A root phloem pole cell atlas reveals common transcriptional states in protophloem-adjacent cells

Otero, Sofia

2022-08

Otero , S , Gildea , I , Roszak , P , Lu , Y , Di Vittori , V , Bourdon , M , Kalmbach , L , Blob , B , Heo , J , Peruzzo , F , Laux , T , Fernie , A R , Tavares , H & Helariutta , Y 2022 , ' A root phloem pole cell atlas reveals common transcriptional states in protophloem-adjacent cells ' , þÿ N a t u r e p l a n t s , v o l . 8 , p p . 9 5 4 9 7 0 . h t t p s : / / d o i . o r g / 1 0 . 1 0 3 8 / s 4 1 4 7 7 - 0

http://hdl.handle.net/10138/354125
https://doi.org/10.1038/s41477-022-01178-y

acceptedVersion

A root phloem pole cell atlas reveals common transcriptional states in protophloem adjacent cells

Sofia Otero[1], Iris Gildea[2,3], Pawel Roszak[1], Yipeng Lu[1], Valerio Di Vittori[4,5], Matthieu Bourdon[1], Lothar Kalmbach[1], Bernhard Blob[1], Jung-ok Heo[1], Federico Peruzzo[6], Thomas Laux[6], Alisdair R. Fernie[4], Hugo Tavares[*1,7], Yka Helariutta[*1,2]

Affiliations

[1] The Sainsbury Laboratory, University of Cambridge, Cambridge, United Kingdom.
[2] Institute of Biotechnology, HiLIFE/Organismal and Evolutionary Biology Research Programme, Faculty of Biological and Environmental Sciences, Viikki Plant Science Centre, University of Helsinki, Helsinki, Finland.
[3] Present address: Department of Plant Biology and Genome Center, University of California, Davis, California 95616
[4] Max- Planck- Institute of Molecular Plant Physiology, Am Müehlenberg 1, Potsdam- Golm, 14476 Germany.
[5] Present address: Dipartimento di Scienze Agrarie, Alimentari ed Ambientali, Università Politecnica delle Marche, Ancona, Italy
[6] Signalling Research Centres BIOSS and CIBSS. Germany
[7]Present address: Department of Genetics, University of Cambridge, Cambridge, United Kingdom.

*Corresponding author
Correspondence and requests for materials should be addressed to:
yrjo.helariutta@slcu.cam.ac.uk
Questions related to code and bioinformatic analysis should be addressed to:
hm533@cam.ac.uk

Abstract

Single cell sequencing has recently allowed the generation of exhaustive root cell atlases. However, some cell types are elusive and remain underrepresented. Here, we use a second-generation single cell approach, where we zoom in on the root transcriptome sorting with specific markers to profile the phloem poles at an unprecedented resolution. Our data highlight the similarities among the developmental trajectories and gene regulatory networks communal to protophloem sieve element (PSE) adjacent lineages in relation to PSE enucleation, a key event in phloem biology.

As a signature for early PSE-adjacent lineages, we have identified a set of DNA-binding with one finger (DOF) transcription factors, the PINEAPPLEs (PAPL), that act downstream of *PHLOEM EARLY DOF* (*PEAR*) genes, and are important to guarantee a proper root nutrition in the transition to autotrophy.

Our data provide a holistic view of the phloem poles that act as a functional unit in root development.

Main text

INTRODUCTION

In plants, organs originate from meristems postembrionically and are patterned by mobile signals and the positional information generated in the individual immobile cell types. Determining cell type-specific transcriptional programs is key to understanding the positional cues guiding plant development[1]. However, despite the importance of phloem in vascular plants and radial growth pre-patterning[2], phloem gene expression is not yet well characterized. During root development, the term phloem is oftentimes used as a synonym of the protophloem sieve element (PSE), the cell type that undergoes a unique differentiation process to specialize in the transport of sap from source photosynthetic organs to distant sink

tissues. This simplification is probably the result of the extensive knowledge we have about PSE specification[2,3] and differentiation [4–11]. However, in the Arabidopsis primary root, the phloem pole is composed of six cells belonging to four distinct cell types: the central PSE is flanked by two phloem pole pericycle (PPP) cells to the outside and one metaphloem sieve element (MSE) cell to the inside, and both SE cells are in direct contact with the two lateral companion cells (CC)[12] (Fig 1a).

In the Arabidopsis root, both conductive elements (MSE and PSE) derive from the same stem cell[13] but MSE differentiates later, when PSE cells are no longer functional. Despite having a similar function to PSE, MSE ontogeny is less well characterized[14] and few factors have been directly related to MSE development. An exception are the partially redundant homologs *OCTOPUS* (*OPS, At3g09070)* and *OCTOPUS-LIKE 2* (*OPL2*, *At2g38070*) identified as important for MSE entry into differentiation[15]. Despite some commonalities between PSE and MSE, a recent study highlighted MSE differentiation is independent of adjacent or preceding PSE[14], underlining the peculiarities of this cell type. The conducting cell types and CC originate from different progenitors in the Arabidopsis root[13]. CC are believed to be essential to support enucleated PSE function[16] and their intimate relationship has been evidenced by a common molecular switch controlling SE/CC fate *in vitro* and in hypocotyls[17], while in the primary root undifferentiated CC and MSE can transdifferentiate to PSE cells if these are misspecified[18]. The CC function in leaves consists of loading nutrients into the SE but their role in the root remains elusive[19]. Traditionally, it was thought they were involved in phloem unloading[20], that is, the exit of the nutrients from the sieve element pipe so that they reach meristematic cells for food. However, it was recently demonstrated this process happens through funnel plasmodesmata connecting PSE to PPP[12].

Despite being considered a non-vascular tissue, PPP and the associated vasculature share a high overlap in gene expression[21] and are different in size and ultrastructure to the xylem pole pericycle (XPP) population[22], exhibiting specific gene expression[23] from early stages, mirroring the diarch pattern in the Arabidopsis vasculature[24].

In the last 15 years, transcriptomics has been the stepping stone to learn about plant organogenesis. However, even if markers for mature CC and PPP were used for transcriptomics[1,25,26], the lack of specific markers for early phloem, combined with the difficulties to access phloem cells, deeply embedded in the root cylinder, have hampered the study of these populations, oftentimes masked under the concept “stele”, that groups pericycle and vasculature [27–29]. The more recent root single-cell atlases confer a detailed root panoramic but even here phloem cells remain underrepresented compared to more accessible root layers[30–32].

Combining fluorescent activated cell sorting (FACS) and SMART-seq single cell technologies allowed the profiling of 758 PSE cells at an unprecedented resolution, identifying the bifurcation of MSE and procambium lineages[33]. In this study, we have generated a phloem pole cell atlas of 10204 cells by sorting phloem marker lines combined with single cell sequencing. This allowed us to gain resolution not just in the PSE lineage but in all the surrounding cells (CC, PPP, MSE) in the phloem poles, all of which are underrepresented in general root cell atlases. We investigated not only the specificities of each cell type but also the transcriptional commonalities between them. We additionally identified a second set of DOF transcription factors (TF) expressed in the PSE adjacent cells, downstream of PEAR TF, that are important in the transition to autotrophy in young seedlings.

RESULTS

In order to profile phloem cells, we took advantage of new and existing fluorescent markers expressed in SEs, CC and PPP from early meristematic cells until differentiation (Fig S1a). This allowed us to enrich our data with cells of interest, by using FACS and preparing single-cell sequencing libraries using the 10x Chromium droplet-based protocol. This resulted in a total of 10,204 high-quality cells, defined as those having at least 2000 detected genes and no more than 10% of reads assigned to mitochondrial genes (the resultant sample of cells had a median of 17,455 reads/cell and a median of 4,564 genes/cell). The raw count data was

normalised using variance stabilising transformation[34] and integrated across batches using the mutual nearest neighbours algorithm[35], although our main conclusions are robust to normalisation and batch effects. These cells were grouped into 15 clusters using the Louvain algorithm on a shared-nearest-neighbour cell graph and visualised using uniform manifold approximation and projection (UMAP)[36] (Fig 1b). Using signature marker genes[1,2,5,12,17,19,37](Fig 1c), we identified all the cell types included in the phloem pole. We manually annotated groups of clusters as: PSE conducting cells (clusters 12, 2, 6), CC (clusters 5, 3) and a third to PPP (clusters 7, 4, 14, 11), all emerging from a central group of less mature cells (clusters 8, 9, 10, 13). Clusters 10 and 1 express MSE genes (Fig 2b). In turn, clusters 13 and 12 contain G2/M cell cycle markers, indicating cells undergoing division. While it is usually difficult to infer the identity of cycling cells, in the case of cluster 12 most of the cells express early PSE markers as well as cell division markers, pointing towards PSE-dividing cells. For example, *PEAR1* or *CVP2* are detected in all of the cells of this cluster and cell-cycle genes such as *KNOLLE*, *AUR1* or *CYCB1* are also detected in over 57% of those cells. Finally, cluster 15 corresponds to the outer layers of the root, as an apparent contamination during cell sorting.

Separated from the rest, clusters 7, 4 and 14 were contributed to mainly by *pS17::GFP* and *pAPL::3xYFP* markers (Fig 2a), and expressed genes characteristic of PPP such as *S17* (*At2g22850)* and *GLUCAN SYNTHASE-LIKE 4* (*CALS8, At3g14570)* (Fig 1c). In turn, cluster 11, mainly contributed to by *pS17::GFP* and the *pMAKR5::MAKR5-3xYFP* sortings, represents mature pericycle cells, since in addition to PPP markers it also expresses markers for XPP (*At1g02460*, *At4g30450*[38], *At2g36120*, Fig 2c) and PPP (Fig 1c). This is likely because *MEMBRANE-ASSOCIATED KINASE REGULATOR 5* (*MAKR5, At5g52870)* is expressed in the whole pericycle layer high up in the root and pericycle cells come together with PPP cells for similarity.

Considering genes that were statistically more highly expressed in PPP-specific clusters, we built reporter lines for two genes, which were confirmed to have PPP-specific expression. One of these, *At3g27030*, was expressed in PPP and late PSE, while the other, *METHYL*

ESTERASE 7 (*MES7, At2g23560),* was expressed early in PPP and soon afterwards becomes more broadly expressed in the vasculature and endodermis (Fig 1d).

In turn, the known CC genes are expressed in cluster 5 (*SISTER OF APL*, (*SAPL, At3g12730*[12])), with cluster 3 expressing mature CC genes (*ATPase3* (*AHA3, At5g57350*[2]), *SODIUM POTASSIUM ROOT DEFECTIVE 1* (*NAKR1)*[39], *SUCROSE PROTON SYMPORTER 2* (*SUC2, At1g22710*[40]). *AHA3* in particular was statistically more highly expressed in this cluster and allowed the discovery of new CC genes by correlation, which were validated building reporter lines (Fig 1d). One of these was *At2g32210*, which is expressed first in PSE and then switches to a strong CC-MSE expression, with a weak expression in the epidermis. In turn, *METACASPASE 3 (MC3, At5g64240),* was expressed in late PSE and started being expressed in CC after enucleation, first in a patchy way and then getting continuous and mostly CC-exclusive. Cloning reporter lines for other genes expressed in these clusters, we found a gene expressed in PSE and CC (*PHOSPHATIDYLINOSITOL-SPECIWC PHOSPHOLIPASE C5 (PLC5, At5g58690*)), previously described to be expressed in vascular tissues[37] and *At2g38640*[41] mostly specific of mature CC (Fig S1b). Therefore, we have been able to validate our cell annotation (shown on the UMAP in Fig 1b) *in vivo* by using new genes highly expressed in these clusters.

Spatiotemporal patterns of differentiation in the atlas

From our initial cell annotation, it seemed clear that our data also captured the temporal aspect of cell differentiation in the phloem. For example, marker genes usually expressed in more differentiated cells, showed higher expression at the terminal clusters of our UMAP projection (3, 6, 11, 14, Fig S1c), while those closer to the cycling cells are less mature. To validate this hypothesis, we compared our data with a microarray dataset[1] of manually microdissected root longitudinal sections (3 to 5 cells thick), assigning each of our cells to the longitudinal section with which they had the highest Spearman correlation (Fig S2a). Using this strategy, we observed that the cells towards the centre of our UMAP matched with the meristematic

sections of Brady *et al.*, with a temporal progression towards the terminal clusters of our UMAP, until the more mature cells cap each trajectory. This analysis validates our hypothesis of a temporal trajectory that is well captured by our UMAP projection and cell clustering.

To further infer developmental trajectories and order our cells along a continuous pseudotime, we used Slingshot[43] (Fig 3a). Setting a unique origin for all in cluster 13 (cycling cells), we obtained 5 different trajectories (Fig 3a), reflecting the known developmental trajectories in the root. Furthermore, these trajectories agreed with RNA velocity analysis using scVelo[44], with velocity vectors aligning towards the end of these trajectories (Fig S2c).

Trajectories 1-3 account for PPP, CC and PSE respectively. Trajectory 5 is for outer layers and we will not focus on it.

While PSE trajectory is independent from all others, PPP and CC have cluster 5 in common. While other clusters were unequivocally assigned to a single trajectory (see for instance cluster 3, with *slingshot* assigning a probability close to 1 of belonging to the CC trajectory, or cluster 4, with a probability close to 1 of belonging to the PPP trajectory, Fig S2e) or shared by all trajectories (like early phloem cells in cluster 8, Fig S2e), cluster 5 was not a clear cut, with a probability of around 0.75% of belonging to trajectory 2 (CC) and around 0.25 of belonging to trajectory 1 (PPP), Fig S2e.

Regarding gene expression, cluster 5 does not express any canonical CC or PPP marker strongly. However, these markers (*SUC2*, *NAKR1*, *AHA3* for CC or *S17* for PPP) are only highly expressed in more mature cells. Cluster 5 has 64% cells expressing the CC marker *SAPL* (409/638 cells) and 20% expressing the PPP marker *S17* (127/638 cells), with 12% of the cells in this cluster expressing both genes simultaneously (76/638 cells). This indicates more cells in cluster 5 express CC markers than PPP markers. This matches our observations in the root, when *SAPL* starts to be expressed earlier in development than S17 (Fig S2g). The fact that a small percentage of cells express both markers at the same time despite being specific for different cell types would indicate transcriptional reporters are not always highlighting weak gene expression, so it is possible that our transcriptional data paint broader expression domains than the ones visible with the specific marker lines (see for example the

196 broader *SAPL* expression domain compared to the cells sorted using *pSAPL::VENUSer*
197 reporter line, Fig 2a,b).
198 We tried to distinguish incipient PPP from early CC in cluster 5 but there is no known PPP-
199 specific marker expressed earlier in development than *S17*. However, these intermediate PPP
200 cells should have been collected in the sorting experiments "*pMAKR5:MAKR5-3xYFP whole*
201 *root*" and "*pAPL:3xYFP*" (Fig 2a), and should be present in the UMAP. These cells would sit
202 in between the early PPP cells, sorted using "*pMAKR5:MAKR5-3xYFP root tip"* enriched in
203 root tips, and those expressing *S17*, sorted using *pAPL::3xYFP* and *pS17::GFP* markers.
204 Therefore, cluster 5 gathers CC and PPP cells that exist in the same transcriptional state but
205 are fated to differentiate into different cell types.
206 The developmental trajectories obtained reinforce clusters 8, 9 and 10 as early CC, PPP and
207 SE cells. Given these populations are contributed mainly by cells sorted using *MAKR5* and
208 *PEAR1del* (Fig 2a), we can conclude that these clusters correspond to the early phloem cells,
209 containing three different identities (MSE, PPP and CC), still undifferentiated.
210 There is no gene statistically enriched in cluster 9 and those few in cluster 8 (Table S1) are
211 broadly expressed in whole root single cell data. Except for PSE, when we detect cycling cells
212 expressing PSE markers in cluster 12, it is hard to distinguish an early identity in the other
213 trajectories. However, when early phloem cells are compared to the early cells in general root
214 cell atlases, phloem early cells cluster together more than expected by chance compared to
215 other early cells, suggesting early phloem cells have a specific signature (Fig 4f,g).
216 An important event in phloem development is the enucleation of PSE, since at that moment
217 this cell type loses the nucleus and stops directing phloem progression, becoming dependent
218 on neighbouring cells for survival and probably triggering changes in their transcriptomes. In
219 order to map the enucleation point in the UMAP and know which cells are neighbouring PSE
220 before and after enucleation, we needed to coordinate trajectories, since each trajectory has
221 a different pseudotime. To coordinate them we used our knowledge of *ALTERED PHLOEM*
222 *DEVELOPMENT* (*APL*) expression, which is expressed at different times in all three
223 trajectories, combined with the enucleation markers *NAC DOMAIN CONTAINING PROTEIN*

86 (*NAC086, At5g17260)* and *NAC45/86-DEPENDENT EXONUCLEASE-DOMAIN PROTEIN 4* (*NEN4, At4g39810)* (Fig 3b, Fig S2f). *APL* is first expressed in PSE and at the time of enucleation is transcriptionally activated in CC and MSE[4]. In reporter lines like *pAPL::3xYFP* we perceive a strong signal in PPP as well (Fig S1a), a circumstance that we took advantage of for sorting, but the phloem pole cell atlas transcriptomics data do not reflect a strong *APL* expression in mature PPP (Fig 3b", Fig S2d). In another reporter line, *pAPL::YFPer* we also observe a signal in PPP that gets weaker going shootward (Fig S2d). Based on reporters and transcriptomics data, the signal in PPP is probably not the product of gene expression in this cell type but likely caused by direct unloading from PSE that lags and gets diluted in successive cell divisions.

While *APL* expression increases in PSE trajectory until enucleation, it starts being detected in PPP and CC trajectories in the common cluster 5 (Fig 3b), indicating this is the transition zone when *APL* starts building up in the neighbouring cell types before enucleation. Therefore, the PSE trajectory is contemporary to the early phloem cells, cluster 5 coincides with PSE enucleation preparation and clusters for mature PPP and CC contain cells that are neighbouring an enucleated PSE (Fig 3b').

First stages of MSE development identified

MSE is difficult to identify since there are no specific markers available for this cell type. However, by reducing the diversity of cells in our sample using cell sorting, we were able to gain some insights about this elusive population of cells. Slingshot identified a trajectory (trajectory 4, Fig 3a) that is mainly formed by cluster 10 (Fig S2b), which is mostly contributed by *MAKR5* sortings, pointing this could be early MSE cells (Fig 2a). In cluster 10, we find cells expressing MSE markers like *sAPL*, *APL* (Fig 2b), and other genes expressed in MSE and other cell types but excluded from PSE (*At5g47920*, *PAPL1*, Fig 2b, Fig 7).

In addition, we know procambial markers like *PIN-FORMED 4* (*PIN4, At2g01420)* become excluded from MSE cells early in development[42] and we find this marker absent from cluster

10 (Fig 2b). Out of 31 genes identified as highly expressed in cluster 10 compared to others (FDR < 1%), 29 were S-phase genes (histones), indicating these are still early cells and therefore harder to characterise further.

We also know that MSE cells should not display PSE markers in early stages, since these are no longer expressed in MSE after lineage bifurcation, but will express these signature genes later in development. For this reason, we interpret that cluster 1 is a more developed MSE, since we find early SE genes like *PEAR1* and *S32* (*At2g18380*) expressed in this cluster, which is mainly contributed by the APL sorting. Cluster 1 belongs to CC trajectory, possibly because CC and MSE at this stage share some transcriptional expression, as evidenced by reporters like *At2g32210* (Fig 2b), *SAPL* and the cases shown in Fig 6b, highlighting how phloem pole cell fates are intertwined along development.

While we have end points for our PSE, CC and PPP trajectories, we don't expect to have an endpoint for MSE, since this cell type differentiates further away from the meristem[14]. Out of the 7 genes identified to be expressed in both sieve elements[14], we detected all the genes in PSE clusters but only *DESIGUAL2* (*DEAL2, At4g21310)* in cluster 1 and CC, confirming we have not sampled mature MSE cells. However, we are convinced we have identified the first stages of MSE development in clusters 10 and 1.

The atlas represents a continuum of phloem development

In order to explore the depth of our data, we integrated our phloem atlas with existing root single cell datasets[30,32,45] (Fig 4a). After filtering, this process rendered a UMAP with 113,340 reclustered cells, of which 9% belonged to our project, 7.69% to Wendrich et al., 4.84% to Denyer et al. and 78.4% to Shahan et al. We used markers to identify cell types (Fig 4b, d) and projected the clusters of the phloem pole cell atlas in the integrated dataset to confirm our trajectories (Fig 4d). The relative position of the original clusters is similar in the integrated data as it was in our analysis (Fig 1b). The exception are the cells which we named as "outer layers", which are dispersed in different parts of the integrated UMAP.

When projecting the cells of each project in the UMAP, a continuity can be observed in the cells contributed by our atlas covering the gaps in the other data (Fig 4e). Indeed, most of PSE cells (cluster 28), a majority of the intermediate PPP and CC cells (cluster 27) and the early cells in cluster 26 (PPP) were provided by our dataset (Fig S3), demonstrating the difficulty to sample phloem without using an active strategy to enrich this population. Most of the cells classified as "Phloem" by Shahan et al. coincide with our clusters 4 and 14, which we annotated more specifically as PPP cells (Fig 4c). There are also a few cells near our cluster 3, which we annotated as CC cells. We also noticed cluster 3 (companion cells) is split in this integrated dataset (Fig 4d, orange arrowheads), between mature CC (orange dots on the right of the plot, that is, cells expressing mature CC markers, like *SUC2* and *NAKR1*, see Fig S3a) and the orange cells in the less mature CC expressing *SAPL* (See Fig S3a). Perhaps the more mature CC have higher overall similarity to more mature cells of other phloem cells (such as PPP for example), more represented in the integrated dataset than in the original atlas.

While other atlases, in particular Shahan et al., excelled in harvesting mature cells (including mature MSE cells, Fig S3a,b), the continuity observed in the UMAP allowed us to track phloem developmental trajectories more accurately (Fig 3a) and enrich populations that were underrepresented in other general root atlases (Fig 4e, Fig S3a,b).

We also wanted to compare root phloem with a recently published single cell dataset on leaf, containing 478 vascular cells[46]. In Arabidopsis leaves (Fig 5a), veins are often formed by multiple sieve elements usually surrounded by at least two CC and one phloem parenchyma cell. In turn, phloem parenchyma cells, which are more irregular and have a much less dense cytoplasm compared to CC, are often in contact with one or more CC, sharing comparatively many more connections than other interfaces[47].

When the root and leaf data were integrated and clusters were annotated using marker genes (Fig 5d), we noticed PPP and phloem parenchyma cells blended in two clusters (Fig 5b,c). Cluster 9 of the integrated data was formed by CC cells, which are present in both leaf veins and roots. However, cluster 6 of the integrated data contained a mixture of cells annotated as

mature root pericycle cells and phloem parenchyma cells from leaves, showing expression of signature PPP (Fig 5e), phloem parenchyma genes (Fig 5f) and XPP (Fig 5g) in both datasets (see methods on how we assessed the degree of mixing of the cells from the two datasets in cluster 6). Phloem parenchyma leaf genes are expressed in clusters 11 and 14 in the phloem pole cell atlas, corresponding to pericycle and PPP respectively (Fig 5f). Pericycle tissue is present in roots and stems, but not in leaves, and phloem parenchyma cells are found in the aerial tissue and root secondary phloem but they are not found in the primary root. Despite being different cell types with different origins, the transcriptional overlap between phloem parenchyma and mature pericycle is another indication of the importance of positional information for cell function in plants, reinforcing the role of PSE as phloem organiser. These data also suggest parenchymatous cells share similarities across different organs and underscore their relevance for phloem.

Phloem pole cells share transcriptional programmes

In order to identify groups of genes showing distinct expression patterns in the phloem poles, we built a gene co-expression network from our scRNA-seq data using the algorithm implemented in *bigScale2*[48], which uses a gene-gene correlation metric specifically tailored for sparse single-cell data. This resulted in a gene-gene network containing 5,238 vertices (genes) and 370,794 edges (connecting two genes if their correlation was above 0.9). The biological validity of this network was confirmed by the fact that out of 59,545 edges containing genes both present in our network and in known TF-target lists (Arabidopsis Gene Regulatory Information Server, AGRIS[49]), 51,658 (~86%) were preserved as linked pairs in our network. To identify groups of genes with correlated expression profiles, we used the Louvain algorithm and obtained a total of 16 gene modules (Fig S4, Table S2), and summarised their expression as the first principal component of a PCA, which we refer to as an eigengene[50]. Among them, most of the modules were broad in all the trajectories with different temporal patterns. Module 6 seems to represent genes with high expression in PSE (Fig S4). In contrast, module 1, which

329 contains 1,367 genes (Table S3), displays an increasing expression in both PPP and CC
330 trajectories and a lower-than-average expression in PSE (Fig 6a). Reporter lines for genes in
331 this module followed these predictions: in addition to genes with broader expression (like
332 *MES7*, Fig1d), we identified genes showing a "ring" pattern, expressed specifically in all the
333 cells around PSE (Fig 6b, Fig S5). While *At3g11930*, *At2g02230* (*PHLOEM PROTEIN 2-B1*,
334 *PP2-B1)*, *At5g47920*, *At3g16330*[2] and its sister gene *At1g52140*, and *At4g27435* do not show
335 a strong expression in PSE, *At5g59090* (*SUBTILASE 4.12*, *SBT4.12), At2g20562* (*TAXIMIN*
336 *2*, *TAX2)* and *At1g26450* are expressed in late PSE in addition to being expressed in a ring
337 pattern. Some of the genes found are expressed in some of the cells around PSE (incomplete
338 ring) and other cell types (Fig S5). For instance, *At4g27435* is expressed in CC and
339 occasionally in PPP and protoxylem plus lateral root cap. *At3g21770* (*PER30*) and *At3g11930*
340 are found in the ring around PSE but extend to procambium higher up (Fig S5, Fig 6b).
341 Out of the nine genes with a ring expression pattern as observed with reporter lines (see
342 above), seven were found in module 1, with *TAX2* (*At2g20562*) not included in our network
343 and *At4g27435* found in module 4, which includes genes expressed in all trajectories. Despite
344 module 1 being the largest on our network, this result is more than would be expected by
345 chance (hypergeometric test, p-value = 0.0005).
346 Because of the large size of module 1, we tried to refine our analysis by sub-clustering the
347 genes within this module, to identify a more specific group of candidate "ring genes" as defined
348 by the reporter analysis above. This resulted in 15 sub-modules, with five of them containing
349 over 100 genes (Fig S6). Six of the seven "ring genes" from module 1 fell within the same sub-
350 module 1 (the exception was *At3g16330*), which again is more than would be expected by
351 chance (hypergeometric test, p-value = 0.0009). While we do not expect that all of the 326
352 genes in this sub-module have a ring expression pattern, this analysis highlights that this
353 pattern is widespread for a variety of phloem genes, which group together by similarity in
354 expression pattern. On the other hand, a gene such as *MES7*, which we saw was not entirely
355 ring-specific, fell in a different sub-module. Therefore, our network analysis suggests that there

356 is a complex ring-specific pattern of expression shared across several genes in the phloem
357 pole.
358 The complex patterns in the cells around PSE point out that PSE-adjacent cells share some
359 common developmental programs that are maintained even when cells differentiate into their
360 specific identities, suggesting the transcriptional signature of phloem cells is influenced by
361 multiple positional cues.
362 This set of genes could be important to understand how PSE relates to its neighbouring cell
363 types before and after enucleation. Indeed, as observed in the UMAPs, the ring pattern is
364 frequent right after PSE enucleation, suggesting a shift in the phloem pole governance after
365 PSE enucleation.

366 *PINEAPPLE* ring genes are expressed in early phloem

367 Among the genes in module 1, sub-module 1, that also extend their expression into the less
368 mature clusters, we found a DOF transcription factor, *DOF1.5* (*COGWHEEL1,* COG1). This
369 gene and the sister gene *DOF2.3* (*CYCLING DOF 4*, *CDF4*), are expressed in early phloem
370 cells (Fig 7a). *CDF4* encodes a differentiation factor in columella cells, repressed by WOX5[51].
371 The role of *COG1* in roots is unknown but this transcription factor is a negative regulator of
372 phytochrome signaling[52] and promotes brassinosteroid biosynthesis by upregulating *PIF4* and
373 *PIF5*, leading to hypocotyl elongation[53]. Both genes have been involved in regulating tolerance
374 to seed deterioration[54,55] as well as flowering time[56].
375 Transcriptional fusions of both genes confirmed the expression of both TF in PPP, CC and
376 MSE from 40 µm from the QC, remarkably earlier than the other ring genes described above.
377 While both genes form a ring around PSE reminiscent of a pineapple slice (the expression is
378 weaker or absent in PSE, Fig S7i), *DOF1.5* (from now on *PINEAPPLE1*, *PAPL1*) is also
379 expressed in the epidermis (Fig 7b) and *DOF2.3* (*PAPL2*) is found in columella cells with a
380 broader domain towards the QC (Fig S7f, 17f'). The ring pattern observed with the GFP fusion
381 construct extends one layer towards procambium when fused to 3xYFP expression (Fig S7a),

indicating a weaker expression in this layer. Translational fusions show these transcription factors are nuclear localised and not mobile (Fig 7d, Fig S7a-c, S7e), since transcriptional and translational patterns are coincident. This indicates that PAPL transcription factors act cell-autonomously. Together with the translational domain of *MAKR5*, the expression domain of *PAPL* genes indicate complex expression patterns in the phloem are relevant from an early stage.

PAPL genes, as other genes in module 1, were predicted to be downstream of *PEAR* in microarray data[2]. PEAR transcription factors move to PSE-adjacent cells to control periclinal cell divisions and other transcriptional programs non-cell autonomously. This is evidenced by markers like *SAPL* and *At3g16330* becoming ectopically expressed after broad *PEAR* overexpression or *SAPL* being expressed in PSE upon PSE plasmodesmata closure[2].

To validate *PAPL* genes are downstream of *PEAR*, *PAPL* reporter lines were expressed in *pear1pear2* double mutant, which resulted in a delay in *PAPL* expression, from 40 to 120 µm from the QC (Fig 7c, S7g). Since *PEAR* genes are highly redundant, we also introduced *PAPL1* constructs in the pear sextuple mutant, *pear sext*[42], where we observed a loss in its usual meristematic expression (Fig S7d). In parallel, closing PSE plasmodesmata connections to the neighbouring cell types using *icals3m* tool, the ring expression of *PAPL1* is altered (Fig 7e) and overexpressing *PEAR1* leads to ectopic expression of *PAPL2* (Fig 7f). These results validate that *PAPL* genes are downstream of *PEAR* and indicate that PEARs are needed and sufficient to express *PAPL* genes in the early phloem.

In addition to the *PAPL* genes, we validated that some of the genes in module 1 act downstream of PEAR TF. Indeed, PEARs are sufficient to induce *SBT4.12*, *At3g11930*, *MES7* and *PER30*, since these genes become ectopically expressed upon induction of *PEAR2* expressed under a ubiquitous promoter (*pRPS5A*) (Fig S7j). In *pear sext.*, the expression pattern of *PER30* and *MES7* was modified, while *SBT4.12* expression was decreased and *At3g11930* spread towards the meristem (Fig S7j).

PAPL proteins link *PEAR* genes to root physiology

Next, we decided to check if *PAPL* genes were downstream of *PEAR* genes to control periclinal cell divisions. Since *PAPL* expression is delayed in *pear1pear2* double mutant and absent from early phloem, we chose this mutant as a background to express *PAPL1* under the *WOODEN LEG* (*WOL*) promoter. When inducing *PAPL1* expression (20h treatment or germinated directly in beta estradiol and grown for 5 days), we did not observe a phenotype similar to *PEAR1* overexpression with increased periclinal cell divisions in the root[2] (Fig S8a-h). A similar result was observed when *PAPL1* was overexpressed in the stele in wild type background (Fig S8i-p). These observations indicate *PAPL* genes do not control periclinal cell divisions downstream of *PEARs*.

To gain insight into the function of *PAPL* genes, and after checking *papl* single mutants didn't show any obvious root phenotype, we generated double mutants (*papl1-1 papl2* and *papl1-2 papl2*). Bulk RNA sequencing identified *CYCLING DOF 2*, *CDF2*, as upregulated in *papl1-1papl2* (Table S4). This gene encodes another DOF transcription factor expressed in the cortex, pericycle and procambium, partially overlapping with *PAPL* expression (Fig S7h). Presuming this gene was upregulated to compensate for the lack of *PAPL* genes, we generated a triple mutant using a *cdf2* T-DNA allele[56] (*papl1-1papl2cdf2-1, 3papl*).

The triple mutant root was shorter than wild type in several conditions (Fig S9a) but the effect was more pronounced growing the seedlings in media without sucrose (Fig 7g, Fig S9a,b). A triple mutant with a new allele for *CDF2* generated using CRISPR/Cas9 technology showed similar results (*3papl-2*, Fig S9h). While wild type plants grown in media without sucrose often showed a bimodal distribution in terms of root growth (Fig S9a,b), the proportion of roots arresting growth in 3*papl* was higher (Fig 7g, Fig S9f). Even if there is high variation between seed batches, the average root length of the mutant is lower than that of the wild-type (Fig S9h). Contrary to other phloem development mutants apl and pear sext., adding 1% sucrose to the media mostly suppressed the mutant phenotype of 3papl (Fig 7h, Fig S9e). In this

scheme, compared to other mutants, root length in *pear1pear2* mutant was not so affected by the absence of sucrose in the media. When grown with sucrose, it was rescued to wt levels. Since the mutants could be rescued by transferring them to sucrose, we aimed to identify the time point at which sucrose is needed for 3*papl*. For this experiment, we transferred plants from sucrose supplemented to sucrose-depleted media and *vice versa*. The more time the mutant seedlings spent without sucrose, the more difficult it was for them to recover root growth (Fig 7h, Fig S9c). Those recovering managed to grow well (Fig S9f). Spending at least 3 days in sucrose was necessary for the mutant seedlings to grow normally while spending only two days in sucrose was not enough for root growth recovery (Fig 7h, Fig S9c). This phenomenon was not observed in wild type roots grown and transferred in parallel (Fig S9g). In the confocal, the root meristem of seedlings that got arrested, looked shorter and stunted (Fig S9d). *PAPL* genes were expressed at this stage in both sucrose and non-sucrose conditions showing similar patterns as observed in more mature seedlings (Fig S10a). Other phloem marker genes, like *MAKR5*, *APL* and *ring gene SBT4.12* were expressed similar to wild type in *3papl* mutant background, suggesting there are no defects in phloem development in *3papl* (Fig S10b-d). On the contrary, *MAKR5* expression is delayed in *pear1pear2* mutant background (Fig S10b) and *APL* expression is highly reduced in *pear sext*[33], suggesting *PAPL* genes do not fulfil the same roles as *PEAR* genes. These markers and *SUC2* are expressed similarly when the plants are grown in media containing or depleted of sucrose (Fig S10e-h). To better understand the *3papl* phenotype, we carried out metabolic profiling of leaves and roots of seedlings grown in a sucrose-depleted media across six developmental stages (2-7 days post-sowing, dps) (Table S5). We identified 7 and 5 metabolites in leaves and roots, respectively, with significant differences between WT and mutant in at least one of the time points (<5% false-discovery rate from a linear mixed model fit to the whole data, see methods; Fig 8a). One of those metabolites was sucrose, with a significant difference only in the roots, where it started at lower levels in the mutant (days 2 and 3) and then continued to increase to reach levels comparable to the WT at the end of the experiment at day 7 (Fig 8b). A similar pattern, with more significant points, was observed in fructose, which is a component of

462 sucrose, and to a lesser extent in glucose, the other monosaccharide forming sucrose (Fig
463 8b). It has been described that by the time the radicle emerges, all the sugars stored in the
464 Arabidopsis seed have been consumed. Within 48 hours after germination (approximately at
465 day 3 after sowing), lipid and protein reserves are exhausted and seedlings need to switch to
466 autotrophic growth [57,58]. The data suggest *PAPL* genes could be important after the seedling
467 has transitioned to autotrophic growth, facilitating sugar transport to sink tissues like roots.
468 The continued increase in sucrose in the mutants could be due to the, on average, smaller
469 size of *3papl* seedlings and stunted growth, which could therefore lead to reduced sucrose
470 consumption and therefore its observed continued accumulation.

471 DISCUSSION

472 Our manuscript demonstrates the power of tissue-specific transcriptomes combining FACS
473 and single cell sequencing to study elusive cell populations underrepresented in organ general
474 cell atlases. The use of droplet-based technologies also allowed us to gather more cells and
475 a higher resolution than plate-associated methods.
476 The phloem pole cell atlas is allowing a holistic understanding of phloem. While there are
477 specific genes for PPP and CC, these cell types share the first stages of their developmental
478 trajectory. Trajectory analysis also revealed the connection between CC and early MSE,
479 providing new insights on early stages of MSE development. The commonalities among the
480 different cell types were validated by gene regulatory network analysis and reporter lines
481 confirmed the relevance of the ring expression pattern in all the cells around PSE.
482 PSE differentiation involves enucleation and becoming dependent on adjacent cells for
483 survival. Using *APL* expression as a standard, we mapped the enucleation point in the atlas.
484 While PSE organizes the phloem pole in the meristem neighboured by unspecialized cells,
485 PSE enucleation marks the onset of cell differentiation for adjacent cells and switches on
486 similar gene regulatory networks in PSE-surrounding lineages, as evidenced by the ring
487 pattern shown by many genes right after PSE enucleation.

The coordinated expression in the cells of the phloem pole highlights the importance of positional information and cell to cell communication to preserve phloem function when PSE delegates control in the adjacent cells. They also underpin the relevance of PPP cells, which we believe should be considered a built-in part of phloem.

A phloem plasticity zone was recently described in the root meristem, when CC and MSE cells could act as a reservoir for PSE identity[18]. This further supports the coordination between the pole identities to ensure correct phloem morphogenesis. It would be interesting to investigate if PPP can also transdifferentiate to PSE if required.

In turn, the similarities between root pericycle cells and phloem parenchyma cells in leaves suggests parenchymatic cells share characteristics despite being present in different organs with variable anatomic configurations and reinforces PSE as the phloem pole organiser.

The modular analysis of the atlas identified the DOF *PAPL* genes, characterised by early expression in the ring domain and the inability to introduce new periclinal cell divisions when overexpressed in procambium.

Contrary to other phloem mutants, like *apl*, the presence of sucrose in the media almost completely suppresses the root growth phenotype of *3papl*. Regarding PEARs, the root length in the *pear1pear2* mutant was not so affected by the absence of sucrose in the media and it was rescued to wt levels when grown with sucrose. The fact that the subtle root length phenotype is rescued by sucrose leaves the possibility open that different doses of the phloem-related DOF genes are responsible for the phenotype as opposed to the type of *DOF* genes. However, we don't favour this scenario because of the functional differences of the DOF genes based on the overexpression phenotypes.

Since phloem is in charge of nutrient transport and a smaller amount of sucrose and its component fructose is detected in both mutant leaves and roots at 3 dps when root anatomy is comparable between wt and mutant, we interpret *PAPL* genes regulate nutrient allocation between the leaf source organs and the root sink in young seedlings, when embryo reserves are scarce. *PAPL* genes could either regulate phloem loading, long distance transport or phloem function and more studies are required to determine their precise role.

MATERIALS AND METHODS

Plant growth conditions

All *Arabidopsis thaliana* lines used in this study were in Col-0 background except *pear1* mutant allele, which is in Ler background, conferring *pear1pear2* mutant a mixed Ler appearance. Plants were grown in ½ MS Basal salts media (0.5 MS Salts, 1% Difco agar, with or without 1% sucrose) at 23ºC and long day conditions, except for sorting experiments, when they were grown using 1x MS Basal salts at 23ºC with 30% humidity and 188 µM of light, long day conditions, to be able to compare with other transcriptomic data.

papl1-1 (*cog1-6*, from gene *At1g29160, PAPL1, DOF1.5, COG1)* has a single nucleotide deletion (G) at position +85, which generates a premature stop codon. This mutant was identified as a *cog1-D* suppressor[53]. *papl2* (*At2g34140, PAPL2, DOF2.3, CDF4)* has a 4 bp deletion (CAAG) at position +99 creating a premature stop codon. The *cdf2* T-DNA allele (GK782H09) is a knockdown allele[56]. Triple mutant was obtained by crossing the double mutant *papl1-1papl2* to *cdf1r235*[56], selecting for mutant *3papl* and homozygous wild type alleles for all other genes. The second triple mutant (*3papl-2*) was obtained by generating a new *cdf2* allele by using CRISPR/Cas9 technology directly on the double mutant *papl1-1papl2*. The process rendered a 5 bp deletion (CCCGG) at position +953 (*cdf2-2*), which generated a premature stop codon shortly afterwards.

5 µM Beta estradiol or 10 µM DEX were used in the inducible constructs for the indicated times. Plants induced with DEX were treated for 24 hours.

Sorting and single cell sequencing

Seedlings from the different marker lines were grown vertically over mesh (Normesh, 100 µm) for five days in the conditions specified above. Approximately one third of the root including

the root tip was chopped with razor blades and the tissue transferred to a 70 µm strainer submerged in 7 ml of the protoplasting solution for an hour with gentle shaking at room temperature[59]. In the case of the sample “MAKR5 enriched in root tips”, we submerged the root tips of intact roots in eppendorfs containing the protoplasting solution for 15 minutes, which is enough time for the meristems to be enzymatically cut from the rest of the root. Then the separated root tips were transferred to 70 µm strainers, incubated with 7ml of protoplasting solution in 4 cm radius petri dishes at room temperature for 45 minutes and from then onwards were treated as the other samples. Washed protoplasts suspended in solution A were taken at room temperature to the sorting facilities and the process from chopping to sorting took approximately 2-2.5h. For the gating, a wild type Col0 sample was run first to establish the fluorescent negative gate. Then this sample was subsequently stained with DAPI and DRAQ5 to gate for intact cells that contained DNA, respectively. The corresponding sample containing fluorescent protoplasts was then stained subsequently with DAPI and DRAQ5 and underwent FACS. Gating helped enrich intact (DAPI negative), YFP/GFP positive, DNA containing cells (DRAQ5 positive) that were sorted with a 130 µm nozzle using a High speed Influx Cell Sorter (BD Biosciences). Sorted protoplasts were harvested in W5 solution (154 mM NaCl, 125 mM CaCl 2, 5 mM KCl, 5 mM MES (2-(N morpholino)ethanesulfonic acid) in BSA coated 1.5 ml Eppendorf tubes. Cells were centrifuged for 12 minutes at 200g to eliminate the excess of supernatant. Immediately, Single-cell RNA-seq libraries were prepared in the Cancer Research UK Cambridge Institute Genomics Core Facility using the following: Chromium Single Cell 3′ Library & Gel Bead Kit v3, Chromium Chip B Kit and Chromium Single Cell 3' Reagent Kits v3 User Guide (Manual Part CG000183 Rev C; 10X Genomics). Cell suspensions were loaded on the Chromium instrument with the expectation of collecting gel-beads emulsions containing single cells. RNA from the barcoded cells for each sample was subsequently reverse-transcribed in a C1000 Touch Thermal cycler (Bio-Rad) and all subsequent steps to generate single-cell libraries were performed according to the manufacturer’s protocol with no modifications. cDNA quality and quantity was measured with

Agilent TapeStation 4200 (High Sensitivity 5000 ScreenTape) after which 25% of material was used for gene expression library preparation.

Library quality was confirmed with Agilent TapeStation 4200 (High Sensitivity D1000 ScreenTape to evaluate library sizes) and Qubit 4.0 Fluorometer (ThermoFisher Qubit™ dsDNA HS Assay Kit to evaluate dsDNA quantity). Each sample was normalized and pooled in equal molar concentration. To confirm concentration pool was qPCRed using KAPA Library Quantification Kit on QuantStudio 6 Flex before sequencing. All samples were sequenced using Illumina NovaSeq6000 sequencer with following parameters: 28 bp, read 1; 8 bp, i7 index; and 91 bp, read 2.

Analysis of single-cell RNA-seq

Here we give a briefer description and overview of our analysis steps, but the full details of our analysis pipeline (e.g. specific package functions and options used) can be seen in our code repository at https://github.com/tavareshugo/publication_Otero2021_PhloemPoleAtlas.

To obtain unique molecular identifier (UMI) counts for each gene, the raw sequencing reads were aligned to the reference Arabidopsis TAIR10 genome using the Araport11 gene annotation (both downloaded from Ensembl release 45) using 10x Genomics Cell Ranger v3.1.0[60]. The data were processed and quality-filtered using several Bioconductor packages[61]. Empty droplets were inferred and removed using dropletutils v1.8.0[62], and data normalisation was done using both the pooling method implemented in scran v1.16.0[63] and the variance-stabilising transformation from sctransform v0.2[34]. To adjust for potential batch effects, data from the different samples (i.e. sorted with different GFP fusion markers and/or from different public datasets) were integrated using the Mutual Nearest Neighbours (MNN) algorithm implemented in batchelor v1.4.0[35]. After initial data exploration and quality checks, we retained cells with at least 2000 detected genes and genes detected in at least 100 cells (a gene was considered to be detected if it had at least 1 UMI count). Downstream analysis was done on these filtered data, batch-normalised using MNN and using variance-stabilised transformed

593 values. However, our conclusions were qualitatively robust to the specific choice of
594 normalisation methods. For data visualisation purposes, we have projected the data to two
595 dimensions using uniform manifold approximation and projection (UMAP), using a
596 neighbourhood size of 30 cells (sizes of 7, 15 and 100 were also explored and give comparable
597 results). We have also visualised the UMAP in three dimensions, which did not provide further
598 insights into the data compared to the two-dimensional projection.
599 Cell clustering was performed by first defining a "shared nearest neighbours" graph and then
600 identifying modules in the graph using the Louvain algorithm (using scran v1.16.0[63] and igraph
601 v1.2.6[64]. To annotate our cells we used a set of genes with known expression patterns (from
602 promoter fusion microscopy experiments) and calculated, for each cluster, the percentage of
603 cells where each marker gene was detected as well as the (z-score scaled) average
604 expression of the gene in that cluster.
605 To identify cluster-specific genes, we used pairwise Wilcoxon rank sum tests between a given
606 target cluster and all others using the *findMarkers()* function in the *R/Bioconductor* package
607 scran v1.16.0[62]. We specifically tested for genes upregulated in the target cluster, to identify
608 highly-expressed genes specific to each cluster (rather than also including genes that are
609 specifically absent from the cluster). The results of the pairwise tests for a given target cluster
610 were then consolidated to obtain a summary p-value (and corrected false-discovery rate) for
611 how enriched each gene is in a given cluster. We summarised the pairwise p-values for a null
612 hypothesis that the gene is not differentially expressed in at least 8 out of the 15 clusters,
613 allowing us to flexibly identify genes that were highly expressed in across multiple cell types
614 (e.g. mature ring cells such as PPP and CC) but not others. We also did a more stringent
615 summary of p-values (null of no differential expression in 12/15 clusters) to obtain genes more
616 specific to particular clusters of interest (namely cluster 10, which was a candidate for early
617 MSE cells).
618 The same pipeline was applied to the public datasets, also integrated using MNN. The quality
619 of this data integration was confirmed by checking that the majority of our annotated cells were
620 clustering together with the same cell types in other datasets. We produced two sets of data

integration, one with root data and another with leaf data. Details of the public datasets used are given in (Table S6).

To explore how well cells from leaf and root datasets mixed in clusters where they co-occurred (namely cluster 6, which contained both leaf phloem parenchyma and root phloem pole pericycle cells) we used the same shared-nearest-neighbours cell graph used for clustering and calculated the proportion of edges between root-leaf cells (the vertices of the graph). This value was then compared with a null expectation, obtained by randomly shuffling the cell tissue labels 1000 times and calculating this proportion each time. The 95% inter-percentile range of this null distribution was then used to compare with the observed value. The graph had 19.2% leaf-root edges in this cluster, which is only slightly lower than expected by chance (median 23.5%, 95% CI 22.8%-24.2%, obtained from 1000 random shuffles of the cell labels). This result suggests that the cells from the two datasets are well mixed. This is in contrast with cluster 17, for example, which consists of poorly clustered cells that occur separated in the UMAP. In this case, there were 26.7% leaf-root edges, almost half of the null expectation for that cluster, which was 44.9%.

To further temporally annotate our phloem pole atlas dataset we used several approaches. Early dividing cells were identified by checking the expression of all annotated cyclins and other cell cycle markers such as *AUR1* (*AT4G32830*) and *KNOLLE* (*AT1G08560*). We also cross-referenced our data with a published dataset that profiled the transcriptome of longitudinal root sections using microarray technology[1]. Based on 9,674 common genes between the two datasets, we assigned each of our cells to the longitudinal section of Brady et al. that had the highest Spearman correlation with it. We also used the RNA velocity method implemented in scVelo v0.2.2 to infer developmental dynamics in our data[44]. Finally, cells were assigned to lineages and ordered by pseudotime using slingshot v1.6.0[43]. We first reduced the dimensionality of the (batch-normalised) counts to 10 components using diffusion maps, which is a dimensionality reduction method suited to capture developmental transitions in the data[65,66]. In this latter case we used a semi-supervised approach, where the starting point for the inferred trajectories was set to the cluster highly expressing cell-cycle markers and

identified as the earliest cluster when cross-referencing with the Brady et al. dataset. In this manner we obtained biologically meaningful trajectories (without setting this constraint several more trajectories were obtained but with an ordering of cells which was the reverse of what was expected from our other analyses). We obtained smooth gene expression patterns for each trajectory using generalised additive models, as implemented in tradeSeq v1.2.0, which were then used to explore gene expression patterns along the slingshot trajectories.

To cluster genes based on their similarity of expression across the cells, we built a co-expression network using a modified version of bigSCale[48], adapted to work on any species (rather than the original version suited only for mouse and human). The modified package is available from https://github.com/tavareshugo/bigSCale2/tree/support-any-species.

Summarily, bigScale builds a gene correlation matrix not from the original count data (which in scRNA-seq is too noisy and sparse), but from a z-score statistic calculated between pairs of cell clusters. These clusters are iteratively generated to ensure the z-scores capture as much diversity in gene expression patterns across the cells as possible. In this way, correlations between genes are more robust to the noisy and sparse nature of single-cell RNA-seq data. This correlation matrix was then thresholded at 0.9 to obtain a gene-by-gene adjacency matrix, resulting in a network with 5,238 vertices (genes) and 370,794 edges. We identified gene modules using the Louvain algorithm, resulting in 16 modules. From each module, we calculated an eigengene following the procedure in WGCNA vX[50], which essentially summarises the expression of all genes of a module as the first principal component score from a principal components analysis (PCA) done on those genes. The largest of these modules - module 1 containing 1,367 genes - contained several genes of interest for our analysis, and was therefore re-clustered with Louvain to generate 15 sub-modules. This was further justified by the fact that the variance explained by this module's eigengene was relatively low (21.44%), suggesting some heterogeneity in expression patterns within the module. To further interpret these results, the eigengenes from these sub-modules were joined with the pseudotime trajectories from slingshot, although we note

that no information about trajectories was used to build the network itself. Therefore, the fact that the different approaches (gene network and pseudotime analysis) reveal groups of genes with similar patterns of expression is a strengthening point in our analysis.

Generation of reporter lines and confocal images

Promoter::VENUSer fusions were generated for the genes *At3g27030*, *At2g23560* (*MES7), At2g32210, At5g64240 (MC3), At5g58690* (*PLC5*), *At2g38640*, *At3g11930*, *At2g02230* (*PP2-B1)*, *At5g47920*, *At4g27435*, *At5g59090* (*SBT4.12), At3g21770* (*PER30*), *At1g26450, At1g29160 (PAPL1, DOF1.5, COG1), At2g34140 (PAPL2, DOF2.3, CDF4), At5g39660 (DOF5.2, CDF2).*

Translational fusions were also generated for *At2g20562* (*TAX2), PAPL1* and *PAPL2*. 3xYFP constructs were also generated for transcriptional fusions of *PAPL1* and translational fusions of *PAPL1* and *MAKR5*.

Promoter fragments between 622-4879 bp were amplified by PCR and cloned using MultiSite-Gateway (Table S7). Transcriptional fusions to *VENUS* with an ER tag or translational fusions to YFP were generated in vectors with either resistance to Basta or Hygromycin or a Fast Green/Fast Red selection system. All the constructs were transformed in Col0 background and at least 2 independent lines were analysed for each.

Roots from 5-7-day-old seedlings were either imaged in the confocal directly after mounting them in 50 µg/ml propidium iodide or fixed for 45 minutes in 4% paraformaldehyde in PBS and cleared using ClearSee solution (10% (w/v) Xylitol, 15% (w/v) sodium deoxycolate, 25% (w/v) urea, water to the final volume)[67]. Cleared roots were then stained with SCRI Renaissance 2200 and observed under the confocal. Images were acquired at 512x512 resolution using the confocal Leica SP8. Images were analysed in ImageJ v2.1.0/1.53c.

Bulk RNA-seq transcriptomics

Wild type and *papl1-1papl2* seedlings were grown on mesh in ½ MS media with sucrose in the above-mentioned conditions for 5 days. Root meristems from wild type and mutant were manually and individually dissected in parallel under a stereomicroscope using 18G needles. Meristems were preserved in RNAlater RNA stabilisation reagent (Qiagen) until 120 meristems per replicate were gathered. 3 replicates for each mutant and wild type were used for RNA extraction.

RNA was extracted using the RNeasy Plant Mini kit from Qiagen and RNA integrity and concentration were checked using TapeStation and Qubit 2.0 fluorometer (Life Technologies) respectively. After quality control in Novogene company, the best 3 replicates for mutant and wild type were used for library construction and sequencing following the Novogene pipeline. Briefly, mRNA was enriched by using oligo dT beads and fragmented randomly. cDNA synthesis was performed using random hexamers and reverse transcriptase. After first-strand synthesis, the second strand is synthesized by nick-translation. Library is ready after a round of purification, terminal repair, A-tailing, ligation of sequencing adapters, size selection and PCR enrichment. Library concentration was quantified using a Qubit 2.0 fluorometer (Life Technologies), Insert size was checked on Agilent 2100 and quantified more accurately by quantitative PCR. Libraries were fed into the HiSeq XTEN platform for sequencing. Original raw data were transformed to Sequence Reads by base calling and raw data recorded in FastQ files. Low quality reads or reads containing adaptors were filtered out. TopHat2[68] v2.0.12 was used to map the reads to the reference genome (TAIR10). HTSeq[69] v0.6.1 software was used to analyze the gene expression level using the union mode. Fragments Per Kilobase of transcript sequence per Millions base pair sequenced (FPKM) value of 0.1 or 1 was set as the threshold to determine whether a gene is expressed or not. To compare gene expression levels under different conditions, FPKM distribution diagram and violin plot were used. For biological replicates, the final FPKM would be the mean value. The differential gene expression analysis consisted of read-count normalization, model-dependent mean

727 value estimation and FDR value estimation based on multiple hypotheses testing. DESeq[70]
728 v1.10.1 software was used for these steps. The results of this analysis are given in Table S4.

729 Root length measurements and statistical analysis

730 To quantify root growth, an EPSON Perfection V700 Photo scanner was used to obtain images
731 of the seedlings in plates. A ruler was also scanned to calibrate the images. Roots were
732 measured manually one by one using ImageJ v2.1.0/1.53c.
733 Because of the nature of the data, which often had a bimodal distribution, we opted for using
734 a non-parametric bootstrap approach for our statistical analysis. This was done by resampling
735 the data 500 times and estimating the difference between groups of interest (either WT vs
736 mutants or between sucrose treatments, as detailed in the respective figure legends). We thus
737 obtained distributions of root length differences, which we used to obtain confidence intervals
738 (based on a 95% inter-percentile range) and a bootstrap p-value calculated as the number of
739 samples with absolute difference less than a “null” distribution centred on zero. Our p-values
740 therefore have a lower bound of 1/501 ~ 0.002, which we deemed to be of sufficient statistical
741 resolution for our analyses (we added an offset of 1 to both the numerator and denominator
742 to avoid p-value = 0, which would mis-represent the precision of our analysis). Whenever
743 relevant, the bootstrap analysis took into account experimental and seed stock batches by
744 summarising the results at those levels first, before then comparing the groups of interest; this
745 ensured that the uncertainty in our estimates captures those different levels of potential
746 variation. The results of these analyses are provided in Table S8.

747 Experimental Design

748 Experiments were repeated independently for the following number of times. In Fig 1d, *MES7*
749 reporter was imaged 3 times and reporters for *MC3*, *At3g27030* and *At2g32210* (also in Fig
750 2b) were imaged twice.

For Fig 6b, reporters for *At3g11930*, *At5g47920* and *At1g26450* were imaged twice, *PP2-B1*, *SBT4.12* and *TAX2* reporters were imaged 3 times. For figure 7, *pPAPL1::GFP* was imaged 6 times, *pPAPL1::GFP* in *pear1pear2* was imaged 3 times, *pPAPL1::PAPL1-YFP* (also in Fig S7b) was imaged twice, *pPAPL1:GFP* in *pPEAR1::icasl3m* was imaged twice and *pPAPL2:YFPer* in *pRPS5A::PEAR1-GR* was imaged once.

For Fig S1a, *pMAKR5::MAKR5-3xYFP* was imaged 7 times, *pS17:GFPer* was imaged twice, *pAPL::3xYFP* was imaged 3 times and *pSAPL::YFPer* (also in Fig 2b) was imaged four times. For Fig S1b, the reporter for *PLC5* and *At2g38640* were imaged 3 times.

For Fig S2d, *pAPL::YFPer* was imaged once. For Fig S5, reporters for *At3g16330* and *PER30* were imaged 3 times, while the reporter for *At4g27435* was imaged 4 times.

For figure S7, *pPAPL::3xYFP* was imaged 6 times, *pPAPL::PAPL1-3xYFP* was imaged 3 times and this construct in *pear sext*. background was imaged 3 times. *pPAPL2:PAPL2-YFPer* was imaged 3 times, *pPAPL2::VENUSer* was imaged 3 times and this construct in *pear1pear2* mutant background was imaged twice. *pCDF2:VENUSer* was imaged 3 times. For constructs in Fig S7j, reporters in the overexpressor background, induced and control, were imaged once while reporters were imaged twice in *pear sext*. background. For Fig S8, each line was observed independently twice. For Fig S9d, roots were imaged for this figure once but these two backgrounds were imaged many times with reporter lines in them.

For Fig S10a, reporters with and without sucrose were imaged twice. For Fig 10b, *pMAKR5::MAKR5-3xYFP* in *3papl* mutant was imaged 3 times and it was also imaged 3 times in *pear1pear2* mutant background. Reporter in Fig S10c was imaged 3 times while the reporter in Fig S10d was imaged once. Reporters in Fig S10e-g were imaged twice and reporters for Fig S10h were imaged once (Col0) or three times (mutant background).

For the experiment shown in Fig 7g and S9e, the total number of seedlings measured for each genotype was: 488 *3papl*; 273 PAPL1-32; 37 PAPL1-51; 33 PAPL1-71; 343 PAPL2-11; 79 PAPL2-23; 37 PAPL2-31; 314 PAPL2-73; 382 wt. Seedlings were split across 5 experimental batches and came from different seed stocks (N = 24 - 46 with a median of 36 seedlings per

778 experimental batch and seed stock combination). Both seed stock and experimental batch
779 were taken into account in the statistical analysis.
780

781 Metabolic profiling

782 Arabidopsis plants were grown across six developmental stages (from day to day 7) on mesh
783 in solid media containing sucrose or devoid of sucrose. Each day of the time course, leaves
784 and roots were harvested separately and snapped frozen in liquid nitrogen. 50 mg of leaves
785 and 20 mg of roots were ground using a Tissue Lyser. Extraction was performed according to
786 Lisec et al. (2006)[71], with modifications. In detail, 750 µl/300 µl of extraction buffer (100%
787 methanol plus the internal standard adonitol, Sigma) were added to root and leaf samples
788 respectively. Samples were vortexed and transferred to a shaker at 70 ℃ for 15 minutes. 375
789 µl/200 µl of chloroform and 750 µl/350 µl of water were added to the tubes for leaves and roots
790 respectively, and samples were centrifuged for 10 minutes at maximum speed. 400 µl (roots)
791 and 200 µl (leaves) of supernatant were dried for each sample using the speedvac. Samples
792 were kept at -80℃ until processing.
793 The dried samples were derivatized for 2 hours at 37 °C in 50 µl of 20 mg ml− 1 methoxyamine
794 hydrochloride (Sigma-Aldrich, cat. no. 593-56-6) in pyridine followed by a 30 min treatment at
795 37 °C with 100 µl of N-methyl-N-(trimethylsilyl)trifluoroacetamide (MSTFA reagent; Macherey-
796 Nagel, cat. no. 24589-78-4). For each sample, 1 µl was injected in splitless mode to a
797 chromatograph coupled to a time-of-flight mass spectrometer system (Leco Pegasus HT TOF-
798 MS; Leco Corp., St Joseph, MI, USA), using an autosampler Gerstel Multi-Purpose system
799 (Gerstel GmbH & Co.KG, Mülheim an der Ruhr, Germany). Chromatograms and mass spectra

evaluation, as well primary metabolites identification based on the expected retention time and mass fragmentation were performed using the software Xcalibur software (Thermo Fisher Scientific). The software ChromaTof (Leco) was used to confirm the peaks and retention times for expected metabolite fragments.

To estimate differences between WT and *3papl* metabolite levels, we fit a joint hierarchical model to the peak areas of all metabolites, including terms for genotype, stage (dps), tissue and their interactions. The advantage of using this model is that we could include a random effect term to account for multiple measurements per sample (each sample contributed 21 data points, one for each metabolite). Due to the skewed distribution of peak areas, the data were modelled on a log-scale, which produced well-behaved normally distributed residuals. The model was fit with the *lme4*[72] v1.1-27.1 R package and we obtained estimates of the difference between the two genotypes for each metabolite and tissue using the *emmeans* v1.6.2-1 R package. The p-values from the *emmeans* contrasts were corrected for multiple testing using the false discovery rate method.

Additional information on metabolomics analysis and metabolites annotation are reported in table S9 (sheets checklist and overview) according to the guidelines provided in Alseekh et al[73].

Data availability

Sequencing data from 10x Chromium single-cell RNA-seq is available from NCBI's Gene Expression Omnibus through GEO accession number GSE181999[74]: https://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE181999.

Sequencing data from bulk RNA-seq is available from NCBI's GEO accession number GSE182672[75]:

https://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE182672.

All other data (phenotypic scoring, microscopy imaging, plasmid maps) are available from the Cambridge Apollo Repository (https://doi.org/10.17863/CAM.74836). A persistent DOI will be available upon acceptance[76].

Code availability

Analysis code, with instructions on how to run it, is available from: https://github.com/tavareshugo/publication_Otero2022_PhloemPoleAtlas.

Acknowledgements

We thank Wolf Frommer and Ji-Yun Kim for providing *pSWEET11:SWEET11-2A-GFP* seeds, Christian Hardtke for providing *pMAKR5:MAKR5-GFP* seeds and plasmids, Chiara Cossetti, Reiner Schulte and all the staff from Flow Cytometry Core Facility at CIMR for their technical support with cell sorting, Katarzyna Kania from Genomics Unit at CRUK for preparing Single-cell RNA-seq libraries, Bruno Guillotin and Kenneth Birnbaum for helpful insights on single cell analysis, Raymond Wightman and Gareth Evans for technical support with microscopy experiments, Gill Hindle, Jemma Salmon and Sally Ward for media preparation, Karolina Blajecka for technical assistance, Kristina Petkovic and Rut Alcaina for technical support. Sebastian Schornack for helpful comments.

S.O. was supported by a Herchel Smith postdoctoral fellowship from the University of Cambridge (2017-2020). L.K. received funding from the SNSF (P2LAP3_178062) and a Marie Curie IEF (No. 795250). This work was supported by Finnish CoE in Molecular Biology of Primary Producers (Academy of Finland CoE program 2014-2019) decision #271832, the Gatsby Foundation (GAT3395/PR3)), University of Helsinki (award 799992091) and the ERC Advanced Investigator Grant SYMDEV (No. 323052). T.L was supported by the German Research foundation (DFG) under Germany's Excellence Strategy (CIBSS-EXC-2189-Project

ID 390939984) and by grant La606/18-1. A.R.F and V.D. acknowledge support from the Max-Planck Society.

Author Contributions

S.O. performed the experiments, I.S. identified *PAPL1* and *At3g16330* expression patterns which appeared as *PEAR* targets in microarray data, P.R. provided *pear1pear2* double mutant, *pPEAR(del)::3xYFP* and advised on experimental design, Y.L. and H.T. analysed gene regulatory networks, P.R., M.B., L.K.,B.B. and J-o.H. participated in sample collection for sorting and metabolomic profiling, M.B. imaged *pSUC2:GFP*, J-o.H. provided *pSAPL::YFPer* line, V.D. and A.R.F. carried out the metabolic profiling and data analysis, F.P. and T. L. provided the *papl2* and *papl1-2* alleles, H.T. designed and performed the single cell data and statistical analysis, S.O., H.T. and Y.H. conceptualised and designed the study. S.O. wrote the manuscript with input from Y.H., H.T., P.R. and L.K. All authors read, edited and discussed the manuscript.

Competing Interests statement

The authors declare no competing interests.

Figure legends

Figure 1. A root phloem pole cell atlas containing PSE, MSE, CC and PPP cells.
a) Root schematic highlighting the cells in the phloem pole coloured by identity (adapted from[42]) with a close-up of the phloem pole (a'). One of the radial cuts shows the middle part of the phloem pole and the other shows the side view of the phloem pole b) UMAP plot showing the classification of 10,204 cells clustered by cell identity and developmental stage (colours indicate clusters, labelled with a number). The sample of cells has a median of 4,564 detected genes (10%-90% percentiles: 2,600-6,780) and a median of 17,445 total UMIs per cell (10%-90% percentiles: 5941-52689). c) Cluster annotation based on markers with known tissue- or cell-specific expression. The size of the points represents the percentage of cells in a cluster where the gene was detected (i.e. at least 1 UMI). The colour shows the scaled average expression of the gene (z-score, i.e. number of standard deviations above/below the gene's mean across all cells). d) Newly identified genes significantly enriched in PPP

(*At2g23560*, *At3g27030*) and CC (*At2g32210*, *At5g64240*). UMAPs show the particular cluster-weighted normalised expression of each gene in the phloem pole cell atlas. UMAP and microscopy pictures are representative images of the transcriptional reporter lines, where the gene promoter is fused to *VENUSer*. Scale bar in the longitudinal sections is 25 µm while it is 10 µm in the cross sections. White arrowheads point to PSE cells as a reference point. The numbers in each panel indicate samples with similar results, of the total independent biological samples observed.

Fig 2. MSE cells identification and identity of cluster 11.
a) Cells were plotted in the UMAP separated by sorting experiment, as indicated in each panel, to show which sorting experiment provided every cell. Colour indicates point density (lighter colour indicates higher density of points), with grey areas meaning an absence of cells. Numbers in each panel indicate the number of filtered cells contributed by that sorting experiment. We sorted *MAKR5* twice, one enriching in root tips (*MAKR5*) and another sorting the usual one third of the root (*MAKR5* differentiated). b) UMAPs showing the cluster-weighted normalised expression of marker genes used to identify MSE identity. *PEAR1*, *S32* and *DEAL2* are expressed in sieve elements. *APL* is genuinely expressed in PSE, CC and MSE. *At5g47920*, *SBT4.12* and *PAPL1* are expressed in a ring expression pattern, including MSE and other cell types. *PIN4* is used as a negative control, since it is excluded from sieve elements early in development[3]. *SAPL* and *At2g32210* are expressed in CC and MSE. Black arrowheads point to clusters 1 and 10. In the confocal cross sections, the scale is 10 µm. White arrowheads point to PSE as a reference point and yellow arrowheads point to MSE. The numbers over each picture indicate samples with similar results, of the total independent biological samples observed c) UMAPs for xylem pole pericycle markers, which are found in cluster 11 together with other PPP markers, indicating this is a late pericycle cluster.

Fig 3. Developmental trajectories and mapping of the PSE enucleation point.
a) Developmental trajectories inferred using Slingshot coloured according to pseudotime, with more mature cells in yellow. The origin for all trajectories was set in the clusters containing cycling cells. b) APL expression is plotted along the PPP, CC and PSE trajectories, with the cells coloured by cluster number in the UMAP. The black line is a smoothed trend estimated from a non-parametric generalised additive model. b') APL is used as a standard to coordinate the three trajectories. Cluster 5 groups the cells with an increasing expression of APL in PPP and CC trajectory, mapping the enucleation point in the adjacent cells. The position of each cell type is indicated in the UMAP in relation to PSE enucleation b'') APL expression plotted in a UMAP of the phloem pole cell atlas

Fig 4. Phloem cell types in the integrated UMAP.
a) A new UMAP containing 113340 cells was generated by integrating cells from Denyer et al. 2019[30], Wendrich et al. 2020[32] and Shahan et al. 2020[45]. Colours are used to differentiate cell clusters. b) Different markers were plotted in the UMAP to identify the phloem pole cell types: *SAPL* (CC and MSE), *S17* (PPP), *PEAR1* (PSE, MSE), *SUC2* (mature CC), *CALS8* (PPP and CC), *KNOLLE* (cycling cells). c) Integrated UMAP showing cells coloured according to the annotation from Shahan et al. d) Integrated UMAP coloured by the original clusters from the Phloem Pole Atlas. Orange arrowheads point to the two parts of cluster 3, split in the integrated dataset e) Integrated UMAP with the cells contributed by each individual project plotted on top (number indicated below, percentage of the total in brackets), using a coloured scale to indicate cell density. Green arrowheads point to the clusters mostly contributed by our dataset. f) Cluster 3 of the integrated dataset containing root early cells and dividing cells. Cells in cluster 3 (early cells) are indicated in the first panel while the other panels in the row show the expression of G2/M genes in the integrated dataset, marking dividing cells g) Contribution of each single cell project to cluster 3. Observe the grouping of early phloem cells (black arrowhead) compared to the higher dispersion of early cells in other datasets.

Fig 5. Similarities in the gene expression between leaf phloem parenchyma and root pericycle.
a) Schematic of the leaf minor vein showing phloem anatomy. Notice the different composition in terms of cell identities, cell number and organization compared to the root. Adapted from[46] b) UMAP integrating the phloem pole cell atlas with the leaf single cell dataset. Cells were combined and reclustered, coloured by source (leaf in green, root in black). Notice the separation of the leaf specific clusters

(bundle sheath and mesophyll cells) and overlap in clusters 6 (PPP / phloem parenchyma) and 9 (CC). c) Percentage of cells contributed by each dataset in each cluster. Y axis shows the cluster number with the number of cells in it between brackets. Root cells are coloured in black, leaf cells are in green. d) Cluster annotation of the root-leaf UMAP based on markers with known tissue-specific expression. The size of the points represents the percentage of cells in a cluster where the gene was detected (i.e. at least 1 UMI). The colour shows the scaled average expression of the gene (z-score, i.e. number of standard deviations above/below the gene's mean across all cells) e) Violin plots showing the expression of PPP markers in leaf (green) and root (black) cells for phloem pole pericycle markers (e), phloem parenchyma markers (f) and XPP markers (g) The confocal picture in f shows the expression of *pSWEET11::SWEET11-2A-GFP* in PPP in roots. In f, the gene expression of the respective genes is shown in the phloem pole cell atlas. The numbers under the black/green violin plots indicate the number of cells in cluster 6 of the leaf/root UMAP expressing each gene, with the percentage between brackets. In the confocal picture, the scale is 10 um and the white arrowhead points to PSE as a reference point.

Fig 6. Identification of a gene expression pattern common to non-PSE cells frequent after PSE enucleation.

a) The module 1 eigengene profile with its expression along PPP, CC and PSE trajectories. b) New genes with an expression pattern validating the gene profiles grouped in module 1. All the genes presented in this panel are expressed forming a ring around PSE at the time of PSE enucleation. *SBT4.12* and *TAX2* are also expressed in late PSE, with *TAX2* also showing expression in the epidermis. UMAPs show the particular cluster-weighted normalised expression of each gene in the phloem pole cell atlas and microscopy pictures are representative images of the transcriptional reporter lines where the gene promoter is fused to *VENUSer*. Scale bar in the longitudinal sections is 25 µm while it is 10 µm in the cross sections. White arrowheads point to PSE cells as a reference point. "X" marks xylem cells. Each gene has also been plotted in PPP (green), CC (orange) and PSE (purple) Slingshot trajectories, showing average expression values in the Y-axis and pseudotime in the X-axis. c) Expression profile of sub-module 1 eigengene, the sub-module of module 1 which is enriched for genes with ring-specific expression. This sub-module contains all the genes in the panel except for *TAX2*, which was not present in our network.
The numbers in each panel indicate samples with similar results, of the total independent biological samples observed.

Fig 7. *PAPL* genes are *PEAR* targets that influence root nutritional status.

a) UMAPs showing the expression of *PAPL1*, *PAPL2* and *CDF2* in the phloem pole cell atlas. Note these genes are also expressed in the early phloem cell clusters. b) *pPAPL1::GFP/GUS* expression domain, showing expression in the cells around PSE from 40µm from the QC and in the epidermis c) Phloem expression of *pPAPL1::GFP/GUS* is delayed until 120µm in *pear1pear2* mutant background d) *pPAPL1::PAPL1-YFP* (Col0) translational domain coincides with the transcriptional domain. e) The ring pattern of *pPAPL1::GFP/GUS* gets distorted upon PSE plasmodesmata closure using the *cals3m* tool (*pPEAR1::XVE>>cals3m*). f) *PAPL2* (*pPAPL2::VENUSer*) becomes ectopically expressed upon *PEAR1* overexpression in the meristem (*pRPS5A::PEAR1-GR*). g) Average root length of 6 days post-sowing (dps) seedlings in *3papl*, WT and complementation lines in *3papl* background with genomic constructs for *PAPL1* (3 lines) or *PAPL2* (4 lines) in sucrose-depleted media. The median and 95% confidence interval are shown (methods). Number of seedlings measured: 488 *3papl*; 273 *PAPL1-32*; 37 *PAPL1-51*; 33 *PAPL1-71*; 343 *PAPL2-11*; 79 *PAPL2-23*; 37 *PAPL2-31*; 314 *PAPL2-73*; 382 WT. The same data is also shown in Fig S9h, separately for each experimental batch and seed stock (see "Experimental Design" section in the methods). Statistical analysis comparing each mutant genotype to the WT is in Table S8. h) Transfer experiment between sucrose and sucrose-depleted plates of *3papl* seedlings. Days spent with and without sucrose are represented by grey and purple bars, respectively, and roots were measured at 8 dps. Number of seedlings: 131 *3papl* control; 24 *3papl* seedlings on average per transfer experiment. Statistical analysis comparing each pair of conditions is in Table S8.

In confocal pictures b, e and f, primed letters show the cross sections of each respective letter. Scale bars: 25 µm in longitudinal sections; 10 µm in cross sections. White arrowheads point to PSE cells and "X" marks xylem cells. The number in each confocal picture indicates samples with similar results of the total independent biological samples analysed.

Fig 8. Difference in WT and *3papl* metabolite levels in leaves and roots.
a) Overview of the different metabolites with significant differences between WT and mutant in at least one of the time points. The point and error bars show, respectively, the mean and 2 times the standard error (i.e. an approximate 95% confidence interval) of the log-fold-change between WT and mutant metabolite levels, estimated from our linear model (see methods). The asterisk highlights points that were statistically significant after adjusting for multiple testing across all the tests (false discovery rate of 5%). b) Average metabolite levels for sucrose in mutant and wild-type. The bars denote the 95% confidence interval estimated from our linear model (see methods). The points show the raw data for individual samples. N = 6 - 8 for each timepoint/tissue/genotype combination (3 of them had 6 replicates, 8 had 7 replicates and 13 had 8 replicates).

REFERENCES

1. Brady, S. M. *et al.* A High-Resolution Root Spatiotemporal Map Reveals Dominant Expression Patterns. *Science* **318**, 801–806 (2007).
2. Miyashima, S. *et al.* Mobile PEAR transcription factors integrate positional cues to prime cambial growth. *Nature* 565, 490–494 (2019).
3. Depuydt, S. *et al.* Suppression of Arabidopsis protophloem differentiation and root meristem growth by CLE45 requires the receptor-like kinase BAM3. *Proc. Natl. Acad. Sci.* 110, 7074–7079 (2013).
4. Bonke, M., Thitamadee, S., Mähönen, A. P., Hauser, M.-T. & Helariutta, Y. APL regulates vascular tissue identity in Arabidopsis. *Nature* 426, 181–186 (2003).
5. Furuta, K. M. *et al.* Arabidopsis NAC45/86 direct sieve element morphogenesis culminating in enucleation. *Science* 345, 933–937 (2014).
6. Dettmer, J. *et al.* CHOLINE TRANSPORTER-LIKE1 is required for sieve plate development to mediate long-distance cell-to-cell communication. *Nat. Commun.* 5, 1–11 (2014).
7. Truernit, E., Bauby, H., Belcram, K., Barthelemy, J. & Palauqui, J.-C. OCTOPUS, a polarly localised membrane-associated protein, regulates phloem differentiation entry in Arabidopsis thaliana. *Development* 139, 1306–1315 (2012).

8. Rodriguez-Villalon, A. *et al.* Molecular genetic framework for protophloem formation. *Proc. Natl. Acad. Sci.* 111, 11551–11556 (2014).
9. Scacchi, E. *et al.* Spatio-temporal sequence of cross-regulatory events in root meristem growth. *Proc. Natl. Acad. Sci.* 107, 22734–22739 (2010).
10. Xiao, Y. & Offringa, R. PDK1 regulates auxin transport and Arabidopsis vascular development through AGC1 kinase PAX. *Nat. Plants* 1–12 (2020) doi:10.1038/s41477-020-0650-2.
11. Marhava, P. *et al.* A molecular rheostat adjusts auxin flux to promote root protophloem differentiation. *Nature* 558, 297–300 (2018).
12. Ross-Elliott, T. J. *et al.* Phloem unloading in Arabidopsis roots is convective and regulated by the phloem-pole pericycle. *eLife* 6, e24125 (2017).
13. Mähönen, A. P. *et al.* A novel two-component hybrid molecule regulates vascular morphogenesis of the Arabidopsis root. *Genes Dev.* 14, 2938–2943 (2000).
14. Graeff, M. & Hardtke, C. S. Metaphloem development in the Arabidopsis root tip. *bioRxiv* 2021.04.30.442082 (2021) doi:10.1101/2021.04.30.442082.
15. Sola, M. A. R. *et al.* OCTOPUS-LIKE 2, a novel player in Arabidopsis root and vascular development, reveals a key role for OCTOPUS family genes in root metaphloem sieve tube differentiation. *New Phytol.* 216, 1191–1204 (2017).
16. van Bel, A. J. E., Ehlers, K. & Knoblauch, M. Sieve elements caught in the act. *Trends Plant Sci.* 7, 126–132 (2002).
17. Tamaki, T. *et al.* VISUAL-CC system uncovers the role of GSK3 as an orchestrator of vascular cell type ratio in plants. *Commun. Biol.* 3, 1–9 (2020).
18. Gujas, B. *et al.* A Reservoir of Pluripotent Phloem Cells Safeguards the Linear Developmental Trajectory of Protophloem Sieve Elements. *Curr. Biol.* 30, 755-766.e4 (2020).
19. Otero, S. & Helariutta, Y. Companion cells: a diamond in the rough. *J. Exp. Bot.* 68, 71–78 (2017).
20. Oparka, K. J. & Turgeon, R. Sieve Elements and Companion Cells: Traffic Control

Centers of the Phloem. *Plant Cell* 11, 739–750 (1999).

21. Parizot, B., Roberts, I., Raes, J., Beeckman, T. & De Smet, I. In silico analyses of pericycle cell populations reinforce their relation with associated vasculature in Arabidopsis. *Philos. Trans. R. Soc. B Biol. Sci.* 367, 1479–1488 (2012).
22. Beeckman, T. & Smet, I. D. Pericycle. *Curr. Biol.* 24, R378–R379 (2014).
23. Lee, J.-Y. *et al.* Transcriptional and posttranscriptional regulation of transcription factor expression in Arabidopsis roots. *Proc. Natl. Acad. Sci.* 103, 6055–6060 (2006).
24. Parizot, B. *et al.* Diarch Symmetry of the Vascular Bundle in Arabidopsis Root Encompasses the Pericycle and Is Reflected in Distich Lateral Root Initiation. *Plant Physiol.* 146, 140–148 (2008).
25. Li, S., Yamada, M., Han, X., Ohler, U. & Benfey, P. N. High-Resolution Expression Map of the Arabidopsis Root Reveals Alternative Splicing and lincRNA Regulation. *Dev. Cell* 39, 508–522 (2016).
26. Zhang, C., Barthelson, R. A., Lambert, G. M. & Galbraith, D. W. Global Characterization of Cell-Specific Gene Expression through Fluorescence-Activated Sorting of Nuclei. *Plant Physiol.* 147, 30–40 (2008).
27. Birnbaum, K. *et al.* A Gene Expression Map of the Arabidopsis Root. *Science* 302, 1956–1960 (2003).
28. Ryu, K. H., Huang, L., Kang, H. M. & Schiefelbein, J. Single-Cell RNA Sequencing Resolves Molecular Relationships Among Individual Plant Cells. *Plant Physiol.* 179, 1444–1456 (2019).
29. Shulse, C. N. *et al.* High-Throughput Single-Cell Transcriptome Profiling of Plant Cell Types. *Cell Rep.* 27, 2241-2247.e4 (2019).
30. Denyer, T. *et al.* Spatiotemporal Developmental Trajectories in the Arabidopsis Root Revealed Using High-Throughput Single-Cell RNA Sequencing. *Dev. Cell* 48, 840-852.e5 (2019).
31. Zhang, T.-Q., Xu, Z.-G., Shang, G.-D. & Wang, J.-W. A Single-Cell RNA Sequencing Profiles the Developmental Landscape of Arabidopsis Root. *Mol. Plant* 12, 648–660

(2019).

32. Wendrich, J. R. *et al.* Vascular transcription factors guide plant epidermal responses to limiting phosphate conditions. *Science* (2020) doi:10.1126/science.aay4970.
33. Roszak, P. *et al.* Cell-by-cell dissection of phloem development links a maturation gradient to cell specialization. *Science* 374, eaba5531.
34. Hafemeister, C. & Satija, R. Normalization and variance stabilization of single-cell RNA-seq data using regularized negative binomial regression. *Genome Biol.* 20, 296 (2019).
35. Haghverdi, L., Lun, A. T. L., Morgan, M. D. & Marioni, J. C. Batch effects in single-cell RNA-sequencing data are corrected by matching mutual nearest neighbors. *Nat. Biotechnol.* 36, 421–427 (2018).
36. A step-by-step workflow for low-level analysis of... | F1000Research. https://f1000research.com/articles/5-2122/v2.
37. Desvoyes, B. *et al.* Looking at plant cell cycle from the chromatin window. *Front. Plant Sci.* 5, 369 (2014).
38. Schürholz, A.-K. *et al.* A Comprehensive Toolkit for Inducible, Cell Type-Specific Gene Expression in Arabidopsis. *Plant Physiol.* 178, 40–53 (2018).
39. Tian, H. *et al.* Arabidopsis NPCC6/NaKR1 Is a Phloem Mobile Metal Binding Protein Necessary for Phloem Function and Root Meristem Maintenance. *Plant Cell* 22, 3963–3979 (2010).
40. Truernit, E. & Sauer, N. The promoter of the Arabidopsis thaliana SUC2 sucrose-H+ symporter gene directs expression of β-glucuronidase to the phloem: Evidence for phloem loading and unloading by SUC2. *Planta* 196, 564–570 (1995).
41. Zhang, Q. *et al.* Knock-Down of Arabidopsis PLC5 Reduces Primary Root Growth and Secondary Root Formation While Overexpression Improves Drought Tolerance and Causes Stunted Root Hair Growth. *Plant Cell Physiol.* 59, 2004–2019 (2018).
42. Roszak, P. *et al.* Analysis of phloem trajectory links tissue maturation to cell specialization. *bioRxiv* 2021.01.18.427084 (2021) doi:10.1101/2021.01.18.427084.
43. Street, K. *et al.* Slingshot: cell lineage and pseudotime inference for single-cell

transcriptomics. *BMC Genomics* 19, 477 (2018).

44. Bergen, V., Lange, M., Peidli, S., Wolf, F. A. & Theis, F. J. Generalizing RNA velocity to transient cell states through dynamical modeling. *Nat. Biotechnol.* 38, 1408–1414 (2020).
45. Shahan, R. *et al.* A single cell Arabidopsis root atlas reveals developmental trajectories in wild type and cell identity mutants. *Dev. Cell 57, 4* (2022).
46. Kim, J.-Y. *et al.* Distinct identities of leaf phloem cells revealed by single cell transcriptomics. *Plant Cell* (2021) doi:10.1093/plcell/koaa060.
47. Haritatos, E., Medville, R. & Turgeon, R. Minor vein structure and sugar transport in Arabidopsis thaliana. *Planta* 211, 105–111 (2000).
48. Iacono, G., Massoni-Badosa, R. & Heyn, H. Single-cell transcriptomics unveils gene regulatory network plasticity. *Genome Biol.* 20, 110 (2019).
49. Davuluri, R. V. *et al.* AGRIS: Arabidopsis Gene Regulatory Information Server, an information resource of Arabidopsis cis-regulatory elements and transcription factors. *BMC Bioinformatics* 4, 25 (2003).
50. Langfelder, P. & Horvath, S. WGCNA: an R package for weighted correlation network analysis. *BMC Bioinformatics* 9, 559 (2008).
51. Pi, L. *et al.* Organizer-Derived WOX5 Signal Maintains Root Columella Stem Cells through Chromatin-Mediated Repression of CDF4 Expression. *Dev. Cell* 33, 576–588 (2015).
52. Park, D. H. *et al.* The Arabidopsis COG1 gene encodes a Dof domain transcription factor and negatively regulates phytochrome signaling. *Plant J.* 34, 161–171 (2003).
53. Wei, Z. *et al.* Brassinosteroid Biosynthesis Is Modulated via a Transcription Factor Cascade of COG1, PIF4, and PIF5. *Plant Physiol.* 174, 1260–1273 (2017).
54. Bueso, E. *et al.* Arabidopsis COGWHEEL1 links light perception and gibberellins with seed tolerance to deterioration. *Plant J.* 87, 583–596 (2016).
55. Renard, J. *et al.* PRX2 and PRX25, peroxidases regulated by COG1, are involved in seed longevity in Arabidopsis. *Plant Cell Environ.* 43, 315–326 (2020).

56. Fornara, F. *et al.* Arabidopsis DOF Transcription Factors Act Redundantly to Reduce CONSTANS Expression and Are Essential for a Photoperiodic Flowering Response. *Dev. Cell* 17, 75–86 (2009).
57. Allen, E. *et al.* Correlation Network Analysis reveals a sequential reorganization of metabolic and transcriptional states during germination and gene-metabolite relationships in developing seedlings of Arabidopsis. *BMC Syst. Biol.* 4, 62 (2010).
58. Vidal, E. A., Moyano, T. C., Canales, J. & Gutiérrez, R. A. Nitrogen control of developmental phase transitions in Arabidopsis thaliana. *J. Exp. Bot.* 65, 5611–5618 (2014).
59. Birnbaum, K. *et al.* Cell type–specific expression profiling in plants via cell sorting of protoplasts from fluorescent reporter lines. *Nat. Methods* 2, 615–619 (2005).
60. Zheng, G. X. Y. *et al.* Massively parallel digital transcriptional profiling of single cells. *Nat. Commun.* 8, 14049 (2017).
61. *Orchestrating Single-Cell Analysis with Bioconductor*.
62. Griffiths, J. A., Richard, A. C., Bach, K., Lun, A. T. L. & Marioni, J. C. Detection and removal of barcode swapping in single-cell RNA-seq data. *Nat. Commun.* 9, 2667 (2018).
63. Lun, A. T. L., McCarthy, D. J. & Marioni, J. C. A step-by-step workflow for low-level analysis of single-cell RNA-seq data with Bioconductor. *F1000Research* 5, 2122 (2016).
64. Csardi, G. & Nepusz, T. The igraph software package for complex network research,. *InterJournal Complex Syst.* (2006).
65. Current best practices in single-cell RNA-seq analysis: a tutorial. *Mol. Syst. Biol.* 15, e8746 (2019).
66. destiny: diffusion maps for large-scale single-cell data in R | Bioinformatics | Oxford Academic. https://academic.oup.com/bioinformatics/article/32/8/1241/1744143.
67. Ursache, R., Andersen, T. G., Marhavý, P. & Geldner, N. A protocol for combining fluorescent proteins with histological stains for diverse cell wall components. *Plant J.* 93, 399–412 (2018).

68. Kim, D. *et al.* TopHat2: accurate alignment of transcriptomes in the presence of insertions, deletions and gene fusions. *Genome Biol.* 14, R36 (2013).
69. Anders, S., Pyl, P. T. & Huber, W. HTSeq—a Python framework to work with high-throughput sequencing data. *Bioinformatics* 31, 166–169 (2015).
70. Love, M. I., Huber, W. & Anders, S. Moderated estimation of fold change and dispersion for RNA-seq data with DESeq2. *Genome Biol.* 15, 550 (2014).
71. Lisec, J., Schauer, N., Kopka, J., Willmitzer, L. & Fernie, A. R. Gas chromatography mass spectrometry–based metabolite profiling in plants. *Nat. Protoc.* 1, 387–396 (2006).
72. Bates, D., Mächler, M., Bolker, B. & Walker, S. Fitting Linear Mixed-Effects Models Using lme4. *J. Stat. Softw.* 67, 1–48 (2015).
73. Alseekh, S. *et al.* Mass spectrometry-based metabolomics: a guide for annotation, quantification and best reporting practices. *Nat. Methods* (2021) doi:10.1038/s41592-021-01197-1.
74. Otero, S., Gildea, I., Roszak, P., Lu, Y., Di Vittori, V., Bourdon, M., Kalmbach, L., Blob, B., Heo, J-O, Peruzzo, F., Laux, T., Fernie, A.R., Tavares, H., Helariutta, Y. A root phloem pole cell atlas reveals common transcriptional states in protophloem adjacent cells, *Gene Expression Omnibus*, GSE181999, 2022.
75. Otero, S., Gildea, I., Roszak, P., Lu, Y., Di Vittori, V., Bourdon, M., Kalmbach, L., Blob, B., Heo, J-O, Peruzzo, F., Laux, T., Fernie, A.R., Tavares, H., Helariutta, Y. A root phloem pole cell atlas reveals common transcriptional states in protophloem adjacent cells, *Gene Expression Omnibus*,GSE182672, 2022.
76. Otero, S., Gildea, I., Roszak, P., Lu, Y., Di Vittori, V., Bourdon, M., Kalmbach, L., Blob, B., Heo, J-O, Peruzzo, F., Laux, T., Fernie, A.R., Tavares, H., Helariutta, Y. A root phloem pole cell atlas reveals common transcriptional states in protophloem adjacent cells, Cambridge Apollo Repository, 2022. https://doi.org/10.17863/CAM.74836

Commented [1]: Hugo, is this the right year?

Commented [2]: Hugo, is this the right year?

Methods References

77. Kang, Y. H. & Hardtke, C. S. Arabidopsis MAKR5 is a positive effector of BAM3-dependent CLE45 signaling. *EMBO Rep.* **17**, 1145–1154 (2016).

78. Brady, S. M. *et al.* A High-Resolution Root Spatiotemporal Map Reveals Dominant Expression Patterns. *Science* **318**, 801–806 (2007).

79. Roszak, P. *et al.* Analysis of phloem trajectory links tissue maturation to cell specialization. *bioRxiv* 2021.01.18.427084 (2021) doi:10.1101/2021.01.18.427084.

80. Miyashima, S. *et al.* Mobile PEAR transcription factors integrate positional cues to prime cambial growth. *Nature* **565**, 490–494 (2019).