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Root trait plasticity and plant nutrient acquisition in phosphorus limited soil

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Abstract

To overcome soil nutrient limitation, many plants have developed complex nutrient acquisition strategies including altering root morphology, root hair formation or colonization by arbuscular mycorrhizal fungi (AMF). The interactions of these strategies and their plasticity are, however, affected by soil nutrient status throughout plant growth. Such plasticity is decisive for plant phosphorus (P) acquisition in P-limited soils. We investigated the P acquisition strategies and their plasticity of two maize genotypes characterized by the presence or absence of root hairs. We hypothesized that in the absence of root hairs plant growth is facilitated by traits with complementary functions, e.g., by higher root mycorrhizal colonization. This dependence on complementary traits will decrease in P fertilized soils. At early growth stages, root hairs are of little benefit for nutrient uptake. Regardless of the presence or absence of root hairs, plants produced average root biomass of 0.14 g per plant and exhibited 23% root mycorrhizal colonization. At later growth stages of maize, contrasting mechanisms with functional complementarity explained similar plant biomass production under P limitation: the presence of root hairs *versus* higher root mycorrhizal colonization (67%) favored by increased fine root diameter in absence of root hairs. P fertilization decreased the dependence of plant on specific root traits for nutrient acquisition. Through root trait plasticity, plants can minimize trade-offs for developing and maintaining functional traits, while increasing the benefit in terms of nutrient acquisition and plant growth. The present study highlights the plasticity of functional root traits for efficient nutrient acquisition strategies in agricultural systems with low nutrient availability.

Key words: arbuscular mycorrhizal colonization / nutrient acquisition / root hairs / root morphology / *roothairless3* mutant / root traits

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1 Introduction

Phosphorus (P) is one of the most growth-limiting macro-nutrients, and root systems display diverse morphological and physiological strategies to enhance its uptake at low and heterogeneous P availability in soil (Lambers et al., 2006; 2013). For example, under P limitation, primary root growth is suppressed and the root architecture changes to a shallower root system featuring more lateral roots and increased root hair density. This enables the roots to explore a larger soil volume (Péret et al., 2011). Root physiological strategies include exudation of various organic anions and release of extracellular phosphatases to mobilize the otherwise unavailable P in the rhizosphere (Lambers et al., 2011; Richardson et al., 2011).

An important root morphological trait, root hairs (single-cell extension of epidermal cells), contribute up to 80% to plant P uptake by increasing the root surface area and, hence, the contact space between root and soil for absorption (Jungk, 2001; Jakobsen et al., 2005; Li et al., 2014). Increased surface area with root hairs, in turn, contributes to the release of root-derived organics and phosphatases which subsequently increase P acquisition. For example, barley roots possessing hairs radially extended the rhizosphere by three times as compared to the mutant lacking root hairs (Holz et al., 2018). Another important root functional trait with complementary function (increased P acquisition) is root colonization by



Supporting Information
available online

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arbuscular mycorrhizal fungi (AMF) (Munyanziza et al., 1997). Plants trade carbon (C) to AMF for in exchange of nutrients. The extraradical mycelia of AMF may also enter the very fine soil pores, thereby increasing the nutrient uptake (Khalvati et al., 2005). Here, we emphasize the rationale to consider root colonization with AMF as a 'trait' because approximately 18% of angiosperm species (e.g., members of Brassicaceae, Chenopodiaceae, Cyperaceae, Zygophyllaceae families) lack any symbiotic associations with fungi and about 30% of angiosperm species establish other (than AMF) types of mycorrhizal associations (Brundrett, 2002; Brundrett and Tedersoo, 2019). Given that a fungus is considered as mycorrhizal only after its successful interaction with roots to form a specific type of symbiotic association, the consideration of root colonization by mycorrhizal fungi as a trait is highly feasible. Mycorrhizal symbiosis may trigger various adaptive strategies into plant such as changes in the root-to-shoot ratio (Veresoglou et al., 2012), root architecture and longevity (Hooker and Atkinson, 1996), root length (Camenzind et al., 2016), and root diameter (Comas et al., 2014). Such allometric changes are plant-species-specific and depend on the duration of the experiments as well as on the identity of the plant and its fungal partner identities (Veresoglou et al., 2012). Much of this information is derived from plant phylogeny by determining changes in root morphological and architectural traits using phylogenetically independent contrasts (Comas et al., 2014). Accordingly, an in-depth understanding requires empirical evidence. The notion that plants colonized with AMF increase their root diameter has been forwarded (Brundrett and Tedersoo, 2019), but explicit observations are missing. Moreover, most studies on plant-mycorrhizal interactions have focused on one plant growth stage, almost ignoring the dynamics of nutrient acquisition related to plant phenology. Such temporal changes in plant microbial interactions are defined as a 'missing factor' and highlight the necessity of incorporating those in future ecological studies (Schofield et al., 2018). Interactions between roots and microorganisms are established at early plant growth stages. At later stages, such interactions gain importance due to plant-growth-associated changes in root morphology, soil properties (Philippot et al., 2013; Wen et al., 2017), and variation in rhizodeposits quality and quantity (Chaparro et al., 2014). Intense competition between plants and soil microorganisms for limited nutrients also play a role (Kuzyakov and Xu, 2013). For example, root exudation changes with plant growth stage (Chaparro et al., 2014) and results in altered enzyme activities in rooted soil (Kumar et al., 2018). Throughout the growth period, plants adapt their strategies to maximize nutrient uptake, but no explicit relationship between specific root traits and nutrient acquisition has been determined (Chen et al., 2016). Such strategies are plant-species-specific and the causes of variations are not conclusive. For example, increased root hair length and density in *Brachypodium* cultivars were insufficient to increase plant P uptake and must be combined with other root traits to enhance P acquisition (Zhang et al., 2018).

The present study focuses on the root trait plasticity for plant P acquisition in P-limited soil and on the response of these traits to increased P availability via P fertilization. To this end, maize with (wild type, WT) and without root hairs (*roothairless3* mutant, *rth3*) were grown for 64 days in a climate cham-

ber under controlled environmental conditions. Subsets of both genotypes were fertilized with KH_2PO_4 . We hypothesized that (1) in P-limited soils and in absence of root hairs (key trait for plant nutrient acquisition), plant growth is maintained by shifting the root traits to attract colonization by AMF for P acquisition, whereas (2) with P fertilization, plants become less dependent on specific root traits for P uptake. This study provides the opportunity to understand the plants' P uptake strategies through plasticity in root traits at three plant growth stages (tillering, stem extension, maize heading).

2 Material and methods

2.1 Experimental setup

The soil was sampled from the long-term fertilizer experiment Dikopshof of the University of Bonn (50°48'17'' N, 6°57'17'' E). The soil was collected from the topsoil (0–20 cm) of an unfertilized control plot (without any fertilizer application since 1942). The soil was classified as a Luvisol derived from loess above sand. The soil texture near the unfertilized plot is 11.8% sand, 71.2% silt, and 17.0% clay (German clay, silt and sand particle-size ranges, DIN ISO 11277) with the following properties: total C ($7.8 \pm 0.02 \text{ g C kg}^{-1} \text{ soil}$), total N ($0.74 \pm 0.01 \text{ g N kg}^{-1} \text{ soil}$), C to N ratio (10.5 ± 0.02), calcium-acetate-lactate extractable P ($23.2 \pm 0.7 \text{ mg P kg}^{-1} \text{ soil}$), and soil pH 6.48. Field moist soil was sieved (2 mm) and 1.5 kg dry weight equivalent was filled in polyvinyl chloride (PVC) pots (KG-tubes, height 20 cm, diameter 10 cm). All soil-filled pots were pre-incubated in a growth chamber for 3 days before sowing.

Seeds of a maize (*Zea mays* L.) wild type (WT) and a mutant lacking root hairs (*roothairless3*; *rth3*) (Hochholdinger et al., 2008) were surface sterilized with 10% H_2O_2 for 3 min, washed 5 times with distilled water, and germinated on moist filter paper in petri plates in the dark for 5 days. After germination, seedlings were transferred to PVC pots containing soil sampled from Dikopshof (1 seedling per pot) and grown under controlled environmental conditions in a climate-chamber with 16 h : 8 h light : dark rhythm with mid-day and night temperatures of 25°C and 15°C, respectively, and a light intensity of approximately $600 \mu\text{mol m}^{-2} \text{ s}^{-1}$. After establishment of seedlings, all pots were fertilized with mineral N (KNO_3 , at the rate of 120 kg N ha^{-1}) to avoid soil N limitation, whereas mineral P was added to the half of total number of pots. Half of the pots received mineral P (KH_2PO_4 , at the rate of 60 kg P ha^{-1}). The soil water content was checked every alternative day and maintained at 70% water holding capacity (WHC) with distilled water throughout the experimental period. To account for effects of plant phenological stage on rhizosphere processes, samples were taken 30 days after planting (DAP), 45 DAP, and 64 DAP constituting tillering, stem extension, and maize heading stage, respectively.

2.2 Harvesting

At each harvesting time, four replicates of both genotypes (WT and *rth3*) with or without P fertilization were destructively

harvested. Maize shoots were cut at the base. The main root system was carefully removed after pulling out the soil from the pot. Roots were picked with tweezers from each pot for a specified time period (15 min). A subsample of roots was collected for measurements of arbuscular mycorrhizal colonization (see description below). All roots were scanned with an EPSON (PERFECTION™ V700 PHOTO) scanner and root length density, fine roots, and average root diameter of fine roots (< 2 mm) were determined using WinRHIZO software (Regents Instruments Inc., Quebec, Canada). Afterwards, roots and shoots were freeze-dried and ball-milled to powder for total C, N, and P analyses. The total P content in plant tissues and soil was measured using an inductively coupled plasma-atomic emission spectrometer (iCAP 6300 Duo VIEW ICP Spectrometer, Thermo Fischer Scientific GmbH, Dreieich, Germany). C and N contents were measured using an elemental analyzer 2000 (Thermo Fischer Scientific, Cambridge, UK).

2.3 Root colonization by arbuscular mycorrhizal fungi

Root colonization by AMF was measured after staining the roots with blue ink in lacto-phenol with modifications (Vierheilig et al., 1998). Briefly, fine roots (< 2 mm) were collected manually with tweezers for 2 min. Fine roots were cut into 1 cm segments and washed with distilled water. Root segments were cleared in 2.5% KOH at 90°C for 1 h. Thereafter, root segments were washed in distilled water to remove access KOH and treated with 3% H₂O₂ for 30 min at room temperature. Afterwards, the root segments were washed again with distilled water and stained with ink for 2 min. Root mycorrhizal colonization was observed at 10 × 40 magnification under a light microscope (Axionplan, Zeiss, Germany) and the percentage of mycorrhizal colonization was counted using the grid-line intersection method (Giovannetti and Mosse, 1980). A total of 108 intersects were inspected per plant.

2.4 Phosphomonoesterase activity in soil

Phosphomonoesterase activity was measured with fluorogenically-labeled artificial substrate (4-methylumbelliferyl-phosphate; MUB) (Marx et al., 2001). For this, soil suspension was prepared with 50 mL autoclaved water followed by 2 min low-energy sonication (50 Js⁻¹). Afterwards, an aliquot of 50 µL of soil suspension and 50 µL of MES (C₆H₁₃NO₄S-Na_{0.5}) buffer (pH 6.5) was added to each well, followed by 100 µL of substrate solution of 4-methylumbelliferyl-phosphate into a black 96-well microplate (PureGrade™, KG, Wertheim, Germany). The microplate was gently shaken and measurements were taken fluorometrically (excitation 360 nm; emission 450 nm) at 0, 0.5, 1, and 2 h after substrate addition with a micro-plate reader (Victor3 1420-050 Multi-label Counter, PerkinElmer, USA). Amounts of MUB cleaved during the reaction were obtained by converting the fluorescence values using specific standards. MUB cleaved in nmol per g soil dry weight per h (nmol MUB cleaved g⁻¹ dry soil h⁻¹) was used to express enzyme activity.

2.5 Statistics

The experiment was conducted with 4 replicates for each treatment at each harvesting time yielding a total of 48 experimental units. The values presented in figures are means ± standard errors of means (± SEM). All statistical analyses were performed in R environment (R Core Team, 2018) and graphs were made with 'ggplot2' library (Wickham, 2016). We performed two factors ANOVA (fixed factors: maize genotype and P fertilization) for plant biomass (shoot and root biomass), root colonization by AMF, average fine root diameter, as well as for plant N and P uptake at each growth stage and fitted linear models using *lm* function. We plotted fitted and residual values of the model to check for any patterns in our data. Moreover, we also scanned our data with *dotchart* function to check for the presence for outliers. Significant ANOVA results were further analyzed with Tukey's post-hoc test for significant differences using *lsmeans* and *cld* functions (*lsmeans*; Lenth, 2016) for which we used the original linear model. Correlation analyses were performed with *stat_cor* function (ggpubr; Kassambara, 2018).

3 Results

3.1 Plant biomass

Total plant biomass (root and shoot biomass) increased from the tillering to maize heading stage for both (wild type and *rth3* mutant) genotypes (Fig. 1a, b). The *rth3* mutant maize (completely lacking root hairs) produced almost similar biomass (shoot and root) as the WT maize (possessing root hairs). Phosphorus fertilization resulted in higher biomass production at each growth stage and increased the biomass by 38% in the mutant (*rth3*) and by 43% in the wild type (WT) at maize heading.

3.2 Root morphology, mycorrhizal colonization, and phosphomonoesterase activity

The average fine root diameter (AFRD; in mm) increased with P fertilization for the WT maize during tillering and stem elongation stages (Fig. 2a). This increase was up to 21% at tillering and 10% at the stem elongation stage. There was a trend for an increase in AFRD for the *rth3* maize with P fertilization up to 8%, 3%, and 10% at tillering, stem elongation, and maize heading, respectively, as compared with no P addition. Comparing the two genotypes, the hairless mutant always had a greater AFRD than the WT maize. The AFRD of unfertilized *rth3* type increased by 16%, 15%, and 20% compared to WT at tillering, stem elongation, and maize heading, respectively. Moreover, the AFRD of the hairless mutant (*rth3*) increased gradually with plant growth stage (0.39 ± 0.01 mm at tillering, 0.45 ± 0.02 mm at stem elongation, and 0.47 ± 0.02 mm at maize heading) (Fig. 2a). Root colonization by AMF decreased with P fertilization by 19%, 24%, and 16% in WT and 17%, 27%, and 19% in *rth3* maize roots at tillering, stem elongation, and heading stage, respectively (Fig. 2b). The AMF colonization increased in both WT and *rth3* with plant growth stage. This increase, however, was more pronounced in *rth3* without P fertilization. The root colonization

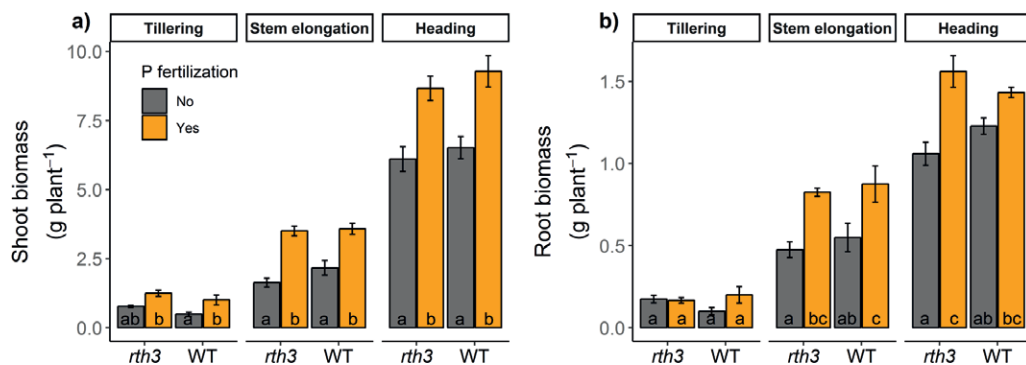


Figure 1: (a) Shoot and (b) root biomass (g plant⁻¹ ± SE) of maize plants with (wild type: WT) and without root hairs (mutant: *rth3*). Letters indicate significant differences (two factor ANOVA, Tukey's post-hoc, $p < 0.05$) between genotypes and P fertilization at each growth stage: tillering, stem elongation, and heading.

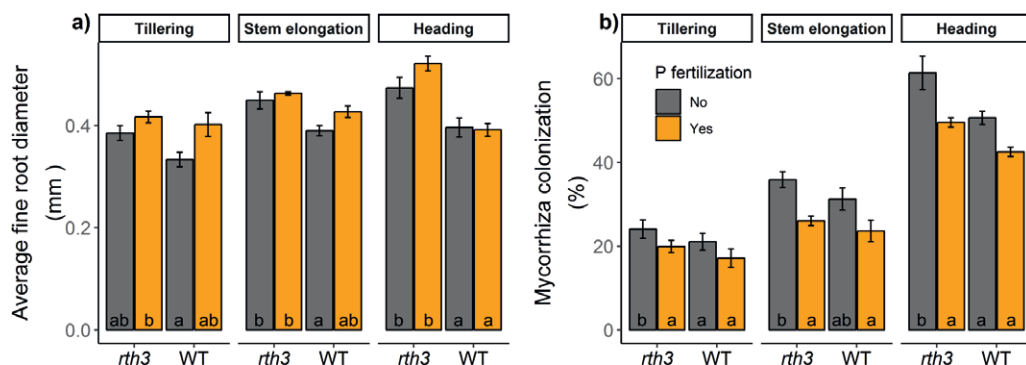


Figure 2: (a) Average fine root diameter (mm ± SE) and (b) root mycorrhiza colonization (%) of maize plants with (wild type: WT) and without root hairs (mutant: *rth3*). Letters indicate significant differences (two factor ANOVA, Tukey's post-hoc, $p < 0.05$) between genotypes and P fertilization at each growth stage: tillering, stem elongation, and heading.

by AMF increased by 14%, 15%, and 21% at tillering, stem elongation, and heading, respectively, in unfertilized *rth3* versus WT maize roots (Fig. 2b). Root colonization by AMF and AFRD correlated ($r = 0.55$, $p < 0.01$) positively for *rth3*, but not in WT (Fig. 3a). Potential activity of phosphomonoesterase (PHO) enzyme increased during plant growth in both WT and *rth3* maize planted soil. At tillering and stem elongation, PHO activity was independent of P fertilization, but the activity at maize heading stage decreased by 18% and 20% in WT and *rth3* maize soil, respectively (compared with unfertilized soil; Supplementary Tab. 1). Moreover, there was a significant correlation between AFRD and PHO activity in *rth3* ($r = 0.67$, $p < 0.01$) but not in WT (Fig. 3b).

3.3 Phosphorus and nitrogen uptake

Shoot P uptake, reported as total P content at each sampling, increased with growth stage in both WT (from 0.71 ± 0.08 mg P plant⁻¹ to 9.30 ± 0.63 mg P plant⁻¹ from tillering to heading stage, respectively) and *rth3* (from 0.94 ± 0.08 mg P plant⁻¹ to 8.78 ± 0.47 mg P plant⁻¹ from tillering to heading stage, respectively) maize. Compared with unfertilized maize, P fertilization increased the shoot P uptake by 311%, 164%, and 61% in WT maize and by 255%, 223%, and 67% in *rth3* maize at tillering, stem elongation, and heading stage, respectively (Fig. 4a). Shoot P uptake was similar

between the genotypes (WT and *rth3*) either with or without P fertilization at every maize growth stage. A similar response of P fertilization and genotypes was observed for the root P uptake (except for the non-significant effect at tillering) (Supplementary Tab. 1). Plant N uptake showed a similar pattern to that of P uptake with respect to P fertilization and genotypes, although the strength of the P fertilization effect was reduced. Similar to the P uptake, shoot N uptake also increased with plant growth stage in both genotypes (18 ± 2.2 mg N plant⁻¹, 32 ± 4.3 mg N plant⁻¹, and 76 ± 2.8 mg N plant⁻¹ in WT and 24 ± 2.7 mg N plant⁻¹, 32 ± 3.1 mg N plant⁻¹, and 67 ± 2.4 mg N plant⁻¹ in *rth3* maize at tillering, stem elongation, and heading stage, respectively) (Fig. 4b). Phosphorus fertilization increased the shoot N uptake by 78%, 57%, and 13% in WT and 76%, 63%, and 15% in *rth3* maize.

4 Discussion

4.1 Plant biomass and root mycorrhizal colonization

Plant biomass increased with P fertilization as often observed for grasses (Sundqvist et al., 2014; Haines et al., 2015), other agricultural crops (Gahoonia et al., 1999; Bakhshandeh et al., 2017), and trees (Davidson et al., 2004). Phosphorus ferti-

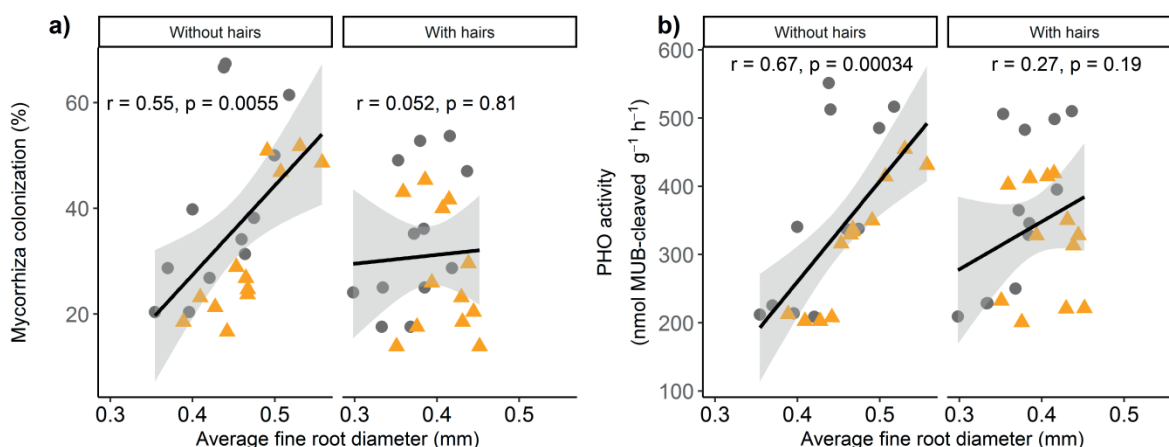


Figure 3: (a) Correlation between average fine root diameter (mm) root AMF colonization and (b) average fine root diameter and PHO activity for maize with and without root hairs including all three growth stages. Orange (triangle) and grey (circle) symbols are with and without P fertilization, respectively.

lization increased the net P and N uptake (Fig. 4), resulting in higher photosynthetic activity and higher biomass production. A similar increase in the biomass (by 38%) of different maize cultivars with P fertilization was observed by Bukvić et al. (2003), however, it should be noted that the overall plant biomass per pot may not represent field conditions.

The stronger root colonization by AMF in the hairless mutant indicated that the lack of one functional root trait (here root hairs) caused shifts to other traits (here mycorrhiza) with complementary functions. These traits may, however, be more C cost intensive and their development may be down-regulated if the respective function is not required. In soils with high P availability, for instance, the importance of functional traits for P uptake is reduced (lower colonization by AMF) (Fig. 2b). Depending on plant identity and fungal partner, about 4–30% of net photo-assimilated products transferred to mycorrhizal fungi (Smith and Smith, 1990) may not benefit the plant directly when sufficient P is available for plant growth. In soils with high P availability, the fungal partner does not benefit P acquisition by plants yet receives a significant amount of photo-assimilated products (Graham and Eissenstat, 1998; Treseder and Allen, 2002). This might provoke negative feedbacks to plants (Kiers et al., 2002). In contrast, when plant growth is limited by P, root colonization by AMF alleviates such negative responses.

4.2 Effect of phosphorus fertilization on mycorrhizal colonization and phosphomonoesterase activity

Phosphorus fertilization increased the total plant biomass (Fig. 1) but reduced root colonization by AMF as compared to unfertilized soil (Fig. 2b). This highlights the importance of mycorrhizal symbiosis for plant P acquisition. Moreover, when plant growth is not nutrient limited, the higher trade-offs for establishing and maintaining mycorrhizal symbiosis exceeds their benefits to plants (Carbonnel and Gutjahr, 2014; Zhang et al., 2018) which might have resulted in reduced root colonization with P fertilization. The inhibitory mechanisms of P fertilization on spore germination, on the growth and develop-

ment of mycorrhizal hyphae, and on root mycorrhizal colonization have been observed in pure cultures (Hepper, 1983) and in soils (Treseder and Allen, 2002; Jakobsen et al., 2005). AMF abundance decreases with increasing nutrient availability across natural gradients of mean annual rainfall (Bohrer et al., 2001) and along with successional and environmental gradients (Tao and Zhiwei, 2005; Zangaro et al., 2014). As the main aim of the present research was to elucidate the temporal root trait plasticity and their interactions with typical soil AMF, we did not differentiate among various mycorrhizal guilds, neither had we included a separate treatment lacking soil AMF. The present study is a step forward because it demonstrates a gradual increase in root colonization by AMF in the successive plant growth stages. Moreover, this increase occurred without P fertilization, indicating that when P becomes limited, the symbiotic association of plant roots with AMF becomes increasingly important for plant P acquisition. The hairless mutant showed higher root colonization by AMF than WT maize (possessing root hairs). Although we did not identify AMF abundance in soil to correlate with root AMF colonization in the present study, a very recent study (Boilard et al., 2019), using almost the similar experimental setup with barley genotypes (with and without root hairs and with and without P fertilization), showed 3 times higher AMF abundance in the absence of root hairs and under low P availability. Thus, in the absence of root hairs (a key morphological trait for nutrient and water uptake), the mycorrhiza counteracts plant P acquisition. Such an increase in mycorrhizal colonization in the absence of root hairs demonstrates the importance of fungal partner. Jakobsen et al. (2005) reported higher root mycorrhizal colonization under nutrient limitation in *brb* (root hairless mutant) than in its wild type (with root hairs) in *Hordeum vulgare* cv. Pallas. The potential PHO activity was up-regulated with plant growth and was higher in unfertilized than P fertilized soils for both hairless and WT genotypes, highlighting higher P demand. Higher PHO activity is most likely due to increased AMF [significant correlation between AMF colonization and PHO activity ($p < 0.001$); data not presented] and the corresponding symbiotic association with P-solubilizing bacteria producing PHO enzymes (Zhang et al., 2016). Such synergistic effects

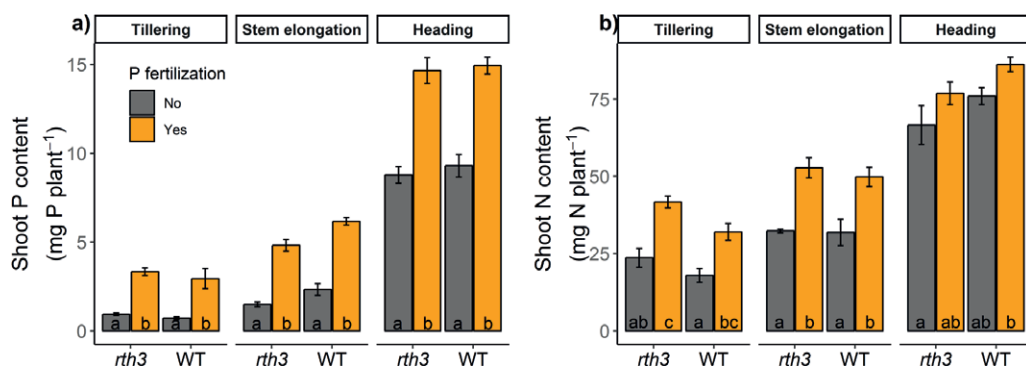


Figure 4: (a) Shoot P uptake (mg P plant⁻¹ ± SE) and b) shoot N uptake (mg N plant⁻¹ ± SE) of maize plants with (wild type: WT) and without root hairs (mutant: *rth3*). Letters indicate significant differences (two factor ANOVA, Tukey's post-hoc, *p* < 0.05) between genotypes and P fertilization at each growth stage: tillering, stem elongation, and heading.

of mycorrhiza and bacteria inoculation on plant growth have been demonstrated by Boldt-Burisch et al. (2018). With P fertilization, plant biomass and the P uptake in plants were higher from the onset, i.e., maize accumulates more P and invests it mainly in shoots, where it is stored (for example, in the storage lipids). At the maize heading stage, the lower P demand (the plants have already become established and switch their resource allocation to aboveground tissues) probably explains the suppression of PHO activity after P fertilization compared to unfertilized plants.

4.3 Plasticity of root traits

The present study empirically demonstrates that, in the absence of root hairs (*rth3* mutant), the average diameter of fine roots (AFRD) increases to facilitate AMF colonization. This increase in *rth3* maize with growth stage, along with the significant correlation (*p* = 0.005) between AFRD and mycorrhiza, highlights the requirement for more root volume to facilitate increased colonization. Several potential benefits for hairless maize are conceivable. An increased AFRD will: (1) provide more root volume to be colonized by AMF (Reinhardt and Miller, 1990), (2) increase root longevity (Eissenstat, 1992; Comas et al., 2014), which is beneficial to maintain the active exchange of nutrients and C between AMF and roots, (3) increase the root surface area for a given unit of root length in *rth3* versus WT maize (Haling et al., 2013), and (4) reduce the metabolic costs such as root respiration in *rth3* maize (Lynch and Ho, 2005). Very recently, Wen et al. (2019) showed that PHO activity and carboxylates amount increased with increasing root diameter under soil P limitation. Such plastic responses of roots (increased AFRD and AMF colonization) are complementary to increase plant P acquisition, which is also a case in the present study. A strong contribution of AMF to shoot P uptake highlighted their importance in plant P acquisition under P limitation. The hairless mutant exhibited higher root colonization by AMF, emphasizing facilitation in the absence of root hairs, whereas the plants were less dependent on symbiotic fungi (AMF) for nutrient acquisition in the presence of root hairs. These results highlight that under P scarcity, root trait plasticity for nutrient acquisition is a common phenomenon.

5 Conclusions

Functional root traits and their plasticity are crucial for plant P uptake in P-limited soils. The absence of root hairs induced an increase in the average fine root diameter thereby promoting root mycorrhizal colonization by AMF (Fig. 5). In turn, the presence of root hairs decreased the dependency of plants on root mycorrhizal colonization for plant P acquisition. Reduced colonization after P fertilization highlighted the

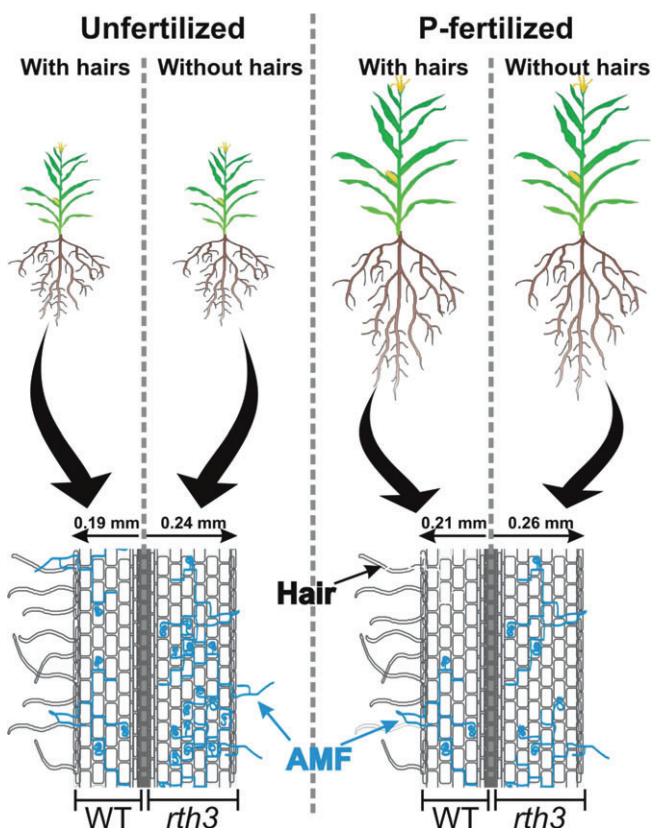


Figure 5: Illustration showing contrasting root traits in the presence (WT) and absence (*rth3*) of root hairs. When root hairs are absent, maize plants increased the average fine root diameter to facilitate root colonization by arbuscular mycorrhizal fungi to maintain P acquisition and growth.

maize plant's resource allocation by lowering trade-offs for P acquisition. Overall, maize alters its root morphology and biological traits as a nutrient acquisition strategy to maximize benefits and therefore, growth.

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