



Exogenous Nitro-Oleic Acid Treatment Inhibits Primary Root Growth by Reducing the Mitosis in the Meristem in *Arabidopsis thaliana*

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Nitric oxide (NO) is a second messenger that regulates a broad range of physiological processes in plants. NO-derived molecules called reactive nitrogen species (RNS) can react with unsaturated fatty acids generating nitrated fatty acids (NO₂-FA). NO₂-FA work as signaling molecules in mammals where production and targets have been described under different stress conditions. Recently, NO₂-FAs were detected in plants, however their role(s) on plant physiological processes is still poorly known. *Although in this work NO₂-OA has not been detected in any Arabidopsis seedling tissue, here we show that exogenous application of nitro-oleic acid (NO₂-OA) inhibits Arabidopsis primary root growth; this inhibition is not likely due to nitric oxide (NO) production or impaired auxin or cytokinin root responses. Deep analyses showed that roots incubated with NO₂-OA had a lower cell number in the division area. Although this NO₂-FA did not affect the hormonal signaling mechanisms maintaining the stem cell niche, plants incubated with NO₂-OA showed a reduction of cell division in the meristematic area. Therefore, this work shows that the exogenous application of NO₂-OA inhibits mitotic processes subsequently reducing primary root growth.*

Keywords: nitro-oleic acid treatment, nitro-fatty acid, root development, signaling, nitric oxide, Arabidopsis

HIGHLIGHT

Nitrated fatty acids regulate root development

INTRODUCTION

The formation of nitrolipids was initially proposed in animals from the observation that nitric oxide (NO) inhibited lipid oxidation propagation reactions (Rubbo et al., 1994). The nitration of fatty acids is induced by species derived from NO (Freeman et al., 2008). In animals, nitrated lipids are signaling molecules, acting as intermediaries in potent cascades of signal transduction, which translate into changes in protein functionality due to post-translational modifications (Batthyany

et al., 2006; Rubbo and Radi, 2008; Trostchansky and Rubbo, 2008; Schopfer et al., 2011). So far, there are few reports about the detection of NO₂-FA in plants. Specifically, adducts between NO₂-OA and Cys (NO₂-OA-Cys) together with nitro-conjugated linoleic acid (NO₂-cLA) were detected in olive fruits and Extra Virgin Olive Oil (EVOO) although nor free NO₂-OA was detected in olives (Fazzari et al., 2014). NO₂-OA was recently detected in the free fatty acid fraction of seeds and seedlings of *Brassica napus* (Vollár et al., 2020). Also, nitro-linolenic acid (NO₂-Ln) was observed in cell suspension cultures, seeds, seedlings and leaves of the model plant *Arabidopsis* (Mata-Pérez et al., 2016a) and in important crops such as rice and pea (Mata-Pérez et al., 2016b). Exogenous application of NO₂-Ln induced both an antioxidant response and the chaperone network in *Arabidopsis* (Mata-Pérez et al., 2016a) and NO production in *Arabidopsis* primary root tip (Mata-Pérez et al., 2016c). Exogenous application of nitro-oleic acid (NO₂-OA) induced reactive oxygen species (ROS) production *via* activation of NADPH oxidases and not NO production in tomato cell suspensions (Arruebarrena Di Palma et al., 2020). *Arabidopsis* NADPH oxidase mutants showed that NADPH isoform D (RBOHD) was required for NO₂-OA-induced ROS production in leaves (Arruebarrena Di Palma et al., 2020).

NO is a well-established second messenger in plants and is involved in the development of the root system. NO regulates processes such as the formation of root hairs in *Arabidopsis* and lettuce (*Lactuca sativa* L.) (Lombardo et al., 2006), as well as the formation of adventitious roots *via* the activation of MAPK in cucumber (*Cucumis sativus*) (Pagnussat et al., 2004). The root is divided in the meristematic/division zone, the elongation zone and the differentiation zone. The meristematic cells, a cell type with a high rate of cell division, coordinates the growth and development of the root. In *Arabidopsis*, NO targets the cells in the elongation zone, inhibiting the cellular elongation mediated by gibberellins (Fernández-Marcos et al., 2012). In addition, NO decreases the levels of the auxin transporters (PINs) in the membrane, affecting the transport and distribution of auxins and altering downstream signaling (Fernández-Marcos et al., 2011). High levels of NO inhibit the development of the primary root, reducing the meristematic zone, directly affecting mitotically active cells (Fernández-Marcos et al., 2011).

Most of the plant hormones (abscisic acid, auxins, cytokinins, ethylene, gibberellins and brassinosteroids) regulate cell division and elongation processes (Benkova and Hejatko, 2009; Wolters and Jürgens, 2009). The root stem cell niche at the root apical meristem is composed of stem cells with high rate of division given rise to specific root cells lineages, which are surrounding a group of cells with a low division rate called the quiescent center (QC) (Scheres, 2007). QC plays an important role in maintaining undifferentiated stem cells (van den Berg et al., 1997). The differentiation of daughter stem cells give rise to several cell types integrating the root architecture, being growth defined by the balance between cell division and elongation (Dolan et al., 1993; Scheres et al., 1994).

In this work we show that NO₂-OA inhibits primary root growth. This inhibition is not due to NO signaling, altered auxine/

cytokinin responses or altered mechanism that maintain the stem cell niche. Here we show that exogenous application of NO₂-OA reduces the cell cycle marker CYCB1:1, resulting in a short meristem.

RESULTS

NO₂-OA Inhibits Primary Root Growth in *Arabidopsis*

Arabidopsis seedlings present basal levels of NO₂-Ln that increase when seedlings are subjected to wounding, cadmium or low temperature stress (Mata-Pérez et al., 2016a). All major nitro lipids share the same electrophilic center, similar reactivity properties and therefore a common mechanism of action (Baker et al., 2004). In animals, NO₂-OA has long been used as a surrogate to study and understand the regulation, signaling and metabolism of nitrated fatty acids given its additional stability and well developed synthetic routes (Freeman et al., 2008). We studied the effect of exogenous application of NO₂-OA on primary root growth of *Arabidopsis* seedlings. **Figure 1** shows dose-dependent inhibition of primary root growth upon NO₂-OA treatments compared to untreated or oleic acid (OA) treated seedlings.

The inhibition of the primary root growth could be due to a lower number of cells at the apical meristem and/or a lower cell size or cell elongation rate on the elongation zone of the root. To determine the processes by which NO₂-OA is modulating root growth, we measured the size and the number of root cells in the meristem. Five-day old *Arabidopsis* seedlings were treated for another five days with NO₂-OA or OA, and the root cells were analyzed by DIC microscopy. The column of cortex cells was counted from the quiescent center (QC) to the last cell where its length was not greater than 50% compared to the previous one according to what was described in Perilli and Sabatini (2010) (**Figure 2A**). As shown in **Figure 2B** control or OA treated roots have an average of 36 ± 5 cortex cells in the division zone. NO₂-OA-treated roots have a significant reduction in the number of cortex cells (**Figure 2B**). Roots treated with 12.5 or 25 μ M of NO₂-OA showed an average of 29 ± 4 and 19 ± 4 cells, respectively. The extension of the meristematic zone was measured as the distance from the QC to the last cell of the division zone (**Figure 2C**). In control roots, the meristematic zone measures $300 \pm 44 \mu$ m, while NO₂-OA treated roots shows a strong reduction of the meristematic zone ($240 \pm 40 \mu$ m and $180 \pm 22 \mu$ m for 12.5 or 25 μ M NO₂-OA respectively). The cell size at the elongation zone was not significantly different between treated or not treated roots, being the size of cortical elongated cells 168.8 ± 2.9 , 171.3 ± 2.6 and $166.7 \pm 1.9 \mu$ m (mean \pm SE, $n = 6$) for control, OA and NO₂-OA-treated roots, respectively (**Figure 2D**). A establish balance between cell division and cell differentiation governs meristem size and thus root growth. Since no differences were found in the size of the cells in the differentiation zone, and a reduction of number of cortical cells is observed, then the inhibition of root growth is probably due to a regulation of cell division process.

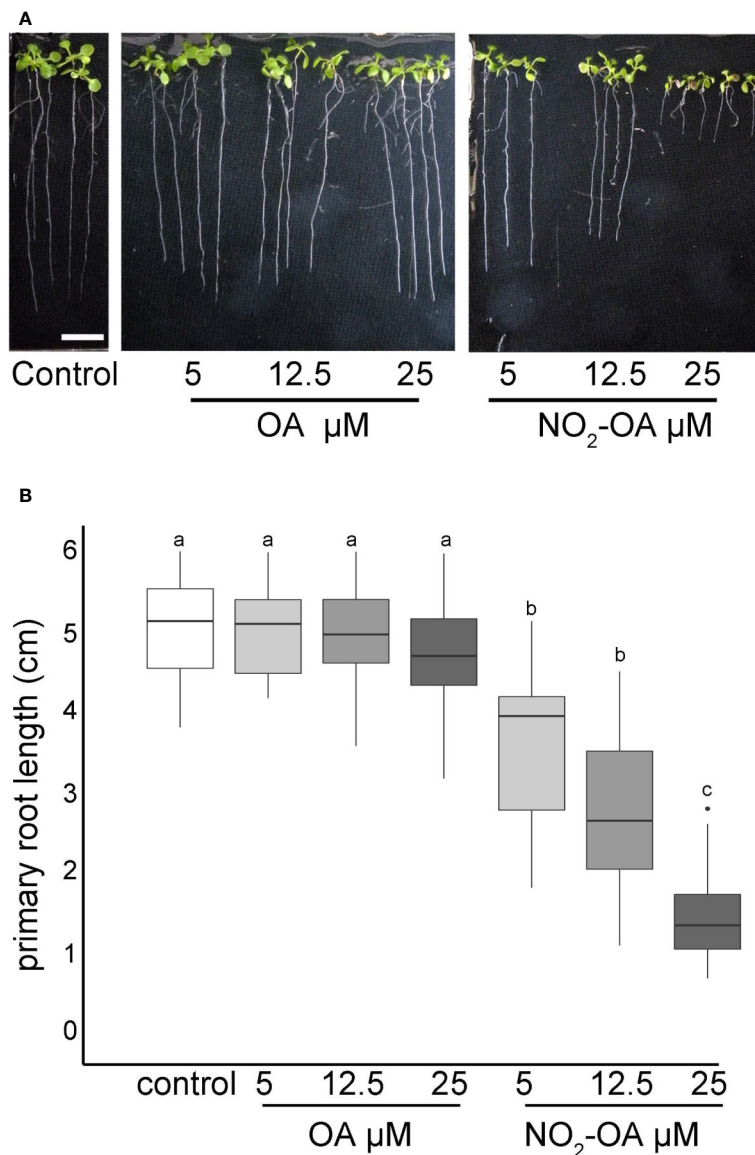


FIGURE 1 | NO₂-OA inhibits primary root growth in Arabidopsis. Seeds were germinated and vertically grown in MS agar for five days, then transferred onto plates with NO₂-OA or OA (25, 12.5 or 5 μM) during five days. **(A)** Representative image of Arabidopsis primary root growth. Scale bar = 1 cm **(B)** Primary root length quantification. Data is depicted in box-plot graphs where the box is bound by the 25th to 75th percentile, whiskers span to minimum and maximum values, and the middle line represents the average of five independent experiments. Different letters indicated statistical significant differences, $n = 25$ (ANOVA, Tukey $p < 0.001$).

It has been previously reported that NO inhibits the growth of the primary root in Arabidopsis (Fernández-Marcos et al., 2011). In addition, in Arabidopsis roots and cell suspensions, NO₂-Ln treatments induced NO production (Mata-Pérez et al., 2016c). Therefore the evidence suggested the NO₂-OA might be affecting root growth in a NO-dependent manner. However, the analysis of NO production, using the fluorescent probe DAF-FM-DA in 25 μM NO₂-OA treated roots shows no fluorescence in OA or NO₂-OA treated roots (Figure 3). We used 100 μM of the NO donor SNP as a positive control in order to confirm the functionality and distribution of the probe within the root. Figure 3 shows an intense and equally distribution of fluorescence throughout the

root tip in SNP treated roots. These results show that NO₂-OA treatment does not trigger NO production in Arabidopsis seedlings suggesting that NO₂-OA is not inhibiting primary root growth *via* NO signaling.

NO₂-OA Reduces the Number of Mitotic Cells

A reduction in the number of meristem cells could be due to a hormonal unbalance. Auxin distribution is important in regulating primary root growth. One of the described roles for auxin in the root tip is to maintain the stem cell niche and promote cell division (Grieneisen et al., 2007). In order to study

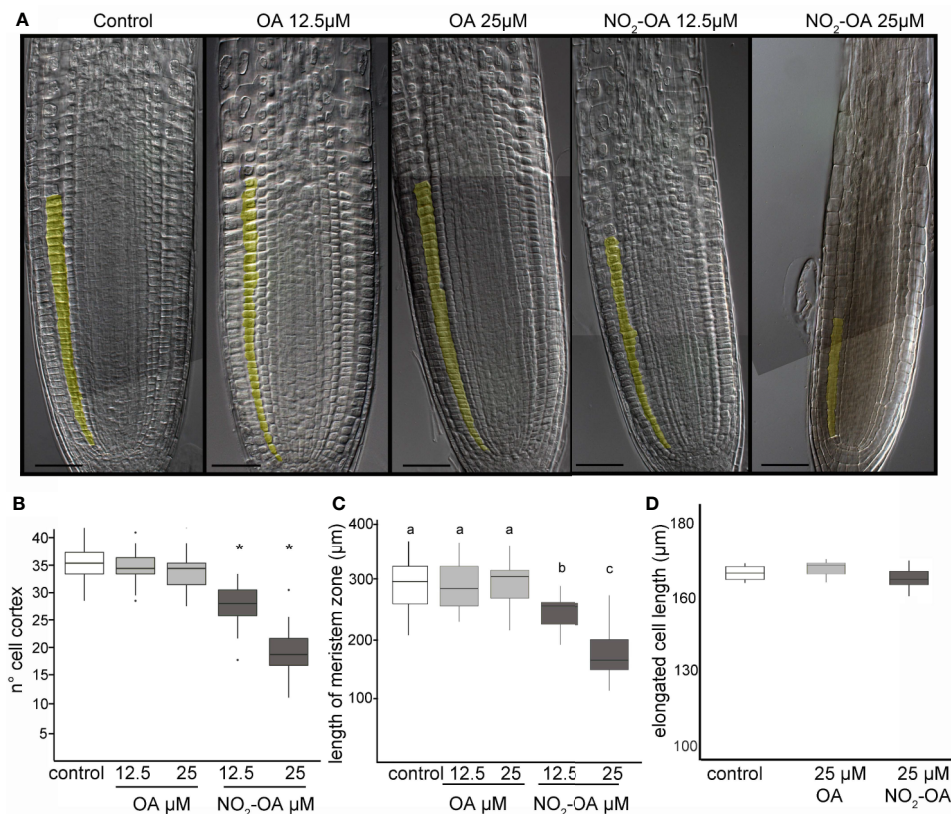


FIGURE 2 | Effect of NO₂-OA on the Arabidopsis root meristem. Five-day old seedlings were treated with NO₂-OA or OA (25, 12.5 μ M) or not treated during other five days. Roots were cleared with Hoyer's solution and observed under DIC microscope. **(A)** Images of roots from seedlings showing cortex meristem cells artificially colored. Scale bars = 10 μ m. **(B)** Meristem cell number. Asterisks indicate significant differences from control, n = 30 ($p < 0.001$, Poisson). **(C)** Size of root meristem. Different letters indicate statistically significant differences, n = 30 (ANOVA, Tukey $p < 0.001$). **(D)** Total cell size in elongation zone.

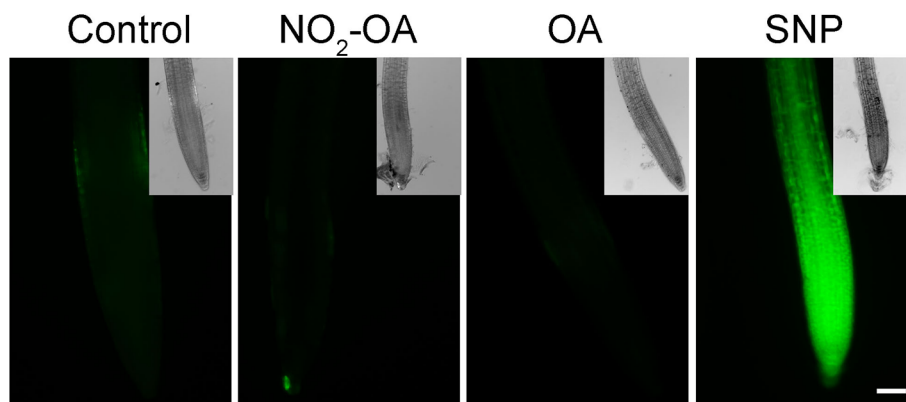


FIGURE 3 | NO₂-OA does not trigger NO accumulation on the meristematic area. Col-0 seedlings were grown for 5 days being after either not-treated or incubated with 25 μ M NO₂-OA or OA for five-extra days. Roots were incubated with DAF-FM DA 10 μ M for 30 min. As positive control for DAF-FM DA probe, roots were treated with 100 μ M SNP for 30 min. Scale bar = 10 μ m. At least 12 roots were visualized of three independent experiments.

auxin-response after NO₂-OA application, we used Arabidopsis plants with auxin response reporter *DR5pro:GUS*. *DR5pro:GUS activity is observed* in the stem cell niche, columella cells and a more subdued staining in vascular tissue in all treatments (**Figure 4A**). Therefore, this data suggests that auxin responses are not altered because of NO₂-OA application. In order to confirm the latter result, we used DII-Venus as an independent reporter that shows endogenous auxin abundance, reflecting the input into the auxin-signaling pathway. DII-Venus is a fusion of auxin-dependent degradation domain II of an Aux/IAA protein to Venus fluorescent protein, such that the absence of fluorescence marks auxin accumulation (Brunoud et al., 2012). In agreement with *DR5pro:GUS* activity, auxin levels (evidenced as the absence of fluorescence) are high in the columella, the quiescent center, and the differentiating xylem cells on control or 12.5 μM NO₂-OA or OA treated roots (**Figure 4B**). In the meristem zone, from QC to TZ, auxin levels are low in control and OA treated roots, visualized as an intense fluorescence of the DII-Venus protein in the nuclei of the cortex and epidermal cells (**Figure 4B**). However, when we quantified the fluorescence intensity, NO₂-OA treated roots showed less fluorescence compared to OA or non-treated roots (**Figure 4C**), suggesting an increase in auxin level. However, exogenous application of auxin to wild-type *Arabidopsis* roots caused an increase in meristem size (Dello Ioio et al., 2007), which is in contraposition to the observed effect that NO₂-OA has on root growth. Thus, we cannot discard other explanations for a slight reduction on the fluorescence levels of DII-Venus in NO₂-OA treated root cells, especially since DII-Venus is a semiquantitative reporter. Despite that fact, both auxin reporters, *DR5pro:GUS* and DII-Venus, unequivocally show that NO₂-OA does not decrease auxin levels at the stem cells, columella or vascular tissue. Thus, auxin responses (**Figure 4A**) and levels (**Figures 4B, C**) are not altered during NO₂-OA application on stem cells, columella and the differentiating vascular cells.

The role of auxins in root growth is associated with that of their hormone antagonists, cytokinins. It has been described that the size of root apical meristem increases in mutants from the cytokinin synthetic pathway and decreases by the exogenous application of cytokinins (Miyawaki et al., 2004; Dello Ioio et al., 2007). We studied the cytokinin response with the cytokinin reporter *TCS : GFP* using confocal microscopy (Zürcher et al., 2013; Zürcher et al., 2016) Under control conditions, *TCS : GFP* is observed at the root tip, particularly in the calyptra (**Figure 4D**). The roots treated with NO₂-OA or OA did not show differences relative to the control (**Figure 4E**). Altogether the results show that the reduction of meristematic cells in NO₂-OA treated roots is independent of auxin or cytokinin responses.

Meristematic cells come from stem cells. Stem cells are in a microenvironment, where hormone concentrations and transcription factors play a fundamental role for its maintenance. The root stem cell niches, is formed by the QC and the adjacent stem cell initials (Petricka et al., 2012), which are specified by two parallel pathways: the PLETHORA (PLT) and SHORTROOT (SHR)/SCARECROW (SCR) pathways

(Petricka et al., 2012; Heyman et al., 2014). SCR maintains QC and stem cell identity (Sabatini et al., 2003), in part by inducing the expression of WUSCHEL-RELATED HOMEBOX5 (WOX5), a QC specific gene (Sarkar et al., 2007). Two types of transcription factors have been well studied regarding the preservation of undifferentiated stem cells, PLETHORA 1 (*PLT1*, at3g20840) and PLETHORA 2 (*PLT2*, at1g51190) (Aida et al., 2004; Galinha et al., 2007; Mähönen et al., 2014). High levels of these PLT genes localize in the area of cell division, whilst low PLT levels lead root cells to expand and differentiate. The presence and distribution of PLT factors in the root tip regulate the size of the meristem (Aida et al., 2004; Kornet and Scheres, 2009; Mähönen et al., 2014). The expression of *PLT1* and *PLT2* has been reported to colocalize with the location of auxin in the root tip (Aida et al., 2004; Xu et al., 2006). In order to determine if NO₂-OA affects stem cells and QC, independent transgenic lines with the transcriptional fusion reporters *proPLT1-CFP*, *proPLT2-CFP* or *proWOX5-GFP* and the translational fusion reporter *proPLT1:PLT-YFP* were treated with NO₂-OA or OA. As seen in **Figure 4F** (*PLT1* promoter activity) and **Figure 4H** (*PLT1* protein levels), untreated seedlings shows the highest level of *PLT1* expression in the QC and stem cells, gradually decreasing the intensity in the meristematic area. No differences were observed in this expression pattern for NO₂-OA-treated roots (**Figures 4G, I**). In the case of the transcription factor *PLT2* the expression is restricted to the QC, showing no changes in any of the treatments (**Supplemental Figure 1**). We analyzed the expression of QC marker *proWOX5-GFP* (Sarkar et al., 2007) and we observed the same expression pattern in NO₂-OA compared to OA or non-treated roots (**Figures 4J, K**). These results show that the expression of PLT and WOX5 are not affected in roots treated with NO₂-OA, indicating that NO₂-FA does not affect the signaling mechanisms related to stem cell niche maintenance.

A reduction in the number of cells in the meristematic zone indicates that the process of cell division is likely to be affected, and consequently the number of cells in mitosis is reduced. To confirm this, we use transgenic plants with the transcriptional fusion reporter *proCYCB1.1-GUS* construct. *Cyclin B1.1* (*CYCB1.1*) is an enzyme that belongs to the cyclin family and it is expressed in the G2/M (Colón-Carmona et al., 1999). **Figure 5** shows a significant reduction on the number of cells in mitosis in NO₂-OA treated roots with respect to control or OA treated roots, indicating the NO₂-OA is affecting cell division pace at the meristematic zone.

DISCUSSION

Nitrated fatty acids are well-described signaling molecules in animals (Batthyany et al., 2006; Freeman et al., 2008; Rubbo and Radi, 2008; Trostchansky and Rubbo, 2008; Schopfer et al., 2011). Detection of NO₂-FA in plants was reported in Arabidopsis, pea, rice, and olives (Fazzari et al., 2014; Mata-Pérez et al., 2016a; Mata-Pérez et al., 2016b). Our study focused

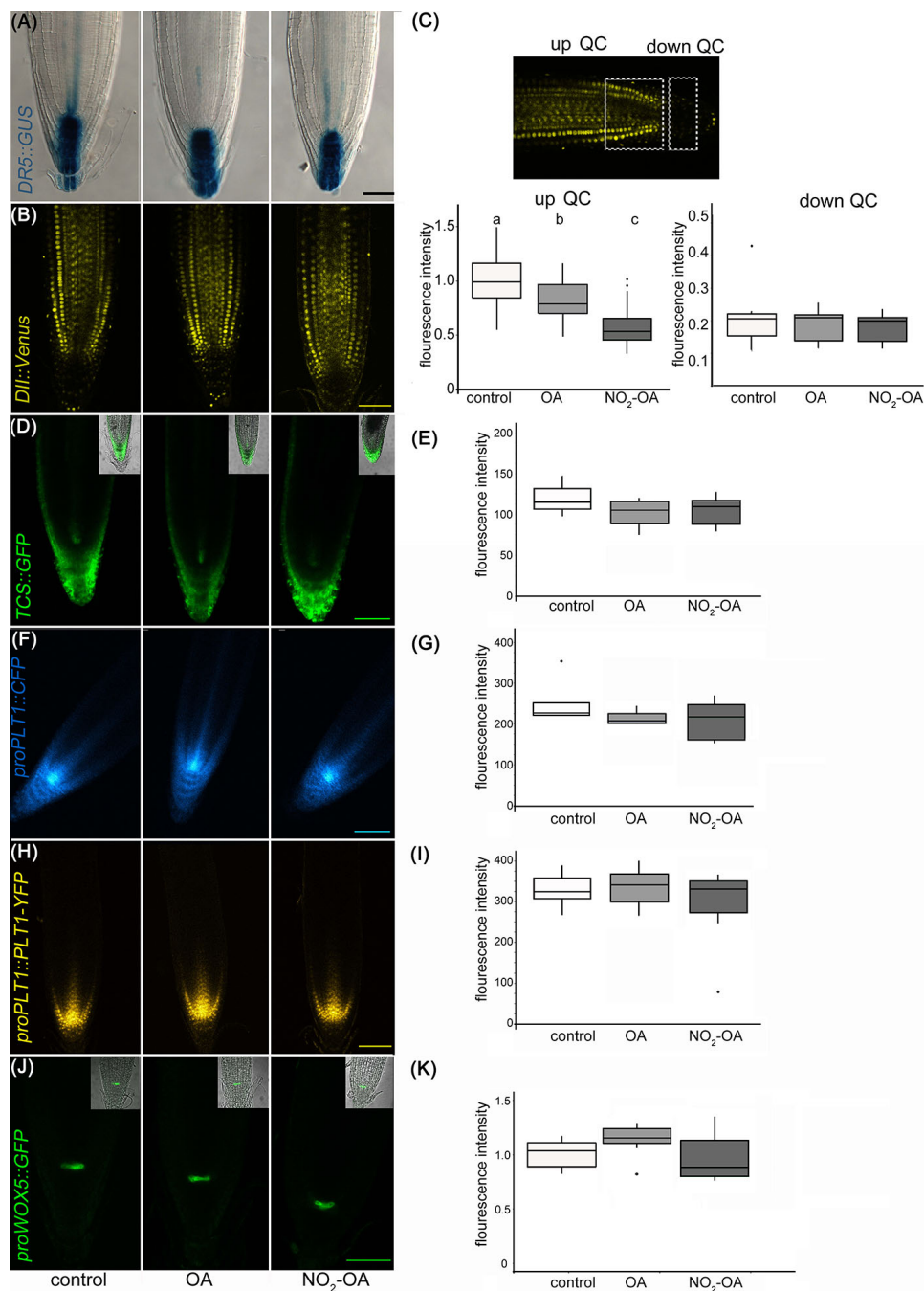
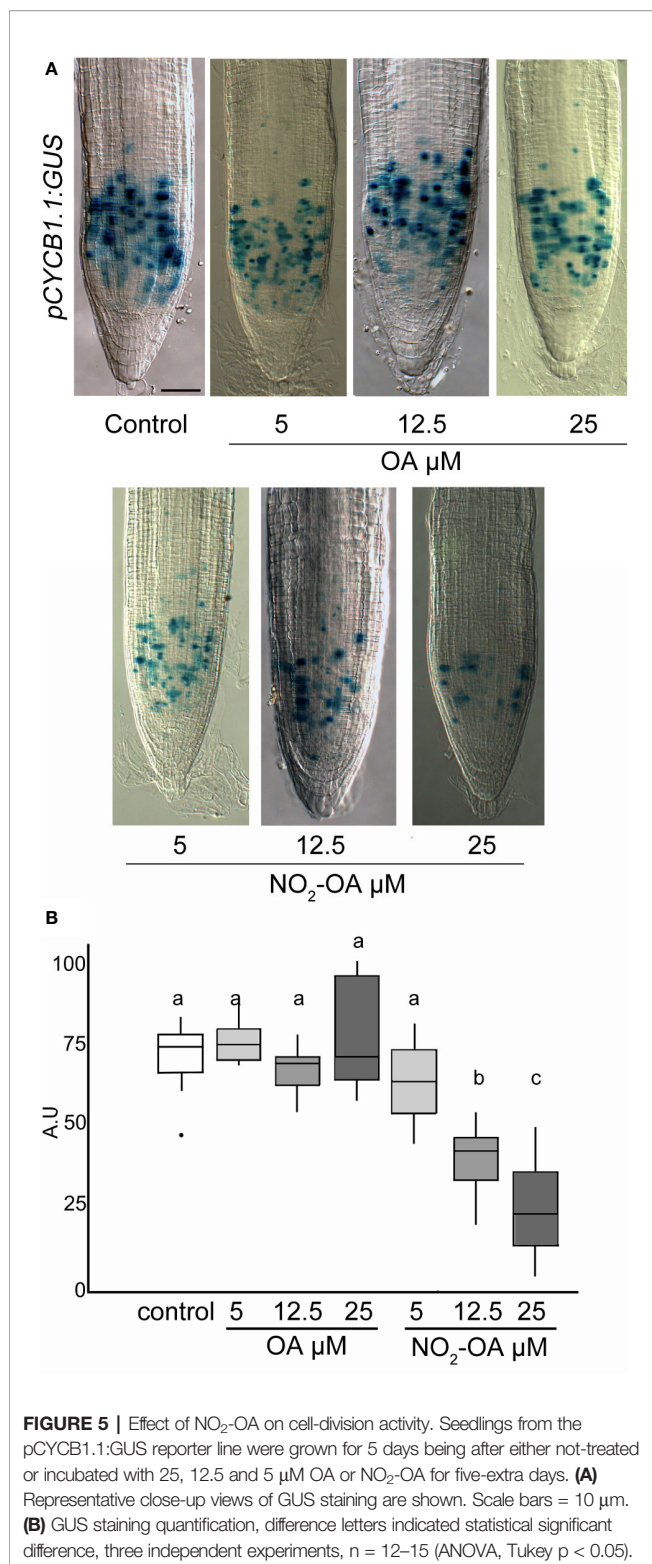


FIGURE 4 | Effect of $\text{NO}_2\text{-OA}$ on hormonal signaling. Seedlings from different reporter lines were grown for 5 days being after either not-treated or incubated with $12.5 \mu\text{M}$ OA or $\text{NO}_2\text{-OA}$ for five-extra days. Representative images are shown. **(A)** Close-up view of GUS staining in $DR5_{pro}::GUS$ seedlings. At least 15 roots were visualized of three independent experiments. **(B)** Confocal images of seedlings with the $Dil1::Venus$ reporter line. **(C)** Fluorescence intensity measured at two different root zones, up which includes the QC or down quiescent center. At least 12 roots were visualized of three independent experiments. Difference letters indicate statistical significant difference (one way ANOVA, *post hoc* Tukey $p < 0.05$). **(D)** Confocal images of seedlings with the $TCS::GFP$ reporter line. **(E)** Fluorescence intensity measured from at least 12 roots from three independent experiments (one way ANOVA, *post hoc* Tukey $p < 0.05$). **(F)** Confocal images of seedlings with the $proPLT1::CFP$ reporter line. **(G)** Fluorescence intensity measured from at least 12 roots from three independent experiments (one way ANOVA, *post hoc* Tukey $p < 0.05$). **(H)** Confocal images of seedlings with the $proPLT1::PLT1-YFP$ reporter line seedlings. **(I)** Fluorescence intensity measured from at least 12 roots from three independent experiments (one way ANOVA, *post hoc* Tukey $p < 0.05$). **(J)** Confocal images of seedlings of $proWOX5::GFP$ reporter line. **(K)** Fluorescence intensity measured from at least 10 roots from two independent experiments (one way ANOVA, *post hoc* Tukey $p < 0.05$). Scale bars = $10 \mu\text{m}$. The fluorescence signal intensities were quantified by using Fiji software in all the experiments. For all markers we used the same ROI (size and shape) to analyze all images of the respective experiment.



on evaluating the role of a prototypical NO₂-FA on Arabidopsis thaliana root development. Even though, in one hand, NO₂-OA has not been detected in Arabidopsis thaliana either by Mata-Pérez (2016a) and coworkers nor in this paper and, in the other

hand, the precursor of this NO₂-FA (oleic acid, OA) is a minority with regard the rest of unsaturated fatty acids detected along the different stages of development in Arabidopsis (**Supplemental Figure S1**, Mata-Pérez et al., 2016a), we decided to emulate the approach used in mammals by using the exogenous application of NO₂-OA, allowing us to reduce the complexity of the study and focus on its functional aspects. As mentioned earlier, in animals, NO₂-OA has long been used as a surrogate to study and understand the regulation, signaling, and metabolism of NO₂-FA given its additional stability and well developed synthetic routes (Freeman et al., 2008). The isomers of NO₂-OA used in our experiments have been extensively characterized and correspond to an equal proportion of the 9-NO₂-OA and 10-NO₂-OA species (Woodcock et al., 2013). Exogenous application of NO₂-OA for functional studies has already been used and reported in plants. In Arabidopsis, while NO₂-OA has not been detected, exogenous application of NO₂-OA regulates the expression of specific genes as demonstrated by qRT-PCR analysis (Mata-Pérez et al., 2016a). Moreover, in tomato and Arabidopsis, the exogenous treatment with NO₂-OA triggers ROS production *via* NADPH oxidase activation (Arruebarrena Di Palma et al., 2020). We acknowledge the limitations of studying NO₂-OA in Arabidopsis root development, as it has not been detected in the free fatty acid fraction in Arabidopsis seedlings (Mata-Pérez et al., 2016a). Nevertheless, the detection of free acid NO₂-OA has been challenging as it rapidly adducts to thiol-containing proteins and glutathione, as demonstrated in mice plasma (Rudolph et al., 2010). This concept is further supported by studies in olives, where NO₂-OA was found conjugated to proteins and not in the free fatty acid fraction (Fazzari et al., 2014). Recently, NO₂-OA was detected in the free fatty acid fraction of Brassica seeds and seedlings, further supporting their formation and important role in plant physiology (Vollár et al., 2020). The discovery of the formation of NO₂-Ln in Arabidopsis seeds and seedlings and the detection of NO₂-OA in Brassica supports the concept of NO₂-FA as a class of signaling species in plants (Mata-Pérez et al., 2016a; Vollár et al., 2020). It is in this context that our findings of the exogenous treatment with NO₂-OA on root development gain relevance, suggesting that NO₂-FAs have common important formation pathways and roles in seeds and seedlings in different plant species. However, the lack of endogenous detection of NO₂-OA in Arabidopsis, together with the low abundance of its precursor (oleic acid, OA) with regard the rest of the unsaturated fatty acids detected in Arabidopsis seedlings (**Supplemental Figure S1**, Mata-Pérez et al., 2016a), remains a major stumbling block in defining the role of NO₂-OA in Arabidopsis.

Here we show that exogenous application of NO₂-OA inhibits the growth of the primary root in Arabidopsis. The study of different root areas showed that cell size in the elongation-differentiation zone is not affected by NO₂-OA. On the other hand, roots treated with NO₂-OA showed a reduction in the size of the division zone. The total number of cortex cells and the total size of the meristematic area are reduced in roots treated

with NO₂-OA, indicating that the process of cell division is affected. The existing bibliography on the biological effects of Nitro Fatty acid in plants, suggest that they are acting as NO donors. In tomato cell suspensions, the exogenous treatment with NO₂-OA was unable to induce NO production (Arruebarrena Di Palma et al., 2020). Interestingly, under our experimental conditions, NO₂-OA is not affecting endogenous NO levels in Arabidopsis seedlings, indication that the inhibition of primary root growth by NO₂-OA does not involve a NO dependent signaling.

Root growth is controlled by cell division and cell elongation rates. Both processes are strongly regulated by hormones, mainly auxins and cytokinins. Although auxins strongly control root growth, it has been shown that the interaction between these two signals is relevant for proper development (Dello Ioio et al., 2008). Auxins help to promote cell division and maintain the niche of stem cells and promote cytokinin biosynthesis, which consequently favors cell elongation and differentiation (Miyawaki et al., 2004; Dello Ioio et al., 2007; Dello Ioio et al., 2008). There is a strong relationship between auxin signaling and NO in root development. Mutants with low endogenous NO levels such as *nia1nia2* and *noa1* have lower auxin endogenous concentration (Sanz et al., 2014). However, NO inhibits the transport of auxins from the stem apical meristem to the root apical meristem (Fernández-Marcos et al., 2011). The inhibitory effect on root growth by NO is related to the inhibition of the signaling cascade caused by auxins, since the reduction in *DR5:GUS* reporter activity is seen in the root tip, as a consequence of lower levels of expression of PIN1 proteins (Fernández-Marcos et al., 2011). Our results show that the exogenous treatment with NO₂-OA has an inhibitory effect on primary root growth and is not due to an unbalance in auxin or cytokinin levels. This further supports the idea that the effect of NO₂-OA on root growth is different than that reported for NO donors. An RNAseq analysis of Arabidopsis cells treated with NO₂-Ln, showed expression regulation of a large number of genes, but none of them related to signaling mediated by auxins or cytokinins (Mata-Pérez et al., 2016a). Consistently, our results show that NO₂-OA does not affect auxins or cytokinins signaling.

Since the meristematic area is reduced, we studied the possibility that NO₂-OA could affect the stem cell niche. To do so, we used the transcriptional *proPLT1:CFP*, *proPLT2:CFP* and the translational *proPLT1:PLT1-CFP* constructions considering PLT are transcription factors essential for QC identity and stem cell activity. The PLT genes are transcribed in response to auxin accumulation and are dependent on auxin response transcription factors. There is a correlation between PLT levels and root location, showing high levels in the division area, moderate in the transition zone and low levels in the elongation/differentiation side (Aida et al., 2004; Galinha et al., 2007). The expression levels of *PLT1* and *PLT2* are related to the size of the meristem. The double mutant *plt1-4;plt2-2* showed a reduction in the size of the meristem and short primary root. On the other hand, overexpression of *PLT2* showed an increase in the size of the meristem, particularly due to an increase in the number of cells (Aida et al., 2004; Kornet and Scheres, 2009; Mähönen et al., 2014). The expression of PLT is strongly related

to cell division and the inhibition of differentiation since the expression of *PLT2* in epidermal cells inhibits the formation of root hairs (Mähönen et al., 2014). Although there is a strong correlation between *PLT1* and *PLT2* and auxin levels (Galinha et al., 2007), there is no decrease of *DR5:GUS* reporter activity in the *plt1-4; plt2-2* double mutant (Aida et al., 2004; Kornet and Scheres, 2009). Roots treated with NO₂-OA had shorter meristem and a lower number of cells, but this was not due to altered levels in terms of expression or location of *PLT1/2*. In addition, we studied the localization of the QC transcription factor *WOX5*. *WOX5* maintains stem cells in Arabidopsis roots (Sarkar et al., 2007). *WOX5* expression was not affected by NO₂-OA treatment. Visualization of *PLT1*, *PLT2* and *WOX5* allowed us to discard the effect of NO₂-OA treatment on those transcription factors. Together these experiments suggest that the auxin and cytokinin balance and the transcription factors *PLT1*, *PLT2* and *WOX5*, which are necessary for the development and maintenance of the stem cell niche, are not affected by NO₂-OA treatments. Based on the observed results in which the division area is affected but not the elongation zone, QC or stem cells, we can conclude that NO₂-OA has a selective effect on the process of cell division.

The *CyclinB1.1* gene codifies to a mitotic cyclin. The transcription of *CycB1.1* is associated with the G2 and M phase and is a marker for active cell division (Ferreira et al., 1994b). The construction of promoter region of *CycB1.1* fused with *GUS* is widely used to study particularly mitotic cell in different plant tissue (Colón-Carmona et al., 1999; Burssens et al., 2000). The results obtained with the *pCYCB1.1-GUS* confirm that NO₂-OA inhibits cell division process in a dose-dependent manner.

Nitrolipids are weak electrophiles that can bind covalently to cysteine or histidine residues of protein by Michael addition and modify stability or function of proteins (Batthyany et al., 2006; Baker et al., 2007). In animal few proteins have been described to be modified by NO₂-FA, being most of them related to anti-inflammatory processes, such as the Nuclear factor (erythroid-derived 2) -like 2 (Nrf2), peroxisome proliferator-activated receptor- γ (PPAR γ) and nuclear factor-kappa B (NF- κ B) (Cui et al., 2006; Li et al., 2008; Kansanen et al., 2011). In plants, post-translational modifications mediated by NO₂-FA were, so far, only reported for APX (Aranda-Caño et al., 2019). In the same review by Aranda-Caño, the authors mention that they identified a high number of nitroalkylated proteins that increase in cell cultures treated with NO₂-Ln. Since, it has been described that defects in the dynamics of the ACTIN cytoskeleton produce different phenotypes in root hairs and primary root (Gilliland et al., 2002; Yi et al., 2005; Kandasamy et al., 2009), it would be interesting to study whether actine can be post-translational modified by NO₂-FA. For instance, recent studies show that the post-translational modification by S-Sulfhydration of ACT2, ACT7 and ACT8 proteins modifies the dynamics of the cytoskeleton, decreasing the levels of the filamentous with respect to the globular form of the protein causing inhibition in the growth of the primary root as well as in the length of root hairs (Li et al., 2018). In the present paper we show that exogenous treatment with NO₂-OA has physiological effects on

root development and, specifically, in the process of cell division in the meristematic zone. Further research will be needed to elucidate the endogenous presence of NO₂-OA in Arabidopsis seedlings in order to establish how this NO₂-FA interfere with cell division by affecting, directly, the order of actin or actin filaments, or through the regulation of other cell cycle regulating proteins.

Here we show that exogenous application of NO₂-OA inhibits Arabidopsis primary root growth, inhibiting cell division in the meristematic area, probably by interfering with mitotic processes.

MATERIALS AND METHODS

Chemicals and Reagents

OA was purchased from Nu-Chek Prep (Elysian, MN). NO₂-OA was synthesized and purified as previously described (Bonacci et al., 2011; Woodcock et al., 2013).

Plant Material and Growth Conditions

Seeds from wild type Arabidopsis (*Arabidopsis thaliana Col-0*), *pCYCB1;1:GUS* (Colón-Carmona et al., 1999), *TCS : GFP* (Zürcher et al., 2013), *DR5_{pro}:GUS* (Ulmasov et al., 1997), *PLT1_{pro}:PLT1-YFP*, *PLT1_{pro}:CFP*, and *PLT2_{pro}:CFP* (Galinha et al., 2007), *CYCB1;1_{pro}:GUS* (Colón-Carmona et al., 1999), *WOX5_{pro}:GFP* (Sarkar et al., 2007) and *DII-Venus* (Brunoud et al., 2012) were surface sterilized in 35% sodium hypochlorite, stratified for 48 h at 4°C in darkness. Seeds were germinated on vertically oriented plates containing 0.5× Murashige and Skoog (MS) salt mixture with Gamborg's vitamins pH 5.7 and 0.8% agar, and grown at 25°C using a 16-h-light/8-h-dark photoperiod.

Seedling Treatments

Five-days old seedlings were transferred onto plates containing Murashige and Skoog (MS) salt mixture with Gamborg's vitamins pH 5.7 and 0.8% agar, and grown at 25°C using a 16-h-light/8-h-dark photoperiod with OA, NO₂-OA or non-treated for other five days. Stock solutions of NO₂-OA and OA were made fresh in sterile water (on glass containers) to reduce exposure of seedlings to solvents. Given that 50% of NO₂-OA is immediately absorbed in the glass during aqueous stock preparation (Arruebarrena Di Palma et al., 2020), stocks solutions were made at double the concentration indicated for each treatment. Then the lipids were applied to sterile MS agar, when the media was just about to get solid, and then pour on plastic plates.

Measurement of Primary Root Length, Meristem Length and Cell Size

Root length and meristem length were assessed in at least five independent experiments. Primary root length was measured using the software analysis package Fiji. For statistical, we used R software, we applied one-way ANOVA and Tukey's multiple comparison test for the experiments.

To measure number of cortex cells, meristem length and cell size, seedlings were fixed in Hoyer's solution for 30 min. The material was observed on a Zeiss Axioplan imaging 2 microscope under DIC optics. We used Poisson's test for the experiment. Images were captured on an AxioCam HRC CCD camera (Zeiss) using the Axiovision program (version 4.2). Images analysis was performed using software package Fiji. The size of elongated cells were measured on two cells per root, on cells immediately before to the first root hair cell on six individuals per treatment.

Nitric Oxide Detection on Roots

Five-days old seedlings were transferred onto plates containing Murashige and Skoog (MS) salt mixture with Gamborg's vitamins pH 5.7 and 0.8% agar, and grown at 25°C using a 16-h-light/8-h-dark photoperiod with 25 μM OA or NO₂-OA or non-treated for other five days. Arabidopsis-treated roots were incubated in the presence of 10 μM of the fluorescent probe 4-aminomethyl-2',7'-difluorofluorescein diacetate (DAF-FM DA) for 30 min. Roots were visualized under epifluorescence microscopy (Ex/Em wavelengths 495/515 nm). As positive control for DAF-FM DA probe, roots were treated with 100 μM SNP for 30 min.

β-Glucuronidase (GUS) Expression

For GUS staining, Arabidopsis treated roots were incubated in GUS-staining buffer [5 mM EDTA, 0.1% Triton X-100, 5 mM K₄Fe(CN)₆, 0.5 mM K₃Fe(CN)₆, and 1 mg/ml X-Gluc (Rose Scientific) in 50 mM NaPi buffer, pH 7.0] for 3 h at 37°C. Then the tissue was cleared with Hoyer's solution for 30 min. The material was observed on a Zeiss Axioplan imaging 2 microscope under DIC optics. Images were captured on an AxioCam HRC CCD camera (Zeiss) using the Axiovision program (version 4.2). GUS staining was measure using Fiji software (Béziat et al., 2017), we defined a ROI to analyze all images of the respective experiment as described by Feraru et al. (2019).

Confocal Microscopy

Plant materials used in this study were previously described: *PLT1_{pro}:PLT1-YFP*, *PLT1_{pro}:CFP*, and *PLT2_{pro}:CFP* (Galinha et al., 2007), *CYCB1;1_{pro}:GUS* (Colón-Carmona et al., 1999), *WOX5_{pro}:GFP* (Sarkar et al., 2007) and *DII-Venus* (Brunoud et al., 2012).

Arabidopsis roots from *pPLT1:CFP* y *pPLT2:CFP* transgenic plants were observed in confocal microscopy (Nikon Eclipse C1 Plus Ex/Em, 458/515).

Arabidopsis roots from *TCS : GFP* transgenic plants and *WOX5_{pro}:GFP* were observed in confocal microscopy (Nikon Eclipse C1 Plus Ex/Em, 488/561) and quantified using Fiji software. We defined a ROI in the region that showed the most representative signal distribution. We used the same ROI (size and shape) to analyze all images of the respective experiment.

Arabidopsis root from *PLT1_{pro}:PLT1-YFP* and *DII-Venus* were observed in confocal microscopy (Nikon Eclipse C1 Plus Ex/Em, 514/550). For *DII-Venus* marker we define two sections of the root, down QC is the calyptra zone, and up QC is the

region above QC including QC, SCN (stem-cell niche) and a portion of meristem as indicated in **Figure 4**. We used the same ROI (size and shape) to analyze all images of the respective experiment.

PLT1pro:CFP, PLT1pro:PLT1-YFP and PLT2pro:CFP fluorescence was measured using Fiji software as described by Ercoli et al. (2018).

Data Analysis

We used R software for all data analysis. The most representative images are shown throughout the article.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

AL and LF conceived the project. LF performed most of the experiment and analyzed the data. LF and IC performed all the confocal experiments, imaging processing and analyzing. FS and SS provide the NO₂-OA and all the knowledge for exogenous application of the lipid. CG-M, AL, and FS designed and supervised the experiments and analyzed the data. LF and AL wrote the article with contributions of all the authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fpls.2020.01059/full#supplementary-material>

SUPPLEMENTAL FIGURE S1 | Effect of NO₂-OA on the expression of PLT2 transcription factor in Arabidopsis roots. Seedling of proPLT2::CFP reporter line were grown for 5 days and then treated with NO₂-OA or OA (12.5 μ M) or not treated during other five days. Representative confocal images are shown. Fluorescence intensity measured from at least 12 roots from 3 independent experiments. Scale bars = 10 μ m.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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