Root developmental programs shape the *Medicago truncatula* nodule meristem

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**ABSTRACT**

Nodules on the roots of legume plants host nitrogen-fixing *Rhizobium* bacteria. Several lines of evidence indicate that nodules are evolutionarily related to roots. We determined whether developmental control of the *Medicago truncatula* nodule meristem bears resemblance to that in root meristems through analyses of root meristem-expressed *PLETHORA* genes. In nodules, *MtPLETHORA 1* and 2 are preferentially expressed in cells positioned at the periphery of the meristem abutting nodule vascular bundles. Their expression overlaps with an auxin response maximum and *MtWOX5*, which is a marker for the root quiescent center. Strikingly, the cells in the central part of the nodule meristem have a high level of cytokinin and display *MtPLETHORA 3* and 4 gene expression. Nodule-specific knockdown of *MtPLETHORA* genes results in a reduced number of nodules and/or in nodules in which meristem activity has ceased. Our nodule gene expression map indicates that the nodule meristem is composed of two distinct domains in which different *MtPLETHORA* gene subsets are expressed. Our mutant studies show that *MtPLETHORA* genes function redundantly in nodule meristem maintenance. This indicates that *Rhizobium* has recruited root developmental programs for nodule formation.

**KEY WORDS:** *Medicago truncatula*, Nodule meristem, *PLETHORA* genes, DR5

**INTRODUCTION**

The interaction between legumes and soil-borne bacteria, collectively known as rhizobia, leads to the formation of new organs called root nodules (Stougard, 2001; Limpens and Bisseling, 2003). As nodules are formed on roots it has been hypothesized that the nodule developmental program is derived from the lateral root developmelntal program (Nutman, 1948; Hirsch et al., 1997; Mathiesius et al., 2000; de Billy et al., 2001; Roudier et al., 2003; Bright et al., 2005; Desbrosses and Stougard, 2011). Recently, the expression of several root meristem regulators has been observed in the nodule meristem (NM) (Osipova et al., 2011, 2012; Roux et al., 2014), thereby providing molecular support for this hypothesis. However, whether the identified genes function in the formation of NM and root meristem (RM), a prerequisite for concluding that the nodule developmental program is derived from that of the root, has thus far remained unclear. Root tissues are continuously replenished by stem cells, and in *Arabidopsis* these stem cells surround the quiescent center (QC) cells (Dolan et al., 1993). The QC functions as a so-called organizer and is essential for maintenance of the surrounding stem cells (van den Berg et al., 1997), and together they form the stem cell niche. The daughter cells of these stem cells form files of transit-amplifying cells and, together with the stem cell niche, they form the RM (Heidstra and Sabatini, 2014). Auxin accumulation is crucial for the specification of the stem cell niche in the *Arabidopsis* RM, which colocalizes with an auxin concentration and response maximum (Sabatini et al., 1999; Biliou et al., 2005; Petersson et al., 2009). Several *Arabidopsis* transcription factors have been identified that are required for proper formation and function of the root stem cell niche, among them WUSCHEL-RELATED HOMEobox 5 (WOX5) (Sarkar et al., 2007), SCARECROW (SCR) (Di Laurenzio et al., 1996; Sabatini et al., 2003) and four *PLETHORA* (PLT) factors (Aida et al., 2004; Galinha et al., 2007). *WOX5* transcript accumulates specifically in the QC and mutant analyses have revealed that it is required for columella stem cell maintenance (Sarkar et al., 2007). *PLT* genes are part of the small *AINTEGUMENTA-LIKE* (*AIL*) gene clade of transcriptional regulators within the large *AP2/ERF* family (Horstman et al., 2014). Among this clade, *PLT1-4* are essential for root formation as their higher order mutants are rootless (Galinha et al., 2007). In *plt1, plt2* double mutants, stem cells and transit-amplifying cells are lost, while ectopic *PLT1* and *PLT2* expression is sufficient to induce root niche formation (Aida et al., 2004; Galinha et al., 2007). This shows that a combination of *PLT1* and *PLT2* is most indicative for RM activity. A gradient of PLT activity controls root zonation and the highest PLT concentration localizes to the stem cell niche (Mählönen et al., 2014).

Legume nodule formation is initiated by dedifferentiation of cortical cells, which divide and form the nodule primordium. Upon infection by the microsymbiont, the NM is formed at the apex of the primordium (Timmers et al., 1999; Stougard, 2001; Limpens and Bisseling, 2003). In the model legume *Medicago*, which forms nodules with a persistent meristem at its apex, nodule development can be divided into six stages based on the sequential pattern of anti-periclinal cell divisions in inner cortical cell layers C3-C5, endodermis and pericycle (Xiao et al., 2014). The cluster of cells formed up until stage V is called the nodule primordium. It consists of six to eight cell layers derived from pericycle and endodermis, about eight cell layers of infected cells derived from the inner cortical cell layers C5 and C4, and a few cell layers derived from cortical cell layer C3 that will develop into the NM (Xiao et al., 2014). From stage VI onward the *Medicago* nodule apical meristem becomes functional and adds cells to different nodule tissues: the central tissue, consisting of infected and non-infected cells,
and the peripheral tissues including the nodule cortex, endodermis and parenchyma. The latter contains vascular bundles that develop from nodule vascular meristems (NVMs) (Roux et al., 2014). The part of the NM that adds cells to the central tissue forms a large domain at the apex and is composed of four to six cell layers. Transition of meristem cells to the central tissue cells is accompanied by a switch from mitosis to endoreduplication in the cells that become infected by rhizobia (Cebolla et al., 1999).

Recent studies confirmed the expression of orthologs of a number of known Arabidopsis RM regulators in the nodule, among them MtWOX5, MtPLT2 and MtBBM/PLT4 (Osipova et al., 2011, 2012; Roux et al., 2014). These genes appeared to be expressed in the central meristem region and at the tip of the nodule vascular bundles, where maximum DR5 activity is also observed (Couzigou et al., 2014), suggesting that a root-like developmental program is operational in the NM. To functionally address whether the nodule developmental program is regulated by factors similar to those that are key in controlling the Arabidopsis root developmental program, we studied the expression of MtPLT genes in the NM and the effect of their knockdown on nodule formation. Based on these results we propose that the NM consists of distinct central and peripheral meristermic domains and that four MtPLT genes (MtPLT1-4) redundantly control nodule formation and NM maintenance. This is reminiscent of the described function of AtPLT genes in root development and suggests that rhizobia have recruited major regulators of root development.

RESULTS
Medicago truncatula orthologs of AtPLT genes
Recent studies showed that orthologs of AtPLT genes, named MtPLT2(Medtr4g65370) and MtBBM/PLT4(Medtr7g080460) are expressed in the NM (Boutillier et al., 2002; Hofhuis et al., 2013; Limpens et al., 2013; Roux et al., 2014). We asked whether the other Medicago PLT orthologs are also expressed in the NM and performed reciprocal BLAST searches (in Mt4.0v1) using the AtPLT protein sequences as a query to identify their homologs in Medicago (Table 1; supplementary material Fig. S1) (Tamura et al., 2011). Alignment of all Arabidopsis and Medicago PLT protein sequences using Vitis vinifera as an outgroup show that there are single Medicago orthologs of AtBBM/PLT4 and AtPLT5, which we named MtPLT4(Medtr7g080460) and MtPLT5(Medtr4g127930), respectively (supplementary material Fig. S1). The phylogeny of the AtPLT1/2 and AtPLT3/7 subclades indicates that in Medicago ancestral gene duplications have occurred, independent from those observed in Arabidopsis, generating Medtr2g09180 and Medtr4g65370 that reside in the AtPLT1/2 clade and Medtr5g031880 and Medtr8g068510 that reside in the AtPLT3/7 clade. Because of the independent gene duplication events in Arabidopsis and Medicago a direct orthology link between genes in the PLT1/2 and PLT3/7 clades cannot be drawn. Nevertheless, comparison of the expression patterns indicates that AtPLT3 and Medtr5g031880 are expressed in the RM, whereas AtPLT7 and Medtr8g068510 are not (Galinha et al., 2007; Prasad et al., 2011; The Medicago truncatula Gene Expression Atlas Project (http://mtgea.noble.org/v3/)). Based on these data and to keep in line with the previously designated MtPLT2 (Limpens et al., 2013), we utilize from now on the following nomenclature: Medtr2g09180 (MtPLT1), Medtr4g65370 (MtPLT2), Medtr5g031880 (MtPLT3) and Medtr7g080460 (MtPLT4) (Table 1). The proposed gene annotations were subsequently used to design primers (supplementary material Table S5) to enable gene expression studies by qPCR. Our data reveal that all four MtPLT genes are expressed in nodules, albeit at lower levels than in roots (Fig. 1A).

A pre-existing and growing root that can be inoculated to induce nodulation is crucial for the analysis of MtPLT function in nodules. Therefore, the maintenance of the RM, a process for which four redundantly acting PLT genes are essential in Arabidopsis (Aida et al., 2004; Galinha et al., 2007; Mähönen et al., 2014), should be ensured. To this end, the function of MtPLT genes must be tested in the Medicago RM. At present, mutants are only available for MtPLT1, 2 and 4 (http://bioinfo4.noble.org/muant), hampering the generation of a quadruple mutant in Medicago as a tool to determine via genetics whether the four MtPLT genes are the redundantly acting orthologs of Arabidopsis PLT1-4. Instead, we reduced the expression of MtPLT1 and MtPLT2 (MtPLT1i,2i), or of MtPLT3 and MtPLT4 (MtPLT3i,4i) or of all four MtPLT genes (MtPLTi) simultaneously by RNA interference (RNAi) under the control of the 35S promoter by Agrobacterium rhizogenes-mediated root transformation (supplementary material Fig. S2) (Limpens et al., 2004). Eight days after transferring the transformed plantlets to perlite, we counted the number of roots growing from transgenic calli. On 18 calli of empty vector-transformed plantlets, 58 transgenic roots of more than 3 cm in length were grown (supplementary material Fig. S2A-C, arrow; Table S1). By contrast, no transgenic roots longer than 3 cm were grown from 16 calli of 35SMtPLTi plants. On these calli, only four transgenic roots of 1-2 cm in length were grown (supplementary material Fig. S2H,I, arrowhead) and numerous small outgrowths were detected (supplementary material Fig. S2E,F, red). Analyses of the transgenic short roots shows that the RM is absent, indicating the rapid differentiation of meristematic cells (supplementary material Fig. S2G-I). On 20 calli of 35SMtPLTi,2i transgenic plants 13 short and 9 long transgenic roots were grown, while on 27 calluses of 35SMtPLTi,3i plants 12 short and 66 long transgenic roots were grown (supplementary material Table S1). Thus, downregulation of MtPLT1 and MtPLT2 has a more profound effect on RM maintenance than downregulation of MtPLT3 and MtPLT4. This shows that, in analogy to Arabidopsis (Aida et al., 2004; Galinha et al., 2007; Mähönen et al., 2014), MtPLTi-4 redundantly act on root formation and growth and that downregulation of all four MtPLT genes severely affects root formation.

Table 1. Accession numbers of A. thaliana and M. truncatula
PLETHORA genes

<table>
<thead>
<tr>
<th>Gene</th>
<th>A. thaliana</th>
<th>M. truncatula</th>
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<tbody>
<tr>
<td>PLT1</td>
<td>At3g20840</td>
<td>Medtr2g09180</td>
</tr>
<tr>
<td>PLT2</td>
<td>At1g51190</td>
<td>Medtr4g065370</td>
</tr>
<tr>
<td>PLT3</td>
<td>At1g05105</td>
<td>Medtr5g031880</td>
</tr>
<tr>
<td>PLT4 (BBM)</td>
<td>At1g17430</td>
<td>Medtr7g080460</td>
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</table>

The annotation for Medicago PLT1 and PLT2 is arbitrary (but following a previous annotation by Limpens et al., 2013) because Medicago and Arabidopsis PLT1 and PLT2 genes were formed by independent gene duplication events (see supplementary material Fig. S1). Medtr5g031880 resides together with Medtr8g068510 in the PLT3/7 clade. Because Medtr5g031880 is, like MtPLT3, expressed in the RM whereas Medtr8g068510 is not, we annotated Medtr5g031880 as PLT3.

MtPLT genes are required for nodule development and NM maintenance
We next asked whether downregulation of individual MtPLT genes influences nodule growth, as it was possible that individual members have specific functions in nodules despite the redundancy in their roles in root development. We reduced the expression of the individual MtPLT genes by RNAi under the control of the 35S
promoter by *A. rhizogenes*-mediated root transformation. We analyzed nodules formed on at least 15 transgenic roots 15 days post inoculation in experimental duplicates. The level of *MtPLT* gene expression reduction was determined by qPCR on RNA isolated from roots and nodules (supplementary material Fig. S3A-E). This showed that different degrees of RNA reduction were obtained for the different genes in roots as well as in nodules. Notably, RNAi was specific for each of the targeted *MtPLT* genes (supplementary material Fig. S3A-D). However, RNAi did not lead to a significant reduction in nodule number compared with the number of nodules formed on control roots in all replicates (supplementary material Table S2).

Next, we investigated in detail the effect of single *MtPLT* gene knockdown on nodule development by analysis of serial microsections of control and transgenic nodules by counting the cell layers in the meristem, infection zone and the fixation zone. Analyses of 20 control nodules collected per replica shows that the NM consists of 4-6 cell layers and the central tissue of 16-19 cell layers distributed over 6-7 cell layers in the infection zone and 10-12 cell layers in the fixation zone (Fig. 2A). We did not observe significant differences between the number of cell layers in single *MtPLT* knockout and control nodules (supplementary material Fig. S4, Table S3). Altogether, these results indicate that downregulation of individual *MtPLT* genes had no significant effect on nodule development. Subtle effects, however, might have gone unseen owing to variation between transgenic roots after a hairy root transformation (Limpens et al., 2004).

Downregulation of *MtPLT1* and *MtPLT2* has a more profound effect on RM maintenance than downregulation of *MtPLT3* and *MtPLT4*. To demonstrate the effect of reducing gene expression of more than one *MtPLT* gene in nodules, we conducted RNAi using the *MtENOD12* promoter. During nodule ontogenesis this gene is activated in the nodule primordium, the NM and in the infection zone of mature nodules (Limpens et al., 2009, 2013). We tested the effect of *ENOD12::MtPLT1i, MtPL2i*, *ENOD12::MtPLT3i, MtPL4i* and *ENOD12::MtPLTi* in triplicate on nodule growth and development. Importantly, *ENOD12::MtPLTi* did not affect transgenic root growth from calluses upon *A. rhizogenes*-mediated transformation (supplementary material Table S1).

The level of downregulation of the *MtPLT* genes was determined by qPCR (Fig. 1B-D). We confirmed that *MtPLT1* and *MtPLT2* RNA levels were reduced in transgenic *ENOD12::MtPLT1i, MtPL2i* nodules, whereas *MtPLT3* and *MtPLT4* RNA levels were not (Fig. 1B). Similarly, *MtPLT3* and *MtPLT4* RNA levels were reduced in *ENOD12::MtPLT3i, MtPL4i* nodules, whereas *MtPLT1* and *MtPLT2* RNA levels were not (Fig. 1C). In transgenic *ENOD12::MtPLTi* nodules, all four *MtPLT* genes were reduced in expression, albeit to different levels (Fig. 1D). On transgenic *ENOD12::MtPLTi*, *ENOD12::MtPLT1i, MtPL2i* or *ENOD12::MtPLT3i, MtPL4i* roots the number of nodules was significantly reduced (Mann-Whitney test, *P*<0.01 for *ENOD12::MtPLTi*, *P*<0.05 for *ENOD12::MtPLT1i, MtPL2i* and *ENOD12::MtPLT3i, MtPL4i*; supplementary material Table S4) compared with control roots.

All compound *ENOD12::MtPLT* RNAi transgenic nodules were smaller than those on control transgenic roots. To determine potential causes of the size reduction, we analyzed longitudinal sections of transgenic nodules collected in triplicate 15 days after inoculation, and observed a high percentage of phenotypically aberrant nodules (Fig. 2, Table 2). We classified the nodule phenotypes into two groups: class I, in which the number of cell layers in meristem and infection zone is reduced (Fig. 2B,D); and
class II, which lack the NM and the infection zone (Fig. 2C,D). These class II nodules only consist of six to ten layers of infected cells (Fig. 2C). Notably, a complete block of meristem formation still permits the generation of nodules with six layers of infected cells, which are derived from the C4 and C5 cortical cells (Xiao et al., 2014). These results indicate that MtPLT activity is needed for proper NM formation and maintenance, but not for the infection of primordium cells. This does not exclude the possibility that MtPLT gene activity may be required for the infection of cell layers in the infection zone derived from the NM.

In nodules formed on ENOD12::MtPLT1i,2i and ENOD12::MtPLT3i,4i roots, the majority of the affected nodules were grouped into class I (Table 2). By contrast, the majority of ENOD12::MtPLTi nodules fell into class II (n=11 out of 16, Table 2). These results show that the downregulation of all four MtPLT genes simultaneously has a more dramatic effect on NM formation and maintenance than the downregulation of a combination of only two MtPLT genes. In conclusion, our results show that MtPLT genes redundantly affect NM formation.

MtPLT promoter activity marks the Medicago RM

A striking difference between PLT-directed root and nodule growth is that MtPLT3i/4i affects nodule growth, whereas Atplt3/Atplt4 knockout and MtPLT3i/4i knockdown minimally affect root growth (Fig. 2, Table 2; supplementary material Table S1) (Galinha et al., 2007). To seek an explanation for this discrepancy, we compared the expression patterns of the different MtPLT genes using pMtPTL::GUS fusions in root and nodule and in situ hybridization (ISH) in nodule. MtPLT mRNA localization in nodules is in agreement with the GUS staining pattern observed from the respective promoter fusion, indicating that the pMtPLT::GUS fusions reflect the true expression pattern of the corresponding genes (Roux et al., 2014) (compare supplementary material Fig. S5 with Fig. 6). In Arabidopsis, AtPLT3 and AtBBM/PLT4 are expressed in the RM in a pattern that overlaps with, but is slightly different from, that of AtPLT1 and AtPLT2 (Galinha et al., 2007). Before testing the activity of MtPLT promoters in the NM, we first identified their activity pattern in the root and compared these to markers for auxin (DR5) and cytokinin (TCS) response and QC activity (WOX5).

In primary Medicago roots, cell files converge to a group of cells that are suggested to be QC cells (Fig. 3A, arrow). Distal to the presumptive QC cells are the columella cells that accumulate starch granules (Fig. 3A). Similar to the pattern observed in Arabidopsis (Sabatini et al., 1999), in Medicago roots the highest level of expression from an integrated DR5::GUS construct is detected in the proposed stem cell niche (Fig. 3B). Comparison of MtPLT1::GUS, MtPLT2::GUS, MtPLT3::GUS and MtPLT4::GUS expression patterns shows that they overlap most in the RM. The highest expression domains coincide with the root stem cell niche, similar to AtPLT gene expression patterns (Galinha et al., 2007). However, the MtPLT3::GUS (Fig. 3E) and MtPLT4::GUS (Fig. 3F) expression patterns extend into the vascular tissue (supplementary material Fig. S6). It is interesting that AtPLT3 and AtBBM/PLT4

Table 2. Phenotypes of MtPLT RNAi nodules

<table>
<thead>
<tr>
<th>RNAI</th>
<th>n</th>
<th>WT (%)</th>
<th>Class I (%)</th>
<th>Class II (%)</th>
<th>Class I+II (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENOD12::MtPLT1i,2i</td>
<td>54</td>
<td>19 (35)</td>
<td>25 (46)</td>
<td>10 (19)</td>
<td>35 (65)</td>
</tr>
<tr>
<td>ENOD12::MtPLT3i,4i</td>
<td>23</td>
<td>9 (39)</td>
<td>9 (39)</td>
<td>5 (22)</td>
<td>14 (61)</td>
</tr>
<tr>
<td>ENOD12::MtPLT1i</td>
<td>21</td>
<td>5 (24)</td>
<td>5 (24)</td>
<td>11 (52)</td>
<td>16 (76)</td>
</tr>
<tr>
<td>Control</td>
<td>50</td>
<td>47 (94)</td>
<td>3 (6)</td>
<td>0 (0)</td>
<td>3 (6)</td>
</tr>
</tbody>
</table>

*n* is the total number of nodules collected over three independent biological replicates. Class I: reduced number of layers of C3-derived meristem cells and of C4- and C5-derived infection zone. Class II: no meristem and no infection zone, only infected primordium cells derived from C4 and C5. Class I+II is the combined number of nodules with a phenotype. Phenotypes are statistically significantly different between ENOD12::MtPLT1i,2i or ENOD12::MtPLT3i,4i versus ENOD12::MtPLT1i (P<0.05, Fisher’s exact test). WT, wild type.
fusion protein accumulation extends into the vascular tissue of the Arabidopsis root as well (Galinha et al., 2007). It has been shown that the activity pattern of MtWOX5::GUS also marks the proposed stem cell niche (Osipova et al., 2012). Hence, MtPLT::GUS, DR5::GUS and MtWOX5::GUS expression patterns can be used to mark RM-like compartments in Medicago nodule organogenesis.

MtPLT::GUS promoter activity in nodule primordia
The dramatic reduction in nodule numbers on the MtPLTi root indicates that MtPLT gene activity is crucial for nodule primordium formation. If so, MtPLT genes should be expressed in nodule primordia. To test this, we analyzed sections of pMtPLT::GUS-containing transgenic hairy roots for promoter activation in stage II-V nodule primordia (Fig. 4) (Xiao et al., 2014). Stage II-III nodule primordia (Fig. 4A,C,E,G) are characterized by active cell division in the pericycle and the innermost cortical cell layer, whereas endodermis cells are yet to divide (Xiao et al., 2014), and are distinct from Medicago lateral root primordia in which endodermis cell division precedes inner cortical cell division (Herrbach et al., 2014). The promoters of all four MtPLT genes are active in cells of stage II-III nodule primordia (Fig. 4A,C,E,G) and remain active in the later stages of nodule primordium development (Fig. 4B,D,F,H). These analyses revealed that the promoters of MtPLT1-4 are indeed activated in nodule primordia (Fig. 4), corroborating their crucial role in nodule formation.

Patterns of MtPLT activation and the auxin and cytokinin response mark distinct domains in the NM
Cells in the Medicago NM divide for a prolonged time, suggesting that stem cells might contribute to the maintenance of the NM. DR5::GFP (Couzigou et al., 2014) and MtWOX5::GUS (Osipova et al., 2012) activity patterns have been allocated to distinct peripheral regions in the NM abutting vascular bundles (Fig. 5A,B, arrows). Assuming that DR5::GUS and MtWOX5::GUS colocalize to areas of stem cell activity in nodules, in analogy to the situation in roots, this suggests that stem cells are present in the NM periphery. Recently, the expression of several auxin-responsive genes in the central part of the NM has been reported (Limpens et al., 2013; Breakspear et al., 2015; Roux et al., 2014), suggesting that auxin signaling occurs in this region of the NM. Indeed, upon prolonged incubation (16 h), DR5 activity becomes detectable throughout the vascular bundles and the nodule apex (Fig. 5C, arrowhead), including the central part of the NM. Such dynamics of GUS staining is only observed in DR5::GUS nodules and suggests that auxin signaling occurs throughout the NM, albeit at different levels in the central and peripheral parts.

For both MtPLT1::GUS and MtPLT2::GUS, we observed GUS activity foci in discrete domains within the nodule apex (Fig. 5D,E, arrows). These domains of high MtPLT1 and MtPLT2 promoter activity appear embedded in a region with lower GUS activation encompassing the NM. By contrast, MtPLT3::GUS and MtPLT4::GUS are activated throughout the nodule apex (Fig. 5F,G, arrowhead).

To determine whether the expression patterns of DR5::GUS, MtWOX5::GUS, MtPLT1::GUS and MtPLT2::GUS in the NM periphery overlap, we analyzed serial sections from the nodule apex downwards. DR5 and MtWOX5 activity is present in a subpopulation of cells within the apex adjacent to the vascular bundle (Fig. 6A,D). In subsequent sections, the radial tissue organization of a vascular bundle becomes apparent and all cells of this vascular bundle display DR5 and MtWOX5 activity (Fig. 6B,E). Finally, within this radially organized domain, xylem (Fig. 6, white arrow) and phloem can be discriminated. At the developmental stage corresponding to this position, the activity of
both DR5 and MtWOX5 decreases (Fig. 6C,F). Serial sections through MtPLT2::GUS nodules reveals that the highest GUS activity is restricted to cells that are contiguous with nodule vascular bundles (Fig. 6G-I, arrow), resembling the DR5 (Fig. 6A-C) and the MtWOX5 (Fig. 6D-F) promoter activity pattern. MtPLT1::GUS also displays its highest activity in NVM cells (Fig. 6J, arrow). These analyses show that MtPLT1, MtPLT2, MtWOX5 and DR5 are active in provascular tissue and cells abutting the provascular, in analogy with their expression pattern in Medicago roots (Osipova et al., 2011, 2012). A lower MtPLT1::GUS and MtPLT2::GUS activity is observed in cells in the central part of the NM (Fig. 6G-J, arrowhead). By contrast, representative sections of MtPLT3::GUS and MtPLT4::GUS stained nodules show that both mark the entire NM and, in addition, are also activated in cells of the infection zone (Fig. 6K,L), albeit at lower levels.

The colocalization of MiPLT gene expression and high DR5 activity in the periphery of the NM suggests that an auxin-driven root-derived developmental program is operational in the nodule. In addition, several genes in the cytokinin signaling cascade are reported to be activated in the NM (Frugier et al., 2008; Plet et al., 2011; Mortier et al., 2014). To determine the cytokinin response distribution in the NM we studied the expression of TCS::GUS, a synthetic cytokinin-responsive promoter (Müller and Sheen, 2008), in transgenic Medicago roots and nodules. In roots, TCS::GUS activity encompasses mainly the QC and root cap and fades in the vasculature (Fig. 7A), which is similar to the activity in Arabidopsis roots (Zürcher et al., 2013). In contrast to the DR5::GUS activity...
pattern (Fig. 5A,C), TCS::GUS activity is equally distributed over the apex of the nodules (Fig. 5H). Longitudinal sections of these nodules show that TCS::GUS activity is confined to cells in the central part of the NM (Fig. 7B).

**DISCUSSION**

Here, we analyzed the expression pattern of Medicago orthologs of Arabidopsis PLT1, PLT2, PLT3 and BBM/PLT4 during root growth and nodule formation and maintenance in Medicago. We examined the effect of their downregulation by RNAi and showed that they act redundantly in Medicago root formation, demonstrating their orthology with AtPLT1-4. Nodulation-specific downregulation of MtPLT genes hampers nodule formation and growth. This is reminiscent of the redundancy in AtPLT function in root formation and growth (Galinha et al., 2007). Therefore, we conclude that root developmental programs have been co-opted for nodulation. Interestingly, whereas root growth in Arabidopsis is minimally affected in plt3,plt4 plants (Galinha et al., 2007), nodule growth is affected in MtPLT3i,4i nodules. To seek an explanation we analyzed MtPLT expression in Medicago RM and NM.

In Arabidopsis roots, the highest expression levels of AtPLT1-4 colocalize in the stem cell niche (Galinha et al., 2007), which is also marked by MtWOX5 (Sarkar et al., 2007) and DR5 (Sabatini et al., 1999; Biliou et al., 2005; Petersson et al., 2009) activity. The root expression patterns of the Medicago and Arabidopsis orthologs are similar, with the exception of the extension of MtPLT3 and MtPLT4 expression higher up in the meristem and elongation zone. Therefore, the pattern of pMtPLT3::GUS and pMtPLT4::GUS in the root might point to a difference in the regulation of these genes between Medicago and Arabidopsis. In nodules MtPLT1 and MtPLT2 are highly expressed in regions located at the periphery of the NM, corresponding to the NVM. The highest auxin response activity and the activation of MtWOX5::GUS (Fig. 2B) (Osipova et al., 2012; Roux et al., 2014) coincide with the NVM. These expression patterns indicate that the developmental program directing peripheral tissue formation bears similarities to root developmental programs involving PLT genes (Galinha et al., 2007). However, in the absence of a suitable promoter that marks the NVM specifically, the effect of knockdown of MtPLT genes could not be tested in the NM periphery.

In addition to the high peripheral NM expression, MtPLT1 and MtPLT2 are expressed at lower levels in the central part of the NM, whereas MtPLT3 and MtPLT4 expression levels are comparable in both central and peripheral zones of the NM. In conclusion, based on the RM markers DR5, MtWOX5, MtPLT1, MtPLT2, MtPLT3, MtPLT4 and TCS, distinct gene expression signatures can be distinguished within the NM. One region is at the periphery of the nodule and includes the NVM; here, the gene activity patterns suggest that an auxin/PLT-directed root-like developmental program is active at each of the vascular bundle tips. A second domain is marked by high TCS, MtPLT3 and MtPLT4 activity. Cells within this second domain are centrally positioned within the NM and give rise to the central tissue. We will refer to this latter domain as the nodule central meristem (NCM). Based on our results we...
propose that the NM is built up of two adjacent meristems: the NVM and NCM. We predict that the different levels of MtPLT transcripts have specific effects in the NVM and NCM.

Whereas the NVM is characterized by a high auxin response, the NCM is characterized by a higher cytokinin and a lower auxin response. The lower level of auxin signaling in the NCM is, however, sufficient to induce the expression of several auxin-responsive genes (Limpens et al., 2013; Breakspear et al., 2015; Roux et al., 2014). The expression of cytokinin signaling and synthesis genes, such as MtCre1, MtARR4 (Gonzalez-Rizzo et al., 2006; Plet et al., 2011) and MtLOG1 (Mortier et al., 2014), in the NM is in line with our observations on the cytokinin response in the NM. To what extent differences in hormone regimes are instructive in shaping the NVM and the NCM remains to be elucidated. Likewise, whether the colocalization of TCS, MtPLT3 and MtPLT4 activity in the infection zone is required for the formation of this zone remains to be determined. Despite the differences in expression patterns of MtPLT1 and MtPLT2 versus MtPLT3 and MtPLT4 in the NM, the phenotypes of MtPLT1i,2i and MtPLT3i,4i nodules were indistinguishable. This might be due either to the fact that RNAi-mediated knockdown was directed using the ENOD12 promoter and not under an NVM-specific promoter, or to redundancy in the activity of MtPLT genes. Therefore, it remains unclear whether the differences in MtPLT activity in the NCM and NVM are instrumental for the formation of functionally distinct meristems. Comparing genes differentially regulated by either set of MtPLT genes and analyses of expression patterns of MtPLT genes in nodules of Medicago lin (Guan et al., 2013; Xiao et al., 2014) and root (Couzigou et al., 2014) mutants, in which the development of nodule vascular bundles and of the NCM are uncoupled, might be informative in this context. Such knowledge might also uncover mechanisms underlying the communication between the NVM and NCM domains that enables proper nodule growth.

Nodules are considered to be modified lateral roots. Like lateral root primordia, nodule primordia are exclusively formed opposite the proto-xylem poles. In Arabidopsis, PLT genes are involved in lateral root formation (Hofhuis et al., 2013; Tian et al., 2014). Hence, it is conceivable that Medicago PLT genes are likewise involved in lateral root formation and have been co-opted by Rhizobium for nodule formation. Our phylogenetic analysis indicates that PLT1/PLT2 and PLT3/PLT7 gene pairs in Arabidopsis and Medicago formed through independent gene duplication events. This suggests that, despite the importance of the PLT1/PLT2 gene pair for root growth in both species (Aida et al., 2004; this study), any putative co-option mechanism for a function in nodulation was independent of the gene duplication event in Medicago. For the PLT3/PLT7 gene pair, in both species the PLT3 orthologs appear to be expressed in the primary root tip, whereas PLT7 orthologs are not (Hofhuis et al., 2013; this study; The Medicago truncatula Gene Expression Atlas Project). We show the importance of MtPLT3 for nodulation, which suggests that for this gene too, co-option was independent of the duplication event. PLT4 and PLT5 are present in both species as a single gene. It will be interesting to investigate whether Rhizobium has also co-opted existing pathways involving the additional MtPLT5 and MtPLT7 orthologs for the initiation and outgrowth of nodule primordia, in analogy to Arabidopsis lateral root formation (Hofhuis et al., 2013; Vilches-Barro and Maizel, 2015).

Finally, it might be revealing to identify Rhizobium-controlled genes involved in regulating the expression of MtPLT genes to find out how root developmental programs are recruited to generate nodule primordia, form the NM and its subdomains, and maintain nodule growth. This knowledge should uncover how Rhizobium has co-opted and subsequently modified existing developmental pathways.

**MATERIALS AND METHODS**

**Constructs**

DNA fragments of putative promoter regions of MtPLT genes (1.5 kb for MtPLT1, 1.3 kb for MtPLT2, 2.7 kb for MtPLT3 and 1.1 kb for MtPLT4) were generated by PCR using Medicago genomic DNA as a template and Phusion high-fidelity DNA polymerase (Finnzymes) and specific primers (supplementary material Table S5). Fragments were cloned into pENTR-D-TOPO (Invitrogen), verified by nucleotide sequence analysis, and recombined into the modified Gateway vector pK7GWIG2(II)-UBQ10::DsRED-GUS-GFP (Karimi et al., 2002).

DNA of single MtPLT genes for RNAi constructs was generated by RT-PCR of cDNA made from Medicago nodule RNA using Phusion polymerase and gene-specific primers (supplementary material Table S5). These fragments were used as templates to obtain DNA fragments for double and quadruple RNAi constructs.

The PCR strategy used to obtain these latter fragments is based on the In-Fusion HD Cloning Kit user manual (Clontech Laboratories) and relies on the use of short overlaps to directionally clone multiple fragments by PCR. The strategy is outlined in supplementary material Table S6 and the primers, which map to exonic DNA, are given in supplementary material Table S5. To generate MtPLT1-MtPLT2 and MtPLT3-MtPLT4 DNA fragments for double RNAi constructs, the DNA fragments of single genes were diluted 1:500 and used as a template in a first PCR to introduce short overlaps. Subsequently, PCR products were diluted 1:500 and used in a second PCR to create a single amplicon (supplementary material Table S6). This final PCR fragment was cloned into pENTR-D-TOPO and recombined into the Gateway-compatible binary vector pENOD12-pK7GWIG2(II)-UBQ10::DsRED (Limpens et al., 2004; Ivanov et al., 2012) to create the final RNAi construct.

Similarly, for the quadruple RNAi of MtPLT genes, the MtPLT1-MtPLT2 and MtPLT3-MtPLT4 PCR fragments generated above were amplified using the primer combinations shown in supplementary material Table S5 to introduce short overlaps. The fragments obtained were diluted and combined in a second PCR to create a single amplicon, which was cloned into pENTR-D-TOPO and subsequently recombined into the Gateway-compatible binary vector pENOD12-pK7GWIG2(II)-UBQ10::DsRED or in 355-pK7GWIG2(II)-UBQ10::DsRED (Limpens et al., 2004; Ivanov et al., 2012).

**Hairy root transformation**

All constructed binary vectors were introduced into *Medicago* through *A. rhizogenes*-mediated transformation as described (Limpens et al., 2004). Plants carrying transgenic roots were grown in perlite for 8 days for root phenotype and for 15 days in the presence of Sinorhizobium meliloti 2011 to induce nodules. For each experiment, at least 15 individual roots and nodules were examined. Statistical analyses on nodule numbers were conducted using the Mann-Whitney test for non-normal distributions, under the assumption that nodule formation in two groups of analyzed nodulated roots is independent and ordinal.

**Expression analysis and histochemical GUS staining**

Plant tissues containing promoter-GUS fusions were incubated at 37°C in 0.1 M NaH2PO4-Na2HPO4 (pH 7) buffer including 3% sucrose, 0.05 mM EDTA, 0.5 mg/ml X-gluc, 2.5 mM potassium ferrocyanide and potassium ferricyanide. Incubation time varied depending on tissues and different promoter-GUS fusions. GUS-stained roots were cleared using chloral hydrate (Mayer et al., 1991). Whole-mount images of roots were taken with an Axio Imager A1 microscope (Zeiss) supplied with Nomarski optics.

**Histological analysis and microscopy**

Root tips and nodules were fixed in 5% glutaraldehyde in 0.1 M phosphate buffer (pH 7.2) for 1-2 h under vacuum, then washed with 0.1 M phosphate buffer four times for 15 min each, once with water for 15 min, and...
dehydration for 10 min in 10%, 30%, 50%, 70%, 90% and 100% ethanol, and sequentially embedded in Technovit 7100 ( Heraeus Kulzer). Sections were prepared at 5-10µm using a microtome (RJ2035, Leica), stained either with 0.05% Toluidine Blue (Sigma) or 0.1% Ruthenium Red (Sigma), mounted in Euparal (Carl Roth), and analyzed with a Leica AU5500B microscope equipped with a DFC425c camera (Leica). At least ten GUS-stained nodules from each transformation experiment were sectioned and analyzed. Representative sections are depicted.

**RNA in situ hybridization**
The 15-day-old nodules were fixed with 4% paraformaldehyde mixed with 3% glutaraldehyde in 50 mM phosphate buffer (pH 7.4) and embedded in paraffin (Paraplast X-tra, McCormick Scientific). Nodule sections of 7µm were prepared by R2035 microscope. RNA ISH was conducted according to the Afinitylex user manual for ViewRNA ISH Tissue 2-plex Assay (http://www.panomics.com/UserDocs). RNA ISH probe sets were designed and produced by Afinityrex. Each set contains 20 oligonucleotide probes, each consisting of a target-specific region and a unique sequence upon which signal amplification is built. Probe sets for MplTL1 covered the region 122-1163 nt (1569 nt), for MplTL2 the region 317-1289 nt (1632 nt), for MplTL3 the region 122-1150 nt (1545 nt) and for MplTL4 the region 586-1529 nt (2070 nt) of the full-length mRNAs. Slides were analyzed with an AU5500B microscope equipped with a DFC425c camera (both Leica).

**Acknowledgements**
We thank Tom Guilfoyle for sharing DR5; Bruno Müller for TCS; and Gabino Sanchez-Perez for help with the phylogenetic analysis.

**Competing interests**
The authors declare no competing or financial interests.

**Author contributions**
H.J.F., O.K. and R.H. developed the approach; H.J.F., T.T.X., O.K. and X.W. performed experiments; H.J.F., O.K., T.T.X., B.S., T.B. and R.H. edited the manuscript prior to submission.

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**Supplementary material**
Supplementary material available online at http://dev.biologists.org/lookup/suppl/doi:10.1242/dev.120774/-/DC1

**References**


Fig. S1. Orthology between Arabidopsis and Medicago PLT genes. Maximal likelihood phylogenetic tree of PLETHORA proteins from Arabidopsis, Medicago and Vitis vinifera (as outgroup). The Arabidopsis protein names are according to Prasad et al 2011, resolving the tree into four clades, the PLT1/2, PLT3/7, PLT4 and PLT5 clades respectively. The Medicago protein sequences were obtained after reciprocal BLAST of Arabidopsis protein sequences through TBLASTN on Mt4.0 v1CDS (http://blast.jcvi.org/er-blast/index.cgi?project=mtbe) followed by BLASTX against the Arabidopsis protein database of the nucleotide sequences of the retrieved Medicago proteins. The Vitis proteins were retrieved by BLASTP of Arabidopsis proteins. The Vitis genome contains one gene copy for each of the four clades. The midpoint rooted tree was constructed with MEGA version 5.1 (Tamura et al., 2011), using default parameters (bootstrap values of 500 replicates).
**Fig. S2.** Transgenic hairy root formation requires *MiPLT1-4* gene expression

(A-I) Vector control transgenic calli readily generate hairy roots (A-C, arrow, arrowhead), in contrast to 35S::*MiPLT1* transgenic calli (D-I). (J-L) Occasionally from some 35S::*MiPLT1* calli short transgenic roots appear (H; arrowhead), compared to long roots formed on vector control transgenic calli (B, arrow). When compared to vector control roots (J), the meristem of these short roots is severely affected or absent soon after emergence (K, L; note the presence of root hairs as a marker for differentiation). (M) Average number of short and long roots formed on transgenic calli of 35S::*MiPLT1*;2i, 35S::*MiPLT3*;4i, 35S::*MiPLT1* and empty vector control transgenic roots, shows that 35S::*MiPLT1* leads to a strong reduction in roots formed from transgenic calli. (A, D, G) Bright field; (B, E, H) dsRed filter, (C, F, I) overlay. (J-L) Bright field with Nomarski objectives.

Bars 240μm (A-I) and 75μm (J-L).
Fig. S3. MiPLT expression levels in single 35S::MiPLT RNAi root and nodules.
(A-E) Relative MiPLT expression in single 35S::MiPLT RNAi roots (A-D, gray bar) and 15 d old nodules (E, gray bar) compared to their expression in control roots and nodules (black bar), respectively. Relative expression levels were determined by qPCR and normalized to 1 in control plants for each MiPLT gene using MiACTIN-2. Shown graphs are the means ± s.e.m. of two biological repeats. Significance of expression reduction of tested MiPLT gene in RNAi versus expression of this gene in control samples is indicated by * as P<0.05 in Student t test.
**Fig. S4.** Longitudinal sections of representative single *MtPLT* RNAi nodules. (A) Median section through a control nodule. (B-E) representative median section through 35S::MtPLT1i (B), 35S::MtPLT2i (C), 35S::MtPLT3i (D) and 35S::MtPLT4i (E) nodule. All nodules were sampled 15 d after inoculation. For statistics on cell layers per zone see Table S3. M, meristem; IZ, infection zone; FZ, fixation zone.

Bars 75μm.
**Fig. S5.** RNA *in situ* hybridization of *MiPLT1*, *MiPLT3* and *MiPLT4* in nodules.

To validate the pMiPLT:*GUS* patterns, we conducted ISH on sections of 15day old nodules with gene specific probes of (A, B) *MiPLT1*, (C) *MiPLT3* and (D) *MiPLT4* visualized as pink grains. (A, B) Note the high expression level of *MiPLT1* in NVM (A, arrow) and the very low level in the NCM (B, arrowhead). (C) *MiPLT3* expression is in the NM and in the infection zone, while (D) *MiPLT4* expression is restricted to NM. The *MiPLT2* ISH expression pattern described (Roux et al., 2014) is in agreement with the pMiPLT::GUS expression pattern (Fig. 6 G-I) and for *MiPLT1,3,4* genes the ISH pattern is similar to the pMiPLT1,3,4::GUS pattern (Fig. 6 G-L), respectively. This indicates that the pMiPLT::GUS patterns are reflecting *MiPLT* transcripts. Arrows point to NVM, arrowheads to NCM. Red arrows in B point to individual grains indicating the low expression of *MiPLT1* in the NCM.

Bars 75μm.
**Fig. S6.** *MtPLT3::GUS* and *MtPLT4::GUS* expression patterns in the root. (A) *MtPLT3::GUS* and (B) *MtPLT4::GUS* expression patterns extend into the root vascular tissue.

Bars 75μm.
Table S1. Root formation and growth upon 35S::MtPLT RNAi transformation

SR, short roots (<3 cm); LR, long roots (>3 cm).

<table>
<thead>
<tr>
<th>transgene</th>
<th>Calli</th>
<th>Roots</th>
<th>SR</th>
<th>LR</th>
<th>Roots/callus</th>
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<td>62</td>
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<td>58</td>
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</tr>
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<td>22</td>
<td>13</td>
<td>9</td>
<td>~1</td>
</tr>
<tr>
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<td>12</td>
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<tr>
<td>pENOD12::EV</td>
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<td>41</td>
<td>2</td>
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<td>pENOD12::MtPLTi</td>
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<td>32</td>
<td>1</td>
<td>31</td>
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</table>
Table S2. Nodule formation on 35S::MtPLT RNAi transgenic roots.

Number of nodules/root in two independent experiments involving at least 15 roots per experiment. Data was collected 15 days after inoculation. EV is empty vector.

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<th>Nodules/root</th>
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<td>35S::EV</td>
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<tr>
<td>35S::MtPLT1i</td>
<td>46</td>
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<td>35S::MtPLT2i</td>
<td>32</td>
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<td>35S::MtPLT3i</td>
<td>42</td>
<td>3.1±0.4</td>
</tr>
<tr>
<td>35S::MtPLT4i</td>
<td>49</td>
<td>3.4±0.2</td>
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Table S3. Quantification of nodule histology upon single 35S::MtPLT RNAi

Analyses of 20 control nodules shows that the meristem consists of 4-6 cell-layers and the central tissue of 16-19 cell layers distributed over 6-7 cell-layers in the infection zone and 10-12 cell layers in the fixation zone. Compared to control nodules, all zones of single 35S::MtPLT RNAi nodules consist of a number of cell layers that is within the variation observed in the control. Data was collected in two biological replicas and 15 days after inoculation.

<table>
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<tr>
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<th>Meristem</th>
<th>Infection zone</th>
<th>Fixation zone</th>
<th>Nodule number</th>
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<td>control</td>
<td>4-6</td>
<td>6-7</td>
<td>10-12</td>
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<tr>
<td>MtPLT1i</td>
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<td>6-8</td>
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<tr>
<td>MtPLT4i</td>
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<td>7-9</td>
<td>8-12</td>
<td>17</td>
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Table S4. Nodule formation on \textit{ENOD12::MtPLT} RNAi transgenic hairy roots in three independent experiments

C represents nodules formed on control transgenic hairy roots generated using the empty vector only expressing the DsRED selection marker. N is the average number of nodules per root (18 roots per construct per experiment). The percentage of reduced number of nodules (%) on \textit{MtPLT} RNAi roots is significant at P< 0.05 for \textit{MtPLT}i,2i and \textit{MtPLT}3i,4i (Mann Whitney test) or at P<0.01 for \textit{MtPLT}i (Mann Whitney test)

<table>
<thead>
<tr>
<th>C (N)</th>
<th>\textit{MtPLT}i,2i (N)</th>
<th>%</th>
<th>\textit{MtPLT}3i,4i (N)</th>
<th>%</th>
<th>\textit{MtPLT}i (N)</th>
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<td>5.8</td>
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Table S5. Primers used in this study

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Table S6. Strategy to obtain *MtPLT* DNA fragments for cloning into RNAi vectors.

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