each intersection between the relative contributions (in percentage) for each set of samples. **D)** Proteomic age index (PAI) of all stresses total proteomes corresponding high values to younger protein genes. **E)** Proteomic age index (PAI) of abiotic stresses all proteomes corresponding high values to younger protein genes. **F)** Intergenerational stress populations experimental design. The divergent local-environment conditions involved, setting Population T as reference, +50 meters elevation, +44 mm mean rainfall, and +1.72 mean ºC. Nevertheless, PopE plants were fertirrigated during the dry months. **G)** Proteomic age index (PAI) of abiotic stresses chloroplast proteomes corresponding high values to younger protein genes.

**Table S1. Transcriptomic data collection and consensus assembly evaluation.**

**Table S2. Primers used for the validation of tissues/age-induced alternative splicing.**

**Table S3. Proteomic data collection.**